Hidden Costs of Energy:
Unpriced Consequences of Energy Production and Use

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use

Committee on Health, Environmental, and Other External Costs and Benefits of
Energy Production and Consumption

Board on Environmental Studies and Toxicology

Division on Earth and Life Studies

Board on Energy and Environmental Systems

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[1]Resigned August 2, 2009 to accept appointment as administrator of the U.S. Energy Information Administration.

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Preface

  The U.S. Congress directed the U.S. Department of the Treasury to arrange for a review by the National Academy of Sciences to define and evaluate the health, environmental, security, and infrastructural external costs and benefits associated with the production and consumption of energy—costs and benefits that are not or may not be fully incorporated into the market price of energy, into the federal tax or fee, or into other applicable revenue measures related to production and consumption of energy.

  In response, the National Research Council established the Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption, which prepared this report. Biographic information on the committee members is presented in Appendix A.

  In the course of preparing this report, the committee met six times. At two of the meetings, oral presentations were made by the following individuals at the invitation of the committee: Christopher Miller (staff for U.S. Senator Harry Reid); Mark Heil and John Worth (U.S. Department of the Treasury); Raymond Braitsch, Thomas Grahame, and Robert Marlay (U.S. Department of Energy); Robert Brenner and James Democker (U.S. Environmental Protection Agency); Arthur Rypinski (U.S. Department of Transportation); Nicholas Muller (Middlebury College), and Richard Tol (Economic and Social Research Institute, Dublin, Ireland). Interested members of the public at large were also given an opportunity to speak on these occasions. Subsequently, the committee held two teleconferences and one subgroup meeting to complete its deliberations.

  In addition to the information from those presentations, the committee made use of peer-reviewed scientific literature, government agency reports, and databases.

  This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following for their review of this report: David T. Allen, University of Texas, Austin; William F. Banholzer, the Dow Chemical Company; Eric J. Barron, National Center for Atmospheric Research; Donald Boesch, University of Maryland; Dallas Burtraw, Resources for the Future; Douglas M. Chapin, MPR Associates, Inc.; A. Myrick Freeman, III, Professor Emeritus, Bowdoin College; Charles H. Goodman, Southern Company Services, Inc. (retired); Dale W Jorgenson, Harvard University; Nathaniel Keohane, Environmental Defense Fund; Jonathan I. Levy, Harvard School of Public Health; Erik Lichtenberg, University of Maryland; Robert O. Mendelsohn, Yale University; Armistead Russell, Georgia Institute of Technology; Kumares C. Sinha, Purdue University; Kerry Smith, Arizona State University; Kirk R. Smith, University of California, Berkeley; Susan Tierney, Analysis Group; and Michael Walsh, Independent Consultant.

  Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lawrence T. Papay, Science

Applications International Corporation (retired) and Charles E. Phelps, University of Rochester. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the author committee and the institution.

We wish to thank Eric Barron (National Center for Atmospheric Research) and Robert Stavins (Harvard University) for their service as members of the committee during the early stages of this study; they resigned from the committee for personal reasons.

Ronnie Brodsky (University of Maryland) and Paulina Jaramillo and Constantine Samaras (both of Carnegie Mellon University) helped with information gathering and literature reviews. Joseph Maher (Resources for the Future) assisted in data analysis and in developing report illustrations.

The committee's work was assisted by staff of the National Research Council's Board on Environmental Studies and Toxicology (BEST); the Board on Energy and Environmental Systems (BEES); and the Board on Science, Technology, and Economic Policy (STEP). We wish to thank Raymond Wassel, project director, and James Reisa (director of BEST) Steve Merrill (director of STEP) and James Zucchetto (director of BEES). Scientific and technical information was provided by David Policansky, Keegan Sawyer, Patrick Baur, Alan Crane, Leah Nichols, Duncan Brown, and Mirsada Karalic-Loncarevic. Logistical support was provided by John Brown and Daniel Mullins. Steve Marcus served as editor. Ruth Crossgrove was the senior editor and Radiah Rose was senior editorial assistant.

Jared Cohon, *Chair*
Committee on Health, Environmental, and Other
External Costs and Benefits of Energy Production
and Consumption

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Summary

Modern civilization is heavily dependent on energy from sources such as coal, petroleum, and natural gas. Yet, despite energy's many benefits, most of which are reflected in energy market prices, the production, distribution, and use of energy also cause negative effects. Beneficial or negative effects that are not reflected in energy market prices are termed "external effects" by economists. In the absence of government intervention, external effects associated with energy production and use are generally not taken into account in decision making.

When prices do not adequately reflect them, the monetary value assigned to benefits or adverse effects (referred to as damages) are "hidden" in the sense that government and other decision makers, such as electric utility managers, may not recognize the full costs of their actions. When market failures like this occur, there may be a case for government interventions in the form of regulations, taxes, fees, tradable permits or other instruments that will motivate such recognition.

Recognizing the significance of the external effects of energy, Congress requested this study in the Energy Policy Act of 2005 and later directed the Department of the Treasury to fund it under the Consolidated Appropriations Act of 2008. The National Research Council committee formed to carry out the study was asked to define and evaluate key external costs and benefits—related to health, environment, security, and infrastructure—that are associated with the production, distribution, and use of energy but not reflected in market prices or fully addressed by current government policy. The committee was not asked, however, to recommend specific strategies for addressing such costs because policy judgments that transcend scientific and technological considerations—and exceed the committee's mandate—would necessarily be involved.

The committee studied energy technologies that constitute the largest portion of the U.S. energy system or that represent energy sources showing substantial increases (>20%) in consumption over the past several years. We evaluated each of these technologies over their entire life cycles—from fuel extraction to energy production, distribution, and use to disposal of waste products—and considered the external effects at each stage.

Estimating the damages associated with external effects was a multistep process, with most steps entailing assumptions and their associated uncertainties. Our method, based on the "damage function approach," started with estimates of burdens (such as air-pollutant emissions or water-pollutant discharges). Using mathematical models, we then estimated these burdens' resultant ambient concentrations as well the ensuing exposures. The exposures were then associated with consequent effects, to which we attached monetary values in order to produce damage estimates. One of the ways economists assign monetary values to energy-related adverse effects is to study people's preferences for reducing those effects. The process of placing monetary values on these impacts is analogous to determining the price people are willing to pay for commercial products. We applied these methods to a year close to the present (2005) for which data were available, and also to a future year (2030) so as to gauge the impacts of possible changes in technology.

A key requisite to applying our methods was determining which policy-relevant effects are truly external, as defined by economists. For example, increased food prices caused by the conversion of

agricultural land from food to biofuel production, are *not* considered to represent an external cost, as they result from (presumably properly functioning) markets. Higher food prices may of course raise important social concerns and may thus be an issue for policy makers, but because they do not constitute an external cost they were not included in the study.

Based on the results of external-cost studies published in the 1990s, we focused especially on air pollution. In particular, we evaluated effects related to emissions of particulate matter (PM), sulfur dioxide (SO_2), and oxides of nitrogen (NO_x), which form criteria air pollutants.[1] We monetized effects of those pollutants on human health, grain crop and timber yields, building materials, recreation, and visibility of outdoor vistas. Health damages, which include premature mortality and morbidity (such as chronic bronchitis and asthma), constituted the vast majority of monetized damages, with premature mortality being the single largest health-damage category.

Some external effects could only be discussed in qualitative terms in this report. Although we were able to quantify and then monetize a wide range of burdens and damages, many other external effects could not ultimately be monetized because of insufficient data or other reasons. In particular, the committee did not monetize impacts of criteria air pollutants on ecosystem services or non-grain agricultural crops, or effects attributable to emissions of hazardous air pollutants.[2] In any case, it is important to keep in mind that the individual estimates presented in this report, even when quantifiable, can have large uncertainties.

In addition to its external effects in the present, the use of fossil fuels for energy creates external effects in the future through its emissions of atmospheric greenhouse gases (GHGs)[3] that cause climate change, subsequently resulting in damages to ecosystems and society. This report estimates GHG emissions from a variety of energy uses, and then, based on previous studies, provides *ranges* of potential damages. The committee determined that attempting to estimate a single value for climate change damages would have been inconsistent with the dynamic and unfolding insights into climate change itself and with the extremely large uncertainties associated with effects and range of damages. Because of these uncertainties and the long time frame for climate change, our report discusses climate change damages separately from damages not related to climate change.

OVERALL CONCLUSIONS AND IMPLICATIONS

Electricity

Although the committee considered electricity produced from coal, natural gas, nuclear power, wind, solar energy, and biomass, it focused mainly on coal and natural gas—which together account for nearly 70% of the nation's electricity—and on monetizing effects related to the air pollution from these sources. From previous studies, it appeared that the electricity *generation* activities accounted for the majority of such external effects, with other activities in the electricity cycle, such as mining or drilling, playing a lesser role.

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[1]Criteria pollutants, also known as "common pollutants" are identified by the U.S. Environmental Protection Agency (EPA), pursuant to the Clean Air Act, as ambient pollutants that come from numerous and diverse sources and that are considered to be harmful to public health and the environment, and to cause property damage.

[2]Hazardous air pollutants, also known as toxic air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects.

[3]Greenhouse gases absorb heat from the earth's surface and lower atmosphere, with the result that instead of that energy being radiated into space much of it is radiated back toward the surface. These gases include water vapor, carbon dioxide, ozone, methane, and nitrous oxide.

Coal

Coal, a nonrenewable fossil fuel, accounts for nearly half of all electricity produced in the United States.We monetized effects associated with emissions from 406 coal-fired power plants, excluding Alaska and Hawaii, during 2005. These facilities represented 95% of the country's electricity from coal. Although coal-fired electricity generation from the 406 sources resulted in large amounts of pollution overall, a plant-by-plant breakdown showed that the bulk of the damages were from a relatively small number of them. In other words, specific comparisons showed that the source-and-effect landscape was more complicated than the averages would suggest.

Damages Unrelated to Climate Change

The aggregate damages associated with emissions of SO_2, NO_x, and PM from these coal-fired facilities in 2005 were approximately $62 billion, or $156 million on average per plant.[4] But the differences among plants were wide—the 5th and 95th percentiles of the distribution were $8.7 million and $575 million, respectively. After ranking all of the plants according to their damages, we found that the 50% of plants with the lowest damages together produced 25% of the net generation of electricity but accounted for only 12% of the damages. On the other hand, the 10% of plants with the highest damages, which also produced 25% of net generation, accounted for 43% of the damages. Figure S-1 shows the distribution of damages among coal-fired plants.
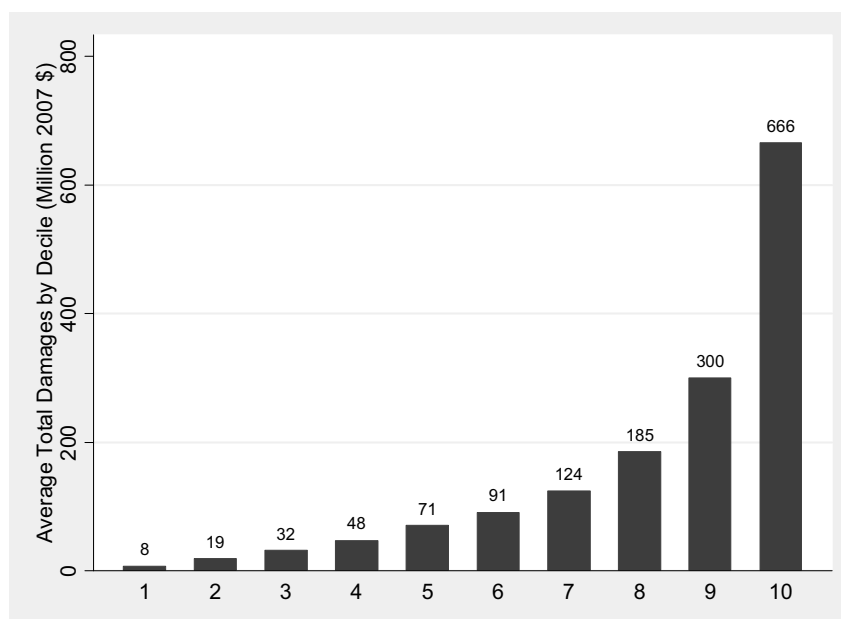
Figure S-1 Distribution of aggregate damages among the 406 coal-fired power plants analyzed in this study. In computing this chart, plants were sorted from smallest to largest based on damages associated with each plant. The lowest decile (10% increment) represents the 40 plants with the smallest damages per plant (far left). The decile of plants that produced the most damages is on the far right. The figure on the top of each bar is the average damage across all plants of damages associated with SO_2, NO_x, and PM. Damages related to climate-change effects are not included.

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[4]Costs are reported in 2007 dollars.

Some of the variation in damages among plants occurred because those that generated more electricity tended to produce greater damages; hence we also reported damages per kWh of electricity produced. If plants are weighted by the amount of electricity they generate, the mean damage is 3.2 cents per kWh. For the plants examined, variation in damages per kWh is primarily due to variation in pollution intensity (emissions per kWh) among plants, rather than variation in damages per ton of pollutant. Variations in emissions per kWh mainly reflected the sulfur content of the coal burned; the adoption, or not, of control technologies (such as scrubbers); and the vintage of the plant—newer plants were subject to more stringent pollution control requirements. As a result, the distribution of damages per kWh was highly skewed: there were many coal-fired power plants with modest damages per kWh as well as a small number of plants with large damages. The 5th percentile of damages per kWh is less than half a cent, while the 95th percentile of damages is over 12 cents.[5]

The estimated air pollution damages associated with electricity generation from coal in 2030 will depend on many factors. For example, damages per kWh are a function of the emissions intensity of electricity generation from coal (e.g., pounds [lb] of SO_2 per MWh), which in turn depends on future regulation of power-plant emissions. Based on government estimates, net power generation from coal in 2030 is expected to be 20% higher on average than in 2005. Despite projected increases in damages per ton of pollutant resulting mainly from population and income growth—average damages per kWh from coal plants (weighted by electricity generation) are estimated to be 1.7 cents per kWh in 2030, compared to 3.2 cents per kWh in 2005. This decrease derives from the assumption that SO_2 emissions per MWh will fall by 64% and that NO_x and PM emissions per MWh will each fall by approximately 50%.

Natural Gas

An approach similar to that used for coal allowed the committee to estimate criteria-pollutant-related damages for 498 facilities in 2005 that generated electricity from natural gas in the contiguous 48 states. These facilities represented 71% of the country's electricity from natural gas. Again, as with coal, the overall averages masked some major differences among plants, which varied widely in terms of pollution generation.

Damages Unrelated to Climate Change

Damages from gas-fueled plants tend to be much lower than those from coal plants. The sample of 498 gas facilities produced $740 million in aggregate damages from emissions of SO_2, NO_x, and PM. Average annual damages per plant were $1.49 million, which reflected not only lower damages per kWh at gas plants but smaller plant sizes as well; net generation at the median coal plant was more than six times larger than that of the median gas facility. After sorting the gas plants according to damages, we found that the 50% with the lowest damages accounted for only 4% of aggregate damages. By contrast, the 10% of plants with the largest damages produced 65% of the air-pollution damages from all 498 plants (see Figure S-2). Each group of plants accounted for approximately one-quarter of the sample's net generation of electricity.

Mean damages per kWh were 0.16 cents when natural gas-fired plants were weighted by the amount of electricity they generated. But the distribution of damages per kWh had a large variance and was highly skewed. The 5th percentile of damages per kWh is less than 5/100 of a cent, while the 95th percentile of damages is about a cent.[6]

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[5]When damages per kWh are weighted by electricity generation, the 5th and 95th percentiles are 0.19 and 12 cents; the unweighted figures are .53 and 13.2 cents per kWh.

[6]When damages per kWh are weighted by electricity generation the 5th and 95th percentiles are 0.001 and 0.55 cents; the unweighted figures are .0044 and 1.7 cents per kWh.
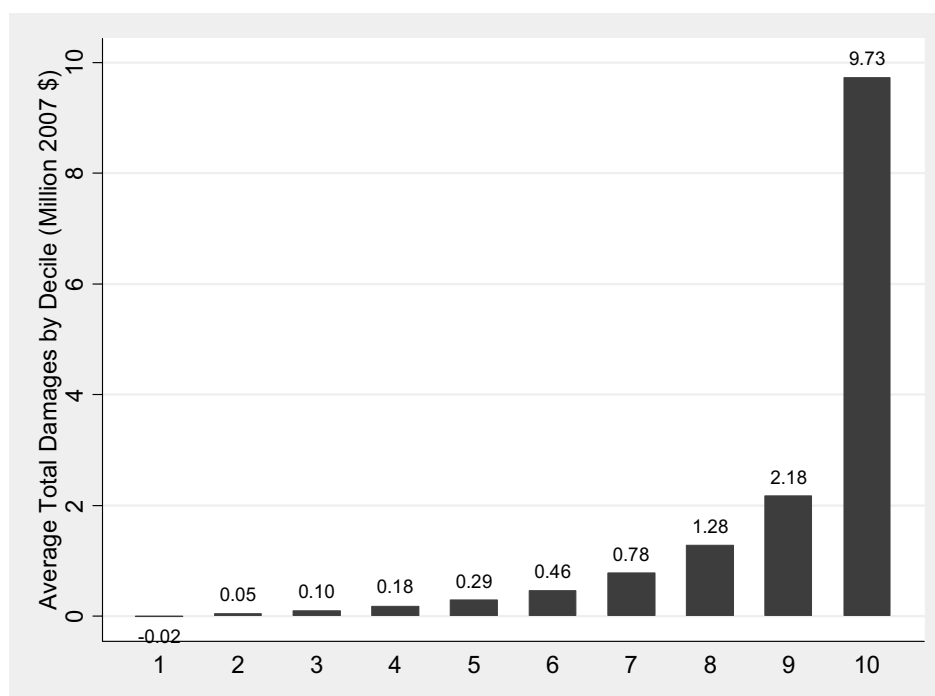
Figure S-2 Distribution of aggregate damages among the 498 natural gas-fired power plants analyzed in this study. In computing this chart, plants were sorted from smallest to largest based on damages associated with each plant. The lowest decile (10% increment) represents the 50 plants with the smallest damages per plant (far left). The decile of plants that produced the most damages is on the far right. The figure on the top of each bar is the average damage across all plants of damages associated with SO_2, NO_x, and PM. Damages related to climate-change effects are not included.

Although overall electricity production from natural gas in 2030 is predicted to increase by 9% from 2005 levels, the average pollution intensity for natural gas facilities is expected to decrease, though not as dramatically as for coal plants. Pounds of NO_x emitted per MWh are estimated to fall, on average, by 19%, and emissions of PM per MWh are estimated to fall by about 32%. The expected net effect of these changes is a decrease in the aggregate damages related to the 498 gas facilities from $740 million in 2005 to $650 million in 2030. Their average damage per kWh is expected to fall from 0.16 cents to 0.11 cents over that same period.

Nuclear

The 104 U.S. nuclear reactors currently account for almost 20% of the nation's electrical generation. Overall, other studies have found that damages associated with the normal operation of nuclear power plants (excluding the possibility of damages in the remote future from the disposal of spent fuel) are quite low compared with those of fossil-fuel-based power plants.[7]

However, the life cycle of nuclear power does pose some risks. If uranium mining activities contaminate ground or surface water, people could potentially be exposed to radon or other radionuclides

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[7]The committee did not quantify damages associated with nuclear power. Such an analysis would have involved power-plant risk modeling and spent-fuel transportation modeling that would have required far greater resources and time than were available for this study.

through ingestion. Because the United States mines only about 5% of the world's uranium supply, such risks are mostly experienced in other countries.

Low-level nuclear waste is stored until it decays to background levels and currently does not pose an immediate environmental, health, or safety hazard. However, regarding spent nuclear fuel, development of full-cycle, closed-fuel processes that recycle waste and enhance security could further lower risks.

A permanent repository for spent fuel and other high-level nuclear wastes is perhaps the most contentious nuclear-energy issue, and considerably more study of the external cost of such a repository is warranted.

Renewable Energy Sources

Wind power currently provides just over 1% of U.S. electricity, but it has large growth potential. Because no fuel is involved in electricity generation, neither gases nor other contaminants are released during the operation of a wind turbine. Its effects do include potentially adverse visual and noise effects, and the killing of birds and bats. In most cases, wind-energy plants currently do not kill enough birds to cause population-level problems, except perhaps locally and mainly with respect to raptors. The tallies of bats killed and the population consequences of those deaths have not been quantified but could be significant. If the number of wind-energy facilities continues to grow as fast as it has recently, bat and perhaps bird deaths could become more significant.

Although the committee did not evaluate in detail the effects of solar and biomass generation of electricity, it has seen no evidence that they currently produce adverse effects comparable in aggregate to those of larger sources of electricity. However, as technology improves and penetration into the U.S. energy market grows, the external costs of these sources will need to be reevaluated.

Greenhouse Gas Emissions and Electricity Generation

Emissions of CO_2 from coal-fired power plants are the largest single source of GHGs in the United States. CO_2 emissions vary; their average is about 1 ton of CO_2 per MWh generated, with a 5th-to-95th-percentile range of 0.95–1.5 tons. The main factors affecting these differences are the technology used to generate the power and the age of the plant. Emissions of CO_2 from gas-fired power plants also are significant, with an average of about 0.5 ton of CO_2 per MWh generated and a 5th-to-95th-percentile range of 0.3–1.1 tons. Life-cycle CO_2 emissions from nuclear, wind, biomass, and solar appear so small as to be negligible compared to those from fossil fuels.

Heating

The production of heat as an end-use accounts for about 30% of U.S. primary energy demand, the vast majority of which derives from the combustion of natural gas or the application of electricity. External effects associated with heat production come from all sectors of the economy, including residential and commercial (largely for the heating of living or work spaces) and industrial (for manufacturing processes).

Damages Unrelated to Climate Change

As with its combustion for electricity, combustion of natural gas for heat results in lower emissions than from coal, which is the main energy source for electricity generation. Therefore health and environmental damages related to obtaining heat directly from natural gas combustion are much less than damages from the use of electricity for heat. Aggregate damages from the combustion of natural gas for

direct heat are estimated to be about $1.4 billion per year, assuming that the magnitude of external effects resulting from heat production for industrial activities is comparable to that of residential and commercial uses.[8] The median estimated damages attributable to natural gas combustion for heat in residential and commercial buildings is approximately 11 cents per thousand cubic feet. These damages do not vary much across regions when considered on a per-unit basis, though some counties have considerably higher external costs than others. In 2007, natural gas use for heating in the industrial sector, excluding its employment as a process feedstock, was about 25% less than natural gas use in the residential and commercial building sectors.

Damages associated with energy for heat in 2030 are likely to be about the same as those that exist today, assuming that the effects of additional sources to meet demand are offset by lower-emitting sources. *Reduction* in damages would only result from more significant changes—largely in the electricity-generating sector, as emissions from natural gas are relatively small and well controlled. But the greatest potential for reducing damages associated with the use of energy for heat lies in greater attention to improving efficiency. Results from the recent National Academies' study *America's Energy Future* suggest a possible improvement of energy efficiency in the buildings and industrial sectors by 25% or more between now and 2030. *Increased* damages would also be possible, however, if new domestic energy development resulted in higher emissions or if additional imports of liquefied natural gas, which would increase emissions from the production and international transport of the fuel, were needed.

Greenhouse Gas Emissions

The combustion of a thousand cubic feet of gas generates about 120 lb (0.06 tons) of CO_2. Methane, the major component of natural gas, is a GHG itself and has a global-warming potential about 25 times that of CO_2. Methane enters the atmosphere through leakage, but the U.S. Energy Information Administration estimates that such leakage amounted to less than 3% of total U.S. CO_2-equivalent (CO_2-eq) emissions[9] (excluding water vapor) in 2007. Thus in the near term, where domestic natural gas remains the dominant source for heating, the average emissions factor is likely to be about 140 lb CO_2-eq/MCF (including upstream methane emissions), while in the longer term—assuming increased levels of liquefied natural gas or shale gas as part of the mix—the emissions factor could be 150 lb CO_2-eq/MCF.

Transportation

Transportation, which today is almost completely reliant on petroleum, accounts for nearly 30% of U.S. energy consumption. The majority of transportation-related emissions come from fossil-fuel combustion—whether from petroleum consumed during conventional-vehicle operation, coal or natural gas used to produce electricity to power electric or hybrid vehicles, petroleum or natural gas consumed in cultivating biomass fields for ethanol, or electricity used during vehicle manufacture.

The committee focused both on the non-climate-change damages and GHG emissions associated with light-duty and heavy-duty on-road vehicles, as they account for more than 75% of transportation-energy consumption in the United States. Although damages from non-road vehicles (for example, aircraft, locomotives, and ships) are not insignificant, the committee emphasized the much larger highway component.

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[8]Insufficient data were available to conduct a parallel analysis of industrial activities that generate useful heat as a side benefit.

[9]CO_2-equivalent (noted as CO_2-eq) expresses the global warming potential of a given stream of greenhouse gases, such as methane, in terms of CO_2 quantities.

Damages Unrelated to Climate Change

In 2005, the vehicle sector produced $56 billion in health and other non-climate-change damages, with $36 billion from light-duty vehicles and $20 billion from heavy-duty vehicles. Across the range of light-duty technology/fuel combinations considered, damages expressed per vehicle-mile traveled (VMT) ranged from 1.2 cents to 1.7 cents (with a few combinations having higher damage estimates).[10]

The committee evaluated motor-vehicle damages over four life-cycle stages: (1) vehicle operation, which results in tailpipe emissions and evaporative emissions; (2) production of feedstock, including the extraction of the resource (oil for gasoline, biomass for ethanol, or fossil fuels for electricity) and its transportation to the refinery; (3) refining or conversion of the feedstock into usable fuel and its transportation to the dispenser; and (4) manufacturing and production of the vehicle. Importantly, vehicle operation accounted in most cases for less than one-third of total damages, with other components of the life cycle contributing the rest. And while life-cycle stages 1, 2, and 3 were somewhat proportional to actual fuel use, stage 4 (which is a significant source of life-cycle emissions that form criteria pollutants) was not.

The estimates of damage per VMT among different combinations of fuels and vehicle technologies were remarkably similar (see Figure S-3). Because these assessments were so close, it is essential to be cautious when interpreting small differences between combinations. The damage estimates for 2005 and 2030 also were very close, despite an expected rise in population. This result is attributable to the expected national implementation of the recently revised "corporate average fuel economy" (CAFE) standards, which require the new light-duty fleet to have an average fuel economy of 35.5 miles per gallon by 2016 (although an increase in vehicle-miles traveled could offset this improvement somewhat).

Despite the general overall similarity, some fuel/technology combinations were associated with greater non-climate damages than others. For example, corn ethanol, when used in E85 (fuel that is 85% ethanol and 15% gasoline), showed estimated damages per VMT similar to or slightly higher than those of gasoline, both for 2005 and 2030, because of the energy required to produce the biofuel feedstock and convert it to fuel. Yet cellulosic (non-food biomass) ethanol made from herbaceous plants or corn stover had lower damages than most other options when used in E85. The reason for this contrast is that the feedstock chosen and growing practices employed do influence the overall damages from biomass-based fuels. We did not quantify water use and indirect land use for biofuels.[11]

Electric vehicles and grid-dependent hybrid vehicles showed somewhat higher damages than many other technologies for both 2005 and 2030. Although operation of the vehicles produces few or no emissions, electricity production at present relies mainly on fossil fuels and, based on current emission control requirements, emissions from this stage of the life cycle are expected to still rely primarily on those fuels by 2030, albeit at significantly lower emission rates. In addition, battery and electric motor production—being energy- and material-intensive—added up to 20% to the damages from manufacturing.

Compressed natural gas had lower damages than other options, as the technology's operation and fuel produce very few emissions.

Although diesel had some of the highest damages in 2005, it is expected to have some of the lowest in 2030, assuming full implementation of the Tier 2 vehicle emission standards of the U.S. Environmental Protection Agency (EPA). This regulation, which requires the use of low-sulfur diesel, is expected to significantly reduce PM and NO_x emissions as well.

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[10]The committee also estimated damages on a per-gallon basis, with a range of 23 to 38 cents per gallon (with gasoline vehicles at 29 cents per gallon). Interpretation of the results is complicated, however, by the fact that fuel/technology combinations with higher fuel efficiency appear to have markedly higher damages per gallon than those with lower efficiency, solely due to the higher number of miles driven per gallon.

[11]Indirect land use refers to geographical changes occurring indirectly as a result of biofuels policy in the United States and to the effects of such changes on greenhouse gas emissions.
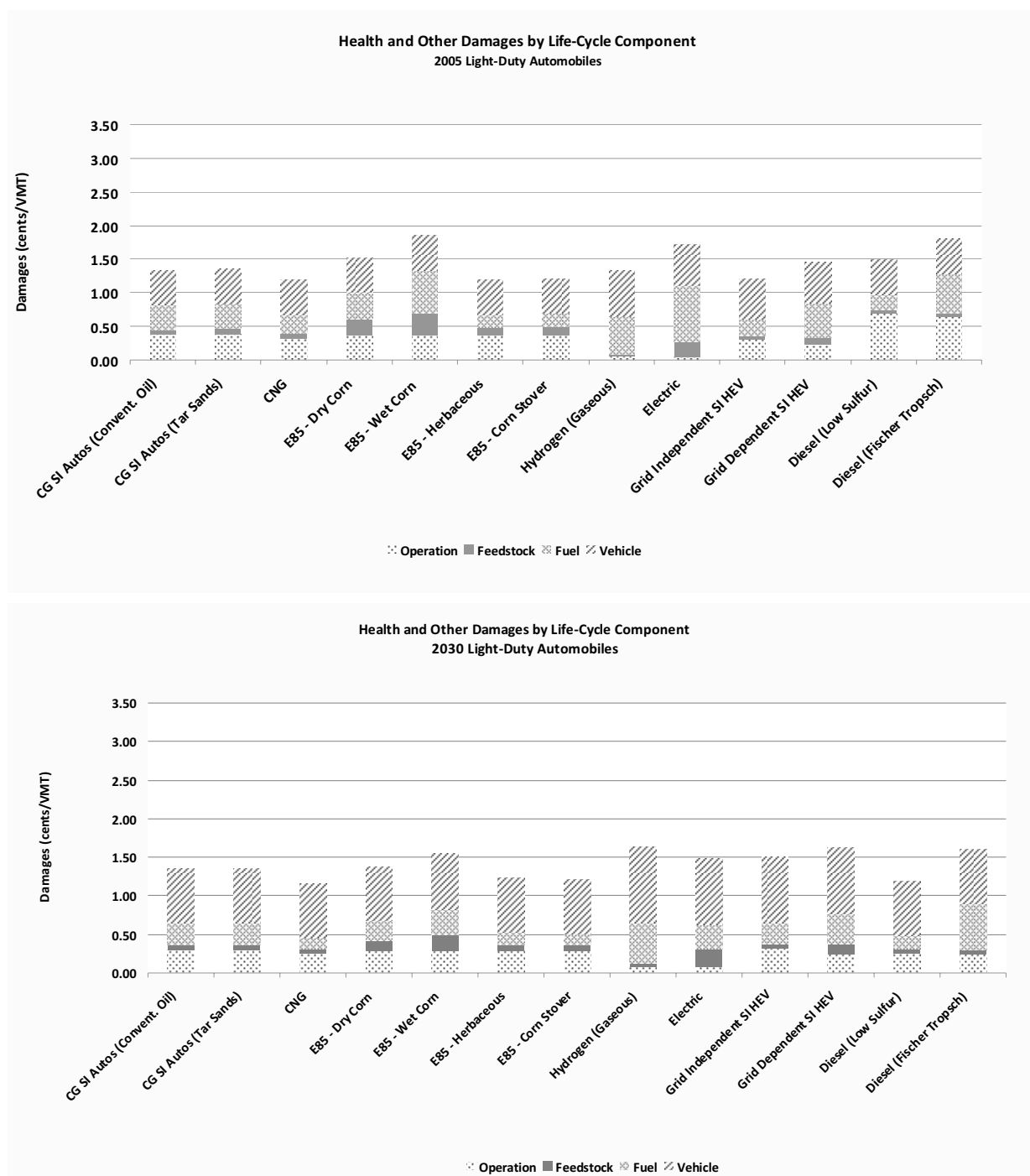
FIGURES S-3 Health and other non-climate damages are presented by life-cycle component for different combinations of fuels and light-duty automobiles in 2005 (top) and 2030 (bottom). Damages are expressed in cents per VMT (2007 USD). Going from bottom to top of each bar, damages are shown for life-cycle stages as follows, vehicle operation, feedstock production, fuel refining or conversion, and vehicle manufacturing. Damages related to climate change are not included. CG SI refers to conventional gasoline spark ignition. CNG refers to compressed natural gas; E85 refers to 85% ethanol fuel; HEV refers to hybrid electric vehicle.

Heavy-duty vehicles have much higher damages per VMT than those of light-duty vehicles because they carry more cargo or people, and therefore have lower fuel economies. However, between 2005 and 2030, these damages are expected to drop significantly, assuming the full implementation of the EPA Heavy-Duty Highway Vehicle Rule.

Greenhouse Gas Emissions

Most vehicle and fuel combinations had similar levels of GHG emissions in 2005 (see Figure S-4). Because vehicle operation is a substantial source of life-cycle GHGs, enforcement of the new CAFE standards will have a greater impact on lowering GHG emissions than on lowering life-cycle emissions of other pollutants. By 2030, with improvements among virtually all light-duty vehicle types, the committee estimates there would be even fewer differences between the GHG emissions of the various technologies than there were in 2005. However, in the absence of additional fuel-efficiency requirements, heavy-duty vehicle GHG emissions are expected to change little between 2005 and 2030, except from a slight increase in fuel economy in response to market conditions.

Both for 2005 and 2030, vehicles using gasoline made from petroleum extracted from tar sands and diesel derived from Fischer-Tropsch fuels[12] had the highest life-cycle GHG emissions among all fuel/vehicle combinations considered. Vehicles using celluosic E85 from herbaceous feedstock or corn stover had some of the lowest GHG emissions because of the feedstock's ability to store carbon dioxide in the soil. Those using compressed natural gas also had comparatively low GHG emissions.

Future Reductions

Substantially reducing non-climate damages related to transportation would require major technical breakthroughs, such as cost-effective conversion of cellulosic biofuels, cost-effective carbon capture and storage for coal-fired power plants, or a vast increase in renewable energy capacity or other forms of electricity generation with lower emissions.[13] Further enhancements in fuel economy will also help, especially for emissions from vehicle operations, although they are only about one-third of the total life-cycle picture and two other components are proportional to fuel use. In any case, better understanding of potential external costs at the earliest stage of vehicle research should help developers minimize those costs as the technology evolves.

Estimating Climate Change Damages

Energy production and use continue to be major sources of GHG emissions, principally CO_2 and methane. And damages from these emissions will result as their increased atmospheric concentrations affect climate, which in turn will affect such things as weather, freshwater supply, sea level, biodiversity, and human society and health.[14]

Estimating these damages is another matter, as the prediction of climate-change effects, which necessarily involves detailed modeling and analysis, is an intricate and uncertain process. It requires aggregation of potential effects and damages that could occur at different times (extending centuries into

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[12]The Fischer-Tropsch reaction converts a mixture of hydrogen and carbon monoxide—derived from coal, methane, or biomass—into liquid fuel.

[13]The latter two changes are needed to reduce the life-cycle damages of grid-dependent vehicles.

[14]In response to a request from Congress, the National Academies has launched America's Climate Choices, a suite of studies designed to inform and guide responses to climate change across the nation.

Greenhouse Gas Emissions by Life-Cycle Component
2005 Light-Duty Automobiles

Greenhouse Gas Emissions by Life-Cycle Component
2030 Light-Duty Automobiles
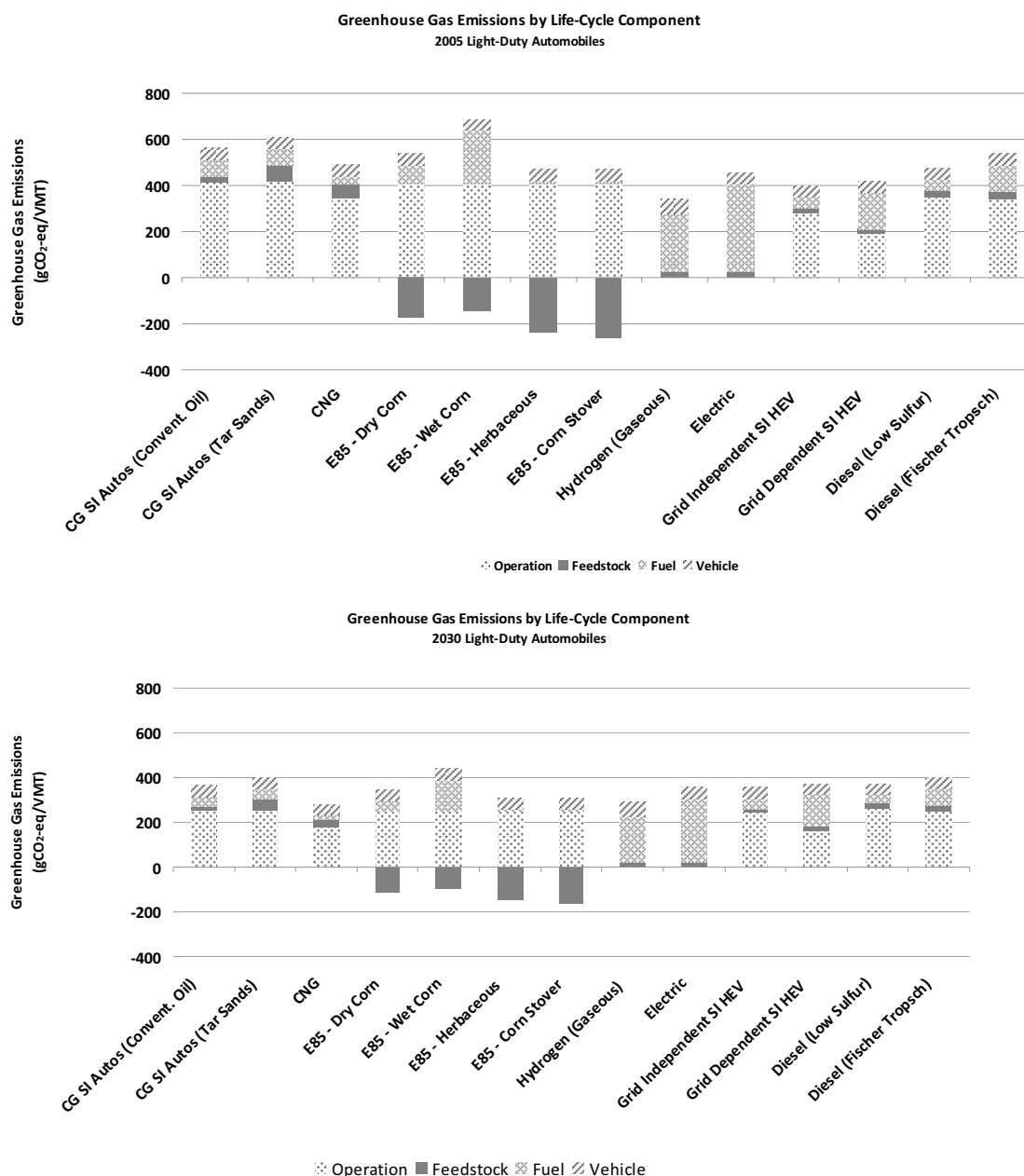
FIGURE S-4 GHG emissions (grams CO_2- eq)/VMT by life-cycle component for different combinations of fuels and light-duty automobiles in 2005 (top) and 2030 (bottom). Going from bottom to top of each bar, damages are shown for life-cycle stages as follows, vehicle operation, feedstock production, fuel refining or conversion, and vehicle manufacturing. One exception is ethanol fuels for which feedstock production exhibits negative values due to CO_2 uptake. The amount of CO_2 consumed should be subtracted from the positive value to arrive at a net value.

the future) and among different populations across the globe. Thus, rather than attempt such an undertaking itself, especially given the constraints on its time and resources, the committee focused its efforts on a review of existing integrated assessment models (IAMs) and the associated climate-change literature.

We reviewed IAMs in particular, which combine simplified global-climate models with economic models that are used to: (1) estimate the economic impacts of climate change; and (2) identify emissions

regimes that balance the economic impacts with the costs of reducing GHG emissions. But because IAM simulations usually report their results in terms of mean values, this approach does not adequately capture some possibilities of catastrophic outcomes. While a number of them have been studied—such as release of methane from permafrost that could rapidly accelerate warming; and collapse of the West Antarctic or Greenland ice sheets, which could raise sea level by several meters—the damages associated with these events and their probabilities are very poorly understood. Some analysts nevertheless believe that the expected value of total damages may be more sensitive to the possibility of low-probability catastrophic events than to the most likely or best-estimate values.

In any case, IAMs are the best tools currently available. And an important factor in using them (or virtually any other model that accounts for monetary impacts over time) is the "discount rate," which converts costs and benefits projected to occur in the future into amounts ("present values") that are compatible with present-day costs and benefits. Because the choice of a discount rate for the long periods associated with climate change is not well established, however, the committee did not choose a particular discount rate for assessing the value of climate change's effects; instead, we considered a range of discount-rate values.

Under current best practice, estimates of global damages associated with a particular climate-change scenario at a particular future time are translated by researchers into an estimate of damages per ton of emissions (referred to as marginal damages) by evaluating the linkage between current GHG emissions and future climate-change effects. Marginal damages are usually expressed as the net present value of the damages expected to occur over many future years as the result of an additional ton of CO_2-eq emitted into the atmosphere. Estimating these marginal damages depends on the temperature increase in response to a unit increase in CO_2-eq emissions, the additional climate-related effects that result, the values of these future damages relative to the present, and how far into the future one looks. Because of uncertainties at each step of the analysis, a given set of possible future conditions may yield widely differing estimates of marginal damages.

Given the preliminary nature of the climate-damage literature, the committee found that only rough order-of-magnitude estimates of marginal damages were possible at this time. Depending on the extent of projected future damages and the discount rate used for weighting them, the range of estimates of marginal damages spanned two orders of magnitude, from about \$1 to \$100 per ton of CO_2-eq, based on current emissions. Approximately one order of magnitude in difference was attributed to discount-rate assumptions, and another order of magnitude to assumptions about future damages from emissions used in the various IAMs. The damage estimates at the higher end of the range were associated only with emissions paths without significant GHG controls. Estimates of the damages specifically to the United States would be a fraction of these levels, because this country represents only about one-quarter of the world's economy, and the proportionate impacts it would suffer are generally thought to be to be lower than for the world as a whole.

Comparing Climate and Non-Climate Damage Estimates

Comparing non-climate damages to climate-related damages is extremely difficult. The two measures differ significantly in their time dimensions, spatial scales, varieties of impacts, and degrees of confidence with which they can be estimated. For 2005, determining which type of external effect caused higher damages depended on the energy technology being considered and the marginal damage value selected from the range of \$1 to \$100 per ton of CO_2-eq emitted. For example, coal-fired electricity plants were estimated to emit an average of about 1 ton of CO_2 per MWh (or 2 lb/kWh). Multiplying that emission rate by an assumed marginal damage value of \$30/ton CO_2-eq, climate-related damages would equal 3 cents/kWh, comparable to the 3.2 cents/kWh estimated for non-climate damages. It is important to keep in mind that the value of \$30/ton CO_2-eq is provided for illustrative purposes and is not a recommendation of the committee.

Natural Gas: The climate-related damages were higher than the non-climate damages from natural gas-fired power plants, as well as from combustion of natural gas for producing heat, regardless of the marginal damage estimate. Because natural gas is characterized by low emissions that form criteria pollutants, the non-climate damages were about an order of magnitude lower than the climate damages estimated by the models, if the marginal climate damage were assumed to be $30/ton CO_2-eq.

Coal: The climate-related damages from coal-fired power plants were estimated to be higher than the non-climate damages when the assumed marginal climate damage was greater than $30/ton CO_2-eq. If the marginal climate damage was less than $30/ton $CO_{2.}$-eq, the climate-related damages were lower than the non-climate damages.

Transportation: As with coal, the transportation sector's climate-change damages were higher than the non-climate damages only if the marginal damage for climate was higher than $30/ton CO_2-eq.

Overall: All of the model results available to the committee estimated that the climate-related damages per ton of CO_2-eq would be 50-80% worse in 2030 than in 2005. Even if annual GHG emissions were to remain steady between now and 2030, the damages per ton of CO_2-eq emissions would be substantially higher in 2030 than at present. As a result, the climate-related damages in that year from coal-fired power plants and transportation are likely to be greater than their non-climate damages.

Infrastructure Risks and Security

The committee also considered external effects and costs associated with disruptions in the electricity-transmission grid, energy facilities' vulnerability to accidents and possible attack, oil-supply disruptions, and other national security issues. We concluded as follows:

- The nation's electric grid is subject to periodic failures because of transmission congestion and the lack of adequate reserve capacity. These failures are considered an external effect, as individual consumers of electricity do not take into account the impact of their consumption on aggregate load. The associated and possibly significant damages of grid failure underscore the importance of carefully analyzing the costs and benefits of investing in a modernized grid—one that takes advantage of new smart technology and that is better able to handle intermittent renewable-power sources.

- The external costs of accidents at energy facilities are largely taken into account by their owners and, at least in the case of our nation's oil and gas transmission networks, are of negligible magnitude per barrel of oil or thousand cubic feet of gas shipped.

- Because the United States is such a large consumer of oil, policies to reduce domestic demand can also reduce the world oil price, thereby benefiting the nation through lower prices on the remaining oil it imports. Government action may thus be a desirable countervailing force to monopoly or cartel-producer power. However, the committee does not consider this influence of a large single buyer (known as monopsony power) to be a benefit that is external to the market price of oil. It was therefore deemed to be outside the scope of this report.

- Although sharp and unexpected increases in oil prices adversely affect the U.S. economy, the macroeconomic disruptions they cause do not fall into the category of external effects and damages. Estimates in the literature of the macroeconomic costs of disruptions and adjustments range from $2 to $8 per barrel.

- Dependence on imported oil has well-recognized implications for foreign policy, and although we find that some of the effects can be viewed as external costs, it is currently impossible to quantify them. For example, the role of the military in safeguarding foreign supplies of oil is often identified as a relevant factor. But the energy-related reasons for a military presence in certain areas of the world cannot readily be disentangled from the non-energy-related reasons. Moreover, much of the military cost is likely to be fixed in nature. For example, even a 20% reduction in oil consumption, we believe, would likely have little impact on the strategic positioning of U.S. military forces throughout the world.

- Nuclear waste raises important security issues and poses tough policy challenges. The extent to which associated external effects exist is hard to assess, and even when identified they are very difficult to quantify. Thus although we do not present numerical values in this report, we recognize the importance of studying these issues further.

In Conclusion

In aggregate, the damage estimates presented in this report for various external effects are substantial. Just the damages from external effects the committee was able to quantify add up to more than $120 billion for the year 2005.[15] Although large uncertainties are associated with the committee's estimates, there is little doubt that this aggregate total substantially underestimates the damages, because it does not include many other kinds of damages that could not be quantified for reasons explained in the report, such as damages related to some pollutants, climate change, ecosystems, infrastructure and security. In many cases we have identified those omissions, within the chapters of this report, with the hope that they will be evaluated in future studies.

But even if complete, our various damage estimates would not automatically offer a guide to policy. From the perspective of economic efficiency, theory suggests that damages should not be reduced to zero but only to the point where the cost of reducing another ton of emissions (or other type of burden) equals the marginal damages avoided. That is, the degree to which a burden should be reduced depends on its current level and the cost of lowering it; the solution cannot be determined from the amount of damage alone. Economic efficiency, however, is only one of several potentially valid policy goals that need to be considered in managing pollutant emissions and other burdens. For example, even within the same location, there is compelling evidence that some members of the population are more vulnerable than others to a particular external effect.

While not a comprehensive guide to policy, our analysis does indicate that regulatory actions can significantly affect energy-related damages. For example, the full implementation of the federal diesel-emissions rules would result in a sizeable decrease in non-climate damages from diesel vehicles between 2005 and 2030. Similarly, major initiatives to further reduce other emissions, improve energy efficiency, or shift to a cleaner electricity-generating mix (e.g., renewables, natural gas, nuclear) could substantially reduce external effects' damages, including those from grid-dependent hybrid and electric vehicles.

It is thus our hope that this information will be useful to government policy makers, even in the earliest stages of research and development on energy technologies, as an understanding of their external effects and damages could help to minimize the technologies' adverse consequences.

ABBREVIATIONS USED IN THE SUMMARY

CAFE	corporate average fuel economy	MCF	thousand cubic feet
CO_2	carbon dioxide	MWh	megawatt hours
CO_2-eq	carbon dioxide equivalent	NO_x	nitrogen oxides
E85	ethanol 85% blend	PM	particulate matter
GHG	greenhouse gas	SO_2	sulfur dioxide
kWh	kilowatt hours	VMT	vehicle-miles traveled
IAM	integrated assessment model		

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[15]These are damages related principally to emissions of NO_x, SO_2, and PM relative to a baseline of zero emissions from energy-related sources for the effects considered in this study.

1

Introduction

GENESIS OF THE STUDY

Energy is essential to the functioning of society. From coal for electricity production to oil products for transportation and natural gas for space heating, every aspect of modern life depends on energy. Yet, as beneficial as energy is, its production, distribution and consumption also cause negative impacts, especially on human health and the environment.

The purpose of this study was to define and evaluate the external effects of energy production, distribution, and consumption. External effects refer to those costs and benefits not reflected in market prices. In the absence of government intervention, external effects associated with energy production and use are generally not taken into account in decision-making (see discussion later in this chapter.)

The external effects of energy are mostly negative, but this does not imply that energy use has an overall negative impact on society. Quite the contrary: the benefits to society of our energy systems are enormous. But, it was not our task to estimate those benefits that are largely "internal" in the sense that they are reflected in energy prices or government policies. We take those benefits as a given, devoting our attention to the external effects.

When external effects are not taken into account in making decisions, such as the siting of a power plant, or they are not reflected in market prices, for example the price of gasoline at the pump, sub-optimal decisions may be made—sub-optimal in the sense that the full social costs of the actions are not recognized, resulting in a loss of social welfare. When market failures like this occur, there is a case for government intervention in the form of regulation, taxes, fees, tradable permits or other instruments that will cause economic agents to recognize these external effects in their decision-making.

Before pursuing such public policies, we need to know what the external effects of energy are and their monetary values. Thus, Congress directed the Department of Treasury in the Energy Policy Act of 2005 (P.L. 109-58), Section 1352 to arrange for a study by the National Academy of Sciences "to define and evaluate the health, environmental, security, and infrastructure external costs and benefits associated with the production and consumption of energy that are not or may not be fully incorporated into the market price of such energy, or into the Federal revenue measures related to that production or consumption." Funding for the study was later provided through the Consolidated Appropriations Act of 2008 (P.L. 110-161).

STATEMENT OF TASK

In response to this mandate from Congress and the request from the Department of Treasury, the National Research Council established the Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption (see Appendix A). A Statement of Task, which is presented in Box 1-1, was developed and served as the point of departure and guide for the committee's

work. In the remainder of this chapter, we define key terms in this Statement of Task and explain the general procedures we followed in executing our task.

Our study is one of many related to energy that the National Research Council has recently undertaken. In the next section, we briefly discuss other NRC studies, the results from which have informed our work, especially the America's Energy Future initiative which is identified in the Statement of Task. We also briefly review previous studies on the external costs of energy.

Also in this chapter, we provide the definition of an externality—the focus and core concept of this study—and provide some examples.

The Statement of Task directed us to evaluate the externalities "associated with the production, distribution and consumption of energy from various selected sources." We explain how we selected the sources and the particular elements of the energy system on which we focused.

The approach that we took for identifying, quantifying and evaluating externalities "in economic terms" is explained. This includes a discussion of "appropriate metrics from each externality category."

Although the committee was not asked to "recommend specific strategies for correcting observable externalities, because those choices will entail policy judgments"—a position with which we agree—it is important to understand and to keep in mind the policy contexts in which our results may be used.

BOX 1-1 Statement of Task

An NRC committee will define and evaluate key external costs and benefits—health, environmental, security, and infrastructure—associated with the production, distribution, and consumption of energy from various selected sources that are not or may not be fully incorporated into the market price of such energy, or into the Federal tax or fee or other applicable revenue measures related to such production, distribution, or consumption. Although the committee will carry out its task from a U.S. perspective, it will consider broader geographic implications of externalities when warranted and feasible. The committee will not recommend specific strategies for internalizing observable externalities, because those choices will entail policy judgments that transcend scientific and technological considerations.

In carrying out its task, the committee will include the following activities:

Seek to build upon the results of the NRC study America's Energy Future: Technology and Transformations.

Identify key externalities to be assessed in the categories of human health, environment, security (including quality, abundance, and reliability of energy sources), and infrastructure (such as transportation and waste disposal systems not sufficiently taken into account by producers or consumers).

Consider externalities associated with producing, distributing, and consuming energy imported from foreign sources.

Define appropriate metric(s) for each externality category considered.

Identify state-of-the-science approaches for assessing external effects (actual or expected) and expressing their effects in economic terms.

Develop an approach for estimating externalities related to greenhouse gas emissions and climate change. Estimate externalities related to those changes.

Present qualitative and, to the extent practicable, quantitative estimates of externalities and associated uncertainties within a consistent framework that makes the discussion of externalities and uncertainties associated with energy production, distribution, and consumption more transparent.

When it was not feasible to assess specific externalities comprehensively, the committee will recommend assessment approaches and identify key information needs to inform future assessments.

The Statement of Task anticipated some of the methodological challenges of evaluating externalities. We discuss the particular difficulties of dealing with space, time and uncertainty. The committee sought to build on the work of companion studies within the National Research Council, particularly the studies referred to as America's Energy Future and America's Climate Choices.

RELATED STUDIES

National Research Council Studies

The National Academies have identified energy as a high priority topic that has received attention from many National Research Council committees, both past and current. These studies were relevant to the work of our committee. We briefly discuss two efforts here, and cite them throughout our report where appropriate.

The America's Energy Future (AEF) effort at the National Academies is concerned with future technology and its potential for reducing U.S. dependence on oil imports and green house gas emissions while ensuring that affordable energy is available to sustain economic growth. The AEF's task was to: critically review recently completed major studies on the potential for change in energy use and technology; compare their assumptions; analyze the currency and quality of the information used; and, assess the relative state of maturity of technologies for potential deployment in the next decade. A secondary focus is on technologies with longer times to deployment (see NAS 2009a).

The AEF study analyzed advanced coal technologies; nuclear power; renewable energy technologies (such as wind, solar-photovoltaic, and geothermal); energy storage and infrastructure technologies; advanced transportation power train technologies; technologies to improve energy efficiency in residential and commercial buildings, industry, and transportation; and the technical potential for reducing reliance on petroleum-based fuels for transportation in three timeframes: now-2020; 2020-2035; and beyond 2035.

In response to a request from Congress concerning a related topic, the National Academies have launched America's Climate Choices, a suite of studies designed to inform and guide responses to climate change across the nation (see NAS 2009b).

The results of the studies are intended to address these key questions:

- What short-term actions can be taken to respond effectively to climate change?
- What promising long-term strategies, investments, and opportunities could be pursued to respond to climate change?
- What are the major scientific and technological advances (e.g., new observations, improved models, and research priorities) needed better to understand and respond effectively to climate change?
- What are the major impediments (e.g., practical, institutional, economic, ethical, and intergenerational) to responding effectively to climate change, and what can be done to overcome these impediments?

The AEF and America's Climate Choices studies are important initiatives that have and will provide valuable information on technology and policy options for the nation's energy future. Indeed, our study has been informed by the AEF's analysis of future technology. However, neither of these efforts is designed to focus on the *monetary value* of energy's external effects, including climate change.

Prior Externality Studies

The concept of externalities dates at least to the early twentieth century (Pigou 1920) and was discussed extensively in the post-war Economics literature (Meade 1952; Scitovsky 1954; Mishan 1965;

Arrow 1975). Interest in the externalities of energy production and use gathered momentum in the following decades. Hohmeyer (1988) was one of the more prominent studies during this period. He took a top-down approach in which he estimated the "toxicity weighted" emissions from electricity generation with fossil fuels and then multiplied this fraction by Wicke's (1986) estimates of total damages from pollution to various endpoints (health, forests, animals, etc.). The most prominent study in the United States during this period (Ottinger et al. 1990) used estimates from previous studies that quantified the environmental costs from electric power generation. Results of Niemi et al. (1984, 1987) were among those used by Ottinger et al.; those studies focused on visibility and health effects of airborne particulate matter. Ottinger et al. followed a five-step procedure in using these studies to value environmental damages: emissions, dispersion, exposure, impacts, and damages.

Research in estimating the external costs of energy peaked in the early-to-mid 1990's when Public Utility Commissions in the United States were interested in tilting electric utility investment choices towards sources with lower negative externalities, such as renewable energy. This policy was to be done with an "adder" equal to the marginal damages associated with each type of generation. During this wave of interest, major studies were done by Oak Ridge National Laboratory and Resources for the Future (ORNL/RFF) for the U.S. Department of Energy, by Hagler Bailly for the New York State Energy Research and Development Authority (NYSERDA), by Research Triangle Institute for the State of Wisconsin (one of several states mounting these studies), and by several teams of European research organizations for the European Commission (EC). This latter study, called ExternE, worked in concert with the ORNL/RFF team to use similar protocols.

Around the same time that work commenced on the ORNL/RFF and ExternE studies, other studies were completed by the Union of Concerned Scientists (1992); Pearce et al. (1992), in their report to the UK Department of Trade and Industry; Triangle Economic Research (1995) for Minnesota; National Economic Research Associates (1993), in its study of Nevada; Regional Economic Research (1991), on California; and the Consumer Energy Council of America Research Foundation (1993).

Later, the EC mounted a companion study on the external costs of transportation as well as other research efforts—the most recent being the New Energy Externalities Development for Sustainability (NEEDS) program—that further refined and developed methodologies extending those developed in ExternE as well as to other energy technologies and study locations. Also in the transportation area were a series of studies by Greene et al. (1997) and Delucchi (2004), Parry et al. (2007), among several performed since the mid-1990s.

The more notable differences between our study and previous studies, particularly the major studies done in the early to mid-1990's, are in the different approaches to, and the extent to which the studies addressed the following:

a. Number of power plants—our study considers almost all coal and natural gas power plants in the country, whereas most other studies focused on a few sites or on plants within a state;

b. Different power generation options considered—our study considered fewer technologies than several of the previous larger studies; in particular, our study did not address the nuclear fuel cycle in the detail done in the ORNL/RFF and ExternE studies, which carried out extensive probabilistic risk modeling;

c. The manner in which the dispersion of airborne pollutants and formation of secondary pollutants were modeled—our study used a reduced form approximation of these processes whereas some previous models used more site-specific, detailed air dispersion and transformation models, albeit to a very limited number of power plant sites and/or regulatory scenarios; the early studies also had no or limited modeling and analysis of ozone and/or fine particulate matter (2.5 microns or less in diameter) formed from the chemical transformation of pollutants emitted by a power plant;

d. Consideration of greenhouse gas emissions and their damages—like all previous externality studies, our study draws on recent literature rather than undertaking new scientific research; our study uses more recent literature than most of the previous studies, though recent studies within the ExternE program used similar literature;

e.   Consideration of externalities associated with infrastructure and energy security—of the latter, ORNL/RFF and ExtenE focused only on oil security;

f.   The extent to which the entire life cycle of an energy technology (from feedstock through conversion through fuel distribution through energy service) was analyzed—the ways in which the different technology fuel cycles were analyzed—the ORNL/RFF, ExternE and our study considered life cycle impacts, whereas most other studies focus just on electricity generation or use of vehicles in transportation, but not the upstream activities in the life cycle; and

g.   The extent that externalities, other than those associated with electricity generation, were addressed in the same study (that is, transportation and energy used for heat).

With some exceptions, the "adders" studies of the early and mid-1990s took a place-based approach to damage estimation. Those previous studies would posit the construction of a new generation plant of a particular type at a given location. Each study considered a limited number of alternative locations for each plant, generally from two to five in number. In those studies, the different results calculated for the different plants would reflect the influence of the specific location of the plant on the magnitude of the damages. In contrast, our study calculates the health-related and some of the environmental damages for most of the power plants in the United States and estimates the damages from each. In this respect, it is similar to the U.S. Environmental Protection Agency's regulatory impact analyses that use the BenMAP model and to the efforts of Muller and Mendelsohn (2007), which, although not studies of externalities per se, are comprehensive in their level of spatial resolution, such as the addressing the specific location of all power-plant emissions.

The ORNL/RFF and ExternE studies included relatively detailed engineering descriptions of the technologies of the power plants, whereas our study and most other studies focused on estimates of emissions from power plants and not on the underlying technologies.

In estimating the health and environmental damages, the ORNL/RFF and ExternE studies used different, detailed models to predict the dispersion of primary pollutants from the power plants and the atmospheric formation of secondary pollutants, specifically ozone and fine particulate matter. Studies of externalities associated with greenhouse gas emissions generally either focus exclusively on these emissions and the associated climate change, as exemplified by the authoritative reports of the Intergovernmental Panel on Climate Change, or focus on other pollutants. Our study, on the other hand, provides a range of quantitative estimates of the damages from climate change, in monetary terms. The previous externality studies either do not include this important issue in their analysis or, as in the case of the ORNL/RFF and ExternE studies, draw on a more dated and limited scientific literature in this area.

Externalities associated with infrastructure and energy security are usually not addressed in other studies. Our report considers electric grid externalities, infrastructure vulnerability to attacks and accidents, and national security. The ORNL/RFF study provided estimates of damages from dependence on foreign oil, and other studies focused on this issue have provided updated estimates. However, as discussed in our report, although damages might result from global dependence on oil in a cartel-dominated market, such damages are not considered externalities.

The ORNL/RFF and ExternE's consideration of damages from different parts of the life cycle, e.g., coal mining, sets them apart from most other studies, which do not consider externalities on a life cycle basis. Several studies have estimated life cycle emissions of some fuels currently, or prospectively, used in ground transportation; these studies do not attempt to estimate the impacts and associated externalities of these emissions. Our study, on the other hand, takes an energy life cycle approach somewhat similar to the ORNL/RFF and ExternE studies, but with more updated considerations and data.

Although many studies have addressed different aspects of the externalities from energy production, distribution or use to varying degrees, they have focused on one type of externality such as health effects or one particular sector, usually electricity generation or transportation, and generally one part of the energy cycle. In contrast, our study has a relatively comprehensive scope that includes all types of externalities in the energy life cycles of both electricity and transportation, as well as from production and use of energy for heat for the residential, commercial and industrial sectors.

DEFINING AND MEASURING EXTERNALITIES

Defining Externalities

External effects or "externalities" are important because the failure to account for them can lead to distortions in making decisions and to reductions in the welfare of some of society's members.

An externality, which can be positive or negative, is an activity of one agent (i.e., an individual or an organization like a company) that affects the wellbeing of another agent and occurs outside the market mechanism. In the absence of government intervention, externalities associated with energy production and use are generally not taken into account in decision making. Externalities can be either positive or negative. Box 1-2 provides definitions of the relevant technical terms used in this report that bear on externalities. Some examples of externalities using these terms are presented below. An additional illustration is presented in Appendix B.

Example 1. A coal-fired electricity generating plant, which is in compliance with current environmental regulations, releases various pollutants to the atmosphere that adversely affect the health of residents. The pollution released by the plant is an example of a negative externality because it contributes to health problems for residents. The damage from this pollution is an additional cost of production to society (a "social cost"). If these social costs were not adequately taken into account in selecting the plant's site or the air pollution control technology that it uses, the true costs of the plant have not have been reflected in these decisions.

Example 2. Many thermal power plants use water for cooling, and they therefore emit heated effluent. This emission sometimes benefits anglers because in cold regions, fish are attracted to the warmer water and therefore the fishing is better in the effluent plume. This is an example of a positive externality. The improved angling is a societal benefit that probably was not reflected in the utility's decisions about where to site the plant and effluent. This societal benefit does not take into account any other ecosystem changes, which might or might not be seen as beneficial.

Example 3. A company is building a new coal-fired power plant in a small community and hires a large number of construction workers. The increase in demand for construction workers drives up the local wage rate and adversely affects homeowners who wish to hire workers to remodel their homes. The price of their remodeling projects has gone up with the increase in wages. This is not an externality since the activity of one agent (the company building the power plant) affects other agents (homeowners wishing to remodel their homes) through a market mechanism: the labor market. The company takes the increase in wages into account because it must also pay the higher wages to attract construction workers.

Example 4. Farmers respond to a demand for corn-based ethanol by diverting land away from food production to fuel production. The reduction in the supply of feed corn and other grains drives up the prices of grains and meat thereby making consumers worse off. This is not an externality since the activity of one agent (fuel buyers bidding up the price of corn for ethanol production) affects other agents (the food-buying public) through the markets for corn and other food products.

Example 5. Workers in high-risk occupations receive a higher wage than workers doing similar tasks in jobs with lower risks. This is not an externality because those bearing the risks are freely choosing within a market, whether to accept this risk and are compensated for the risks they face through higher wages. Note that the increased costs faced by a firm do not by themselves indicate whether the firm's activities are an externality. As an example, electricity generating plants participating in the Acid Rain Program of the U.S. Clean Air Act face higher costs from their need to surrender valuable permits for each ton of sulfur dioxide emitted. This higher cost is the result of a government program to reduce the externality associated with acid rain. In the case of elevated costs to compensate for high-risk jobs, no government policy is involved in addressing the risks faced by employees due to the nature of the work they are offered.

BOX 1-2 Definitions of Key Terms

Much of the nomenclature for the key terms is taken from the damage function approach, which has been the standard approach to examine the costs and benefits of environmental regulations, required by OMB (NRC 2002a). This approach begins with some burden, say emissions, which ultimately has some physical effect; this effect is then monetized and termed damage. The monetary value of reductions in burdens is termed benefits (the opposite of damages).

Burdens: Externalities from economic activities are always by-products of those activities, some of which are useful and some of which cause health and environmental effects, for example. The by-products themselves are termed burdens. Emissions of air pollutants and discharges of pollutants into a river are examples of burdens.

Effects and Impacts: These burdens have a real effect in the environment, i.e., they have a physical component which affects health, damages ecosystems or reduces visibility, for example. Sometimes, as with energy security, the physical component is not directly present. In any event, these physical effects are termed effects or impacts.

Damages: Damages are the monetary value of the physical effects, in its simplest form calculated by multiplying the quantity of physical effects of interest by a monetary value for that effect. This monetary value represents, ideally, the population average of the maximum willingness to pay for a unit improvement in this physical metric. That is, it reflects the preferences people have for reducing this physical effect, given their income and wealth. It is analogous to the price people are willing to pay for a product for sale in a market. Benefits are the opposite of damages.

Total versus Average versus Marginal Damages: To be most helpful for policy, we want to estimate marginal damages and compare these to marginal costs to reduce these damages. The marginal damage is the damage that arises from the last unit of emissions or other type of burden. In many cases, marginal damages are constant over the relevant range of emissions. That is, the damage from the last unit is no different than the damage from the first unit of emissions. But, in some cases, say for pollutants that accumulate in the environment, marginal damages grow with more emissions.

In any event, for policy purposes, if the marginal damages from the last unit of emissions exceed the marginal costs from eliminating that unit, then it would benefit society to eliminate that last unit, since the damage prevented would exceed the cost of preventing that damage.

Total damages, in contrast, are the sum of marginal damages for all units of emissions. Average damage is the total damage divided by the number of units of emissions or other burdens in question. Average and marginal damages may equal one another under certain conditions, but in general they are different. In this report, sometimes we assume that they are equal because it is easier to calculate average rather than marginal damages and actual differences are expected to generally be within error margins.

Externalities: An externality, which can be positive or negative, is an activity of one agent (i.e., an individual or an organization like a company) that affects the wellbeing of another agent and occurs outside the market mechanism. In the absence of government intervention, externalities associated with energy production are generally not taken into account in decision making.

Externalities matter because, when they are not accounted for, they can lead to a lower quality of life for at least some members of society than could otherwise be obtained. For example, suppose that the power plant in the first example has access to technology that, at a cost of $40/ton, can cut its emissions by 10 tons. Suppose further that the full cost of the effects that residents suffer (e.g., health and psychological costs) is $50/ton. If the plant were to install the technology, total social welfare would increase—the additional cost to the plant would be $400, but the "savings" to the residents (i.e., the reduction in adverse effects they suffer) would be $500. Human well-being is increased by this change. But, unless the externality is accounted for in the plant's decisions, aggregate well-being of all members of society is lower than it could otherwise be.

It is important to distinguish true negative externalities from unfortunate market signals (such as higher prices of food) that hurt some members of society but are not externalities. The reason for this distinction is that in the case of a true externality we can raise the possible wellbeing of society by

accounting for it—we enlarge the "pie" that represents the value of society's goods, services, and related intangibles. But, if it is not a true externality, then market intervention cannot alter the size of the pie but can only reallocate it.

Note the following additional points about externalities:

- The agents that produce externalities can be organizations or individuals. For instance, a restaurant diner who smokes an after-dinner cigarette (besides breaking the law in most states) creates an externality for others in the restaurant.
- The activities that produce negative externalities usually also produce benefits for someone in society. The electricity that is produced by the coal-fired power plant provides value to the consumers who purchase that electricity. The externality arises from the side-effects of that benefit-producing activity that are not reflected in its market price.

How Externalities Are Characterized in This Study

Most of the externalities associated with the production and consumption of energy have been addressed, or corrected, to some degree, through public policies. Coal mining and oil and gas extraction are subject to federal, state and local regulations that are intended to limit the environmental damages from fuel extraction. Air pollution emissions by power plants are regulated under the Clean Air Act, and tailpipe emissions from motor vehicles are regulated at the federal and state levels. Indeed, regulations designed to correct externalities have substantially reduced their magnitude over the past 30 years. What we evaluate in this study are the externalities that remain in 2005—and the externalities that are predicted to remain in 2030—after such regulations have been implemented.

To make clear what we evaluate in this study, consider Figure 1-1, which shows the marginal damage associated with sulfur dioxide emissions and the marginal cost of emitting SO_2 for a hypothetical power plant in a particular year. According to the graph, the damages of emitting each additional ton of SO_2 are \$1,000. The cost of emitting another ton of SO_2 declines as more is emitted—equivalently, the marginal cost of reducing SO_2 emissions (moving from right to left on the horizontal axis) increases as less SO_2 is emitted. If Firm 1 (the hypothetical power plant) in 2005 is emitting E1 tons of SO_2, the external damages we quantify equal the shaded area in Figure 1-1—that is, we quantify the total damages associated with the firm's current level of emissions.[1] If the firm were emitting E* of SO_2, the external damages we evaluate in the study would correspond to the rectangle 0ABE*. We also express these damages per kilowatt-hour of electricity produced and quantify the marginal damage of each ton of SO_2 produced by the plant for a specific year.

It is important to note that, from the viewpoint of economic efficiency, the externalities that we characterize may be too large or too small. The economically optimal level of SO_2 emissions occurs at E* where the cost of reducing the last ton of SO_2 equals the corresponding reduction in damages. Even at the optimal point, damages occur—an externality remains, even though emissions are at an economically optimal level.[2]

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[1]We calculate aggregated damages by estimating the damages per ton of SO_2 (the horizontal line in Figure 1-1) and multiplying by the number of tons of SO_2 emitted in 2005, to which we add similar calculations for NO_x and directly emitted PM. We therefore calculate the marginal damage per ton of SO_2 (and per ton of NO_x and PM) at each plant, which are reported in Chapter 2.

[2]Some economists might say that there is no externality if emissions are at the optimal level (E* in Figure 1-1). We, however, follow Baumol and Oates (1988) in saying that an externality still exists, even though it may be at an optimal level.
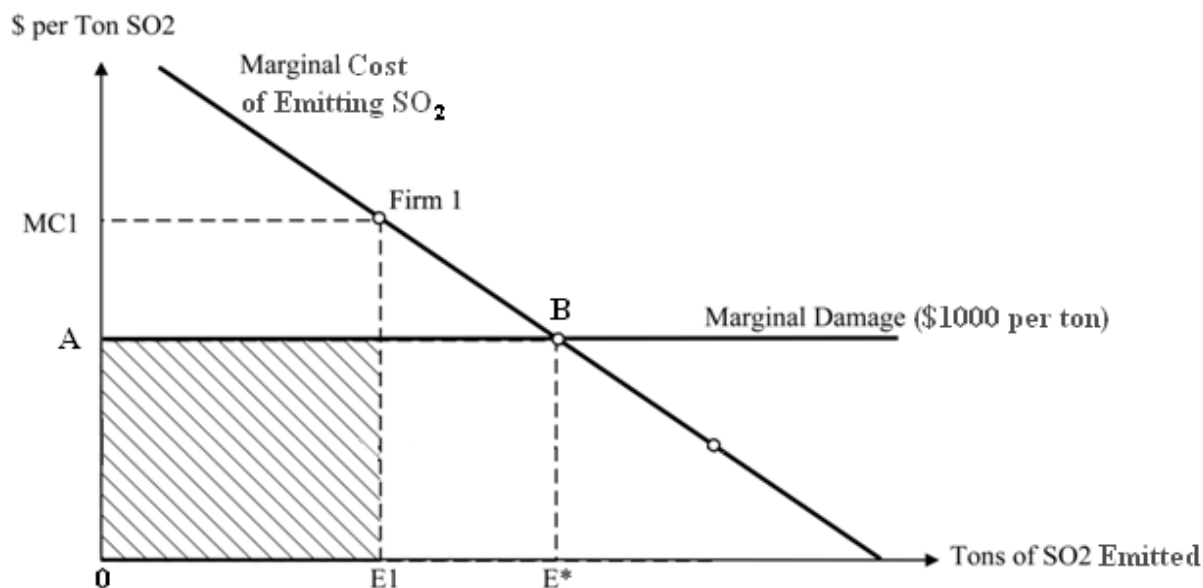
FIGURE 1-1 Marginal damage associated with SO_2 emissions in a year (x-axis) and the marginal cost of emitting SO_2 in a year (y-axis) for a hypothetical power plant (Firm 1) emitting SO_2; E1 = amount of SO_2 (tons) emitted by firm 1; E* = economically optimal level of SO_2 emissions. Damages of emitting each additional ton of SO_2 are assumed to be constant.

What then is the significance of the externalities presented in this study? As is clear from the diagram, whether emissions should be reduced or increased from the viewpoint of economic efficiency depends on the current level of emissions and the cost of reducing them; it cannot be determined from the size of total damages alone. However, evaluating economic efficiency requires information about the costs of abating SO_2, which are outside the scope of this study. This does not mean that information about total damages is without value on its own: plants with large total damages should likely be subject to a benefit-cost analysis of pollution control measures to see whether further pollution control is warranted.

Economic theory also suggests efficient methods of regulating the externalities associated with air pollution. The theory suggests that the first-best solution to internalizing the damages in Figure 1-1 could be achieved by imposing a tax on SO_2 emissions equal to the marginal damage the emissions impose—a tax equal to the height of the marginal damage curve. This solution could also be achieved by a pollution permit market in which firms traded rights to pollute denominated in damage terms (Roumasset and Smith 1990; Hung and Shaw 2005).[3] In either case, a firm would have an incentive to reduce its rate of SO_2 emissions to E*.[4] Information on the marginal damages associated with various pollutants, which we quantify for fossil fueled power plants, are relevant to the efficient regulation of air pollution externalities.[5]

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[3]An important caveat to these points is that they assume there are no significant market distortions in the rest of the economy (e.g., other externalities left unregulated or imperfectly competitive markets).

[4]Imposing a tax equal to SO_2 damages per kilowatt-hour, i.e., to the size of damages divided by electricity production, would not provide the same incentive—indeed, it need bear no particular relationship to the marginal damages associated with SO_2.

[5]External damages per unit of output (i.e., damages per kilowatt-hour or per mile) may also help to inform the choice among technologies. (Should a new power plant be gas-fired or coal-fired?) However, the choice among technologies should be based on the private as well as social costs.

Non-externality Market Distortions and Impacts

There are many other distortions that occur in markets related to energy production and consumption that create opportunities for improvement of social welfare, but that are not externalities. Since these distortions are outside the purview of our study, we touch only briefly on them here, largely to be clear that we do not attempt to identify and quantify the social costs associated with those distortions and to recognize that the magnitude of externalities can be directly affected by the presence of these distortions.

One form of market distortion that affects energy markets is the presence of market power: in the extreme, a single supplier of energy (monopoly) or a single buyer (monopsony). In such cases, a firm with market power can affect the price and quantity traded to its advantage but impose costs on others that exceed its gains. Cartels such as OPEC, or large purchasers of oil such as the United States, can exhibit market power.

Another form of market distortion that affects energy markets is the presence of taxes or subsidies (tax breaks) that do not correct externalities, but are imposed to raise revenue, provide support to an industry, or for some other purpose. Of chief concern for our study is that these subsidies can affect the amount of an externality generated by an industry. For example, subsidies for gas exploration have encouraged the expansion of the petroleum industry and thereby enlarged the magnitude of the externalities generated by the production and consumption of petroleum.

Information asymmetries and public goods are two additional cases of market failure that could impact energy markets. In this study, we quantify to the extent possible the non-internalized externalities conditional on the existing set of market regulations, taxes, subsidies, and market distortions from all sources.

In addition to market distortions that are not externalities, there are impacts of energy production and use which may be of public concern but which are not externalities. For example, as discussed earlier, increased corn prices due to the production of biofuels do not represent an externality as they result from the proper functioning of a market. This is not to say that higher corn prices are unimportant or that they shouldn't be the subject of public concern and policy. However, there is no market failure to correct, nor is there an externality to internalize. Another important example is the distribution of social costs across space, time or different population groups. Such distributional issues may be of great concern to policy makers, but they do not represent externalities.

In this study, we have restricted our attention to externalities, but we do point out some non-external impacts when relevant. For example, occupational injuries in coal mining and oil and natural gas extraction do not qualify as externalities according to our definition; however, there is interest in many quarters in documenting the magnitude of these impacts and so they are quantified (but not monetized) below.

SELECTING ENERGY SOURCES AND USES FOR THIS STUDY

The committee's task was the evaluation of externalities "associated with the production, distribution and consumption of energy from various selected sources." Studying selected sources was necessary because it would have been infeasible to evaluate the entire energy system with the time and resources available to the committee. In selecting the sources for study, the committee was careful to include major elements of the energy system and the most significant externalities.

To create a basis for the committee's selection of energy sources and their end-use services, we started with the general framework shown in Figure 1-2. Depicted in the figure are energy sources: fossil fuels (coal petroleum, natural gas), nuclear energy and the various "renewables" (biomass, solar, wind, etc.) Also shown are the various forms of energy that these sources represent or into which they are
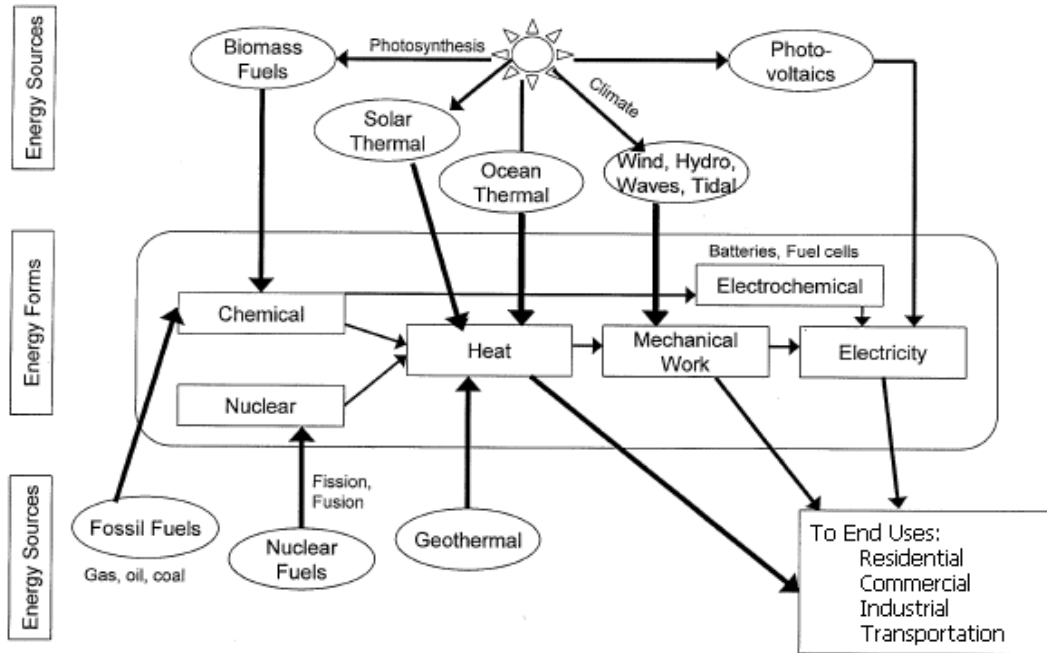
FIGURE 1-2 Sources and forms of energy that provide the ability to do useful work. Source: Tester et al. 2005. Reprinted with permission; copyright 2006, MIT Press.

converted for use by industry and residential users and in transportation. For example, coal is combusted in electrical power plants to produce heat that is used to turn turbines (mechanical work) which turn generators which produce electricity that is transmitted to houses and factories.

Some energy sources, e.g. solar, produce heat directly without a combustion step, while others e.g. wind, produce mechanical work directly. Furthermore, heat is, of course, used directly in, for example, home-heating by natural gas, without further conversion into mechanical work or electricity. Although they are not depicted in the diagram, it is worth keeping in mind that there are energy losses associated with the conversion, movement and use of energy. In general, the more steps in the process, the less efficient our use of energy is.

Figure 1-3 shows energy flows from primary energy sources to end uses in the United States in 2007. Total U.S. energy usage in 2007 amounted to 101.5 quadrillion British thermal units (quads), so the numbers shown on the figure also approximately correspond to percentages. We note that electricity is an intermediate form of energy. From the perspective of the impacts of energy use in the United States, electric power is especially important, even though it's not an energy source or end use, per se. The losses associated with energy transformation and transport are also shown as "rejected energy" or loss of useful energy. The amount of rejected energy (58.47 quads) exceeds the amount of energy that is actually providing energy services (43.04 quads).

The percent contribution of each energy source to total U.S. energy consumption is shown in Figure 1-4. Primary energy use, and energy delivered by sectors are shown in Figures 1-5 and 1-6, respectively. In Figure 1-5, the shaded regions in the end-use and electric power bars show how much each source contributed to the total U.S. energy use of 101.5 quadrillion Btu's (or "quads") in 2007. For example, petroleum use for transportation was approximately 28 quads in 2007. Figure 1-5 also shows that, of the 101.6 quads used in 2007, 40.6 quads were in the form of electricity.

Energy Flows in the U.S. Economy 2007
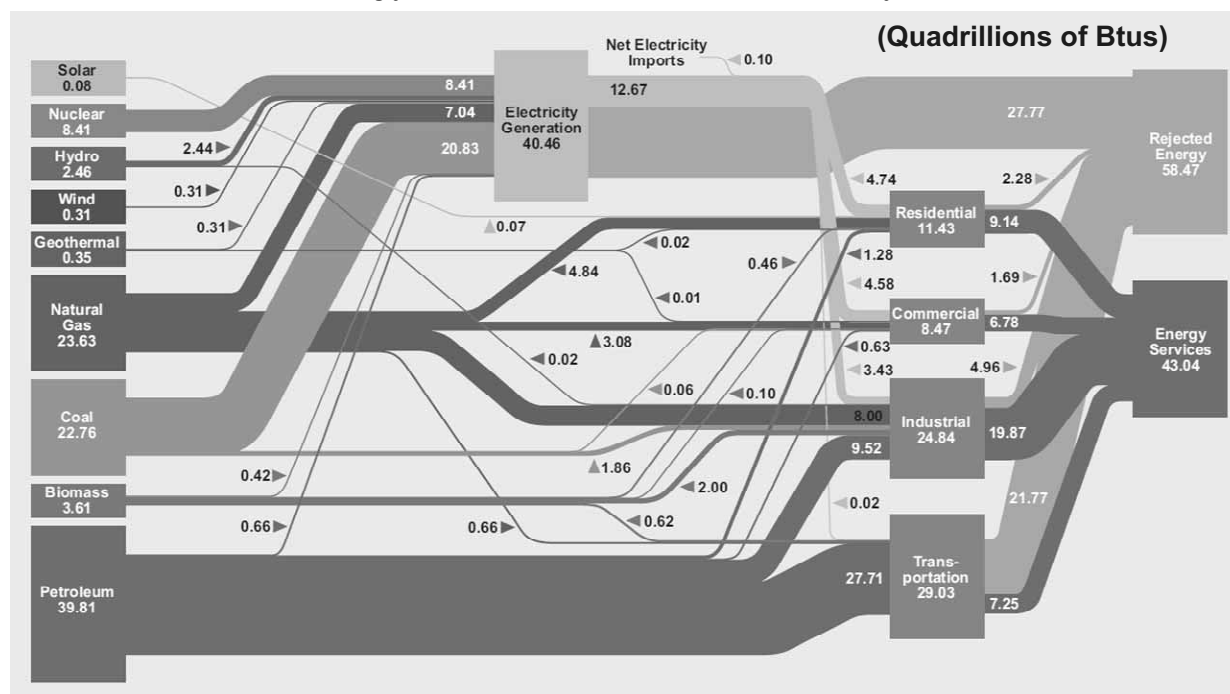
FIGURE 1-3 Energy flows in the U.S. economy, 2007. An illustration of energy movement from primary sources, boxes on the left side, to consumption by end-use sectors (residential, commercial, industrial, and transportation), boxes on the right side. Source: Prepared by Lawrence Livermore National Laboratory and the Department of Energy (NAS/NAE/NRC 2009a, p. 17).
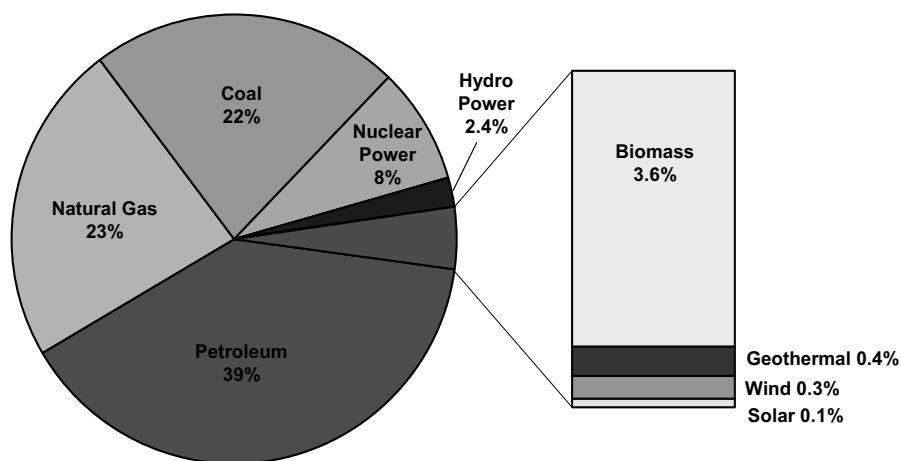
FIGURE 1-4 U.S. consumption of primary energy sources in 2007. Data for figure obtained from EIA2008a, Table 2.1a.
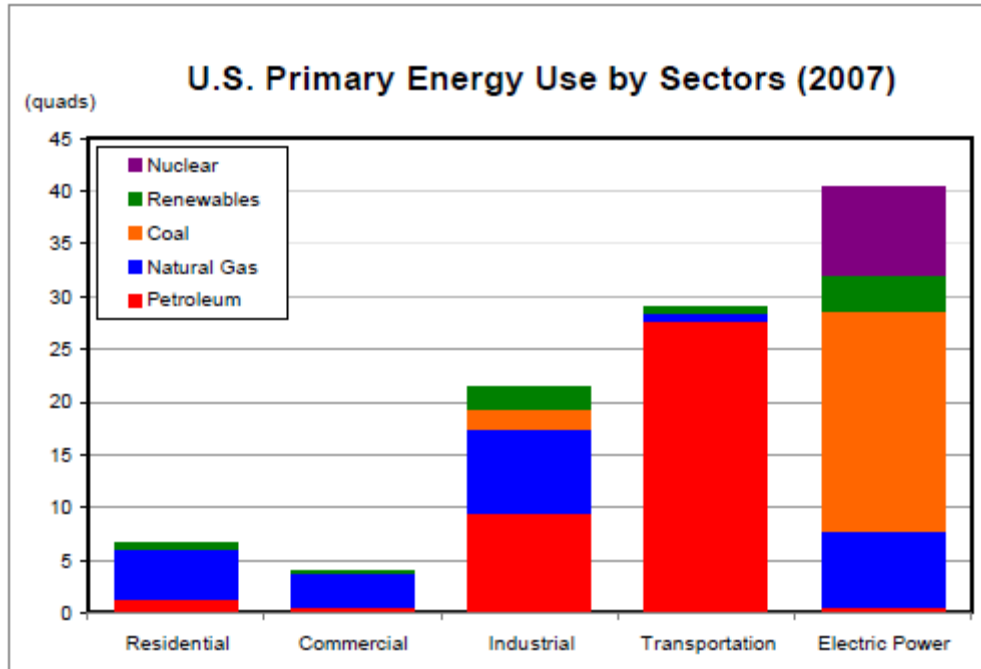
FIGURE 1-5 U.S. consumption of energy by sector in 2007. Primary energy consumption by sector and fuel type in the United States in 2007. Natural gas is the major fuel type for the residential and commercial sectors. Petroleum and natural gas are the major fuel types for the industrial sector. Petroleum is by far the major fuel type for the transportation sector. For electric power, coal is the major fuel type, followed by natural gas and nuclear power. Energy consumed by the electric power sector is used to produce electricity consumed by the end-use sectors. Source: EIA 2008b, in NAS/NAE/NRC 2009a, p. 22, Figure 1.8.

In Figure 1-6, each end use sector shows the total 2007 energy use in that sector, comprised of electricity and "primary" energy sources. For example, the figure shows that industrial end users used 33.4 quads in 2007, 12.0 quads of which were in the form of electricity.

Figures 1-3, 1-4, 1-5, and 1-6 contain several notable facts about U.S. energy production and use. In addition to the overwhelming dependence of transportation on petroleum, noted above, we also see, for example, that the vast majority of coal use in the United States is for electricity generation and that renewables and nuclear energy each represent relatively small fractions of total energy use.

Table 1-1 displays the selected sources and end uses for the analysis of external effects for this report. The energy sources are arrayed as rows. (Note that we have listed each of the renewables separately.) The end uses are shown as columns; here, for convenience, we have listed electric production as an end use, and we have focused our attention in the industrial sector and commercial/residential sectors (buildings) on their use of energy for heating.

The committee discussed every cell in Table 1-1 at length and selected the shaded cells for evaluation. Given the available time and resources, we chose those cells which represented the largest portions of the U.S. energy system or those that represent energy sources with substantial increases (>20%) in consumption over the past 5 years (2002 to 2007). Thus, coal for electricity production and petroleum for transportation, which are the two largest single components of the U.S. energy system, were obvious choices. Natural gas is an important fuel, comparable to coal as a source. We included its use for electricity production and space heating in buildings. Wind, biomass, and solar were also included due to increased consumption in recent years.

The committee also included cells which represented sources and uses of particular current policy interest and/or which are expected to grow in significance (such as nuclear energy for electricity production).
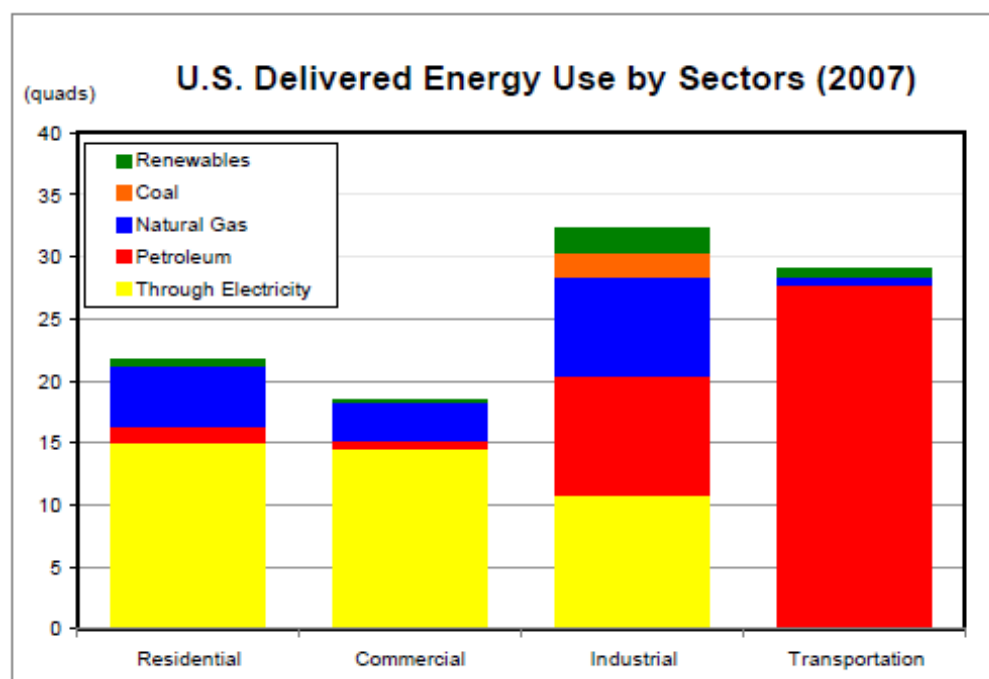
FIGURE 1-6 U.S. delivered energy consumption by end-use sector in 2007. Delivered energy consumption in the United States in 2007 shown by sector and by fuel type. Delivered energy consumption assigns primary energy sources consumed to produce electricity to the appropriate end-use sector. Electricity predominates in the residential and commercial sectors. Electricity, petroleum, and natural gas are the main forms of delivered energy for industry. Petroleum is by far the major fuel type for the transportation sector. Source: EIA 2008b, in NAS/NAE/NRC 2009a, p. 22, Figure 1.9.

TABLE 1-1 Committee Study Approach for Energy Sources and Consumption Sectors[a]

Energy Source	Electricity Production (See Chapter 2)	Transportation (See Chapter 3)	Industry – Heat (See Chapter 4)	Buildings – Heat (See Chapter 4)
Oil		MA	QE	QE
Coal	MA			
Natural Gas/Liquid	MA	MA	QE	MA
Uranium	QL			
Biomass	QL	MA		
Hydropower				
Geothermal				
Wind	QL			
Solar Power	QL			QE
Other Fuels[b]		MA		
Electricity[c]	—	MA	QE	QE

[a]The shaded cells indicate where the committee focused its consideration. MA = modeling analysis conducted by the committee; QL = quantitative information obtained from the literature; QE = qualitative evaluation.
[b]Other fuels includes hydrogen fuel cells and coal-based liquid fuels.
[c]Electricity is considered an intermediate energy source (generated from the combustion/use of coal, natural gas, uranium, and renewables). Electricity is included in this table because it is treated as a "whole" in Chapters 2 and 4, rather than by individual primary energy sources. For the transportation column, electricity also includes the manufacture and use of lithium batteries.

The base year for our analyses was 2005 (or the nearest year for which data were available). The committee also decided to choose a future year so as to gain insight into the impact of future technologies on energy externalities. We chose 2030 for this purpose so as to be consistent with and leverage the work of the AEF.

Identification of significant alternative energy technologies that are being considered for implementation before 2030 was guided by the AEF reports and other sources. Those that were evaluated are already in various stages of development and commercialization, so that some information on potential externalities is available. Other technologies that are still in research and early demonstration phases may be available for commercialization by 2030, but the committee decided that credible evaluation of externalities would be premature before more was known about actual performance. The future technologies evaluated for the 2030 timeframe are as follows:

- Electricity Sector (Chapter 2): Nuclear power impacts are included in the present electricity generation portfolio and will apply to continuing or expanding use of this source. Biomass, wind, and solar photovoltaics (PV) are already deployed to some extent in the present electricity production portfolio. In 2030, all of these technologies may be advanced and be a more important part of the electricity mix, so it is important to assess their externalities—both positive and negative. The AEF Panel Report on Electricity from Renewables (NAS/NAE/NRC 2009b) states that a "reasonable target" for 2020 is to have non-hydropower renewables as 10% of the generation mix. Most of this is expected to come from wind, as solar PV technologies still face challenges of costs and technology development that limit likely deployment to a few percent on this timescale. Not evaluated were: hydropower (about 2.5% of the sector and unlikely to grow much); geothermal (about 0.3% of present use and unlikely to grow much until enhanced geothermal system technologies, for example, deep-heat mining, are improved); and, fossil fuel power plants with carbon capture and sequestration (CCS) which seem technically feasible but still are far from large-scale implementation and will require new infrastructure for carbon dioxide transportation to sequestration sites of proven integrity. The addition of significant amounts of variable and non-dispatchable electricity sources (solar, wind) also presents challenges to the operability and reliability of the electric power grid, which has aging systems that need upgrading. These issues are considered in more detail in the AEF Electricity from Renewables and Technology and Transformation reports and were not a major focus in this study, but we do discuss them in the context of "network externalities" in Chapter 6.

- Transportation Sector (Chapter 3): In the 2030 timeframe, petroleum is still likely to be the major transportation fuel. There may be increased use of ethanol as a blend with gasoline or as a pure fuel. The analysis considers corn, cellulosic ethanol and cellulosic synthetic gasoline and other feedstocks as biofuel options. Electric cars and plug-in hybrids are discussed and tied to externalities from the electricity sector analyses. Compressed natural gas (CNG) is also an alternative fuel that may find use in both light and heavy duty vehicles. Some of the gasoline in use today comes from energy intensive production of Canadian oil sands; synthetic gasoline (or diesel) also can be made from coal, natural gas or biomass. The AEF panel assessing possible options for producing alternative liquid transportation fuels concluded that CCS would likely be needed to reduce GHG emissions resulting from production of liquid fuels from coal. CCS systems are not yet well enough evolved for any sort of a meaningful externalities analysis.[6] The committee evaluated hydrogen (made from fossil fuels or by electrolysis of water) to some extent, as a possible conveyor of energy for transportation in the 2030 timeframe, although its use will be limited since storage and infrastructure technologies will require considerable further development. Although aviation jet fuel is likely to remain petroleum based until alternative synthetic fuels are developed, there are some special externalities associated with aviation that will be addressed separately with regard to climate change (Chapter 5).

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[6] To allow for widespread deployment of CCS technology starting around 2020, its technical and commercial viability will need to be demonstrated for a variety of 15-20 fossil fuel fired electricity generating plants (NAS/NAE/NRC 2009a).

- Energy for Heat (Chapter 4): Consumption of energy for the production of heat for the buildings sector mostly involves natural gas, along with a little petroleum. The primary change for 2030 was assumed to be efficiency gains due, for example, to changes in building design and construction. Much of the information about potential efficiency gains was based on the AEF Efficiency Panel report, *Real Prospects for Energy Efficiency in the United States* (NAS/NAE/NRC 2009 in press). Because of its diversity and complexity, the industrial sector was discussed from a general perspective.

FRAMEWORK FOR EVALUATING EXTERNAL EFFECTS

The Life Cycle of Energy Use

When considering the external effects of using energy, people often focus on the end use, for example the air pollution from burning gasoline in an automobile. But, in fact, identifying energy's external effects requires a broader view that reflects energy's entire life cycle, from extraction of the energy source as it's found in nature through conversion, transportation, and/or transmission to its point of use and then to the ultimate fate of waste products from end uses. Thus, the committee adopted Life Cycle Assessment (LCA) as its approach to identifying the external effects of energy.

There are two general types of LCA: process-analysis-based and economic input-output (EIO) analysis-based LCA. Process-based LCA considers all inputs, including raw materials, energy, water; and all outputs, including air emissions, water discharges, and noise of included processes associated with all life-cycle stages of a product or service. EIO-LCA helps address boundary-selection problems and data intensity by creating a consistent analytical framework for the economy of an area based on government-compiled input-output tables of commodity production and use coupled with material and energy use, and emission and waste factors per monetary unit of economic output. It may not provide the level of detail of a process-based LCA. An important metric of the system studied is referred to as a functional unit (e.g., vehicle miles traveled can be used as the functional unit for LCAs related to transportation). Because of the significant variability in assumptions, boundaries, and approaches, comparisons across different assessments must be done with caution (see discussions, especially in Appendix E, in NAS/NAE/NRC 2009b).

Figure 1-7 depicts the major elements of energy use from an LCA perspective. Taking the use of domestic petroleum for automobiles as an example, the first box in Figure 1-7 would include the exploration and drilling for oil and sending it via pipeline, tanker or truck to a refinery; the second, refining to produce gasoline; the third, transport of gasoline by pipeline and trucks to service stations; and the fourth, the burning of gasoline in automobiles. Each stage in the life cycle produces impacts, and, all of them should be considered in estimating the external effects of energy use. Staying with our gas-powered auto as an example, the externalities associated with burning a gallon of gasoline are composed of the external effects of all of the "upstream" activities necessary to produce and deliver that gallon of gas to the pump, as well as the direct impacts of burning the gas in your car. Further, on a basis of a vehicle miles travelled, there are externalities associated with the car itself—the extraction and production of materials used in the manufacture of the car, the sales distribution network, the maintenance required during its life, and the ultimate disposal of the vehicle.

Energy efficiency and energy conservation are important aspects of overall energy policy, and often are considered as being equivalent to increasing the energy supply. Energy conservation refers to reducing energy use by reducing services that require energy; examples include lowering indoor temperatures in winter and raising them in summer to reduce the use of energy, and walking or riding a bicycle to reduce the use of gasoline. Energy efficiency refers to using less energy to achieve the same level of energy-based service; examples include using compact fluorescent light bulbs instead of incandescent ones to achieve the same ambient light level using less electricity, and using more efficient internal combustion engines or hybrid systems to achieve the same transportation capacity using less fuel.
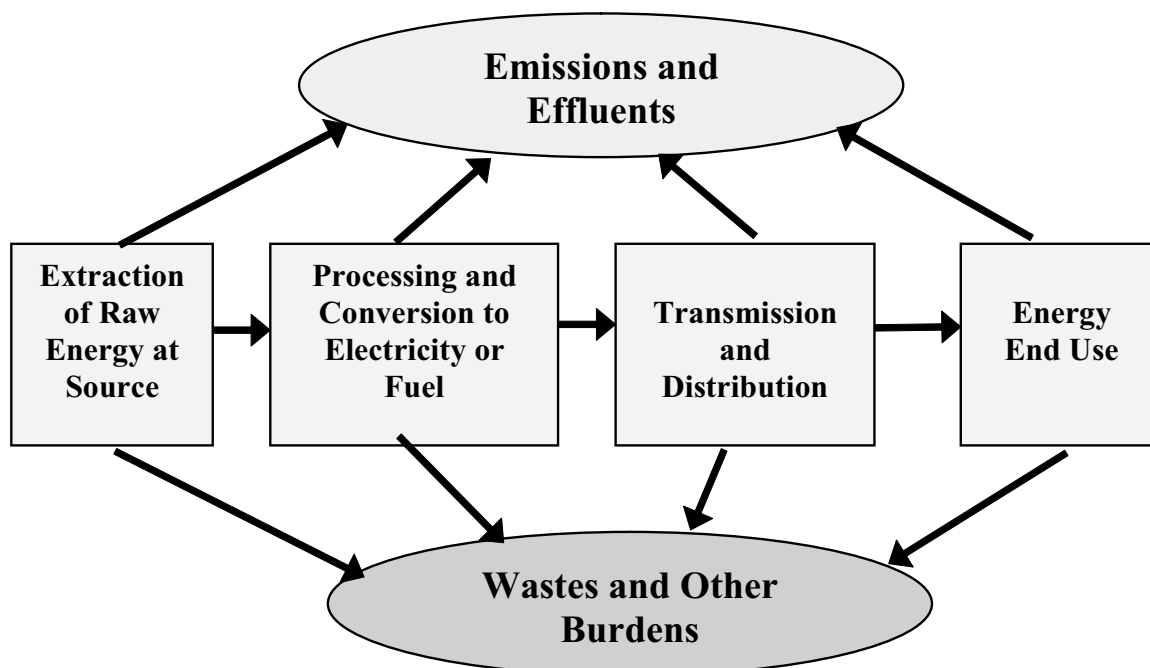
FIGURE 1-7 Life-cycle analysis for energy use.

Identifying and Quantifying Burdens, Impacts and Damages

With the life cycle stages identified, determining the externalities of energy requires us to identify the burdens, impacts and damages associated with each stage. Basically, our methodology follows what is termed the damage function approach (Jolliet et al. 2004). The burdens come in many forms (e.g., air emissions, liquid discharges, solid wastes); they move through all media (air, water and land); and, they have a range of effects or impacts (on human health, natural eco-systems and the built environment.) All of these must be accounted for in order to produce a complete estimate of damages, although, as we will see, for many energy uses some impacts and damages are far more important than others. Furthermore, some impacts are not externalities (see Box 1-2). The committee made judgments about what damages were likely to be externalities or are widely considered to be externalities (such as those associated with energy security) and focused its work on those.

Table 1-2 shows impacts at each stage of the life cycle for generating electricity from coal. These impacts are all externalities, with the exception of occupational injuries among coal miners, which are viewed as a job characteristic that is traded in labor markets. The table is intended to be illustrative; Chapter 2 provides a more thorough discussion of the external effects of electricity generation.

Some impacts are direct, easy to understand and often well-supported by data. The deaths and injuries suffered by coal miners, while not externalities, represent an example of this. Other impacts, such as the alterations in water availability or ecosystems due to climate change, are the result of very complicated physical, chemical and biological processes about which there is great uncertainty.

In this study, given the constraints on time and resources, we relied on past work in the identification of impacts and their value as damages. We did not attempt to develop new methods for estimating impacts and damages, but we did identify areas where additional research would be particularly valuable.

TABLE 1-2 Illustrative Impacts of Producing Electricity from Coal

	Human Health	Ecosystems	Security and Infrastructure
Coal Mining	Coal miners' mortality and morbidity	Land disturbance river alteration, acid mine drainage	
Transportation of coal to power plants	Death and injury from accidents	Vegetation damage from air pollution	Load on transportation systems
Burning of coal	Mortality and morbidity From air pollution	Ecosystem effects from cooling Water discharges Ecological changes from climate change	Degradation of building materials Agricultural shifts and coastal community impacts due to climate change
Disposal of waste	Health effects of heavy metals in ash and other waste	Ecosystems effects of ash and other wastes	
Transmission of electricity		Disturbance of ecosystems by utility towers and rights of way	Vulnerability of transmission system to attack or disaster

It is important to realize that estimating most of these impacts and damages is a several-step process based on many assumptions; this is true for even relatively well-understood impacts. Let's take one of the boxes in Table 1-2: human health effects of air pollution from coal-fired power plants. Arriving at an estimate requires us to

1. Estimate *burdens:* air emissions (which depends, among other things, on the particular coal that is used, the boiler technology and pollution control technology)
2. Estimate the ambient concentration of air pollutants (which depends, among other things, on the height of the exhaust stack, the location of the plant, and prevailing wind patterns)
3. Estimate the exposure of people to air pollutants (which depends, among other things, on where people live, and how much time they spend outside)
4. Estimate *effects or impacts:* the health consequences of the exposures (which depends, among other things, on the age and health status of the exposed population and their life styles, e.g., whether they smoke.)
5. Estimate *damages:* the value of avoiding these impacts to society (which depends, among other things, on incomes of individuals in society, the seriousness of the impact, as judged by individuals, etc.)

This emission → ambient concentration → exposure → impact → damage estimation process is generalizable and underlies each box in Table 1-2 and the estimation of most of the damages considered in this study. Security of energy supplies and network externalities, both discussed in Chapter 6, do not fit so neatly into this framework, but virtually everything else does.

There are, as noted, many assumptions that must be made. Many of the assumptions are specific to the case at hand, and we make clear in the context of each analysis what the key assumptions are. One cross-cutting issue is the matter of the distribution of impacts and damages, both spatially and within populations. This is discussed later in the chapter.

Evaluating Impacts

Evaluating damages requires an estimation of the impacts, the tangible manifestation of the burdens of energy use. Thus, we have to express impacts in tangible terms and associate with each impact a metric or measure.

Let's return to Table 1-2 for a moment. The impacts shown there are all in physical or biological terms. Describing some of them is fairly straightforward, e.g. death and injury from transportation accidents, and we can associate with each a metric. So, for example, a metric for the human health effects from coal transportation is the annual deaths from transportation accidents. Another metric is the number of injuries from transportation accidents. Both are meaningful, easily understood measures or indicators of the impact we're interested in, and there are data available for quantifying them.

Other impacts are not nearly so straightforward. Virtually all of the ecosystem impacts—no matter their cause—present a real challenge for evaluation. One could say that the overarching concern is ecosystem health, but this is not a useful metric: how would one define it or quantify it? We could use physical, chemical and/or biological surrogates, e.g. changes in water temperature, the concentrations of key chemical constituents in water, and biological productivity. Each of these is well-defined and measurable, but it's arguable whether they adequately reflect changes in ecosystem health, individually or collectively (see EPASAB 2009)

A potential source of complexity in impact assessment is cumulative effects which can be important and are often inadequately assessed. Our discussion here largely follows NRC (2003a).

Concern about cumulative effects started in a formal sense with the passage of the National Environmental Policy Act (NEPA) of 1969, motivated by the environmental effects of multiple electric-power plants. In 1978, the president's Council on Environmental Quality (CEQ) promulgated regulations

for implementing the NEPA (40CFR Parts 1500-1508 {1978}) that defined a cumulative effect as "the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions. . . . Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." Thus a single power plant might have only minor, or acceptable, impacts on, say, an estuary but the effects of multiple plants might be substantial and qualitatively different from the effects of only one plant. In other words, the effects can accumulate. Similarly, some of the effects of smokestack emissions from power plants can interact with those of automobile and industrial emissions; in addition, effects can accumulate over time. As NRC (2003a) pointed out, effects can be synergistic or antagonistic (in other words, they can be greater or smaller than the sum of their parts), and they can have thresholds.

Indeed, thresholds are an important complication in measuring impacts, especially for some environmental effects. Here, we're concerned not just with (say) increased water temperatures but temperatures above a certain level at which especially significant biological impacts occur, e.g. massive fish kills.

Many threshold effects like water temperatures are relatively well-understood and predictable, based on scientific knowledge. Others are more controversial, due to the uncertainty of the underlying science and the economic and other consequences of dealing with the impact. For example, there has been a long standing disagreement over whether there is a non-zero level of exposure to radioactivity which is safe for humans. A more recent example relates to climate change and the potential for relatively rapid and perhaps irreversible shifts in certain of earth's subsystems producing, for example, accelerated melting of ice sheets and caps.

Since our ultimate concern is human health and the environment (or more, generally, social welfare), these threshold effects are important. We can measure water temperature reliably, but it's not the temperature that we really care about; it's how life forms respond to that temperature that matters. If the two are proportional, then a physical measure like water temperature can be a useful surrogate metric. When that proportionality breaks down, as it does when there's a sharp threshold, the surrogate loses its utility.

Beyond cumulative effects, thresholds and other physical complexities, some impacts are just very hard to quantify because they are highly subjective. Aesthetics is a good example of a factor whose quantification is highly uncertain. For example, harvesting trees in a forest affects the aesthetic appearance of the forest. One might consider the number of trees removed as a metric. Of course, the problem with such a metric is that it's not just the number of trees; it's which trees.

Qualitative impacts present a special challenge to communicate, particularly to do so in a way that decision makers take them into account. The adage, "You can't manage what you can't measure," can be dangerous or, at least, limiting if the absence of quantification is taken to mean a value of zero. See our discussion of uncertainty at the end of this chapter.

Table 1-3 summarizes impact pathways and associated effects evaluated in an ExternE study on electricity and transportation.

Damage Estimation: Monetizing Impacts

It is relatively straightforward to monetize goods that are routinely traded in markets as the market prices give us direct information about the monetary worth of the good. Thus, if a family is willing to purchase salmon at the market price, then the value of the salmon must be at least as great as the price it paid, otherwise the family would not have been willing to give up the other items they could have purchased with that money. The market price gives us important information about how much this family is willing to tradeoff other items to have salmon for dinner. However, many of the externalities that we are interested in for this report do not trade in markets so information on people's preferences is not readily available. Nonetheless, these "nonmarket" goods may have as much or more value to people as goods that do trade in markets (that is, if required, they would be willing to give up a lot to have them).

TABLE 1-3 Illustrative Impact Categories Pathways[a]

Impact Category	Pollutant/Burden	Effects
Human Health - mortality	PM, SO_2	Reduction in life expectancy
	Benzene, Benzo[a]pyrene 1,3-butadiene Diesel particles	Cancers
	Noise	Loss of amenity, impact on health
	Accident risk	Fatality risk from traffic and workplace accidents
Human Health - morbidity	PM, O_3, SO_2 PM, O_3 PM, CO	Respiratory hospital admissions Restricted activity days Congestive heart failure
	Benzene, Benzo[a]pyrene 1,3-butadiene Diesel particles	Cancer risk (nonfatal)
	PM	Cerebro-vascular hospital admissions Cases of chronic bronchitis Cases of chronic cough in children Cough in asthmatics Lower respiratory symptoms
	O_3	Asthma attacks Symptom days
	Noise	Myocardial infarction Angina pectoris Hypertension Sleep disturbance
	Accident risk	Risk of injuries from traffic and workplace accidents
Building Material	SO_2 Acid deposition	Ageing of galvanized steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	NO_x, SO_2	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O_3	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
Global Warming	CO_2, CH_4, N_2O, N, S	World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	Acid deposition, nitrogen deposition	Acidity and eutrophication (avoidance costs for reducing areas where critical loads are exceeded)

[a]ExternE developed this list to indicate the types of health and other impacts that were included in its investigations.
Source: EC 2003, p.3. Reprinted with permission; copyright 2003, European Communities.

The main goal in monetizing the impacts of externalities is to place externalities on equal footing with other goods and services. When decision makers must decide whether to tax an externality, increase public funding for education, or reduce support for anti-smoking programs, it is important for them to understand how their constituents view the value of these services vis-à-vis each other as well as other uses of funds. The economic value of a good indicates the rate that someone is willing to trade off having that good in terms of the other things they are willing to forgo. The goal is simply to understand the tradeoffs people are willing to make to get more of a good (or avoid doing without). This is a very useful concept for public policy decisions.

To monetize the impacts of externalities, we follow standard practice and define the monetized value of an externality to an individual as the maximum amount that an individual would be willing to pay to obtain the good. This concept is often abbreviated as willingness-to-pay or just WTP.[7]

There are both practical and conceptual arguments for attaching monetary values to impacts. One practical reason for monetization derives from the multiplicity of external effects and the difficulty of evaluating them in the context of national policy making. Taking just the partial list of metrics from external effects of coal-fired power plants, we have: deaths from coal transportation, injuries from coal transportation, and water temperature increases from cooling water discharges. Our goal is to make sure that these effects are factored into decisions related to producing electricity from coal. This requires a method for weighing these metrics against each other and, for policy, against the costs of reducing these effects.

One class of methods is to use a numeraire to develop weights for each effect and aggregate them. Indeed, in this report, the numeraire we use is dollars, with the weights developed through the literature on the willingness to pay for reducing a given type of effect. Another class of methods is to not establish specific weights but to use multiattribute utility functions or more, generally, multiple-criteria approaches. (see, for example, Keeney and Raiffa [1993] and Cohon [2004]). Such an approach has been used in the past in the evaluation of federal water projects, but that approach dealt with three or four metrics at a time, not the dozens of metrics associated with the externalities of energy production and use. In contrast, using a monetary metric, to the extent practicable, converting all of these metrics into the single unit of dollars, and adding them up, produces a single grand metric of all of the external effects. This is a powerful result of great potential use to policy makers.

By estimating willingness to pay we can place a monetary value on each external effect and add them up, producing a single dollar value for total external effects, which represents an estimate of the value that society places on those effects.

In this study, we did not have the time or resources to undertake new valuation studies and have therefore relied on existing studies of the monetary values of the externalities we study. One important example of a value we take from the literature is commonly referred to as the "value of a statistical life" (or VSL) which characterizes the rate at which people are willing to trade increased risk of death for other goods and services. By observing in many occupational and other settings how much people have been willing to pay to reduce the risk of death (or are paid in compensation for taking additional death risks), or by conducting surveys that ask people how much they are willing to pay to lower their death risks, estimates have been made for the VSL which are used in regulatory decision making around the world, including various agencies in the U.S. government. We used these values in our study, as explained in Chapters 2 through 5.

Using willingness to pay as a monetary metric can make some people uncomfortable. There are some effects that are especially difficult to value, for example ecological impacts because there are many components of ecosystem services that we do not understand and for which people retain inherent cultural values. So at first blush, potential ecological impacts from climate change, such as lost polar bear habitat, seem to defy monetization. While in practice estimating the effect on polar bear habitat is indeed very difficult due to the poorly understood relationship between changing greenhouse gas concentrations, climate effects, and therefore reduced habitat, the fundamental economic valuation questions remains conceptually straightforward: how much of other goods and services (education, housing, health care) would people be willing to give up in exchange for preserving polar bear habitat? This conceptual answer will differ depending on whether there are many polar bears left in the wild, or whether there are only a few. Whether we are able to estimate a monetary value that is accurate enough for use in policy decisions remains a challenge for many ecological services. We have used willingness to pay to monetize external effects wherever possible, recognizing its limitations and controversies. Some effects are not monetized

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[7]There is an analogous concept of willingness to accept that is defined as the minimum amount of money an individual would be willing to receive to give up a good that he owns. The relationship between WTP and WTA and their technical counterparts, compensating and equivalent variation, can be found in graduate level textbooks.

at all, while others are monetized with great uncertainty. Indeed, some effects cannot even be estimated, much less quantified, even though we know they exist.

The committee is especially aware that ecological impacts, including impacts on ecosystem services, have not been monetized in this report. Evaluating these impacts economically has a long and challenging history (e.g., EPASAB 2009; NRC 2004a; Cropper 2000). Ecological effects that influence the production of economic goods, such as agricultural products, timber, fish, and recreational benefits, often have been monetized, although often incompletely. Indeed, this report includes some aspects of agricultural production in its monetization of the damages from emissions from electricity generation that contribute to the formation of criteria air pollutants. But changes in ecosystem services such as nutrient cycling and provision of habitat, and more subtle changes in ecosystem functioning that can affect ecosystem performance, have not generally been monetized, largely because it is difficult to quantify those changes at present (e.g., Cropper 2000). Although the committee has described these impacts qualitatively, at least to some degree, they likely are significant monetarily and otherwise.

Despite these limits, we believe that using our results will improve federal policymaking.

Consideration of External Benefits

There are obviously considerable benefits to having energy. Most of these benefits are reflected in the prices paid for energy and are not *external* benefits. For the most part, external benefits are relatively few in number and small compared to the external damages that have been identified. For example, ORNL/RFF (1994-1998) identified the crop fertilization benefits of the nitrogen and sulfur from NO_x and SO_2, respectively; the crop fertilization benefits of CO_2; and the recreation benefits of enhanced fishing opportunities in reservoirs formed from large hydro projects.

Of those, our study explicitly considered the crop fertilization benefits of CO_2; the results of the integrated assessment models we considered in Chapter 5 account for these impacts. However, we did not explicitly consider other external benefits for the following reasons. ORNL/RFF (1994-96) found the crop fertilization benefits of NO_x and SO_2 to be small compared to the health-effect damages. We did not consider reservoir recreation benefits because we did not consider hydropower as important, for the purposes of this study, as the other technologies we considered (refer to Chapter 2).

THE POLICY CONTEXT FOR THIS STUDY

Externalities are important to analyze and understand because they provide an example of a situation where government involvement can potentially improve on the market outcome. While our committee is not tasked to suggest policy recommendations to address energy-related externalities, it is instructive to indicate how knowledge about the value of externalities can be used to improve on market outcomes. This section relates the results of our study to existing policies that address externalities and discusses how the results of the study should and should not be used.

The Nature of Externalities Evaluated in This Study

As noted earlier in this chapter, what we evaluate in this study are the externalities associated with energy production and consumption that have not been corrected through existing policies; i.e., the externalities remaining after policies have been implemented. The study therefore does not document the substantial progress that has been made in reducing the external damages associated with energy production and consumption over the past few decades. To illustrate, emissions from electric power plants that contribute to criteria pollutant formation are regulated by a variety of state and federal regulations. In particular, one of the goals of Title IV of the 1990 Clean Air Act Amendments is to

reduce SO_2 emissions from coal fired power plants by 50% from 1985 levels by the year 2010. Most of these reductions were already achieved by 2005, the year of our study. What we quantify are the damages associated with remaining SO_2 emissions from fossil fueled power plants in 2005. A similar statement can be made regarding tailpipe emissions from motor vehicles. Emissions from cars per mile traveled have declined by 90% since the passage of the 1970 Clean Air Act, as a result of various regulations. We calculate remaining emissions from the fleet in 2005 and 2030.

The damages we evaluate are those associated with emissions in the years of our study, relative to zero emissions: For example, in the case of coal-fired power plants, we characterize the per plant aggregate damages associated with SO_2 emissions in 2005 compared with no SO_2 emissions. The same is true of the air pollution damages associated with motor vehicles: we evaluate the per vehicle total damages from current emissions relative to zero emissions. This is not because emissions should be reduced to zero, but because any other baseline would be arbitrary. The appropriate level of SO_2 emissions from power plants depends on the costs of reducing those emissions (see Figure 1-1), and estimating these is beyond the scope of this study. It should be noted that the methods used to estimate air pollution damages from fossil fueled power plants and motor vehicles assume that the damages of each additional ton of pollution from a source are constant[8]—hence we also compute the damages per ton of pollutant, which could be compared with control costs.

In the case of power plants, we provide estimates of the distribution of air pollution damages across power plants. This is important for two reasons: First the damages associated with a plant depend on where the plant is located, so damages vary spatially; second, total damages vary greatly across plants, due to difference in plant size and existing pollution controls. Variation in damages across plants is useful information from the perspective of pollution control: plants with large total damages may warrant further air pollution controls.

We also distinguish damages by the stage of the life cycle at which they are generated. While it is possible to aggregate NO_x damages associated with passenger transportation across all stages of the life cycle—oil exploration and extraction, oil refining, transportation of gasoline to the consumer and consumption of gasoline by a car—regulations to limit NO_x emissions will be targeted at different stages of the life cycle: regulations to limit tailpipe emissions will differ from regulations of emissions from oil refineries. This is also true of damages associated with electricity generation: it is important for policy purposes to separate mining damages from damages associated with electric power generation, because policies to control each set of externalities will differ. Thus, although we do present aggregate estimates of damages—per kilowatt hour or per mile traveled—these should be placed into proper context for policy.

Policies to Correct Externalities

Policies to address or correct externalities include taxes, transferrable pollution permits, performance standards and technology based standards. Economic theory dictates that the most efficient policies to correct externalities are those targeted at the externality itself—for example a tax on SO_2 emissions rather than a tax on the electricity associated with those emissions; a tax on NO_x emissions from motor vehicles rather than a tax on gasoline.[9] Taxing SO_2 emissions (or regulating them through a permit market or performance standard) provides an incentive to reduce SO_2 through the use of pollution

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[8]This is a common assumption in the air pollution literature. The concentration-response functions in the literature are essentially linear over the relevant range of ambient air pollution in our study. Also, the emission-to-concnetration relationship and unit costs of various health effects and other impacts are treated as constant. Unit costs are not necessarily constant across time and location.

[9]Policies that associate a price with the externality—for example a tax or a permit market—are, in general, more efficient than policies that dictate the method of correcting the externality; for example, requiring coal-fired power plants to install flue gas desulfurization units (scrubbers).

control equipment or by switching to low-sulfur coal, as well as by reducing the level of electricity produced. A tax on electricity generation does not provide the incentives to reduce SO_2 emissions per se. The same is true of a gasoline tax and NO_x emissions.

For emissions related to criteria pollutants, we therefore note that our estimates of externalities associated with emissions per kilowatt hour of electricity produced or per gallon of gasoline should not be interpreted as recommendations for electricity or gasoline taxes equal to these monetized damages. Economically efficient methods of correcting emissions that contribute to criteria air pollutants include taxes on the emissions themselves or permit markets in which rights to pollute are denominated in terms of damages.[10] A similar statement can be made for carbon dioxide emissions.   For fossil-fueled power plants we provide estimates of the damages per ton for key emissions that contribute to criteria air pollutants, as a function of plant location. For carbon dioxide emissions, we provide ranges of estimates of marginal damages.

Externalities and Technology Choice

A frequent use of estimates of the externalities associated with electric power generation and transportation is to inform technology choices when making public investment decisions. Should expansion of electricity generating capacity take the form of coal, natural gas, nuclear power or wind power? What technologies should be pursued as alternatives to gasoline-powered internal combustion engines for passenger vehicles? Our study can help to inform these choices; however, it must be emphasized that we evaluate the externalities associated with various technologies independently of their costs. For example, an integrated gasification combined cycle (IGCC) coal plant with carbon capture and storage is an extremely clean plant, but it is also an expensive one. Externalities are an important component of the choice among various technologies, but must be supplemented by estimates of private costs.

SOME METHODOLOGICAL ISSUES: SPACE, TIME, AND UNCERTAINTY

Defining and evaluating externalities is unavoidably complicated by their spatial nature, by the fact that they occur over time, perhaps very far into the future, and by uncertainty. We discuss each of these in this section.

Spatial Scales of Analysis

The external effects of energy, by their very nature, vary spatially. Some individuals and groups experience far greater effects from energy production and use than is reflected by the average amount, i.e. were the effects evenly distributed, others far less. In carrying out our task we quantitatively focused on the spatial distribution of damages caused by coal-fired or gas-fired power plants wherever they are located and by transportation emissions in each of the 3,100 counties in the U.S. Note, however, that a lack of location data for stages upstream of the power plants and vehicle operations prevents us from estimating these damages in a spatially explicit manner.

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[10]For example, if a power plant in a densely populated area creates more damages per ton of SO_2 emitted than a power plant in a remote area, the former plant would require more damage-denominated permits than the latter to emit a ton of SO2.

Consideration of Effects on U.S. vs. Global Scales

While our task specifically stipulated that the external costs and benefits of energy be analyzed from a U.S. perspective, we were also charged with consideration of broader, more global, implications when warranted and feasible. Some effects considered by the committee occur mainly in the United Sates, such as effects related to ozone-forming emissions from motor vehicles. However, other effects, such as those related to CO_2 emissions and climate change, will occur on a global scale. Likewise, for some of the security-related issues, or in transportation, which rely on energy production and distribution occurring outside the U.S., ignoring the global consequences would entail substantial distortions. Moreover, as is apparent for climate change-related effects, some parts of the world are likely to suffer inherently different, and to some extent larger, burdens of these effects than the U.S. In such situations we have elected to characterize effects *both* in the U.S. and on a global scale as consideration of these on different spatial scales might impact policy choice. For practical reasons, we have provided sparing detail regarding differential impacts among non-U.S. regions.

Consideration of Differential Effects on Local and Regional Scales *Within* the United States

Within different locations in the United States many external costs and benefits related to energy are heterogeneously distributed as well—for reasons inherent to the nature of the economic activity, or geography, or as a consequence of one or another policy choice. For example, one of the substantive health consequences of climate change in the United States is the impact on heat - and cold - related morbidity and mortality, e.g., heat waves. These impacts are far stronger in northern, cities with moderate climates within which temperatures fluctuate widely year to year. Because of differences in the extent of human physiologic adaptation to higher temperatures, more people die in heat waves in Chicago than, say, in Birmingham, AL, and rising average temperatures will accentuate that disparity further. Likewise, because of greater population density and prevailing winds, the distribution of harmful effects from emissions that form criteria air pollutants is highly non-homogeneous; for example, populations in eastern seaboard counties bear more of the health-related external costs of this external impact of electricity production from fossil fuels than do populations in upwind areas, and will continue to, irrespective of any short-term policy choices. Thus, when aggregate damages are presented, the differential impact may be partly obscured.

For other impacts, such as the local--potentially devastating--effects of a power plant disaster or disruption occurring in a distribution line (e.g., an oil or gas line), local choices may be extremely important in determining "who pays." Often, siting of these types of facilities is partially determined by geographic factors such as where production and utilization actually occur.

There are other situations in which aggregate damages may be juxtaposed *against* local damages, creating not only heterogeneity, but complex policy alternatives. For example, there is at least some evidence that centralized, rather than decentralized management of spent nuclear fuel results in an inherently lower risk of adverse external consequences; yet arguably for the site or sites chosen for a centralized activity the local "costs" can be higher. Another similar consideration is that the damages of power plant emissions vary by the population affected by the emissions.

Differences in Susceptibility over Spatial Scales

Even within the same locations, regions, or countries, there is compelling evidence that some parts of the human population or species within an ecosystem are more vulnerable than others to a particular external effect. One of the factors responsible for differential effects is age. For example, the very young and the very old are more susceptible to energy-related burdens, such as those imposed by heat-stress, water constraints or pollution. Likewise, the underlying health status of individuals or groups

creates large disparities in effects. In highly developed societies, risks of nutritional consequences of climate change or diarrheal illness are essentially nil, while these impacts dominate in societies with lower levels of overall health status. Conversely, air pollutants from electricity or transportation tend to affect, to a greater degree, individuals and societies with higher underlying rates of cardiovascular and chronic disease, which are more prevalent in richer societies. This same factor differentiates the consequence to an individual with chronic disease from his/her healthy partner, even living in the same house! All this may be confounded by disparities created by differential access to resources, e.g., socioeconomic differences, within a nation or region. For example, during the last highly publicized heat wave—Chicago 2003—almost all of the excess deaths occurred among poorer minorities without air-conditioning or ready access to health or social services. Once again, aggregate cost data would tend to mask, rather than emphasize such differences.

Temporal Issues

Some effects related to the current production and use of energy may take years, decades, or longer to manifest. For example, chronic health effects of air pollution attributable to fuel combustion are not the consequence of an exposure that occurred yesterday or a few weeks ago, but the cumulative result of a condition that develops over longer periods. As a more extreme example, health risks from the disposal of nuclear waste generated from electricity production may persist over millennia because of the long-lived nature of the radioactive waste. This persistence presents challenges in making judgments about the performance of a waste repository, the behavior of human society, and other key factors over a very long period.

One challenge is that it is very difficult to predict both the future physical effects and their future monetary values because these depend on a host of uncertainties about how people in the future will live. A second challenge arises in comparing effects that are quantified in monetary values at different times (such as expenditures on control equipment now and fewer adverse health effects in the future). In making such evaluations, two factors should be considered. One is that many opportunities exist for investing resources now to yield future benefits. The future benefits of the proposed action should be compared with the future benefits that could be achieved by investing the same resources in other ways. The other is that the people affected may differ, especially if the delays are long enough that the people are necessarily members of different generations.

It is conventional and appropriate to discount future values by a factor that depends on the distance in the future and the discount rate. (It is also necessary to account for future inflation. This is usually accomplished by valuing all consequences in "real"—i.e., "constant" or "inflation-adjusted"—dollars.) But difficulties arise in identifying the appropriate discount rate. Two approaches are often used. The first is commonly referred to as "descriptive"; the second, as "prescriptive." The descriptive approach uses a discount rate that is similar to market interest rates, which are market prices that are determined by the interactions of individuals, firms, and other institutions seeking to borrow or save for various time periods. The prescriptive approach is often used for time periods of more than about 30 years, for which market interest rates rarely exist. This approach explicitly considers two factors: the rate at which future generations' utility should be valued relative to the current generation's utility (an ethical question), and the rate at which incremental resources will enhance the future generations' utility (a descriptive question). (See Chapter 5 for further discussion.)

Estimates of the appropriate discount rate derived from the prescriptive approach are typically smaller than those derived from the descriptive approach. This divergence raises a number of ethical questions, such as whether current individuals and governments are consuming too much and investing too little, and the ethical question of how much current individuals should sacrifice to potentially benefit many future generations.

For valuation of climate change effects (see Chapter 5), the discounted value referred to as the social cost of carbon is often used. It is the combined present-day value of the damages and benefits that

will occur over many future years if an additional ton of greenhouse gas is emitted today. Estimating the discounted cost involves consideration of how current greenhouse gas emissions will affect climate over the next century or more, environmental and human welfare effects caused by climate change, how the effects may vary globally, the course of future economic development, the range and likelihood of economic and social effects arising from climate change, and the extent to which human society might adapt to climate change. Because the choice of a discount rate for such long periods involves great uncertainty, the committee will not recommend a particular discount rate for assessing the value of these effects.

Model Selection and Evaluation

The committee made extensive use of computational models to evaluate available knowledge, compare alternative technologies, and provide a framework to assess damage. The committee recognizes that all models face inherent uncertainties, because human and natural systems are more complex and heterogeneous than can be captured in a model. Moreover, the committee also recognizes that once a model is selected and applied, large uncertainties remain regarding input selection and choices of scale. In its selection and use of models, the committee relied on a report of the National Research Council's Committee on Regulatory Environmental Models (NRC, 2007), which recommended that models cannot be validated (declared true) but instead should be evaluated with regard to their suitability as tools to address a specific question. In following this approach, the committee first identified its specific questions, then identified the tools available, and finally made model selections.

The committee recognized that its analysis involved four key activities: (1) characterizing a range of technologies that provide electricity, transportation, and heating; (2) identifying the pollutant emissions (and other environmental hazards) attributable to each technology; (3) linking emissions (hazards) to exposures; (4) linking exposures to effects; and translating effects into damages that can be monetized. The committee recognized that for electricity production and heating steps 3, 4, and 5 would require the use of models and that for transportation impacts steps 2, 3, 4, and 5 would require modeling. The committee then reviewed a number of models that could support this task and considered several alternatives including the use and comparison of several models in order to address issues of model uncertainty. Ultimately, the committee recognized that the use of a single model would make its results more transparent and open to evaluation then trying to interpret results from several models. The committee selected the APEEP model (see Chapter 2) for steps 3, 4, and 5 and the GREET model (see Chapter 3) for step 2 in transportation technologies. In making these choices, the committee did not consider that these two models were necessarily the only or even the best models for this task. Instead the choice reflects the committee's recognition that these models were clearly appropriate for the task, were accessible to the committee, were transparent in their applications, and had received sufficient prior use and performance evaluation. In order to further evaluate the performance of these models for use in calculating external impacts, the committee carried out comparative evaluations where that was feasible.

Intake Fraction and Other Tools for Model Evaluation

Where feasible, the committee sought other studies with comparable results in order to evaluate the consistency of its model approach with others engaged in similar research. In making these evaluations, the concept of "intake fraction" was useful and transparent. The concept of an intake fraction as defined by Bennett et al. (2002) is the integrated incremental intake of a pollutant, summed over all exposed individuals, and occurring over a given exposure time, released from a specified source or source class, per unit of pollutant emitted. Since that time, numerous studies have estimated intake fractions for various source categories (e.g., power plants, mobile sources, residential wood burning, indoor cleaning products, and aircraft) and pollutants (such as particulate matter and toxic air pollutants). Most

importantly, use of the intake fraction approach has increasingly become a tool for model performance evaluation and model comparisons.

For source-receptor estimates from power plants, recent work by Nishioka et al. (2002) provided a model evaluation opportunity. In order to assess the health benefits of increased pollution, Nishioka et al. (2002) modeled state-by-state exposures to PM $_{2.5}$ originating from power plant combustion and used intake fraction as an intermediate output. The committee was able to compare its power plant intake fraction obtained from APEEP with theirs and got consistent results. Moreover, Nishioka et al. (2002) multiplied their population-weighted exposures derived from intake fractions by exposure-response functions for premature mortality and selected morbidity outcomes, providing the committee with further opportunity to evaluate APEEP results.

In the transportation impact modeling, there were two studies that provide key evaluation opportunities. In an effort to better characterize the relationship between mobile source emissions and subsequent fine particulate matter ($PM_{2.5}$) exposure, Greco et al. (2007) characterized PM $_{2.5}$ exposure magnitude and geographic distribution using the intake fraction. They modeled total U.S. population exposure to emissions of primary $PM_{2.5}$ as well as particle precursors SO_2 and NO_x from each of 3,080 counties in the United States. Their mean PM $_{2.5}$ intake fraction was 1.6 per million with a range of 0.12 to 25 per million compared to 1.0 per million with a range of 0.04 to 33 per million obtained from APEEP. Greco et al. (2007) concluded that long-range dispersion models with coarse geographic resolution are appropriate for risk assessments of secondary $PM_{2.5}$ or primary $PM_{2.5}$ emitted from mobile sources in rural areas, but that more-resolved dispersion models are warranted for primary $PM_{2.5}$ in urban areas due to the substantial contribution of near-source populations. One of the advantages of APEEP is better spatial resolution in urban counties, but it may still lack the necessary level of spatial detail, giving rise to some uncertainty about results.

Marshall et al. (2005) used three alternative methods to estimate intake fractions for vehicle emissions in U.S. urban areas. They report their best estimate of the urban intake fraction for diesel particles as 4 per million, results that are consistent with the urban-county results in APEEP. However the need for future efforts to provide exposure resolution below the county scale remains a priority.

Addressing Uncertainty

Assessment of uncertainty in model outputs is central to the proper use of model results for decision making. There are a number of uncertainties that arise in the calculation of damages from energy use. The committee elected to confront uncertainty using approaches recommended by the National Research Council's Committee on Regulatory Environmental Models (NRC, 2007). This committee considered the use of probabilistic (Monte Carlo) approaches to quantify all uncertainties to be problematic in many situations. This is especially true if uncertainty analysis is used to reduce large-scale analyses of complex environmental and human health effects to a single probability distribution or when uncertainty is dominated by decision variables, as is the case for the current study. In the current study, uncertainty is dominated by factors such as the selected value of statistical life, which cannot easily be captured in a probability distribution. In situations where detailed probabilistic modeling is not appropriate, the models committee (NRC 2007a) recommended the use of scenario assessment and sensitivity analysis. The current committee elected to use this approach and where feasible has used alternative scenarios and sensitivity analysis to characterize uncertainties.

ORGANIZATION OF THE REPORT

The discussion in Chapter 2 focuses on external effects and their valuation resulting from electricity generation. Chapter 3 addresses externalities related to the production and use of transportation fuels. Chapter 4 discusses energy used to supply heat for industrial processes and for conditioning indoor

spaces. Chapter 5 addresses effects attributable to climate change and their valuation. Chapter 6 discusses effects and valuation related to infrastructure and security. Chapter 7 presents overall conclusions from the committee's evaluations, including a comparison of climate and non-climate damage estimates, and discusses factors to keep in mind when interpreting the results of the evaluations. The chapter also recommends research to inform future consideration of various issues.

2

Energy for Electricity

BACKGROUND

This chapter considers sources of energy used for the generation of electricity. Our analysis includes utilities, independent power producers, and commercial, and industrial sources. The generation data we used are available at the web site of the U.S. Energy Information Administration (www.eia.doe.gov) of the U.S. Department of Energy, and are the official energy statistics from the U.S. government.

The Current Mix of Electricity Sources

Electricity is used by the residential, commercial, industrial, and transportation sectors. In terms of electricity used, the largest sector is residential, with 36.6% of the total, followed by commercial (36.3%), industrial (26.9%), and transportation (0.2%).

The total electricity generation[1] in the United States during 2008[2] was 4.11 million gigawatt hours (GWh), down very slightly from 2007. The energy sources and the amount of electricity they contributed are given in Table 2-1.

The two largest classes of "other renewables" in terms of electricity generation were wind, for 52,026 GWh or 1.3%; and wood and wood-derived energy sources, for 38,789 GWh, or 0.9%. Other renewable sources individually amounted to less than 0.5% of the total electricity generated in 2008; the largest was other biomass, for 16,099 GWh, or 0.4%. Generation from Solar/PV was approximately 600GWh.

Rationale for Choice of Fuel Sources to Analyze

This chapter provides detailed analyses of electricity generation by coal, natural gas, nuclear fission, wind, and solar. The first three sources were chosen because they account for 88% of all electricity generated in the United States, and because they all feature prominently in current policy discussions about energy sources. Wind energy also is prominent in policy discussions concerning electricity, and it appears to have the largest potential among all renewable sources to provide additional electricity in the medium term according to current projections (see discussion later in this chapter). Solar energy for electricity (photovoltaics) also is discussed, although not in detail, because of recent

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[1]The amount of electricity used is less than the amount generated due to transmission losses. In 2007, the EIA reports usage of 93.4% of the amount generated.

[2]We provide the latest data available here to provide the most recent context. Our analyses of damages from power plants are based on 2005 data, the latest for which we have full emissions information.

TABLE 2-1 Net Electricity Generation by Energy

Energy Source	Net Electricity Generation (GWh)	Percent of Total Net Generation
Coal	2,000,000	48.5
Petroleum Liquids[a]	31,200	0.8
Petroleum Coke	14,200	0.4
Natural Gas	877,000	21.3
Other Gases[b]	11,600	0.3
Nuclear	806,000	19.6
Hydroelectric	248,000	6.0
Other Renewables[c]	124,000	3.0

Net electricity generation numbers are rounded to 3 significant figures reported by the EIA.
[a]Distillate fuel oil, residual fuel oil, jet fuel, kerosene, and waste oil
[b]Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels
[c]Wind, solar thermal, photovoltaic energy, geothermal, wood, black liquor, other wood waste, biogenic municipal solid waste, landfill gas, sludge waste, agriculture byproducts, and other biomass.
Source: EIA 2009a, 2008 data.

legislative and public interest and because of the rapid increase in use over the past 10 years. For the above reasons, the committee concluded that analyzing the external costs and benefits associated with these sources would be of the greatest value to policy makers.

We mention biomass (briefly) because it is such a dispersed source of electricity (many very small generators). We did not focus on hydropower generation of electricity, even though its current contribution is far greater than that of all other renewable sources combined, because the potential use of hydropower to increase significantly is modest and hydropower currently receives little attention in energy-policy discussions.

Describing the Effects Caused By Life-Cycle Activities

In its analyses, the committee describes externalities—indeed, all *effects* caused b*y* life cycle activities—as being upstream or downstream. By "upstream," in the context of energy for electricity, the committee means effects that occur before electricity is generated at an electricity-generating unit (EGU; steam turbine, wind turbine, solar cell, etc). For fossil-fuel and nuclear EGUs, the largest upstream effects are associated with obtaining and transporting fuel. They include effects of exploration, development, and extraction of geologic deposits of fuel or ore, refining and processing, and transportation of primary energy sources (e.g., coal or natural gas). For solar, wind, and hydropower EGUs, the main upstream effects are associated with obtaining, fabricating, and transporting materials required for the EGU and with the construction of the EGU, including road-building and other activities. Fossil-fuel and nuclear EGUs also have these effects, but they typically are smaller than those associated with the ongoing production and transportation of the primary energy sources. The committee's upstream limit for consideration of effects was exploration for fuel. Although effects even further upstream can occur, such as reactions to the announcement of a lease sale for oil, gas, or even the announcement of a proposed mine (e.g., NRC 2003a), those effects are generally unquantified. By "downstream" the committee means effects that are associated with generation of electricity and the subsequent transmission and distribution of electricity to end-users. In other words, effects associated with the operation of an electricity-generating facility or with electricity transmission and distribution (i.e. delivery to the end user) are considered downstream effects.

General Approach Taken

The goal of this chapter is to describe and, when possible, to quantify the monetary value of the physical effects[3] (i.e., the "damages") of electricity production. For electricity generation from nuclear fission, wind power, solar power, and biomass, our analysis summarizes effects reported from previous studies, but does not monetize damages from externalities. For electricity generation from coal and natural gas we are able to quantify and monetize the externalities associated with local and global air pollution, both upstream and downstream. We express these externalities in costs per kWh of electricity generated and also in costs per ton of pollution generated.

As summarized in Chapter 1, this study is preceded by a large literature on the social cost of electricity. Two notable studies are those by Oak Ridge National Laboratory and Resources for the Future (ORNL-RFF) (1992-1998) and the ExternE project (EC 2003). The goal of each study was to estimate the life cycle externalities associated with electricity production from various fuel types. Externalities were expressed in monetary terms per kWh in order to permit comparisons across fuel types. The social costs of electricity generation, together with the private costs of electricity generation, could thus be used to inform choices among fuel types when expanding or replacing generation capacity. Both studies conducted their analyses using representative plants in two geographic locations. Both studies were exhaustive in their descriptions of, and attempts to quantify, various categories of externalities throughout the fuel cycle.

In addition to literature on social costs of electricity, there have been studies on the environmental effects of electricity production. The National Research Council recently (2007b) reported on environmental effects of wind-energy projects, and the New York State Energy Research and Development Authority recently (NYSERDA 2009) reported on effects and risks to vertebrate wildlife in the northeastern United States from six types of electricity generation[4]. Both reports included assessments of all life-cycle stages, but did not quantify or monetize the effects.

This chapter builds on and extends these studies. We have attempted to describe externalities and other effects broadly, and to analyze them wherever possible. However, we have focused our efforts to monetize external costs for the categories of externalities that earlier studies found to be a significant component of damages. We extend the studies by measuring the externalities associated with local and global air pollution—a significant component of the costs of electricity generation—for individual coal-fired and gas-fired power plants in the United States. This allows us to characterize the diversity in the damages of electricity generation from fossil fuel across plants and to relate damages per kWh to the pollution intensity of the plant (i.e., to pounds of sulfur dioxide (SO_2) or particulate matter (PM) emitted per kWh) and the location of the plant, which affects the size of the human and other populations exposed to pollution generated by the plant. We also express damages per ton of pollution emitted. While a comparison of damages per kWh may (together with information about private costs) help inform the choice of fuel type, it is not particularly useful if the goal is to internalize the externalities associated with pollution emissions.[5] Economic theory suggests that the most economically efficient policy to address air pollution externalities is a policy that targets the externality itself rather the output associated with it. We therefore present information on damages per ton of emissions from coal and natural gas plants that contribute to the concentrations of criteria pollutants.[6]

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[3]The committee uses the term "physical effects" broadly, to include biological and human-health effects, to distinguish them from monetary effects.

[4]The six types were coal, oil, natural gas, nuclear, hydro, and wind.

[5]An electricity tax equal to marginal damage per kWh is a blunt instrument for internalizing the social costs of air pollution because it does not target the pollutants (e.g., SO_2 or $PM_{2.5}$) that are the source of the problem.

[6]As part of the U.S. Clean Air Act, the U.S. Environmental Protection Agency (EPA) establishes National Ambient Air Quality Standards (NAAQS) for particulate matter (PM), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), ozone (O_3), lead (Pb) and carbon monoxide (CO). These are referred to as criteria pollutants, which were established by the Clean Air Act as pollutants that are widespread, coming from numerous and diverse sources and are considered to be harmful to public health and the environment and to cause property damage.

The core of our analysis of local air pollution damages uses an integrated assessment model (the Air Pollution Emissions Experiments and Policy, or APEEP model) (Appendix C), which links emissions of sulfur dioxide (SO_2), oxides of nitrogen (NO_x), particulate matter ($PM_{2.5}$ and PM_{10}),[7] ammonia (NH_3), and volatile organic compounds (VOCs) to ambient levels of SO_2, NO_x, $PM_{2.5}$ and PM_{10} and ozone. (See Box 2-1.) The model calculates the damages associated with population exposures[8] to these pollutants in six categories: health, visibility, crop yields, timber yields, building materials and recreation. Health damages include premature mortality and morbidity (e.g., chronic bronchitis, asthma, emergency hospital admissions for respiratory and cardiovascular disease), and are calculated using concentration-response functions employed in regulatory impact analyses by EPA. Damages to crops are limited to major field crops, and recreation damages are those associated with pollution damages to forests. A description of the concentration-response functions used in the model is in Appendix C, which also provides details on the choice of unit values used to monetize damages. Damages associated with CO_2 emissions are computed based on a review of the literature, and are described in Chapter 5. Not all impacts and externalities associated with electricity production have been quantified and monetized in this study. Table 2-2 summarizes which impacts are quantified, monetized, or qualitatively discussed within this chapter.

Regulations

As noted in Chapter 1, the externalities examined in this study are those that have not been eliminated by regulation. Most stages of electricity production are subject to regulations at the federal, state and local levels. Surface mining of coal, for example, is regulated under the 1977 Surface Mining and Control Act. Air pollution emissions from electric generating units are regulated under the Clean Air Act. The Nuclear Regulatory Commission regulates and licenses nuclear power plants.

BOX 2-1 Airborne Particulate Matter

PM is a heterogeneous collection of solid and liquid particles that can be directly emitted from a source (primary pollutants) or can be formed in the atmosphere by interaction with other pollutants (secondary pollutants). Secondary PM can be formed by oxidation of NO_x and SO_x to form acids which can be neutralized by ammonia to from sulfates and nitrates. Organic particulate matter may be chemically transformed by oxidants in the air to form secondary pollutants. Soot particles can be altered by adsorption of other pollutants on their surface.

PM is monitored for both mass and size. Ultrafine particles (less than 0.1 micron in aerodynamic diameter) can be emitted from combustion sources or can be formed by nucleation of atmospheric gases, such as sulfuric acid or organic compounds. Fine particles (less than 2.5 microns) .are produced mainly by combustion of fossil fuels, either from stationary or mobile sources. Coarse particles (sometimes called $PM_{102.5}$) are mainly primary pollutants that may come from abrasive or crushing processes or the suspension of soil. PM larger than 10 microns is not of great concern for this report because they are not readily respirable and do not have a long half-life in the atmosphere.

Current research on PM is exploring the influence of particle composition (in addition to mass and size) on its toxicity as recommended by the NRC (1998, 1999, 2001, 2004b). However, enough data are not yet available from this research to inform the estimation of damages in this report.

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[7] $PM_{2.5}$ refers to particulate matter with an aerodynamic diameter less than or equal to 2.5 microns; PM_{10} refers to particles less than or equal to 10 microns in diameter. Ultrafine particles–those less than 100 nanometers–were not treated as a separate category in this study.

[8] An estimate of population exposure is an aggregate estimate based on estimates or measurements of personal (individual) exposures extrapolated to a population based on statistical, physical, or physical-stochastic models (Kruize et al. 2003).

TABLE 2-2 Energy for Electricity: Impacts and Externalities Discussed, Quantified, or Monetize

	Impact or Burden	Coal	Natural Gas	Nuclear	Wind	Biomass	Solar
			Energy Sources for Electricity				
Upstream	Air emissions (SO$_x$, NO$_x$, PM)	√	√	q	q		q
	CO$_{2e}$ emissions	√	√	q	q		q
	Metals, radionuclides, and other air pollutants	q	q	q	q		q
	Effluents	q	q	q			
	Solid wastes	q	q	q			
	Land cover/footprint	q	q	q		q	q
	Ecological effects	q	q			q	
	Occupational and transport injuries	†	†				
Downstream	Air emissions (SO$_x$, NO$_x$, PM)	$	$	√	√		√
	CO$_{2e}$ emissions	√	√	√	√		√
	Metals, radionuclides, and other air pollutants	q	q		√		q
	Effluents	q	q	q			
	Solid wastes	q	q	q			q
	Land cover/footprint	q	q	q	q		q
	Ecological effects	q			†, q		

q = qualitative discussion.
√ = emissions quantified.
† = impacts quantified.
$ = impacts monetized.

Relevant regulations for upstream and downstream activities related to electricity generation are varied and extensive. Their details are not necessarily of great import *for this study*, although they obviously are important for other reasons. For this study, though, the *existence* of regulations is of great importance, because in large part regulations are an attempt to reduce upstream and downstream damages from electricity generation, and they have substantially reduced these damages over time. We discuss only those damages that remain, with emphasis on those that can be quantified and monetized. Most of the committee's quantitative analyses of damages in this chapter focus on emissions from electricity generating facilities that are fired by coal or natural gas. Under the Clean Air Act, electric utilities are regulated at both the state and federal levels. The Clean Air Act requires states to formulate State Implementation Plans (SIPs) to pursue achievement of the National Ambient Air Quality Standards (NRC 2004c). Under SIPS, electric generating units (EGUs) are assigned emissions limits for SO$_2$, NO$_x$, PM, and other pollutants, usually stated as performance standards (for example, maximum annual average tons of SO$_2$ that may be emitted per million British thermal units [MMBtu] of heat input). These performance standards vary widely across states. In addition, EGUs are subject under the Clean Air Act to New Source Review, a series of regulations that pertain to newly constructed facilities and to modifications of existing facilities.[9] Coal-fired power plants built after 1970 are also subject to New Source Performance Standards (NSPS) which impose strict limits on emissions that contribute to the formation of criteria air pollutants. For example, the 1978 NSPS for coal-fired power plants requires the installation of flue gas desulfurization units (scrubbers) on all new coal-fired EGUs.

Emissions of SO$_2$ and NO$_x$ are also regulated under various cap-and-trade programs. The goal of Title IV of the 1990 amendments to the Clean Air Act was to reduce SO$_2$ emissions from EGUs to 8.95

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[9]New source review applies to facilities in areas of pristine air quality where the goal is to prevent significant deterioration of air quality and also to facilities in areas that are out of attainment with the NAAQS. Regulations governing each facility are determined on a case-by-case basis. See the regulatory overview in Chapter 2 of NRC 2006a.

million tons by 2010. That goal has been achieved by issuing SO_2 permits (allowances) to EGUs equal to 1.2 pounds of SO_2 per MMBtu (based on 1985-87 heat input) and allowing utilities to trade allowances, which may not violate the NAAQS. In 1998, EPA issued a call for state implementation plans (SIPs) to reduce emissions of NO_x. The rule provided the option for states to participate in a regional NO_x Budget Trading Program. This program operated from 2003-2008, when it was replaced by a NO_x ozone season trading program.

The net effect of the environmental regulations describe above, as well as others, is that emissions per MWh that contribute to criteria air pollution vary greatly among plants. Newer power plants have, on average, much lower emissions rates. As discussed later in this chapter, SO_2 (and NO_x) emissions per MWh are much lower for units installed after 1979 than for units installed before that date.

ELECTRICITY PRODUCTION FROM COAL

Current Status of Coal Production

Coal, a non-renewable fossil fuel, accounts for approximately one-third of total U.S. energy production, and nearly half of all electricity produced. Coal is classified into four types based upon the relative mix of carbon, oxygen and hydrogen: lignite, sub-bituminous, bituminous, and anthracite (Table 2-3). The greater the carbon content, the greater the energy (heating) value of coal. Sub-bituminous and bituminous coal account for more than 90% of coal produced in the United States. Sub-bituminous coal has as much lower sulfur content but also as much lower energy content than bituminous coal. In electricity generation, replacing a ton of bituminous coal requires about 1.5 tons of sub-bituminous coal (NRC 2007c).

The United States has more than 1,600 coal mining operations that produced more than 1.18 billion short tons[10] in 2008. Major coal-producing regions are shown in Figure 2-1. The EIA estimates that 70% of coal production comes from surface mines, the majority of which are in Wyoming, Montana, West Virginia, Pennsylvania, and Kentucky. Large mining operations in the Powder River Basin (PRB) in Wyoming and Montana accounted for more than 50% of surface-mine coal production and 40% of nationwide coal production in 2007. Coal in the PRB is mainly sub-bituminous; coal in Appalachia is mainly bituminous (NRC 2007c). The top five coal-producing states in 2007 are listed in Table 2-4.

TABLE 2-3 Coal Classification by Type

Type	Carbon Content (%)	Heating Value (Thousand Btu/lb)	U.S. Production (%)
Lignite	25-35	4.0-8.3	6.9
Sub-Bituminous	35-45	8.3-13.0	46.3
Bituminous	45-86	11.0-15.0	46.9
Anthracite	86-97	~15.0	<0.1

Source: EIA 2008a, Table 7.2; NEED 2008; EIA 2009b.

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[10]A short ton is 2,000 pounds, or 907.2 kilograms.
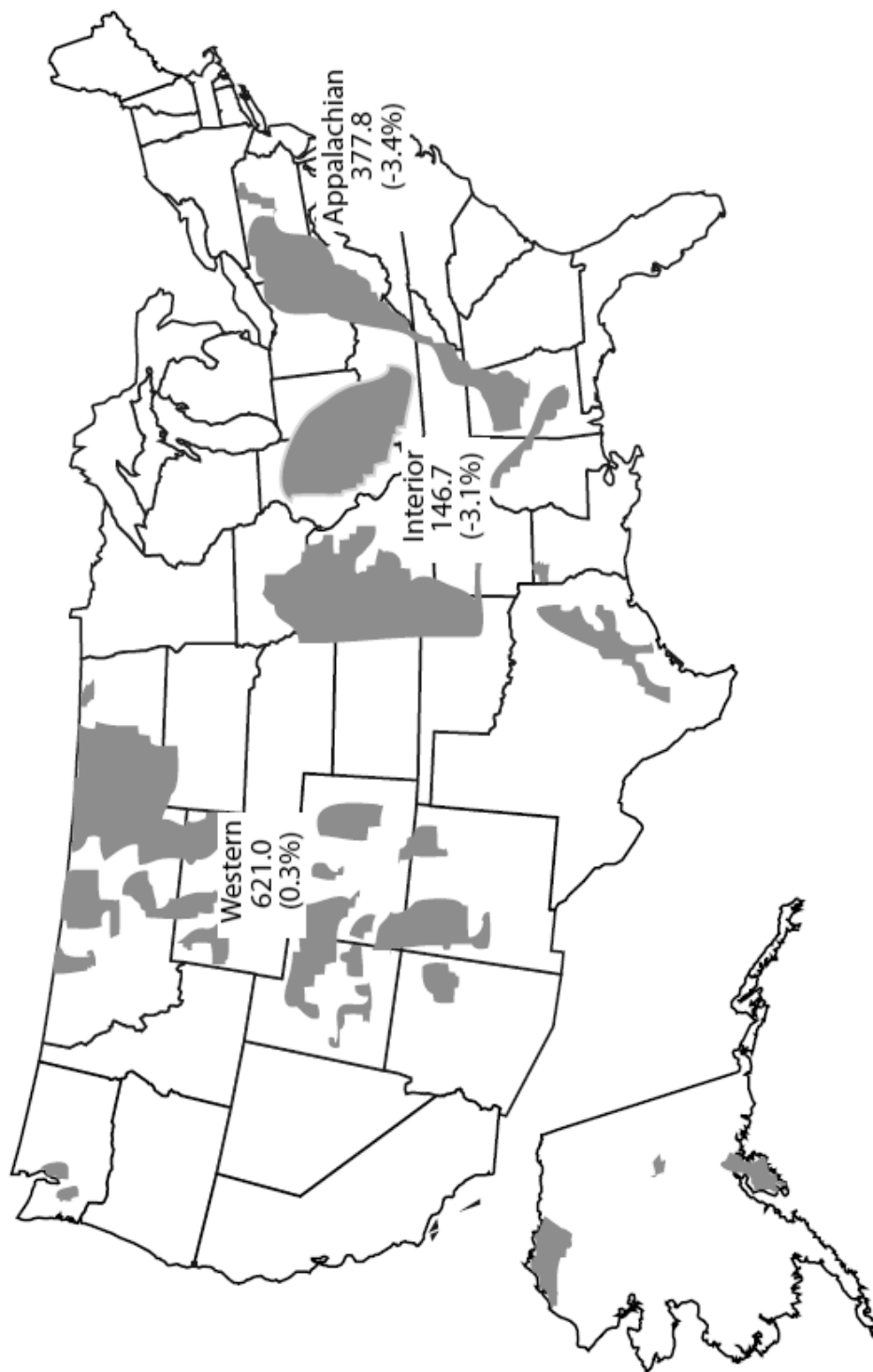
FIGURE 2-1 Major coal-producing regions in the United States (million short tons and percent change from 2006). Source: EIA 2009c, p. 2.

TABLE 2-4 Five Leading Coal-Producing States, 2007, by Mine Type and Production (Thousand Short Tons)

State	Number of Mines	Production
Wyoming	20	453,568
Underground	1	2,822
Surface	19	450,746
West Virginia	282	153,480
Underground	168	84,853
Surface	114	68,627
Kentucky	417	115,280
Underground	201	69,217
Surface	216	46,064
Pennsylvania	264	65,048
Underground	50	53,544
Surface	214	11,504
Montana	6	43,390
Underground	1	47
Surface	5	43,343
Total, Top Five States	989	830,766
Underground	421	210,483
Surface	568	620,284
Total, United States	1,358	1,145,480

Source: Adapted from EIA 2009c, p. 11, Table 1.

On average, more coal is produced in the United States than is consumed. The EIA estimates that nearly 95% of U.S. mined coal is consumed domestically. In 2008, the United States exported 23.0, 7.0, and 6.4 million short tons to Canada, the Netherlands, and Brazil, respectively.

U.S. coal production is focused in a relatively small number of states but coal is consumed throughout the country. As a result, coal is transported by all major surface transportation modes (Figure 2-2). Once mined, coal is typically transported to power plants, steel mills, and other commercial and industrial companies by rail. In 2007, approximately 70% of coal production was distributed by rail. The remaining 30% was transported by barge, tramway and pipelines, or truck.

U.S. Coal Shipments to Final Destinations in 2006

Legend:
- Railraod
- Truck
- Water
- Minemouth

7%, 10%, 11%, 71%
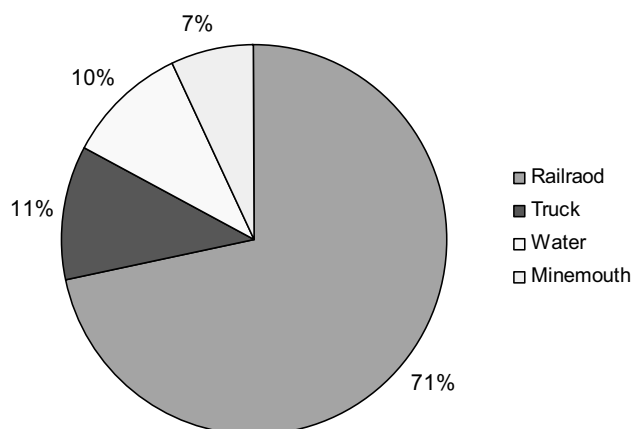
FIGURE 2-2 Methods of U.S. coal transport. Note: Data exclude a small unknown component. Source: EIA in AAR 2009.

Looking forward, it can be expected (barring shifts in current coal consumption trends) that western states will increase their production relative to other states (EIA 2008a). Table 2-5 below lists the ten states with the largest Estimated Recoverable Reserves (ERR). The ERR is derived by the Energy Information Administration (EIA) for each state by applying coal mine recovery and accessibility factors to the Demonstrated Reserve Base (NRC 2007c).

Brief History of Coal Production

Coal was the predominant source of U.S. energy from the late 19th century through the mid 20th century. Coal was used for space heating, industrial process heating for iron, steel, and other commodities, fuel to power ship and train steam engines, and for electricity. During the latter 20th century, however, coal was rapidly replaced by petroleum and natural gas for fuel and space heating, respectively. Today, approximately 7% of coal is consumed to generate heat for a variety of industrial processes, including paper, concrete, and steel production.

Upstream Impacts and Externalities of Electricity Production from Coal

Injuries and Illnesses in Coal Mining Operations. Although the gravity of occupational injuries and illnesses cannot be underestimated, the tradition in economics is to treat occupational injuries and deaths as job characteristics that are traded in labor markets rather than as externalities. In general, miners receive compensating wage differentials for the higher risks that they face on the job (Viscusi 1993).[11] In addition, some proportion of injuries and deaths are compensated after the fact, through Workmen's Compensation, insurance, or court judgments. We also note that previous studies of the social cost of electricity (e.g., ORNL-RFF) did not count occupational injuries and illnesses as externalities. However, occupational injuries are briefly discussed because it is an important societal concern related to energy production.

Coal mining-related fatalities and nonfatal injuries have generally decreased over time, even though employee hours have not steadily declined (Figure 2-3). This is the result of increased regulation and safer mining technology. In 2008,[12] 29 fatal injuries (corresponding to 2 deaths per 10,000 workers) and 4,760 nonfatal injuries (an incidence rate of 3.83 per 100 workers) were reported.[13] This marked a 27% decrease from 2000 to 2007 in the incidence of both fatal and nonfatal injuries, and, more dramatically, 35% and 54% decreases, respectively, in the incidence of fatal and nonfatal injuries from the previous decade. The majority of both fatal and nonfatal injuries occur in underground mines (67% in 2008), followed by strip mines (19%) and processing plants (8%).[14]

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[11]It can be argued that wage differentials do not fully compensate for risk of death or injury due to monopsony power on the part of employers or lack of information on the part of workers. These are both examples of market imperfections, but do not constitute externalities.

[12]All 2008 figures are preliminary.

[13]Injury experience data includes all coal operations incidents having occurred in mines, independent shops, processing plants, and offices. Contractors are included.

[14]Coal mining disasters, defined by the Mine Safety and Health Administration as incidents resulting in five or more deaths, decreased substantially in frequency and in number of fatalities since 1970 until a series of disasters in 2006 which resulted in the deaths of 19 miners. These events, particularly the January 2006 Sago Mine disaster, which resulted in the deaths of 12 miners, received nationwide attention and were the stimulus for the Mine Improvement and New Emergency Response (MINER) Act of 2006.

TABLE 2-5 Estimated Recoverable Reserves for the 10 States with the Largest Reserves by Mining Method for 2005 (million short tons)

State	Underground Minable Coal	Surface Minable Coal	Total
Montana	35,922	39,021	74,944
Wyoming	22,950	17,657	40,607
Illinois	27,927	10,073	38,000
West Virginia	15,576	2,382	17,958
Kentucky	7,411	7,483	14,894
Pennsylvania	10,710	1,044	11,754
Ohio	7,719	3,767	11,486
Colorado	6,015	3,747	9,762
Texas	—	9,534	9,534
New Mexico	2,801	4,188	6,988
Total, Top 10 States	137,031	98,896	235,927
Total United States	152,850	114,705	267,554

Source: EIA 2006a. Adapted from NRC 2007c, p. 51, Table 3.2.
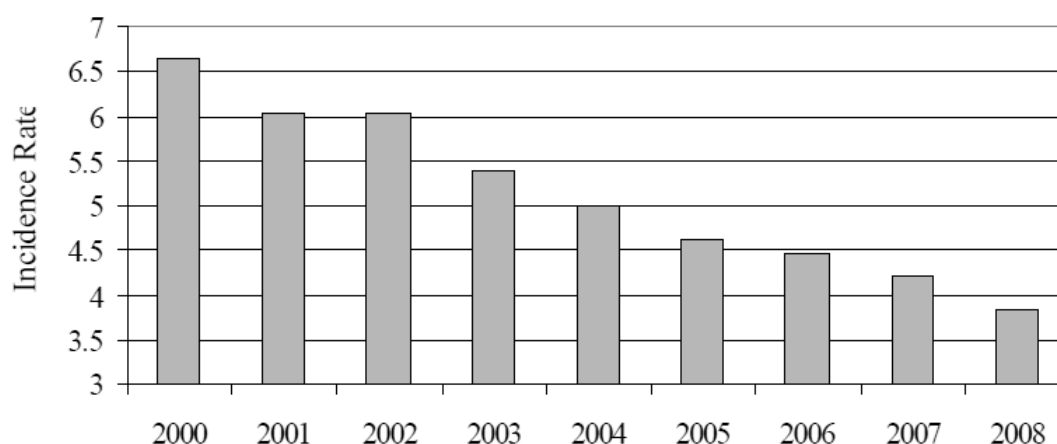
FIGURE 2-3 Injuries in U.S. coal mining operations from 2000 to 2008. Source: Data from MSHA 2008, Table 08; MSHA 2009.

Most injuries in coal mining operations result in workdays lost (WDL). In 2007, nonfatal injuries accounted for 220,284 WDL. Injuries classified as strain/sprain, cut or puncture, and fracture accounted for 76% of all injuries (31%, 24%, and 18%, respectively) but only 67% of nonfatal WDL and 6% of fatalities. Multiple injuries and bruises or contusions accounted for 79% and 12%, respectively, of fatalities, while accounting for only 3% and 11%, respectively, of total injuries. Coal mining operations also reported a total of 159 occupational illnesses in 2007, 80 being disorders associated with repeated trauma and 40 being dust diseases of the lungs.

Injuries and Fatalities in Coal Transport. Coal transport introduces risks to the public and to employees of the transportation industry (primarily railroad, truck, and barge), which we describe below. As discussed above, occupational injuries and fatalities are not considered to be externalities. However, non-occupational injury and fatalities probably are. That is, one could argue that the railroad operator might not take the full risk of death or injury to another person into consideration when choosing driving speed or safety equipment unless required to do so by law.

Domestic coal shipments represented 730 billion ton-miles in 2006, a 47% increase from 498 billion ton-miles in 1996. According to the Energy Information Administration, 71% of these U.S. coal

shipments were delivered to their final domestic destinations by rail, followed by truck (11%) and barge (10%, mainly on inland waterways). Rail's share, along with the average length of haul for rail coal movements, has been increasing over the past 15 years (from 57% in 1990 to 71% in 2006). This is largely due to the growth of western coal. Waterborne traffic's share of coal shipments has been declining, while the share of coal shipped by truck has fluctuated. Trucks transport coal over short distances, thus accounting for a small proportion of coal ton-miles (less than 2% in 2002) but a more substantial amount of tonnage (12% that same year). The average distance traveled by truck per shipment of coal increased from 51 miles in 1997 to 88 miles in 2002.

Coal is by far the most significant commodity carried by rail. In 2007, coal transport accounted for almost 44% of tonnage, 24% of carloads, and 21% of gross revenue for U.S. Class I railroads as well as a significant portion of non-Class I railroad freight. The commodity dominates originated rail traffic in major coal-producing regions. For example, coal accounted for 79% of total rail tons originated in Kentucky, 95% in West Virginia, and 96% in Wyoming in 2006. Coal (not including coal coke) is also a significant commodity in waterborne commerce, accounting for approximately 9% of tonnage. Large trucking, by contrast, only owes 0.2% of vehicle miles traveled to coal transport. For these reasons, we focus on the externalities associated with the shipment of coal by rail.

Over the past several decades, rail transportation has seen considerable drops in accident/incident rates, thanks in part to numerous initiatives on grade crossings and trespasser prevention. In 2008, there were 571 freight rail fatalities and 4,867 nonfatal injuries, indicating a 9% decline in fatalities and 11% decline in nonfatal injuries since 2007, and, more notably, 48% and 76% declines, respectively, since 1990. Ninety-seven percent of fatalities occur among the public, while, in contrast, the majority of nonfatal injuries and illnesses are borne by employees.

To estimate fatal and nonfatal injuries attributable to coal transport via rail, we use revenue ton-miles[15] as a quantifiable proxy for risk of rail-associated injury. The reasoning for using revenue ton-miles as a proxy for risk of injury to railroad employees is that the number of employee-hours, and hence the number of injuries, is more closely correlated with the revenue ton-miles measure than with train-miles or carloads. The reason for using revenue ton-miles as a proxy for risk of injury to the public is based on availability of information. A train-miles measure of coal transport would be the preferred metric for assessing risk to the public, but no such recent measure is available. We chose ton-miles of coal transport as the "next-best" measure for assessing risk to the public because it includes distance.

Our estimate of the number of fatal and nonfatal rail injuries attributable to shipping coal for electric power generation appears in Table 2-6. The estimate is computed by multiplying the total number of occupational and public injuries occurring on freight railroads[16] in 2007 by the proportion of ton-miles of commercial freight activity on domestic railroads accounted for by coal (43%).[17] This estimate is then multiplied by the percent of coal transported that is used for electric power generation (91%).

By analogy with coal-mining, we assume that occupational deaths and injuries are not externalities. A key issue is whether deaths among the public constitute externalities. One can argue that that they are externalities (most are people struck by a moving train); however, based on the magnitude of the resulting damages, we have not monetized them and they are not included in our aggregated damages. Valuing the 241 lives lost in 2007 by using a value of a statistical life (VSL) of $6 million 2000 USD (approx $7.2 million 2007 USD) would result in damages less than $2 billion annually.

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[15]A revenue ton-mile is defined as the movement of one ton of revenue-generating commodity over the distance of one mile. It is calculated by multiplying tons moved by the number of miles moved.

[16]Counts of injury incidents at freight railroads include those occurring on Class I and switching freight railroads. While coal trains will be freight only, some freight railroads also operate passenger lines; to correct for this we remove passenger injuries and fatalities from the data.

[17]The most recent available statistics on ton-miles of coal transported via rail are for 2002 (DOT/DOC 2004).

TABLE 2-6 Estimated Injuries, Illnesses, and Fatalities during Rail Transport of Coal for Electricity Power, 2007

| | Fatalities | Nonfatal Cases | | | | | |
		Injuries	Illnesses	NFDL	NDL	Total NF	Total Cases
Employees on Duty	5	1,408	36	991	453	1,444	1,449
Other (Public, etc)	241	-	-	-	-	698	939
Total	246	-	-	-	-	2,142	2,388

NFDL = non-fatal days lost; NDL= no days lost; NF = non-fatal.
Source: FRA 2008.

Land-use and Runoff Externalities from Surface and Underground Mines. This section describes, but does not quantify or monetize, environmental effects of coal-mining. Over the past 58 years there has been a relative shift to surface mining and to coal from western states (Figures 2-2 and 2-4). Surface mining is used for shallow deposits. Techniques range from area strip mining more typical in the West to contour strip mining and mountaintop mining/valley fill (also known as "mountaintop removal") more typical in the East. Underground mining techniques range from drift mines and slope mines for deposits relatively near the surface to shaft mines for deposits deep underground.

Wyoming's Powder River Basin (PRB) has near-surface deposits of coal that are more than 100 feet thick, making surface mining easy and productive, and the coal is almost always shipped to market "raw" (i.e., without processing). A single PRB surface mine can yield more than 90 million tons annually. In contrast, coal in Appalachia, whether from surface or underground mining, is generally produced at smaller, lower-yield mines, and the coal often is processed in order to lower ash and moisture content (NRC 2007c).

The negative environmental externalities of coal mines, both during operation and after closure, depend in part on the mining method:

- *Underground mining*. In addition to human-health and safety threats, underground mining can also have environmental externalities. Collapses or gradual subsidence above the mined void can affect surface and subsurface water flows. Mine fires can occur, especially in abandoned mines. The disposal of mine wastes, especially wastes resulting from coal processing, can present environmental problems (NRC 2002b, 2007c). Treating raw coal can produce as much as 50% waste, often in the form of slurry, which usually is pumped into an impoundment. Impoundments can give way, as in the October 2000 breakthrough of a 72-acre coal waste impoundment near Inez, Kentucky (NRC 2002b). Environmental problems also can be triggered by acid mine drainage caused primarily by pyrite (FeS_2), which is found in coal, coal overburden, and mine waste piles (USGS 2009a).
- *Surface mining* (area and contour). Surface mining shares with underground mining the problem of mine waste disposal and acid mine drainage. It also poses the environmental challenge of reclaiming large tracts of land. The 1977 Surface Mining Control and Reclamation Act was intended to address surface-mining effects. It requires that sites be returned to their prior condition or to a condition that supports "higher and better uses."
- *Mountaintop mining/valley fill* (MTM/VF). MTM/VF is a type of surface mining used on steep terrain. Since its inception in the 1970s, this mining method has become widespread in Appalachia. Mountaintop mining often generates a large volume of rock, or "excess spoil," that cannot be returned to its original locations and typically is placed in adjacent valleys. MTM/VF shares the negative externalities of other types of surface mining (see above) and has other externalities as well.
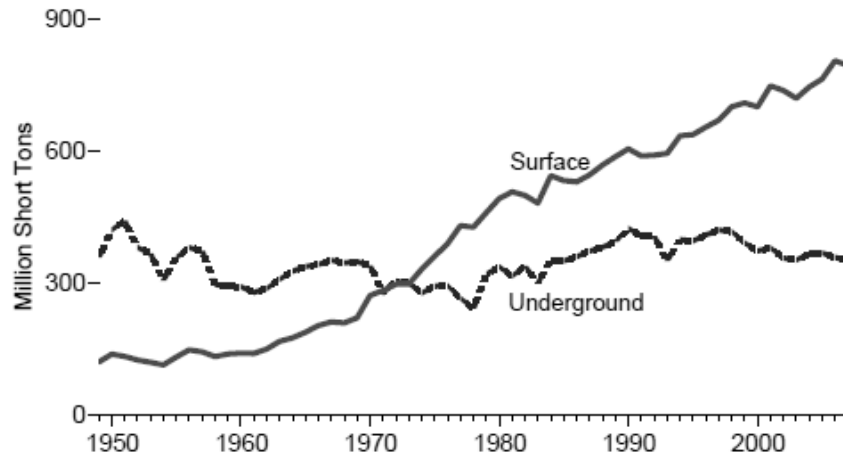
FIGURE 2-4 U.S. coal production 1949-2007, by mining method. Source EIA 2008a, p. 224, Figure 7.2.

A Final Programmatic Environmental Impact Statement (FPEIS) on MTM/VF was released in October 2005 to consider developing agency policies regarding the adverse environmental effects of MTM/VF. Prepared by the U.S. Army Corps of Engineers, the U.S. Environmental Protection Agency (EPA), the U.S. Department of Interior's Office of Surface Mining and Fish and Wildlife Service, and the West Virginia Department of Environmental Protection, the FPEIS focused on approximately 12 million acres encompassing most of eastern Kentucky, southern West Virginia, and western Virginia as well as scattered areas of eastern Tennessee. About 6.8% of the study area (i.e., 816,000 acres) has been or may be affected by recent and future (1992-2012) mountaintop mining (EPA 2002, 2005a).

The study area is largely forested and contains about 59,000 miles of streams, most of which are considered headwater streams. The FPEIS comments that "headwater streams are generally important ecologically" and that "the study area is valuable because of its rich plant life and because it is suitable habitat for diverse populations of migratory songbirds, mammals, and amphibians" (EPA 2005a, p. 3).

The EPA Region 3 website on MTM/VF and the FPEIS note that valley fills generally are stable but that

> "based on studies of over 1200 stream segments impacted by mountaintop mining and valley fills the following environmental issues were noted:
>
> - An increase of minerals in the water—zinc, sodium, selenium, and sulfate levels may increase and negatively impact fish and macroinvertebrates leading to less diverse and more pollutant-tolerant species.
> - Streams in watersheds below valley fills tend to have greater base flow.
> - Streams are sometimes covered up.
> - Wetlands are, at times inadvertently and other times intentionally, created; these wetlands provide some aquatic functions, but are generally not of high quality.
> - Forests may become fragmented (broken into sections).
> - The re-growth of trees and woody plants on re-graded land may be slowed due to compacted soils.
> - Grassland birds are more common on reclaimed mine lands as are snakes; amphibians such as salamanders, are less likely....
> - Cumulative environmental costs have not been identified ...." (EPA 2009a).

The website also notes that there may be social, economic, and heritage issues with MTM/VF. Similarly, a USGS study of the Kanawha Basin (Paybins et al. 2000) shows significant degradation in the biotic communities of this mid-Atlantic river basin as a result of coal mining operations, and other USGS studies show similar effects elsewhere (see USGS 2009b).

A possible benefit of coal mining can be the roads, utilities, and other infrastructure that accompany a mining operation. With proper planning, especially integration of the mine decommissioning and closure plan with local master plans, this infrastructure can be used for other economic enterprises following mine closure (NRC 2007c).

Upstream emissions of GHGs and other pollutants. The upstream life cycle of power generation from coal includes many relevant activities such as construction of infrastructure and power plants (see, e.g., Pacca and Horvath 2002), but the most significant, from a perspective of GHG emissions and criteria-pollutant forming emissions, are surface and underground mining and transportation of coal. Mining and transport are fuel- and energy-intensive, requiring combustion of fossil fuels for cutting, moving, and preparing the coal from the mine and delivering it to power plants and other industrial facilities. Beyond emissions from engines, there are also significant emissions of methane, a GHG that exists within coal seams and is released as the seams are cut to extract the coal. As methane is a much more potent GHG than CO_2, methane emissions are a significant concern.

In surface mining, the overburden (layers of rock and earth above the coal) is broken and removed to get to the underlying coal. The breaking and removal of both overburden and coal, and its movement from mine to transportation network is done with enormous machinery and engines that operate mostly by burning liquid fuels that release GHG emissions and criteria-pollutant forming emissions. Underground mining uses similar technologies, but shafts need to be drilled down to the seam depth, and the subsurface coal cutting and moving equipment is generally less energy efficient due to its smaller size since it has to fit beneath the surface.

Prior studies have assessed the relative contribution of air emissions from mining and transport of coal in the life cycle of coal-fired power generation (Jaramillo et al 2007, Spath et al 1999, ORNL/RFF 1992-1998). While not negligible, these studies found that upstream activities lead to relatively small life cycle air emissions because of the dominance of GHG emissions and criteria- pollutant forming emissions onsite at coal-fired power plants. For example, Jaramillo et al (2007) reports that the mid-point GHG emission factors for coal combustion (at the power plant) and the entire coal life cycle are 2100 lb CO_2 equivalent/MWh and 2270 lb CO_2 equiv/MWh, respectively.

Downstream Externalities of Electricity Production from Coal

Analysis of Current Air Pollution Damages from Coal-Fired Power Plants. The air pollution emissions from fossil-fueled power plants constitute a significant portion of the downstream damages associated with electric power generation. In this section we quantify the impacts on human health, visibility, agriculture and other sectors associated with coal-fired power plant emissions contributing to criteria pollutant formation. The effects of those emissions on ambient air quality are modeled using the APEEP model (Muller and Mendelsohn 2006) and are calculated for each of 406 coal-fired power plants for the year 2005. We use the APEEP model to calculate the damages associated with emitting a ton of each of four pollutants (SO_2, NO_x, $PM_{2.5}$ and PM_{10}) at each power plant. Damages per ton are multiplied by the tons of each of the four pollutants emitted by the plant in 2005. This produces an estimate of aggregate damages associated with criteria-pollutant forming emissions from each plant. Damages are also expressed per kWh.

Choice of Modeling Platform

Calculating the damages associated with air pollution emissions involves three steps: (1) translating changes in emissions into changes in ambient air quality; (2) using concentration-response functions to calculate health, environmental, and other impacts; (3) valuing those impacts. This section describes the choices the committee made along each of these dimensions and discusses their strengths and limitations.

Approach to Air Quality Modeling

There are two general approaches one can take to air quality modeling: process-based modeling and reduced form modeling. A process-based model captures the complexities of environmental processes by including exhaustively detailed representations of each mechanism in the atmosphere. Process-based models attempt to reflect the natural processes which govern the relationship between emissions and concentrations. The models are often applied to simulations with very fine spatial and temporal scales. The Community Multiscale Air Quality (CMAQ) model is widely considered the state-of-the-science in process-based air quality modeling (Byun and Schere 2006).

Despite these advantages, there are downsides to process models. Because of their exhaustive embodiment of a multitude of atmospheric processes, such models are time-intensive and expensive to operate. The implied cost of running process models limits the number of times researchers can run these models for a particular application. This constraint forces policy analyses using these models to make other compromises. For example, process models cannot be used to conduct large numbers of experiments. As a result, national applications of CMAQ and other process models feature a relatively small number of modeling runs in which many sources have their emissions modified at once. While this may be appropriate for simulating a national or regional policy, this simulation design is fundamentally unable to isolate the impact of emissions from individual sources over a large modeling domain. If that is the objective of the research, which is the objective is this study, then one must employ a simpler, reduced form air quality model.[18]

The reduced form modeling approach depicts the environment with a simple representation that mimics the overall behavior of the entire system. Reduced form models do not include all the complex relationships of the process-based models. Their advantages are that they are relatively fast, inexpensive to operate, and easy to interpret. The most critical drawback of reduced form models is that they may omit or misrepresent a key element in the environmental process. The model employed in this analysis, APEEP, employs a source-receptor matrix with county-level sources and receptors that are derived from a Gaussian air quality model. The cells of the matrix, which are generated by the Gaussian model, represent estimates of the concentrations of a given pollutant (per unit of emission.). The cells were systematically adjusted to implicitly represent the spatial effects of the dispersion and transformation processes embodied in the CMAQ model. An alternative approach to develop a reduced form model is to fit a "response surface" to CMAQ output, which has been used by EPA. The latter is a purely statistical approach.

APEEP has been carefully calibrated to CMAQ in order to reflect the relationships between emissions and concentrations that CMAQ estimates. However, APEEP has some drawbacks: It cannot effectively represent episodic events because of the use of annual and seasonal average meteorologic data. Also, while its use of county-level resolution is quite fine-grained for a national study, a preferred approach would be grid-cell level resolution for large western counties.

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[18]Both approaches are valid. The use of CMAQ in regulatory impact analysis considers a limited number of scenarios in which emissions from many sources are simultaneously reduced as a result of the contemplated regulation. In contrast, we wish to consider separately the impacts of emissions from each power plant.

Our choice of air quality modeling approach in this study is motivated by the desire to model the impact of emissions from individual power plants. Power plants vary greatly in the amount of pollution they emit and, by virtue of their location, in the impact of this pollution on human health and on ecosystems. Exploring the heterogeneity of pollution impacts across space is important from a policy perspective because it provides regulators with a means to prioritize emissions abatement by identifying the relative damage caused by emissions from different sources. In order to explore these effects many model runs must be conducted. Reduced form models are the optimal modeling choice in such a context.

Choice of Concentration-Response Functions

In analyses of air pollution damages and the benefits of reducing them (e.g., The Benefits and Costs of the Clean Air Act, 1990-2010 [EPA 1999]) impacts on human health constitute the vast majority of monetized damages, with premature mortality constituting the single largest damage category. The concentration-response functions for human health endpoints (including premature mortality, chronic bronchitis, and hospital admissions) used in APEEP are listed in appendix Table C-1 of Appendix C. They are the same concentration-response functions as those used in the EPA's regulatory impact analyses, and those functions have therefore been vetted by the EPA's Clean Air Science Advisory Committee. In particular, the impact of particulate matter on premature mortality is calculated using the relationship between $PM_{2.5}$ and all-cause mortality in Pope et al. (2002).[19] The concentration-response functions used to calculate impacts on agriculture, forestry and other sectors are listed in Appendix C and further described in Muller (Muller and Mendelsohn 2006).

One limitation of the APEEP model as used in this analysis is its limited treatment of ecosystem damages. For example, the model does not measure the impacts of acid rain associated with NO_x and SO_2 emissions, either on tree canopy or on fish populations. It also fails to capture eutrophication of fresh water ecosystems from nitrogen deposition.

Valuation

As in most analyses of damages associated with criteria-pollutant forming emissions, health damages figure prominently in aggregate monetized damages—especially premature mortality associated with $PM_{2.5}$. The value of monetized damages is particularly sensitive to the Value of a Statistical Life (VSL) used to monetize cases of premature mortality. The value that we use for our central case analysis is $6 million 2000 USD. This value is supported by recent meta-analyses of the literature on the VSL as well as by values used in EPA regulatory impact analyses. In their 2003 meta-analysis Viscusi and Aldy (2003) report a mean value of $6.7 million (2000 USD) while Kochi et al. (2006) report a value of $5.4 million based on an empirical Bayes estimator. These values are line with values used in recent EPA regulatory impact analyses: the Clean Air Interstate Rule RIA uses a value of $5.4 million (1999 USD), while EPA's National Center for Environmental Economics recommends using a $7.4 million VSL (2006 USD). (This is equivalent to $6.3 million in 2000 USD.) A $6 million VSL (2000 USD) is also used by other researchers (e.g., Levy et al. 2009) who have recently examined the health impacts of power plant emissions.

We apply the same the VSL to persons of all ages. While these is some evidence that WTP for changes in mortality risks varies with age, EPA's Environmental Economics Advisory Committee of the Science Advisory Board judged in 2007 that the literature on this issue was not sufficiently mature to determine exactly how the VSL varies with age. The practice of valuing lives lost by multiplying the

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[19]We have chosen not to calculate the Quality Adjusted Life Years (QALYs) or Disability Adjusted Life Years (DALYs) associated with power plant emissions. The goal of this study is to monetize damages. A recent NAS-IOM study (IOM 2006) recommends that QALYs and DALYs not be monetized.

number of life years lost by the value of a statistical life year (VSLY) was also rejected. The empirical evidence on the impact of age on the VSL does support the use of the VSLY approach, which assumes that the VSL is proportional to remaining life expectancy (EPASAB 2007).

In calculating the value of premature mortality, we treated the lives lost due to changes in $PM_{2.5}$ concentrations as occurring in the same year as the change in the concentrations. EPA (EPA 1999, Appendix D) assumed that the impact of a reduction in $PM_{2.5}$ concentrations was spread over five years, with 25% of the change in deaths occurring in same year as the change in concentrations, 25% the next year, and one-sixth of the change occurring in each of the following three years. Using a 3% discount rate, the present discounted value of damages using EPA's lag structure would be 95% of the mortality damages we calculated. At a discount rate of 7%, the damages would be 89% of the mortality damages we calculated. However, selecting a particular lag structure is associated with great uncertainty. In its review of the National Ambient Air Quality Standards for PM, EPA indicated that it is difficult to assess the time between the occurrence of a cause and its purported effect based on the studies it reviewed of PM exposures, given that airborne PM concentrations are generally correlated over time in any given area. For all-cause mortality and cardiovascular mortality, EPA observed that the greatest effect size is generally reported for the 0-day lag and 1-day lag. The effect generally tapered off for longer lag periods (EPA 2005b).

Treatment of Uncertainty

The version of APEEP used in our analysis does not provide error bounds that reflect either statistical uncertainty in the concentration-response functions used in the model or in the range of VSL estimates in the literature. The relationship between emissions and ambient air quality is likewise treated as certain, as is the case in regulatory impact analyses of air quality regulations. Due to the importance of the VSL in determining the size of air pollution damages we used a value of $2 million (2000 USD) as a sensitivity analysis. The likely impact of using alternative concentration-response functions (e.g., Dockery et al. 1993) is discussed below.

Methodology. The APEEP model calculates the damages associated with emitting an additional ton of each of 6 pollutants (SO_2, NO_x, $PM_{2.5}$, PM_{10}, NH_3 and VOCs) as a function of the county in which the pollutant is emitted and the effective stack height of the emissions. The categories of damages covered by APEEP and reflected in our estimates include premature mortality associated with $PM_{2.5}$, cases of chronic bronchitis and respiratory and cardio-vascular hospital admissions associated with $PM_{2.5}$ and PM_{10}, changes in crop and timber yields associated with ozone, damage to building materials from SO_2, impairments to visibility associated with $PM_{2.5}$ and recreation damages associated with ozone-related changes in forest canopy. As described in more detail in Appendix C, APEEP calculates the impact of a ton of emissions of each pollutant on ambient air quality, and the effect of the change in ambient air quality on population-weighted exposures to PM, ozone, SO_2 and NO_x. The impact of changes in exposure on health, crop yields, visibility, and other categories of damages is estimated using concentration-response functions from the literature. Damages are monetized using unit values from the literature. (Appendix C lists the concentration-response functions used in the analysis and the unit values used to monetize damages.)

We calculated damages associated with each plant by multiplying the damages per ton of each pollutant by the number of tons of each pollutant emitted by the plant in 2005. This implies that we calculated the damages associated with 2005 emission levels compared with zero emissions. In practice, installing additional pollution control devices (or switching to low sulfur coal) could reduce emissions very close to zero at most plants. We could have calculated damages relative to some estimate of the lowest emissions levels achievable using existing control technologies; however, a zero baseline is more

transparent. This implies that the damages calculated at each plant are an upper bound to the benefits from additional pollution controls.[20]

Results. The monetized damages associated with emissions of SO_2, NO_x, $PM_{2.5}$, and PM_{10} in 2005 are calculated for each of 406 coal-fired electricity generating facilities by combining damages per ton from APEEP with emissions data from the 2005 National Emissions Inventory (NEI).[21] Estimates of the damages associated with a ton of each of four kinds of emissions (SO_2, NO_x, $PM_{2.5}$, and PM_{10}) that form criteria air pollutants are obtained from APEEP as a function of the county in which the pollutant is emitted and the effective stack height of the emissions. These are combined with data on emissions of these pollutants, by stack, from the 2005 NEI.[22] This allows us to calculate the monetized damages associated with each pollutant at the plant level. Data from the Energy Information Administration on net generation of electricity from coal were used to compute monetized damages per kWh.

Damages from the criteria-pollutant forming emissions were calculated, as described above, for each of 406 plants that generated electricity from coal in 2005.[23] Table 2-7 and Figure 2-5 present the distribution of monetized damages across plants. (In Table 2-7 all plants are weighted equally, hence the mean figures are arithmetic means of damages across all plants.) As Table 2-7 makes clear, most damages come from SO_2 (85%), followed by NO_x (7%), $PM_{2.5}$ (6%) and PM_{10} (2%). This reflects the size of SO_2 and NO_x emissions from coal-fired power plants and the damages associated with fine particles formed from SO_2 and NO_x.[24] Directly emitted $PM_{2.5}$ has very high damages per ton (see Table 2-8), but very little $PM_{2.5}$ is emitted directly by power plants; most is formed from chemical transformations in the atmosphere.

Table 2-8 shows how the damages per ton of pollutant vary across plants, again weighting all plants equally. Variation in damages per ton reflects differences in the size of the populations (human and other) exposed to pollution from each plant, as well as differences in effective stack heights across plants. The assumption implicit in our calculations—that the damage per ton of pollutant emitted is independent of the number of tons emitted at the plant—is consistent with the epidemiological literature and with the calculation of air pollution damages by EPA and other agencies.[25]

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[20]The installation of some pollution control devices may lower the efficiency with which the plant operates, but this effect is likely to be small. It should be emphasized that lowering emissions is not equivalent to closing the plant. Net generation of electricity, and hence the benefits of the electricity generated by the plant, would remain essentially unchanged if damages were reduced.

[21]APEEP calculates damages associated with ammonia (NH_3) and volatile organic chemicals (VOCs). These pollutants were dropped from our analysis due to missing emissions data for a significant fraction of plants. Damages from ammonia were recorded for 310 out of our sample of 406 coal plants. When the damage per kWh estimates were recalculated to include the impacts of ammonia (PM_{10}-related visibility reduction and morbidity, as well as $PM_{2.5}$-related mortality), these components were found to be small, accounting for less than 1% of damage per kWh in all but 19 plants. The latter group contained significant outliers, for which ammonia-related impacts accounted for as much as 14% of these facilities' adjusted damages per kWh. Consequently, the ammonia-inclusive damages per kWh are generally very close to the original estimates in the report.

[22]Specifically, we obtained emissions data for each stack associated with coal-fired generation at each plant and used information on meteorological conditions and exit velocity to approximate the effective height of the stack.

[23]Each of our plants is classified as SIC 4911. Together they accounted for 94.6% of electricity generated from coal and sold to the grid (EIA 2009d, Table 1.1).

[24]Approximately 99% of the damages associated with SO_2 come from secondary particle formation, i.e., the transformation of SO_2 into PM_{10} and $PM_{2.5}$.

[25]The concentration-response functions in the air pollution literature are approximately linear in ambient concentrations. The unit values assigned to health and other endpoints are likewise assumed to remain constant over the relevant ranges of the endpoints.

TABLE 2-7 Distribution of Criteria Air Pollution Damages Associated with Emissions from 406 Coal-Fired Power Plants in 2005 (USD 2007)

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	1.6E+08	1.9E+08	4.3E+06	2.4E+07	6.5E+07	1.6E+08	5.2E+08
NO_x	1.1E+07	1.1E+07	7.5E+05	3.1E+06	7.2E+06	1.6E+07	3.0E+07
$PM_{2.5}$	9.0E+06	1.3E+07	2.3E+05	1.3E+06	4.0E+06	1.0E+07	3.6E+07
PM_{10}	5.2E+05	6.9E+05	1.8E+04	9.8E+04	2.6E+05	6.2E+05	1.9E+06
Total	1.6E+08	2.0E+08	8.7E+06	3.4E+07	8.1E+07	1.8E+08	5.8E+08

Note: All plants are weighted equally, rather than by the fraction of electricity they produce.

TABLE 2-8 Distribution of Criteria Air Pollution Damages per Ton of Emissions from Coal-Fired Power Plants (USD 2007)

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	5,800	2,600	1,800	3,700	5,800	6,900	11,000
NO_x	1,600	780	680	980	1,300	1,800	2,800
$PM_{2.5}$	9,500	8,300	2,600	4,700	7,100	10,000	26,000
PM_{10}	460	380	140	240	340	490	1,300

Note: All plants are weighted equally, rather than by the fraction of electricity they produce.
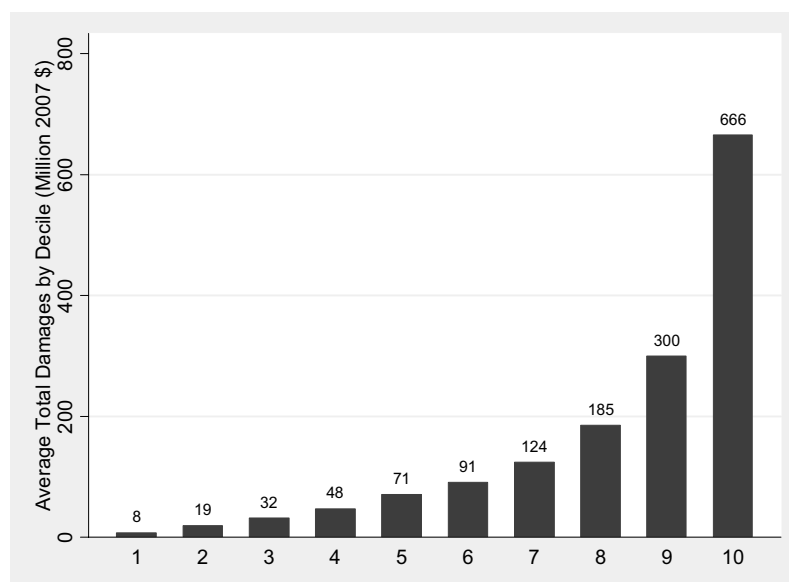
FIGURE 2-5 Distribution of aggregate damages in 2005 by decile: Coal plants. (2007 USD). Note: In computing this graph plants were sorted from smallest to largest based on aggregate damages. The lowest decile represents the 40 plants with the smallest aggregate damages. The figure on the top of each bar is the average, across all plants, of damages associated with SO_2, NO_x, $PM_{2.5}$, and PM_{10}.

Damages from the criteria-pollutant forming emissions in 2005 averaged $156 million per plant, but the range of damages across plants was wide—the 5th and 95th percentiles of the distribution are $8.7

and $575 million dollars, respectively (2007 USD). As Figure 2-5 shows, the distribution is highly skewed. After ranking all of the plants according to their damages, we found that the most damaging 10% of plants produced 43% of aggregate air pollution damages from all plants, while the least damaging 50% of the plants produce less than 12% of aggregate damages.[26] Where are the plants with the highest damages located? The map in Figure 2-6 shows the size of damages created by each of the 406 plants, by plant location. Plants with large damages are concentrated to the east of the Mississippi, along the Ohio River Valley, in the Middle Atlantic and the South.

Some of the variation in damages across plants occurs because plants that generate more electricity tend to produce greater aggregate damages; hence we also report damages per kWh of electricity produced.[27] Table 2-9 and Figures 2-7 and 2-8 show damages per kWh for all four pollutants. Mean damages per kWh (2007 USD) from four criteria-pollutant forming emissions are 4.4 cents per kWh if all plants are weighted equally and 3.2 cents per kWh if plants are weighted by the electricity they generate. The lower figure reflects the fact that larger plants are often less damaging per kWh.[28] What is equally important as mean damages is the distribution of damages across plants. As Table 2-9 indicates the 95th percentile of the distribution—damages of 12 cents per kWh—is more than an order of magnitude larger than the 5th percentile. The distribution of damages per kWh (Figure 2-7) is very skewed: there are many coal-fired power plants with low damages per kWh as well as a small number of plants with high damages. Using generation-weighted figures, the damages per kWh from the least damaging 5% of plants were very small: 94% lower than the average coal-fired plant and almost as low as the average damage per kWh at natural gas power plants (0.16 cents). Figure 2-8 maps damages per kWh for each power plant. As in the case of aggregate damages, the plants with lowest damages per kWh are in the West. Plants with the largest damages per kWh are concentrated in the Northeast and the Midwest.

TABLE 2-9 Distribution of Criteria Air Pollutant Damages per kWh Associated with Emissions from 406 Coal-Fired Power Plants in 2005 (2007 Cents)

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	3.8	4.1	0.24	1.0	2.5	5.2	11.9
NO_x	0.34	0.38	0.073	0.16	0.23	0.36	0.91
$PM_{2.5}$	0.30	0.44	0.019	0.053	0.13	0.38	1.1
PM_{10}	0.017	0.023	0.001	0.004	0.008	0.023	0.060
Total (equally weighted)	4.4	4.4	0.53	1.4	2.9	6.0	13.2
Total (weighted by net generation)	3.2	4.3	0.19	0.71	1.8	4.0	12.0

Note: In the first 5 rows of the table, all plants are weighted equally; i.e., the average damage per kWh is 4.4 cents, taking an arithmetic average of the damage per kWh across all 406 plants. In the last row of the table, the damage per kWh is weighted by the electricity generated by each plant to produce a weighted damage per kWh.

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[26]Each set of plants—the most damaging 10% and the least damaging 50%—account for approximately one quarter of electricity generated by the 406 plants.

[27]It is, however, the case that less than half of the variation in damages is explained by variation in the amount of electricity generated. A regression of damages on net generation yields an $R^2 = 0.32$; the R^2 is 0.48 when the logarithms of the variables are used.

[28]The correlation coefficient between damages per kWh and net generation is = -0.26, significant at <0.01 level of significance.
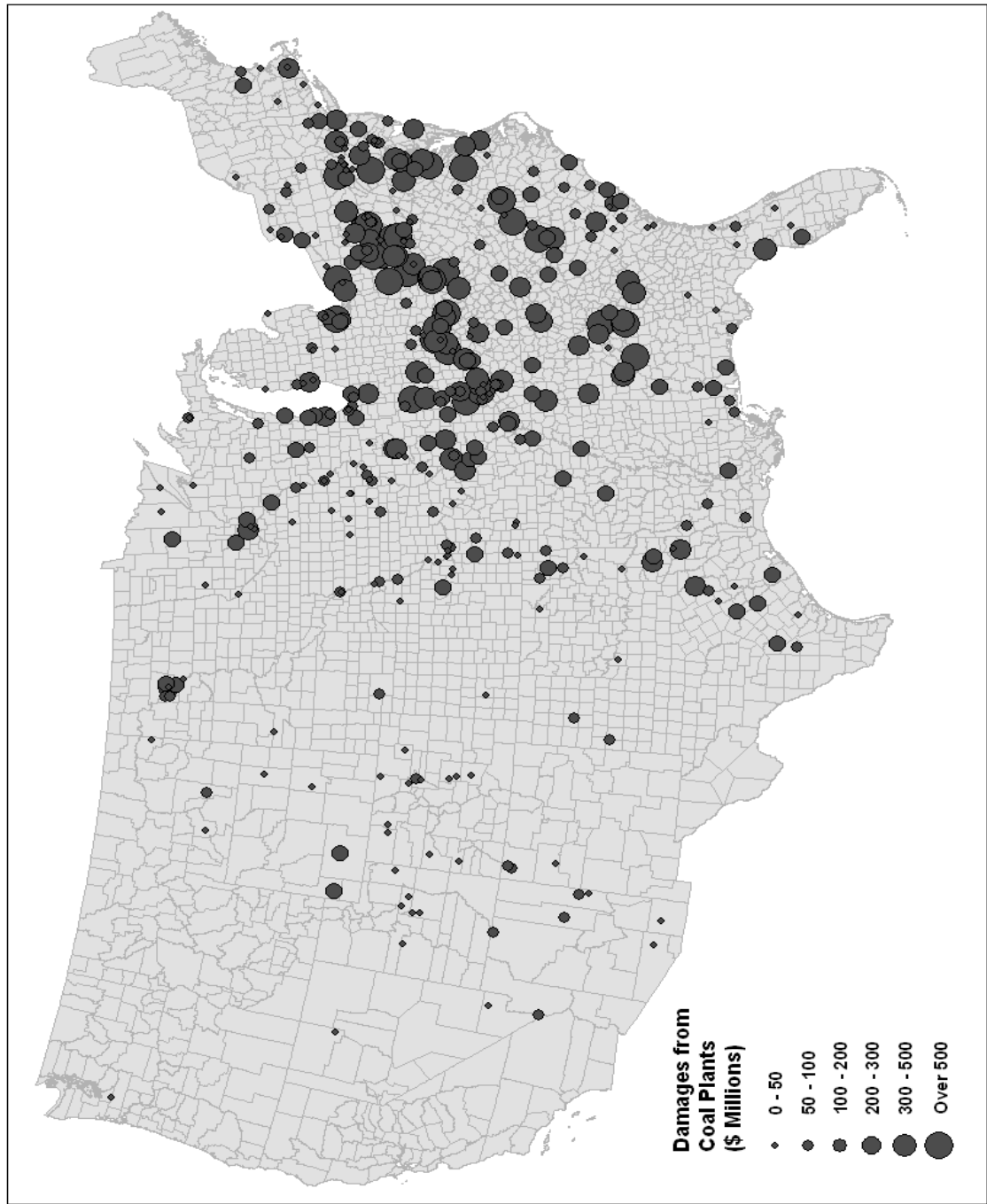
FIGURE 2-6 Air pollution damages from coal generation for 406 plants, 2005 (2007 USD). Damages related to climate changes effects are not included.
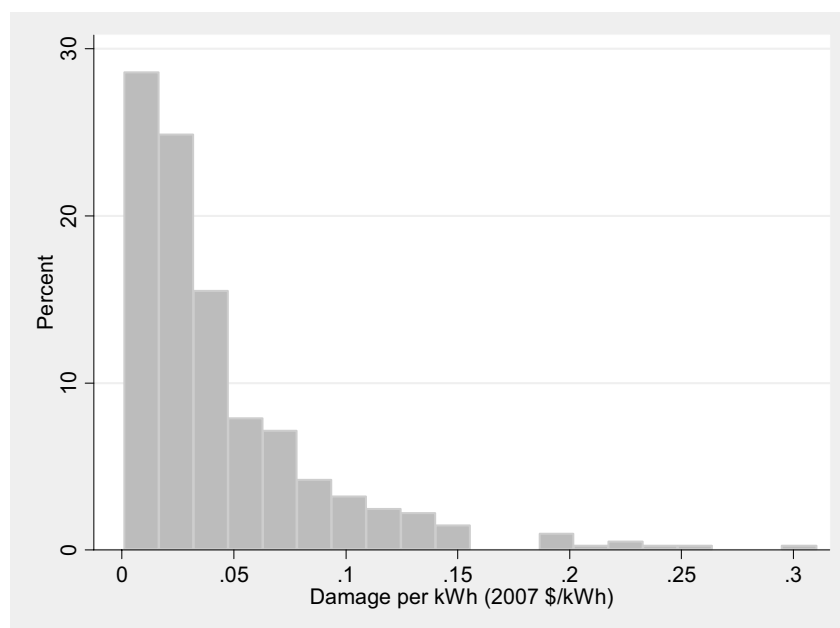
FIGURE 2-7 Distribution of air pollution damages per kWh for 406 Coal Plants, 2005 (USD 2007). Note: All plants are weighted equally rather than by the electricity they produce.

What explains variation in damages per kWh across plants? Damages per kWh associated with a criteria air pollutant (e.g., SO_2) are the product of emissions per kWh and the damage per ton of pollutant emitted. For the 406 plants examined, variation in damages per kWh is primarily due to variation in pollution intensity (emissions per kWh) across plants, rather than variation in damages per ton of pollutant, which varies with plant location. In the case of SO_2, emissions per kWh reflect the sulfur content of the coal burned, adoption of control technologies (e.g., scrubbers), as well as the vintage of the plant. Pounds of SO_2 emitted per MWh (see Tables 2-10 and 2-11) vary greatly across plants, and this variation explains approximately 83% of the variation in damages attributed to SO_2 emissions per kWh. As Table 2-11 indicates, pounds of SO_2 and NO_x emitted per MWh vary significantly with plant vintage, reflecting the fact that newer plants are subject to more stringent pollution controls. Variation in damages per ton of SO_2 emitted (see Table 2-8) accounts for only 24% of the variation in damages per kWh.[29] A ton of pollution emitted by plants located closer to population centers does more damage than the same ton emitted in a sparsely populated area; however, while plant location is important, coal plants are not located in counties with the highest damages per ton of SO_2 in the United States.

To summarize: the aggregate damages associated with criteria-pollutant forming emissions from coal-fired electricity generation in 2005 were approximately $62 billion (USD 2007), or 3.2 cents per kWh (weighting each plant by the fraction of electricity it produces); however, damages per plant varied widely. The lowest-damage 50% of plants, which accounted for 25% of net generation, produced 12% of

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[29]A regression of SO_2-related damages per kWh on pounds of SO_2 emitted per kWh produces an R2 of 0.83. Regressing SO_2-related damages per kWh on damages per ton of SO_2 emitted produces an R2 of 0.24. Even so, this last result does not elucidate the substantial heterogeneity in marginal damages that arises purely because of location. To more clearly highlight the role of geography, we took the SO_2 emission intensity of a notional tall-stack coal-fired integrated gasification combined-cycle (IGCC) plant (0.043 tons/kWh-NETL 2007) and applied this value to the marginal damages in the year 2030 estimated by APEEP for 485 counties in which there are currently coal-fired electric generating facilities. (The use of the APEEP model to generate marginal damages for 2030 is discussed later in this chapter.) The coefficient of variation of the resulting estimates is 0.38.
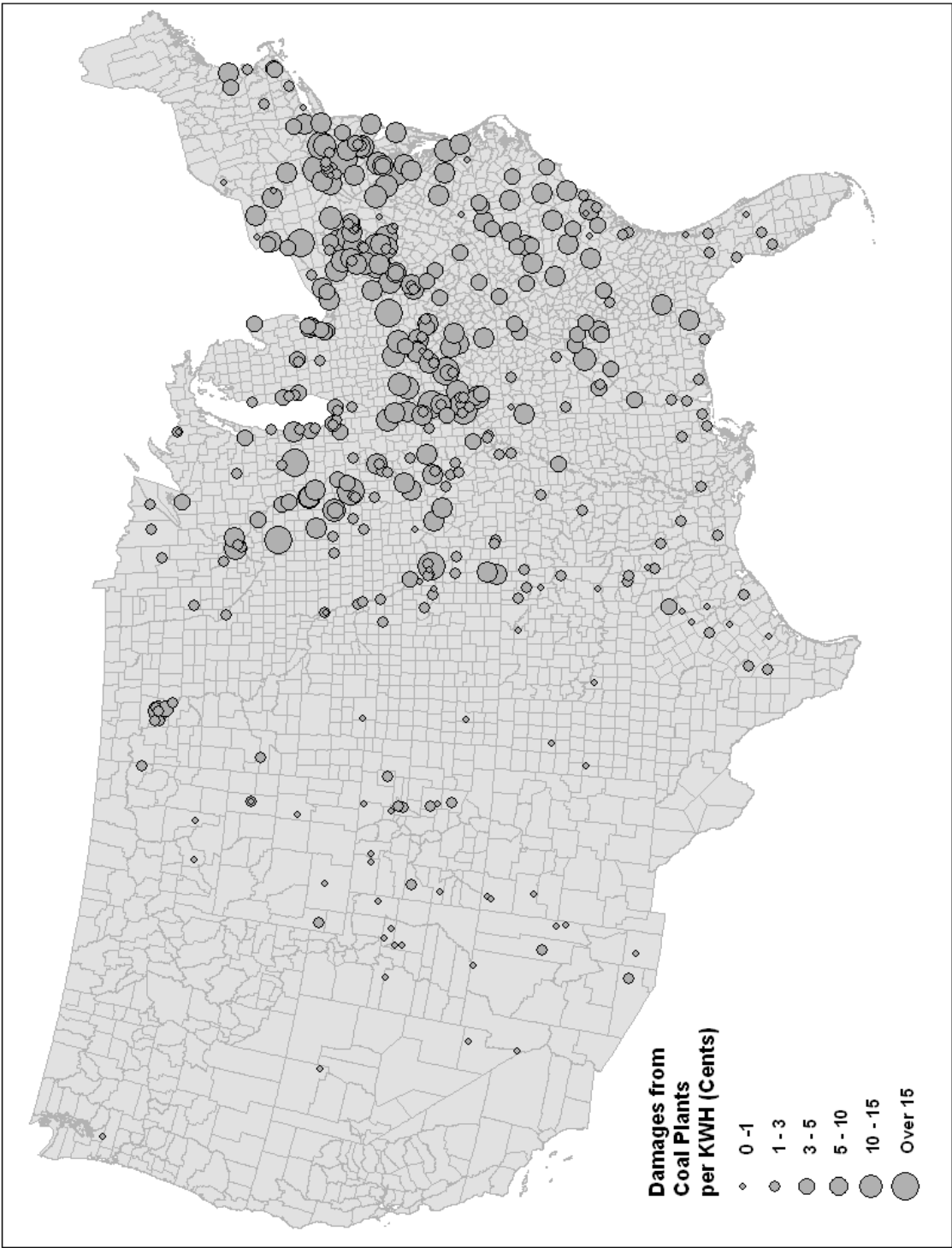
FIGURE 2-8 Regional distribution of air pollution damages from coal generation per kWh in 2005 (USD 2007). Damages related to climate change are not included.

TABLE 2-10 NO$_x$ and SO$_2$ Emissions (2002) from Coal-Fired Electricity Generation by Age of Power Plant

a. 2002 NO$_x$ Emissions and Share of Generation of Coal-Fired Capacity by Vintage

Power Plant Established	Avg. NO$_x$ Emission Rate (lb/MWh)	% Total NO$_x$ Emitted	% of Coal-Fired Electricity Generation	% of NO$_x$ Emitted per % of Electricity Generated[a]	% of Coal-Fired Electricity Capacity
Pre-1950	5.51	0.65	0.50	1.31	0.92
1950-1959	5.07	15.11	12.56	1.20	14.32
1960-1969	4.56	21.27	19.65	1.08	20.51
1970-1979	4.28	39.31	38.76	1.01	38.13
1980-1989	3.53	21.74	25.97	0.84	23.84
Post-1990	3.15	1.92	2.56	0.75	2.27

b. 2002 SO$_2$ Emissions and Performance of Coal-Fired Capacity by Vintage

Power Plant Established	Avg. SO$_2$ Emission Rate (lb/MWh)	% of Total SO$_2$ Emitted	% of Coal-Fired Electricity Generation	% of SO$_2$ Emitted per % of Electricity Generated[a]	Average Capacity Factor (%)[b]	Average Heat Rate (Btu/kWh generated)
Pre-1950	20.58	1.02	0.50	2.04	36.35	12,549
1950-1959	15.78	19.64	12.56	1.56	58.93	10,668
1960-1969	13.92	27.12	19.65	1.38	64.37	10,150
1970-1979	9.31	35.75	38.76	0.92	68.29	10,270
1980-1989	6.02	15.49	25.97	0.60	73.17	10,401
Post-1990	3.88	0.98	2.56	0.38	75.80	9,982

c. 2002 NO$_x$ Emissions and Share of Generation of Coal-Fired Capacity by NSPS[c]

NSPS Status According to EIA 767	Avg. NO$_x$ Emission Rate (lb/MWh)	% Total NO$_x$ Emitted	% of Coal-Fired Electricity Generation	% of NO$_x$ Emitted per % of Electricity Generated[a]	% of Coal-Fired Electricity Capacity
Unknown	2.93	0.16	0.23	0.69	0.27
Not Affected by NSPS	4.67	65.90	59.51	1.11	62.62
Subject to Aug. 1971 Standards (D)	3.57	26.73	31.58	0.85	29.56
Subject to Sept. 1978 Standards (Da)	3.50	7.21	8.68	0.83	7.56

d. 2002 SO$_2$ Emissions and Performance of Coal-Fired Capacity by NSPS[c]

NSPS Status According to EIA 767	Average SO$_2$ Emission Rate (lb/MWh)	% of Total SO$_2$ Emitted	% of Coal-Fired Electricity Generation	% of SO$_2$ Emitted per % of Electricity Generated[a]	Average Capacity Factor[b] (%)	Average Heat Rate (Btu/kWh generated)
**Unknown	4.56	0.10	0.23	0.45	56.58	11,247
Not Covered by NSPS	12.93	76.25	59.51	1.28	63.85	10,250
Subject to Aug. 1971 Standards (D)	6.66	20.86	31.58	0.66	71.79	10,519
Subject to Sept. 1978 Standards (Da)	3.23	2.78	8.68	0.32	77.17	10,185

[a]If the generators of a particular vintage (or in a particular NSPS category) emitted a particular pollutant in proportion to its share of total electricity generation, the value would be 1.

[b]Capacity factor of units that operated that are strictly associated with boilers in CEM system database.

[c]The Subpart D standards apply to fossil-fuel-fired steam boilers for which construction began after August 17, 1971. The Subpart Da standards affect those boilers that began construction after September 18, 1978. For boilers not covered by NSPSs construction began before August 17, 1971. A new NSPS for NO$_x$ was promulgated in 1998, but no new coal-fired generating facilities have been permitted since this new standard was issued.

Notes: All quantities, including percentages of emissions and generation capacity, are calculated with reference only to coal-fired generating units. Percentages (taking account of rounding) add to 100% because other types of generating capacity are not considered. These tables and the associated dataset were constructed by David Evans of Resources for the Future. Data used to make these tables come from three sources: emission data are from EPA's CEM system database; generation and capacity data are from EIA's 767 dataset; and information on vintage of generating units is from EIA's Form 860 dataset.

Source: EIA 2004a,b; EPA 2004. As presented in NRC 2006a.

TABLE 2-11 Distribution of Pounds of Criteria-Pollutant Forming Emissions per MWh by Coal-Fired Power Plants, 2005

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	12	11	1.5	5.4	8.9	16	33
NO_x	4.1	2.3	1.3	2.6	3.7	4.9	9.0
$PM_{2.5}$	0.59	0.58	0.092	0.20	0.35	0.81	1.8
PM_{10}	0.72	0.67	0.12	0.28	0.48	0.94	2.1

damages, while the highest-damage 10% of plants, which also accounted for 25% of net generation, produced 43% of the damages. Although damages are larger for plants that produce more electricity, less than half of the variation in damages across plants is explained by differences in net generation.

Damages per kWh also varied widely across plants: from approximately half a cent (5th percentile) to over 13 cents per kWh (95th percentile). [These are unweighted figures.] Most of the variation in damages per kWh can be explained by variation in emissions intensity across plants. In the case of SO_2, which accounts for 85% of the damages associated with SO_2, NO_x and PM, over 80% of the variation in SO_2 damages per kWh is explained by variation in pounds of SO_2 emitted per kWh. Damages per ton of SO_2 emitted, which vary with plant location, are less important in explaining variation in SO_2-related damages per kWh. (They are, by themselves capable of explaining only 24% of the variation in damages per kWh.)

Of the 14 categories of criteria air pollution damages included in APEEP, 6 relate to human health and the remainder to physical impacts (materials damage, ozone damage to crops and forests, the cost of foregone recreation due to SO_2, NO_x, ozone and VOCs, and the cost of reduced visibility due to airborne particulate matter).

Sensitivity Analysis and Comparison with the Literature

The results of any analysis of the damages associated with air pollution emissions depend critically on (a) the size of the emissions reduction analyzed; (b) the air quality model used to translate emissions into ambient air quality; (c) the choice of concentration-response function for premature mortality and (d) the VSL used to monetize premature mortality. Premature mortality constitutes 94% of the damages reported above. When a VSL of $2 million is used (Mrozek and Taylor 2002), premature mortality constitutes 85% of total damages and the weighted-average cost per kWh falls to 1.2 cents. On the other hand, had we chosen to use Dockery et al. (1993) as the concentration-response function for premature mortality instead of Pope et al. (2002), our damages would have been approximately three times as large as what is reported above.

How do our estimates of damages compare with the literature? Levy et al. (2009) estimated the criteria air pollutant damages associated with individual coal-fired power plants using a methodology similar to what is used here; however, their estimates of damages are much higher, ranging from $0.02 to $1.57 per kWh, with a median estimate of 14 cents per kWh (1999 USD).[30] Converting the results of Levy et al. to 2007 USD, their median estimate is almost 6 times as high as our median estimate of 2.9 cents per kWh (Table 2-9).[31] It is, however, possible to reconcile the two sets of estimates. Two notable differences are that Levy et al.'s estimates are based on emissions data for 1999 rather than 2005 and their estimates depend on a concentration-response function for premature mortality based on Schwartz et al.

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[30]The mean value of a statistical life used in Levy et al. (2009) is identical to ours--$6 million USD. They report monetary values in 1999 USD.
[31]The figures in Levy et al. (2009) are unweighted by electricity production.

(2008) rather than Pope et al. (2002).[32] Emissions of NO_x from coal-fired power plants were approximately 50% higher in 1999 than in 2005; emissions of SO_2 were approximately one-third higher. The concentration-response function in Schwartz et al. (2008) yields about three times the deaths associated with a microgram of $PM_{2.5}$ than those estimated using Pope et al. (2002), the concentration-response function used in APEEP. These differences lead to much higher estimates of mortality associated with $PM_{2.5,}$ and over 90% of the damages associated with air emissions in our study come from $PM_{2.5}$ mortality. Levy et al. (2009) also performed uncertainty propagation involving asymmetric triangular distributions, which would contribute modest upward bias to the median damage estimates. In short, if Levy et al. (2009) had used the same mortality concentration-response function and the same emissions as APEEP, and had not done uncertainty propagation, the results would have been nearly identical to ours.

Estimates of the benefits of reducing SO_2 and NO_x emissions under the Clean Air Interstate Rule (EPA 2005b) are also higher than ours, due to differences in air quality modeling. The regulatory impacts analysis of the Clean Air Interstate Rule (CAIR) examined the benefits of reducing emissions of SO_2 and NO_x at power plants in 28 states in the eastern United States. The analysis predicted that, in 2015, a reduction in SO_2 emissions of approximately 4 million tons and a reduction in NO_x emissions of approximately 1.5 million tons would reduce premature mortality by 17,000 deaths. Our analysis, in contrast, estimates that a reduction in SO_2 and NO_x in these states that is approximately twice as large would result in 10,000 fewer deaths in the year 2005. This result is due to differences in air quality modeling: the use of CMAQ in the CAIR regulatory impact analysis leads to an estimate of 1.15 micrograms per cubic meter reduction in population-weighted $PM_{2.5}$ exposure, a much larger effect than is predicted by APEEP.[33] A study evaluating the performance of the version of CMAQ used in the CAIR study (version 4.3) found that it overestimated sulfate PM concentrations at sample locations in the eastern United States by 9% at one sample of sites (the Interagency Monitoring of Protected Visual Environments, largely rural sites) and by 6% at another set (Speciated Trends Network, largely urban sites) (EPA 2005c). This estimation bias was higher in the summer months, when sulfate concentrations are higher—14%. The estimation bias still does not fully account for the difference between the CMAQ and APEEP predictions, however.

Air quality modeling results from APEEP agree well with other studies that use Gaussian plume models to model dispersion of pollutants from power plants (Levy et al. 2009; Nishioka et al. 2002) but estimate lower concentrations of $PM_{2.5}$ from power plants than CMAQ (EPA 2005c; Fann et al. 2009).[34] One of the advantages of APEEP is better spatial resolution in urban counties, but it may still lack the necessary level of spatial detail in urban areas, giving rise to some uncertainty about results.

In contrast to Levy et al. (2009), Muller, Mendelsohn, and Nordhaus (2009) report estimates of criteria air pollutant damages from coal-fired power plants that are slightly lower than those presented here (mean damages of approximately 2 cents per kWh, on the basis of 2007 USD), using a value of a statistical life year approach.

Downstream CO_2 Emissions of Electricity Generation from Coal. The emissions of CO_2 from coal-fired power are the largest single source of GHG emissions in the United States. The heat rate (energy of coal needed to generate 1 kWh of electricity) varies widely among coal-fired plants; thus the CO_2 emissions vary (with an average of about 1 ton of CO_2 per MWh of power generated [the 5th-95th percentile range is 0.95-1.5 tons]). The main factors affecting differences in the CO_2 generated are the

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[32]The concentration-response function for premature mortality in APEEP is the all-cause mortality function in Pope et al. (2002).

[33]The CAIR RIA uses the same concentration-response function as APEEP (all cause mortality from Pope et al. (2002)) and a slightly lower VSL ($5.5 million 1999 USD). The U.S. population in 2015 is predicted to be about 9% higher than in 2005.

[34]Fann et al. (2009) using the Response Surface Model based on CMAQ, find damages per ton of SO2 from power plants of $15,000 in Atlanta and $18,000 in Chicago. The 95th percentile of damages in our study is $11,000.

technology used to generate the power and the age of the plant. The effect of CO_2 and other GHG emissions on global warming are discussed in Chapter 5.

Externalities Associated with Heavy Metal Emissions of Electricity Generation from Coal.

Heavy metals are toxic both to the environment and to public health. The combustion of coal to produce electricity results in emissions of some heavy metals, depending on the source of the coal, the conditions of combustion, and the cleanup technologies used. Among heavy metals found in coal combustion wastes are antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag)thallium (Tl), vanadium (V), and zinc (Zn). To determine the risks for human health and for the environment associated with the heavy metals, one must consider both the toxicity of the metal and the potential for exposure to the metal.

Information on the toxicity of individual metals and their various metallic species can be found in the Integrated Risk Information System (IRIS) database at the EPA website (epa.gov/IRIS). Highly toxic metals for humans and the environment include Hg, As, Cd, Pb, and Se. Major routes of exposure are through air emissions and through leaching of contaminants from landfills or surface impoundments of wastes.

Trace metals, including heavy metals, have been classified according to how they partition among waste streams from coal combustion (EPA 1995):

Class 1. Elements that are approximately equally concentrated in the fly ash and bottom ash, or show little or no small particle enrichment (that do not contain many small particles). Examples include manganese, beryllium, cobalt, and chromium.

Class 2. Elements that are enriched in fly ash relative to bottom ash, or show increasing enrichment with decreasing particle size. Examples include arsenic, cadmium, lead, and antimony.

Class 3. Elements emitted in the gas phase (primarily mercury and in some cases, selenium).

The main concern for human health is the risk associated with metals that end up in small, respirable particles and in the gas phase. Unfortunately, some of the most toxic heavy metals (arsenic, lead, cadmium) are enriched in the smaller particles. Particle control technologies will have limited impact on the emissions of mercury, which is emitted as a gas. Metals, notably mercury, are deposited from the atmosphere and enter the food chain, where they can affect humans who eat contaminated organisms, mainly fish, as described in more detail below.

Mercury from coal-fired power plants has been the subject of regulatory attention for some time. In March 2005, the EPA issued the Clean Air Mercury Rule (CAMR) to establish emissions limits and a voluntary cap-and-trade system for mercury from electricity generating units (EGUs). Concurrently, it "delisted" EGUs as a source of hazardous air pollutants that would be regulated according to the strict requirements of Section 112 of the Clean Air Act as amended. In February 2008, the D.C. Circuit Court vacated both CAMR and the delisting. In February 2009, the EPA withdrew its appeal of this vacatur; instead, it is developing standards for EGU emissions of hazardous air pollutants, including mercury, under Section 112. (A companion rule—CAIR, which was promulgated in May 2005—targets EGU emissions of sulfur dioxide and nitrogen oxide that cross state boundaries. In December 2008, the D.C. Circuit Court decided to remand rather than vacate CAIR, leaving the rule in place while EPA addresses concerns raised in a July 2008 D.C. Circuit Court decision.) This and additional information are at EPA's web site (EPA 2009b).

The EPA has recently developed a draft, site-based, probabilistic (Monte Carlo) risk assessment of onsite coal combustion waste disposal practices at coal-fired power plants across the United States (RTI 2007). The risk assessment includes a screening step to determine if the toxicity of the contaminant

and the known routes of exposure constitute a risk of excess lifetime cancer greater than 1 in 10^5 or a hazard quotient for non-cancer endpoints greater than 1. These risk assessments include those for trace metals, including heavy metals, and should be published soon. The metals exceeding the human health risk criteria described above at the 90th percentile for cancer included arsenic and for non-cancer endpoints included boron, molybdenum, selenium, and cadmium. For ecological receptors, exceedances were found for lead, boron, arsenic selenium, and cadmium at the 90th percentile. A limitation of the risk assessments is that while they take into account exposure from leachates of landfills and impoundments, they do not appear to take into account emissions into the air nor do they consider speciation of metals.

Unlike most of the other heavy metals, the dominant human exposure pathway for mercury is dietary. Mercury is emitted atmospherically from burning coal in elemental, particle-bound, and reactive forms that are deposited locally, regionally, and globally. After deposition, Hg enters water bodies where it is converted to methylmercury by microbes in the water column and sediment. Methylmercury bioaccumulates in aquatic species, reaching its highest concentration in high trophic-level fish such as shark, swordfish, and tuna; it also is found in many freshwater species. Consumption of fish is the major source of human exposure. Prenatal exposure to methylmercury is associated with subtle cognitive deficits and adult exposure may increase risk of fatal heart attack (Salonen et al. 1995; NRC 2000). Because of the complex pathway that mercury follows from its emission by power plants to its ingestion by people, affected by meteorological, chemical, physical, biological, and behavioral factors, it is difficult to estimate ecological and human health effects, which include impairment of cognitive function due to mercury exposure. Estimating monetary damages is even more difficult due to the lack of information on willingness to pay for reducing the risk of subtle cognitive effects from mercury exposure.

Coal Combustion By Products. Byproducts of burning coal to generate electricity include fly ash, bottom ash, flue gas desulfurization (FGD) materials, and fluidized bed combustion (FBC) residues (OSMRE 2009). In 2007, approximately 131 million tons of coal combustion byproducts (CCBs) were produced in the United States (ACAA 2008a).[35] Of this total, about 56 million tons were reused. CCBs and their reuse by type of CCB in 2007 are summarized in Table 2-12. As shown in Figure 2-9 the tonnage of CCBs produced annually has increased more than fourfold since 1966. Reuse of CCBs also has increased but has not kept pace.

CCBs can contain traces of naturally-occurring radioactive materials (regarding NORMs, see USGS 1997), as well as mercury, arsenic, lead, and other toxic materials. While CCBs have not been made subject to hazardous waste regulations under Subtitle C of the Resource Conservation and Recovery Act (RCRA), a 2006 NRC report noted that "CCRs [coal combustion residues] often contain a mixture of metals and other constituents in sufficient quantities that they may pose public health and environmental concerns, if improperly managed. … Risks to human health and ecosystems may occur when CCR-derived contaminants enter drinking water supplies, surface water bodies, or biota" (NRC 2006b, p. 3). In addition, while inhalation of dust from CCBs is primarily a worker safety issue, precautions are needed to protect the public from CCB dust if it becomes airborne (EPA 2009c).

Under RCRA, states may regulate CCBs as a solid waste, a special waste, or, on a case-by-case basis, as a hazardous waste; they may do so by statute, generic or specific regulations, policy, or guidance (Archer 2000). States vary widely in the extent to which they regulate CCBs. Unlike disposal of other solid wastes such as household wastes, no uniform practices have been required by federal regulation (Buckley and Pfughoeft-Hassett 2007).

If only because of the quantities of fly ash produced annually (71 million tons in 2007, of which 31 million tons were directed to reuse), fly ash storage and disposal are of particular concern. With the spill in December 2008 of more than 1 billion gallons of fly ash sludge from a retention pond at the

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[35]The osmre.gov website distinguishes between CCBs and CCPs. The latter are "beneficially used" and are thus a subset of CCBs; however, this nomenclature is not universally used. The more generic term "CCB" is used in this text.

TABLE 2-12 2007 Coal Combustion Combustion Product (CCP) Production and Use Survey Results

CCP Categories	Fly Ash	Bottom Ash	Bolier Stag	FGD Gypsum	FGD Material Web Scrubbers	FGD Material Dry Scrubbers	FGD Other	FBC Ash (not including ARIPPA FBC Ash data)	CCP Production/ Utilization Totals	FBC Ash combined with ARIPPA FBC Ash production	CCP Production/ Utilization Totals (including ARIPPA FBC Ash data)
Total CCPs Produced by Category	71,700,000	18,100,000	2,072,695	12,300,000	16,600,000	1,812,511	2,449,731	1,273,061	126,307,998	6,092,756	131,127,693
Total CCPs Used by Category	31,626,037	7,303,538	1,663,980	9,228,271	810,080	150,365	113,298	323,741	51,219,310	5,143,436	56,039,005
Concrete/ Concrete Products/Grout	13,704,744	665,756	0	118,406	0	21,266	0	5,518	14,515,690	5,518	14,515,690
Blended Cement/Raw Feed for Clinker	3,635,881	608,533	6,888	656,885	0	0	81,801	0	4,989,988	0	4,989,988
Flowable Fill	112,244	0	0	0	0	12,417	2,735	0	127,406	0	127,406
Structural Fills/ Embankments	7,724,741	2,570,163	158,767	0	97,610	555	0	46,282	10,598,118	46,282	10,598,118
Road Base/Sub-base	377,411	802,067	20	0	0	0	0	0	1,179,509	0	1,179,509
Soil Modification/ Stabilization	856,673	314,362	169	0	0	154	429	199,441	1,371,228	199,441	1,371,228
Mineral Filler in Asphalt	17,223	21,771	63,729	0	0	0	0	0	102,723	0	102,723
Snow and Ice Control	0	736,979	44,367	0	0	0	0	0	781,346	0	781,346
Blasting Grit/ Roofing Granules	0	71,903	1,377,658	0	0	0	0	0	1,449,561	0	1,449,561
Mining Applications	1,306,044	165,183	0	0	299,793	111,195	0	0	1,882,215	4,819,695	6,701,910
Gypsum Panel Products	0	0	0	8,254,849	0	0	0	0	8,254,849	0	8,254,849

TABLE 2-12 Continued

CCP Categories	Fly Ash	Bottom Ash	Bolier Stag	FGD Gypsum	FGD Material Web Scrubbers	FGD Material Dry Scrubbers	FGD Other	FBC Ash (not including ARIPPA FBC Ash data)	CCP Production/ Utilization Totals	FBC Ash combined with ARIPPA FBC Ash production	CCP Production/ Utilization Totals (including ARIPPA FBC Ash data)
Waste Stabilization/ Solidification	2,680,328	7,056	0	0	10,378	1,416	28,333	72,500	2,800,031	72,500	2,800,031
Agriculture	49,662	2,546	0	115,304	9,236	3,352	0	0	180,100	0	180,100
Aggregate	135,331	806,645	450	70,947	0	0	0	0	1,013,373	0	1,013,373
Miscellaneous/Other	1,025,724	530,574	11,932	11,880	393,063	0	0	0	1,973,173	0	1,973,173
Totals by CCP Type/ Application	31,626,037	7,303,538	1,663,980	9,228,271	810,080	150,365	113,298	323,741	51,219,310	5,143,436	56,039,005
Category Use to Production Rate (%)	44.11%	40.35%	80.28%	75.03%	4.88%	8.30%	4.62%	25.43%	40.55%	84.42%	42.74%
Supplemental: Cenospheres Sold (Pounds)	12,659,597										

Source: ACAA 2008a. Reprinted with permission; copyright 2008, American Coal Ash Association.
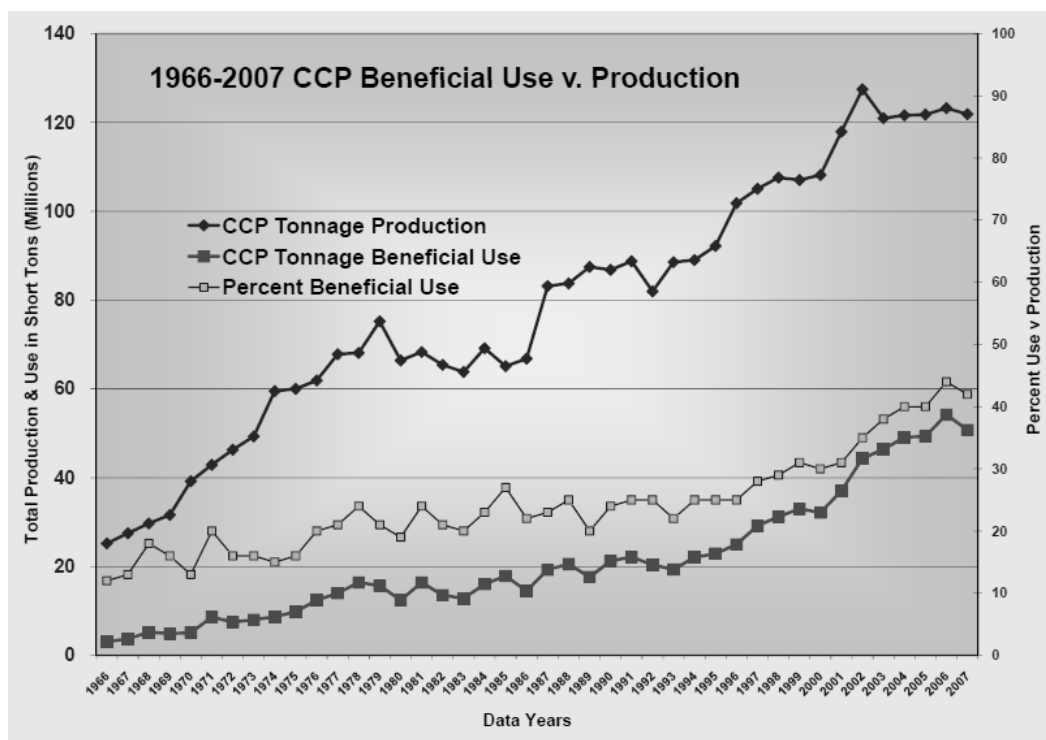
FIGURE 2-9 Coal combustion product beneficial use versus production. Source: ACAA 2008b. Reprinted with permission; copyright 2008, American Coal Ash Association.

Tennessee Valley Authority's coal-fired plant in Kingston, Tennessee, fly ash became a matter of national attention. Fly ash usually is stored in ponds or landfills on or near to their power plant sites, which typically are located on waterways because of the plant's need to use and release water. Storing fly ash dry in landfills is considered safer, but even then, fly ash landfills often do not have the liners, leachate collection systems, and caps required under RCRA Subtitle D regulations for municipal solid waste landfills (EPA 2008a).

EPA has identified 431 slurried CCB impoundments through a national survey. Of the impoundments identified, 49 have been given a "high-hazard" rating by EPA(EPA 2009d).

Externalities from Coal in 2030

Technology in 2030. It is impossible to consider the future of coal-fired generation without considering the prospect of carbon capture and sequestration (CCS). CCS is a technology where the carbon dioxide emissions are first separated from the stack emissions, then collected and typically sent for offsite storage via small pipelines. Most current discussions about this nascent technology relates to where the carbon would be stored, with the most prominent discussions suggesting storage in underground geological sites such as aquifers or depleted gas fields, as well as in oil fields via enhanced oil recovery (EOR). CO_2 could also be liquefied, with potential storage in oceans. While beyond the scope of this chapter, there are significant risks due to accidental release of sequestered carbon.

The most common coal-fired technology being discussed for the future is IGCC (Integrated Gasification Combined Cycle), in which coal is first gasified before being used to generate electricity. IGCC plants are not only the most obvious next step in coal technology, but are more compatible with carbon capture systems. CCS is expected to be able to divert 80-90% of the CO_2 generated at these power

plants. However, an IGCC/CCS system has an energy penalty in that more energy is needed to run the system, and thus more coal is required per kWh of electricity generated.

The current dominant technology, pulverized coal (PC), is compatible with CCS, but is generally more costly. As PC will remain the dominant technology in the "fleet" of power plants for several decades, and PC plants are being used decades past their original design lifetimes, the need for considering CCS for PC plants is inevitable. It is likely that PC technology will also have CCS and, depending on incentives and motivations, could be the dominant source of sequestered carbon. In general, IPCC estimates the cost per kWh of electricity from IGCC to be less than PC, including CCS systems (Table 2-13 [IPCC 2005, Table 8.3a]).

There are few IGCC projects in the world as of 2009, and relatively few CCS demonstration projects, especially for geological sequestration other than EOR. If IGCC and CCS technology is to be incorporated into the electricity sector, then ramp-up of siting, design, and construction of these plants needs to begin immediately for it to have any significant impact on air emissions within 20 years.

A relevant scenario is that in a future with 80-90% capture of CO_2 from coal-fired power, the upstream air emissions from mining and transportation will become much more significant, and possibly the largest single source of emissions in the coal power life cycle. Further, if the EIA's long-term scenarios related to electricity mix hold true (i.e., still 50% coal in 2030) [EIA 2009e], then significantly more coal will be mined, and these upstream externalities, while still relatively small on a per-kWh basis, will likely grow in magnitude in the local areas where coal is mined and where unit trains of coal deliveries pass through.

TABLE 2-13 IPCC Range of Aggregate Costs for CO_2 Capture, Transport, and Geological Storage

	Pulverized Coal Power Plant	Natural Gas Combined Cycle Power Plant	Integrated Coal Gasification Combined Cycle Power Plant
Cost of electricity without CCS (US$ MWh^{-1})	43-52	31-50	41-61
Power plant with capture			
Increased Fuel Requirement (%)	24-40	11-22	14-25
CO_2 captured (kg MWh^{-1})	820-970	360-410	670-940
CO_2 avoided (kg MWh^{-1})	620-700	300-320	590-730
% CO_2 avoided	81-88	83-88	81-91
Power plant with capture and geological storage[a]			
Cost of electricity (US$ MWh^{-1})	63-99	43-77	55-91
Electricity cost increase (US$ MWh^{-1})	19-47	12-29	10-32
% increase	43-91	37-85	21-78
Mitigation cost (US$/t$CO_2$ avoided)	30-71	38-91	14-53
Mitigation cost (US$/tC avoided)	110-260	140-330	51-200
Power plant with capture and enhanced oil recovery[b]			
Cost of electricity (US$ MWh^{-1})	49-81	37-70	40-75
Electricity cost increase (US$ MWh^{-1})	5-29	6-22	(-5)-19
% increase	12-57	19-63	(-10)-46
Mitigation cost (US$/t$CO_2$ avoided)	9-44	19-68	(-7)-31
Mitigation cost (US$/tC avoided)	31-160	71-250	(-25)-120

[a]Transport costs range from 0-5 US$/t$CO_2$. Geological storage cost (including monitoring) range from 0.6-8.3 (US$/t$CO_2$).
[b]Transport costs range from 0-5 US$/t$CO_2$ stored. Costs for geological storage including EOR range from -10 to -16 US$/t$CO_2$ stored.
Source: IPCC 2005, Table 8.3a, p 347. http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter8.pdf. Reprinted with permission; copyright 2005, Intergovernmental Panel on Climate Change.

Air Pollution Damages from Coal-Fired Power Plants in 2030. The air pollution damages associated with electricity generation from coal in 2030 depend on many factors. Aggregate damages depend on the growth in electricity demand and the extent to which coal is used to satisfy this demand, as opposed to other fuels. Damages per kWh are a function of the emissions intensity of electricity generation from coal (e.g., pounds of SO_2 per MWh), which depends on future regulations governing power plant emissions. The damages per ton of SO_2 and NO_x depend on the location of coal fired power plants and on the size of the populations affected by them.

To give a sense of how damages in 2030 might compare with estimates for the year 2005, we use EIA forecasts of electricity production from coal and of SO_2 and NO_x emissions, together with estimates of damages per ton of pollutant emitted in 2030 from APEEP. The assumptions underlying our analysis are outlined below. Because of the greater uncertainties associated with the 2030 analysis, we focus on estimates of aggregate damages from coal-fired power generation, rather than presenting a detailed distribution of damages, as in the section above.

Methodology. The 2030 thermal power plant analysis relied on EIA's Annual Energy Outlook 2009 projections(EIA 2009f, Table 72-100) for the growth of net generation and emissions of SO_2 and NO_x. On average, net generation from coal-fired power plants is estimated to be 20% higher in 2030 than in 2005. Estimates are available by type of generator, fuel type, and NERC region generation. EIA does not project changes in $PM_{2.5}$ and PM_{10} emissions. These were imputed as the average of the projected changes in these two species. These regional trends were used to construct multipliers for 2005 net generation by plant and emissions by stack. We applied each regional multiplier to all the plants with a given fuel in that region of the country. We assumed that coal plants in 2030 will be sited in the same locations as current plants.

Our 2030 results therefore embody all of the regulatory and technological assumptions made by EIA. We deliberately took this analytical tack because our charge precluded us from considering policies to remedy externalities. Thus we did not attempt to substitute our own judgments about future regulatory developments in place of EIA's projections, which are widely used and generally regarded as authoritative.

We use EIA estimates of SO_2 and NO_x from electricity generation in 2030, together with estimates of electricity generation by fuel type and emission intensities by fuel type in 2005 to estimate the percentage reduction in tons of SO_2 and NO_x per MWh at coal plants. On average, pounds of SO_2 per MWh are assumed to decrease from 10.1 pounds (weighted by electricity generation) in 2005 to 3.65 pounds in 2030. The corresponding figures for NO_x are 3.42 pounds per MWh in 2005 (weighted by electricity generation) and 1.90 pounds in 2030.[36] Estimates of 2030 emissions intensities together with forecasts of net generation produce estimates of emissions of SO_2, NO_x, $PM_{2.5}$ and PM_{10} at the location of each plant in 2030.

APEEP was used to generate estimates of damages per ton of pollutant, by county and effective stack height, in 2030. These estimates assume that the meteorological conditions and other assumptions used in modeling the impact of a change in emissions on ambient air quality are the same in 2030 as in 2005, and that emissions are emitted at the same effective stack heights at each plant as in 2005. The same concentration-response functions used in the 2005 analysis are used to translate changes in ambient concentrations into cases of premature mortality and morbidity in 2030; however, the U.S. population will have changed, according to forecasts from the U.S. Census Bureau. An increase in population size was reflected in the 2030 analysis, but the age structure of the population was not changed. The Value of a Statistical Life is assumed to increase with income growth. Using an elasticity of the VSL with respect to income of 0.50 (Viscusi and Aldy 2003) and assumptions in EPA's national Energy Modeling System (NEMS) about growth in per capita income, the VSL is 27% higher in 2030 (in 2000 USD) than in 2005, as are the unit values applied to other health endpoints. The combined effect of increases in population and increases in the VSL and other health values is to increase damages per ton of pollution, on average,

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[36]The corresponding figures for $PM_{2.5}$ are 0.215 pounds per MWh (2030) v. 0.491 pounds per MWh (2005). For PM_{10} the emissions intensities are 0.263 pounds per MWh (2030) v. 0.594 pounds per MWh (2005).

by over 50% compared to 2005 values. The percentage change, however, varies considerably by pollutant and county. In the counties in which coal plants are currently located—where we assume they will be located in 2030—the mean increase in damage per ton of pollutant emitted is 36% for SO_2 and 32% for NO_x.

Results. Damages from NO_x, SO_2, PM_{10} and $PM_{2.5}$ were calculated, as described above, for each of 406 plants that generated electricity from coal in 2005. In spite of the fact that net generation is 20% higher in 2030 than in 2005, monetized air pollution damages (in 2007 USD) are approximately $38 billion—about 40% lower than in 2005. Damages per kWh (weighted by electricity generation) are 1.7 cents per kWh, compared to 3.2 cents per kWh in 2005. The fall in damages per kWh is explained by the assumption that pounds of SO_2 per MWh will fall by 64% and that NO_x and PM emissions per MWh will fall by approximately 50%. This counteracts the increase in damages per ton.

For future technologies at coal-fired plants, such as IGCC with CCS, criteria-pollutant forming emissions per kWh are expected to be significantly lower than emissions per kWh from a typical plant in 2030 (NETL 2007). Plants using future technologies would also be expected to have damages at the lower end of current distributions. On the other hand, damages that would be attributable to providing the expected infrastructure (e.g., pipelines and geologic sites) for long-term geological sequestration of CO_2 are much more uncertain.

ELECTRICITY PRODUCTION FROM NATURAL GAS

History and Current Status of Natural Gas Production

Natural gas, a non-renewable energy source that consists primarily of methane, is consumed in the United States for heat, fuel, and electricity. During the mid 20th century, natural gas was predominantly used for residential and commercial space heating, as well as for industrial process heating. Since then, natural gas has taken an increasing share in production of electricity. In 2008, approximately 30% of produced natural gas was used to produce electricity.

U.S. natural gas production matched domestic consumption until the early 1970s. Natural gas productivity (volume of natural gas extracted per well) peaked in 1971 with 119,251 wells producing on average 159 million cubic feet per year (Figure 2-10). Total domestic production reached 22.6 trillion cubic feet in 1973, after which it began to decline (Figure 2-11). By 2007, the United States had 452,768 producing gas wells, nearly four times as many as in 1971, indicating that the mean productivity per well has declined substantially. However, preliminary data from EIA suggest that 2008 gross withdrawals of natural gas were the highest recorded, exceeding 26 trillion cubic feet; marketed production was 21.4 trillion cubic feet. Currently, more than 75% of domestic NG production comes from Texas, Wyoming, Oklahoma, New Mexico, Louisiana, and the federal off-shore Gulf of Mexico.

The United States has increased its reliance on natural gas imports to keep pace with consumption, which was 23.0 trillion cubic feet in 2007 and 23.2 trillion cubic feet in 2008. Imports have increased since 1970. In the past few years (2003-2008), gross imports have averaged around 4 trillion cubic feet annually. Exports have increased from about 0.7 trillion cubic feet in 2003 to just over 1 trillion cubic feet in 2008. More than 90% of imported NG is transported by pipeline from Canada and Mexico. The United States also imports liquid natural gas (LNG) by ocean tankers from Trinidad, Egypt, Norway, Nigeria, and Qatar.

Natural gas is gathered and transmitted from producing fields and storage sites by pipeline. The United States has more than 300,000 miles of inter- and intrastate NG transmission pipelines. Domestic and imported NG is stored underground in natural geologic spaces. The United States had 400 storage sites (depleted fields, aquifers, and salt caverns) with greater than 8,400,000 million cubic feet of storage in 2007.
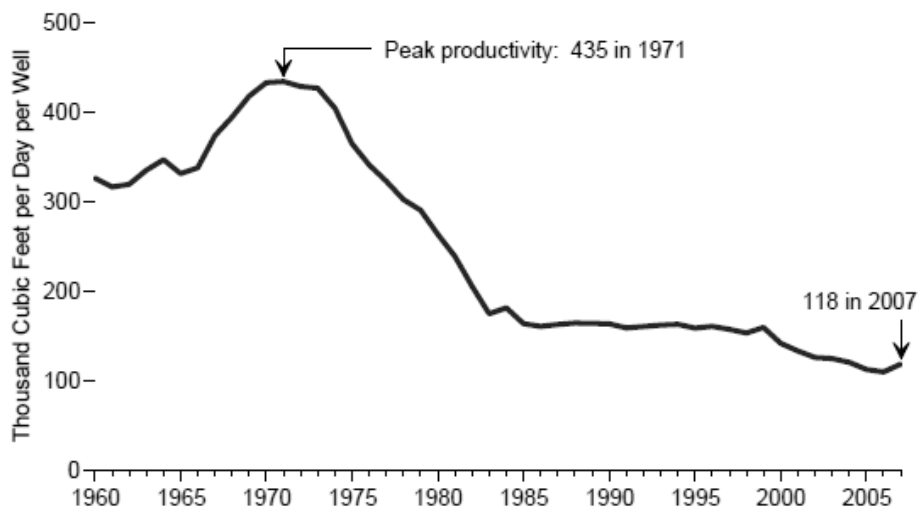
FIGURE 2-10 U.S. natural gas well average productivity. Source: EIA 2008a, p. 188, Figure 6.4.
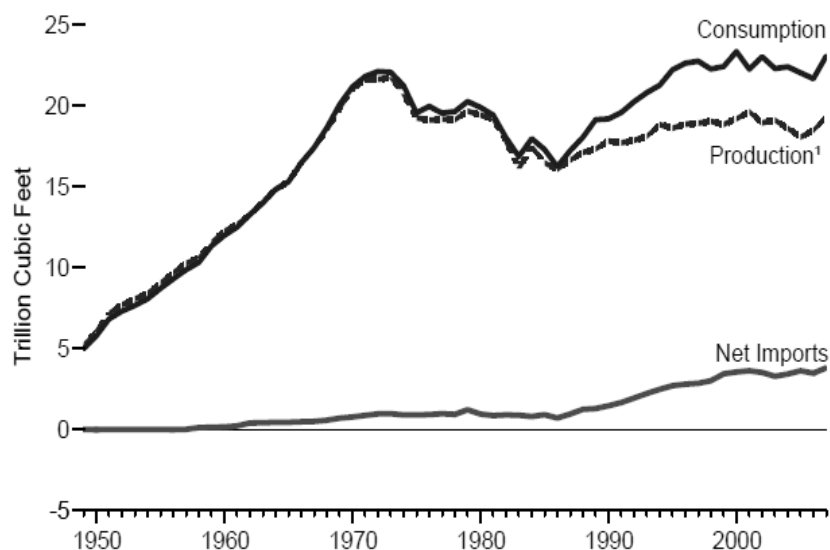
1. Dry-gas production.

FIGURE 2-11 Natural gas production, consumption, and imports in the United States. Source: EIA 2008a, p. 182, Figure 6.1.

Upstream Externalities of Electricity Production from Natural Gas

Natural Gas Exploration and Drilling

Exploration and Development. Exploratory activities to locate natural gas reservoirs are similar to those for oil. Exploratory drilling for natural gas uses the same rotary equipment and methods for development and production drilling, and it produces wastes mostly in the form of pollutants in water, primarily from the use of drilling fluids. Drilling also produces drill cuttings and mud. Exploration and development of natural gas occurs onshore and offshore, with potentially different types and levels of pollution. Initial exploration often uses seismic operations—the use of artificial shock waves directed

into the earth to assess geologic strata based on reflection of the energy—both onshore and offshore. On land, transportation of the equipment can damage terrestrial ecosystems, especially in roadless areas (NRC 2003a). Offshore seismic exploration can adversely affect fish and marine mammals, especially if explosives are used (NRC 2003a).

For onshore drilling, significant proven reserves in the United States are along the Gulf Coast and in the Rocky Mountain region. Although rotary drilling is generally for exploration and development, cable-tool drilling can be utilized for shallow, low-pressure gas reservoirs. The amount of land required for a typical gas field of approximately 120 wells ranges from 420 to 640 acres depending on the size of the natural gas reservoir (on average 3.5 to 5.33 acres per gas well). This is a smaller area than is required for oil wells, which require approximately 40 acres per well. The primary waste products from gas well exploration and development are oils, heavy metals, and dissolved solids contained in the drilling mud or produced water. Specifically, the waste products are oil and grease, suspended solids, phenol, arsenic, chromium, cadmium, lead, and barium. These drilling wastes do not change significantly from region to region.

Drilling operations potentially create significant amounts of air pollution. Large diesel engines typically power the drilling equipment and emit significant quantities of particulate matter, sulfur oxides, and oxides of nitrogen. These emissions can be substantial during drilling of deep wells requiring large power outputs or in large fields where multiple drilling operations occur simultaneously. Other sources of air pollution include organic compounds that may volatilize from reserve and other holding pits used as waste repositories during drilling operations, although the volume of these compounds is insignificant compared to diesel engine emissions. Oil and gas wells abandoned at the end of their productive life may cause environmental damage to the surrounding land surfaces and underground freshwater aquifers.

A considerable amount of natural gas exploration and development is offshore on platforms, primarily in the Gulf of Mexico. For offshore drilling operations, drilling rigs may either be stationary or mobile. For drilling in waters up to 300 feet deep and marsh areas, mobile drilling rigs are mounted on barges and rest on the bottom for drilling. In water greater than 300 feet deep, drilling rigs are on floating or semi-submersible vessels with special submerged hulls that support the drill rig above the water level. To transport drill rigs to marsh areas, canals are dredged to the drill sites to float the rigs into place.

The produced waters from offshore platforms include production wastes, deck drainage, and sanitary and domestic wastes. The produced waters can contain oils, toxic metals, and organic chemicals. Significant pollutants in produced waters include oil and grease, arsenic, cadmium, copper, cyanide, lead, mercury, nickel, silver, zinc, and organic carbon. Spilled oil and grease can adhere to fish and destroy algae and plankton, thereby altering the aquatic food chain. Additionally, damage is likely to occur to the plumage and coats of water animals and fowl. Lead, zinc, and nickel are toxic to fish in low concentrations. However, offshore drilling rigs attract fish and can reduce fuel costs to recreational fishermen, an economic benefit.

Extraction. Natural gas is extracted by using either the existing pressure of the gas reservoir or by using pumps. Gas wells produce not only dry gas but also can produce varying quantities of light hydrocarbon liquid condensates and salt water. The resulting produced water (also known as "formation water" or "brine water") includes all waters and particulate matter associated with the gas producing formation. Produced water is the primary waste from offshore platforms. It can contain oils, toxic metals, salts, and organic compounds, which can cause environmental damage. For both onshore and offshore extraction, the type of technology used to treat produced water depends on state or local regulations as well as cost effectiveness. Additionally, air emissions can include hydrogen sulfide that can be as high as 6% by volume in sour gas (i.e., natural gas that contains hydrogen sulfide).

Natural gas is also produced using enhanced gas recovery extraction (EGR) methods. The primary technologies used for EGR are fracturing and directional drilling. Fracturing involves the use of either chemical explosives or water under pressure. The concerns about these technologies are different for each of the methods used. Adverse impacts from the use of advanced hydraulic fracturing include air emissions and noise from the pressurized injection process. Preparing the well casing can cause leaks to

groundwater or the surface. Water forced into gas bearing shale can cause contamination or disruption of nearby wells. The use of chemical explosive fracturing has environmental impacts that are similar to advanced hydraulic fracturing. When the wells are constructed, noise, air emissions, soil erosion, soil loss, and aesthetic deterioration may occur. There is also the danger of gas leaks or explosions from pipelines or storage tanks.

Directional or slant drilling (i.e., drilling that is not vertical) for recovery of natural gas can result in air emissions, erosion, and soil loss during the preparation of the drilling site. Drilling and production activities result in noise and risk of explosions. EGR processes have a considerably greater potential for causing air-quality degradation than do conventional recovery technologies. In both conventional and EGR processes, air-quality impacts result from emissions associated with production and injection pumps and fugitive emissions from wellheads and handling and storage facilities. Additionally, EGR technologies produce emissions from the combustion engines of compressors and from steam boilers in steam flood operations.

Other Impacts. The "footprint" for locations for natural gas exploration, development, and extraction is smaller than that for similar oil wells. While the impacts may not be as great for natural gas field operations, there are a number of additional impacts for both land and offshore activities that should be mentioned, in addition to those described above, that can have significant, although difficult to quantify, impacts.

For land-based operations, seismic measurements are a problem due to noise, aesthetics, and land use impacts, although most of these are temporary (e.g., NRC 2003a). For the longer term, there are potential impacts related to habitat destruction. Wastewaters from all aspects of operation must be treated or they can cause significant degradation to the surface waters.

Offshore operations have different impacts in some cases. First, there is the overall impact of land degradation along the Gulf Coast. For both land-based, but nearshore operations, and for offshore operations, there is significant deterioration of onshore land, leading to salt water encroachment, land subsidence, and loss of land to the sea. The offshore operations can also have an impact on the surrounding ecosystem. Despite previous comments on benefits to recreational fishermen, natural gas platforms can have deleterious effects on larger ecosystems and can impact commercial fishing operations.

In a life cycle analysis performed by Dones et al. (2005), it is estimated that approximately 25% of carbon dioxide emissions come from the processes discussed above, as treated as total production emissions (exploration, field production, purification). Other values include 10% of the methane, 50% of the non-methane volatile organic hydrocarbons, 40% of the particulate matter, 20% of the nitrogen oxides, and 80% of sulfur dioxide emissions for the total fuel cycle.

Occupational Injuries Associated with Oil and Gas Extraction and Transport

Fatal and Non-fatal Injuries in Oil and Natural Gas Extraction.[37] As in the case of mining, we assume that fatal and nonfatal occupational injuries do not constitute externalities, but we briefly discuss them due to their societal importance. In 2007, oil and gas industry fatalities accounted for almost two-thirds of fatal work injuries in mining. Unlike coal mining, the number of fatalities in oil and gas extraction has been increasing, reaching in 2006 levels seen only decades ago (Figure 2-12). The incidence of fatalities, approximately 3 per 10,000 workers, is also higher than in coal mining (2 per 10,000 workers). The number of reported injuries has also increased (Figure 2-13).

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[37]It is difficult to separate injuries associated with oil extraction from injuries associated with natural gas extraction.
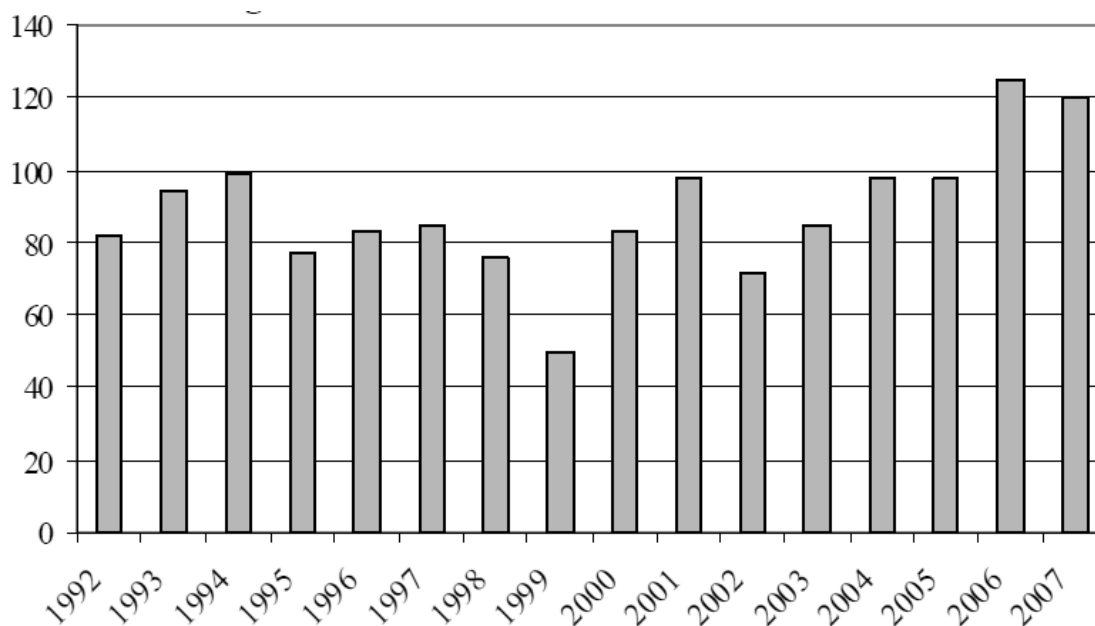
FIGURE 2-12 U.S. fatalities in oil and gas extraction from 1992 to 2007. Source: Bureau of Labor Statistics, Census of Fatal Occupational Injuries (CFOI).
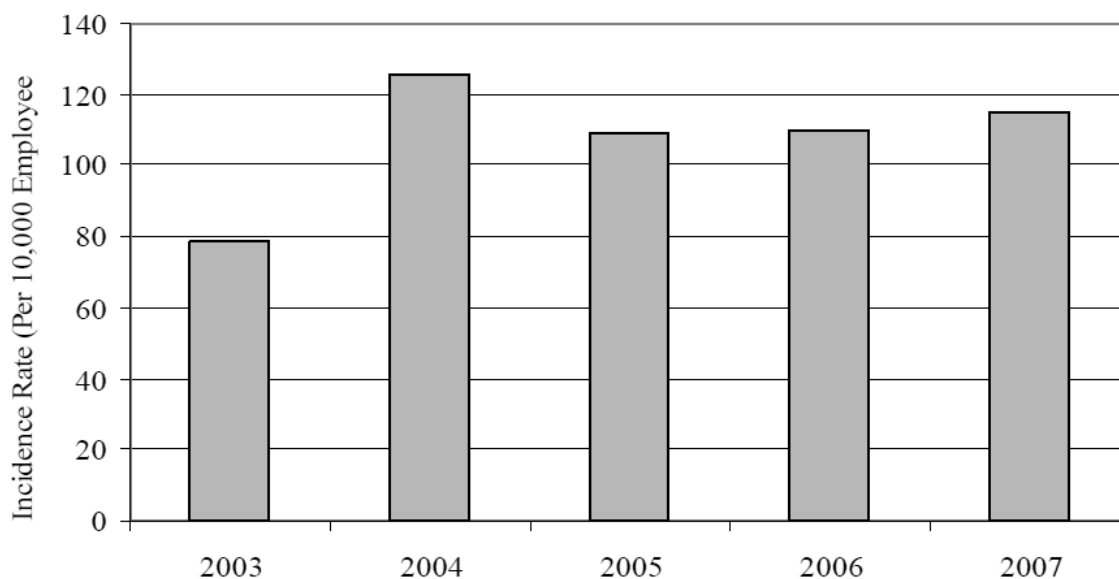
FIGURE 2-13 Injuries and illnesses in U.S. oil and natural gas extraction operations. Source: Bureau of Labor Statistics, Occupational Injuries/Illnesses and Fatal Injuries Profile.

Fatal and Non-fatal Injuries in Transportation of Natural Gas. In 2003, U.S. pipelines moved 590 billion total ton-miles of crude oil and petroleum products, and 278 billion ton miles of natural gas (Dennis 2005). This includes gathering pipelines, which carry products from production fields; transmission pipelines, which transport products to terminals and refineries; and distribution pipelines, which carry products to final market and consumption points. Electric power plants receive 98% of their natural gas from direct mainline pipeline deliveries; 2% is provided by local distribution companies. In 2007, natural gas transport involved 2 fatalities and 7 injuries. Natural gas distribution involved 8

fatalities and 35 injuries. While the numbers of fatalities from natural gas pipeline activity has fluctuated, averaging 12 from 2000 to 2007, related injuries have steadily decreased over time (BTS 2009, Table 2-46). The majority of fatal and nonfatal injuries during natural gas transport are occupational and therefore are not treated as externalities.

Upstream GHG Emissions and Other Pollutants. The upstream life cycle of power generation from natural gas includes many relevant activities such as construction of the infrastructure and power plants, but the most significant from a perspective related to GHG emissions and criteria-pollutant forming emissions are the extraction and transportation of gas. These activities are generally fuel- and energy-intensive, requiring combustion of fossil fuels for drilling and removing the gas from underground and delivering to the power plant. Beyond emissions from engines, there are also significant GHG emissions of methane, which is from fugitive emissions of natural gas.

Of increasing relevance is the use of liquefied natural gas (LNG) to generate power. Over the past decade, a global market has begun for the extraction of gas for export via liquefying it, shipping it by tanker (similar to petroleum), and regasification. Each of these stages increases the energy use and air emissions (related to criteria pollutants and GHG) associated with the life cycle of the power generated.

Transportation of natural gas in the United States occurs via pipelines. While pipelines are a very cost-and energy-efficient transportation mode, they use significant amounts of fuels and electricity to move the gas from well to power plant. In addition, pipelines leak natural gas as methane into the air. As noted above, the transportation of LNG involves ocean tankers.

The prior studies mentioned above for coal also assessed the relative contribution of the upstream life cycle of gas-fired power generation for domestically sourced NG (Jaramillo et al 2007, Meier et al 2005, Spath and Mann 2000, ORNL/RFF 1992-1998). As was the case for coal, these studies found that upstream activities lead to relatively small life cycle effects because of the dominance of criteria-pollutant forming emissions and GHG emissions from gas-fired power plants (although the percentage share of upstream emissions in the life cycle are higher). For example, Jaramillo et al (2007) reports that the mid-point GHG emission factors for domestic natural gas combustion (at the power plant) and the entire natural gas life cycle are 1100 lb CO_2 equivalent/MWh and 1250 lb CO_2 equiv/MWh, respectively. Thus in this study we have focused on quantifying the air emissions associated with the burning of gas at power plants. This assumption would need to be revisited in a future scenario that had order-of-magnitude increases in the amount of LNG consumed for power generation (and its higher per unit emissions), but it is not considered in this study.

Downstream Externalities of Electricity Production from Natural Gas

Analysis of Current Air Pollution Damages from Gas-Fired Power Plants

The air pollution emissions from gas-fueled power plants constitute a significant portion of the downstream damages associated with electricity generation. In this section we quantify the impacts of criteria-pollutant forming emissions from gas-fired power plants on human health, visibility, agriculture, and other sectors, using the methods outlined in section for coal. The effects of emissions on ambient air quality are calculated for each of 498 facilities that used gas to generate electricity in 2005. These facilities, which include electric utilities, independent power producers and combined heat and power facilities, each generated at least 80% of their electricity from gas and had installed capacity of at least 5 MW. Together they accounted for 71% of electricity generation from natural gas in 2005.[38]

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[38]Emissions data in the National Emissions Inventory are reported at the stack level. When generating units powered by different fuels use the same stack, an attempt is made to apportion emissions by fuel type. To avoid errors in emissions data we analyze gas plants that use no coal and generate 80% of more of their electricity from natural gas.

Damages related to emissions of NO_x, SO_2, PM_{10}, and $PM_{2.5}$ were calculated for each of the 498 plants described above. Table 2-14 presents the distribution of monetized damages across the 498 natural gas fired power plants. (All plants are weighted equally in the table; hence the mean figures are arithmetic means of damages across all plants.) Most damages are related to directly emitted $PM_{2.5}$ (56%), followed by NO_x (37%), SO_2 (4%) and PM_{10} (3%), unlike coal plants where most damages (85%) are related to SO_2 emissions. Damages, however, are much lower than for coal plants. Average annual damages per plant are $1.49 million, which reflects both lower damages per kWh at natural gas fired power plants, but also smaller plants: net generation at the median coal plant is more that 6 times as large as at the median gas facility.[39]

Some of the variation in damages across plants reflects differences in net generation; hence we also report damages per kWh of electricity produced.[40] Table 2-15 presents the distribution of air pollution damages per kWh. (All plants are weighted equally in the first five rows of the table; in the last row, plants are weighted by the fraction of electricity they produce.) Mean damages per kWh from the criteria-pollutant forming emissions are 0.43 cents per kWh if all plants are weighted equally and 0.16 cents per kWh if plants are weighted by the fraction of electricity they generate. Damages per kWh are, on average, an order of magnitude lower—0.16 cents per kWh for natural gas compared to 3.2 cents per kWh for coal.[41] The lower figure reflects the fact that larger plants are often cleaner.[42] It should, however, be emphasized that the distribution of damages per kWh has a high variance and is very skewed: Although, on average, damages from natural gas fired plants are an order of magnitude lower than damages from coal-fired power plants, there are some gas facilities with damages per kWh as large as coal plants.

As Figure 2-14 shows, the distribution of damages across plants is highly skewed. After sorting the plants according to damages, we found that the 10% of plants with highest damages produce 65% of the air pollution damages from all 498 plants, while the lowest emitting 50% of plants within the lowest damages account for only 4% of aggregate damages. Each group of plants accounts for approximately one-quarter of sample electricity generation. The map in Figure 2-15 shows that the natural gas plants that produce the largest damages are located in the Northeast (along the Eastern seaboard), Texas, California, and Florida.

TABLE 2-14 Distribution of Criteria Pollution Damages Associated with Emissions from 498 Gas-Fired Power Plants in 2005 (2007 USD)

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	6.40E+04	2.58E+05	1.80E+02	1.96E+03	1.02E+04	2.92E+04	2.23E+05
NO_x	5.49E+05	1.25E+06	4.86E+03	4.32E+04	1.43E+05	4.74E+05	2.37E+06
$PM_{2.5}$	8.31E+05	3.23E+06	4.70E+02	1.50E+04	1.04E+05	4.12E+05	3.17E+06
PM_{10}	4.47E+04	1.75E+05	4.07E+01	9.72E+02	5.44E+03	2.22E+04	1.62E+05
Total	1.49E+06	4.10E+06	1.02E+04	1.02E+05	3.57E+05	1.28E+06	5.50E+06

Note: All plants are weighted equally.

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[39]Median annual net generation is 3.01 billion kWh for coal plants and 0.469 billion kWh for gas plants.

[40]It is, however, the case that less than 40% of the variation in damages is explained by variation in the amount of electricity generated. A regression of damages on net generation yields an $R^2 = 0.09$; the R^2 is 0.37 when the logarithms of the variables are used.

[41]Both figures weight damages per kWh at each plant by electricity generated by the plant.

[42]The correlation coefficient between damages per kWh and net generation is = -0.18. It is -0.49 between the logarithms of the variables.

TABLE 2-15 Distribution of Criteria Pollution Damages per kWh Associated with Emissions from 498 Gas-Fired Power Plants in 2005 (cents based on 2007 USD)

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	0.018	0.067	0.00013	0.00089	0.0022	0.006	0.075
NO_x	0.23	0.74	0.0014	0.013	0.038	0.16	1.0
$PM_{2.5}$	0.17	0.56	0.00029	0.007428	0.026	0.08	0.75
PM_{10}	0.009	0.029	0.00003	0.00043	0.0014	0.0042	0.036
Total (unweighted)	0.43	1.2	0.0044	0.041	0.11	0.31	1.7
Total (weighted by net generation)	0.16	0.42	0.001	0.01	0.036	0.13	0.55

Note: In the first 5 rows of the table, all plants are weighted equally; i.e., the average damage per kWh is 0.43 cents, taking an arithmetic average of the damage per kWh across all 498 plants. In the last row of the table, the damage per kWh is weighted by the fraction of electricity generated by each plant to produce a weighted damage per kWh.
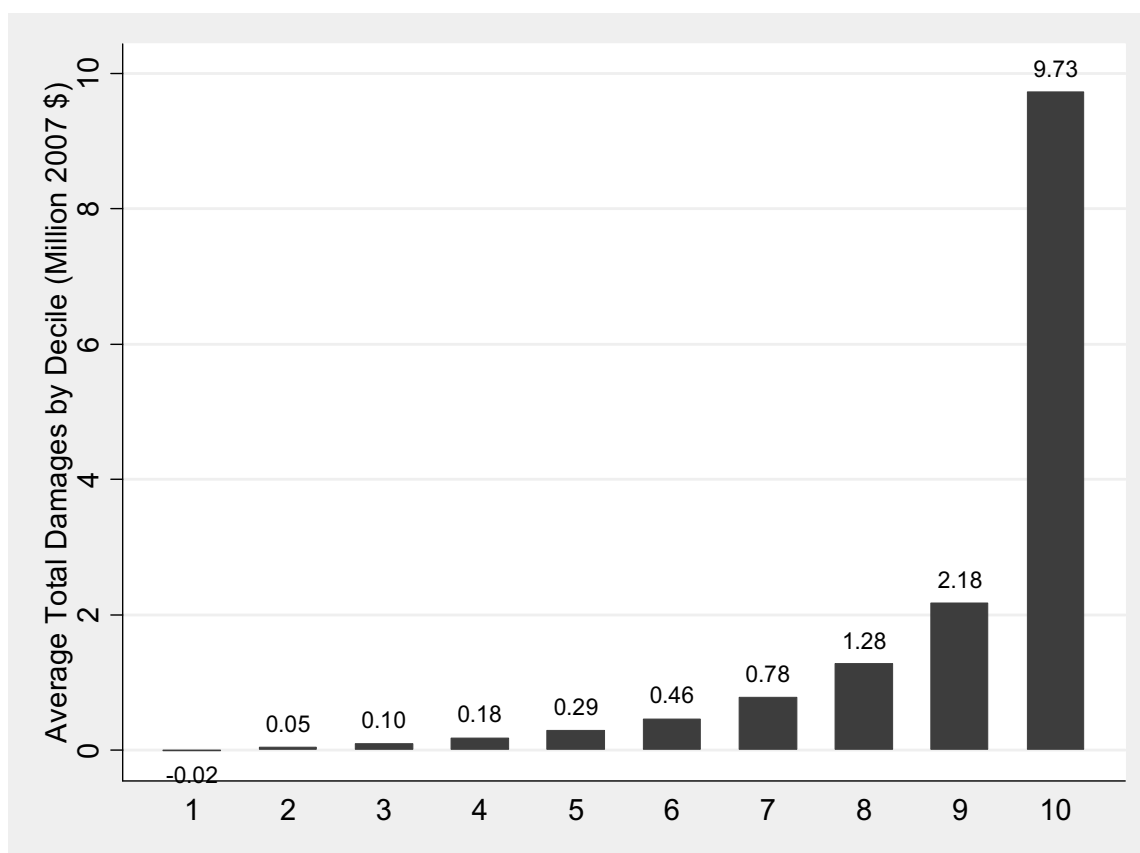
FIGURE 2-14 Distribution of aggregate damages in 2005 by decile: Natural gas fired plants. Note: In computing this graph plants were sorted from smallest to largest based on aggregate damages. The lowest decile represents the 50 plants with the smallest aggregate damages. The figure on the top of each bar is the average across all plants of damages associated with SO_2, NO_x, $PM_{2.5}$ and PM_{10}. Damages related to climate change are not included.
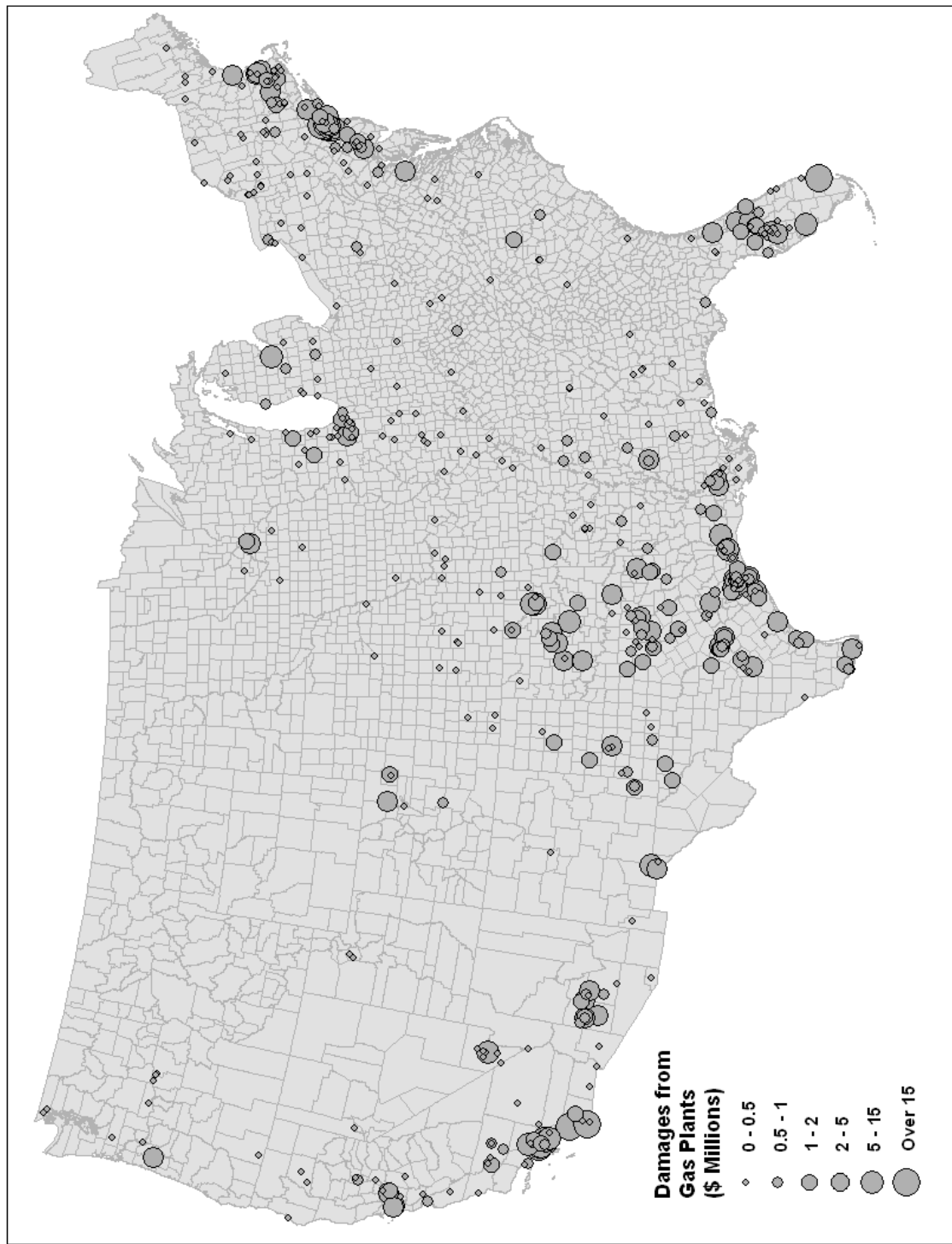
FIGURE 2-15 Criteria air pollution damages from gas generation for 498 plants, 2005 (USD 2007). Damages related to climate change are not included.

Table 2-16 shows amounts of pollutants emitted and Figures 2-16 and 2-17 show damages per kWh. Figure 2-17, which maps damages per kWh for the natural gas fired power plants in our sample, shows where these facilities are located. As in the case of coal-fired power plants, variation in damages per kWh across natural gas plants is explained both by variation in emissions of pollution per kWh and also by variation in damages per ton pollutant. In the case of $PM_{2.5}$, variation in pollution intensity and variation in damages per ton of $PM_{2.5}$ explain equal amounts of the variation in $PM_{2.5}$ damages per kWh.[43] In contrast to coal plants, natural gas plants are located in areas of high marginal damages per ton of $PM_{2.5}$ (Table 2-17). However, variation in damages per ton of NO_x accounts for only 5% of the variation in NO_x damages per kWh, while variation in pounds of NO_x emitted per MWh accounts for 75% of the variation in NO_x damages per kWh.

To summarize: the aggregate damages associated with criteria-pollutant forming emissions from the facilities in our sample in 2005, which generated 71% of the electricity from natural gas, were approximately \$ 0.74 billion , or 0.16 cents per kWh (2007 USD); however, damages per plant varied widely. The 50% of plants with the lowest damages per plant, which accounted for 23% of net generation, produced 4% of the damages, while the 10% of plants with the highest damages per plant, which accounted for 24% of net generation, produced 65% of the damages. Although damages are larger for plants that produce more electricity, less than 40% of the variation in damages across plants is explained by differences in net generation.

Damages per kWh also varied widely across plants: from about one-thousandth of a cent (5th percentile) to 0.55 cents per kWh (95th percentile). [These are weighted figures.] Most of the variation in NO_x damages per kWh can be explained by variation in emissions intensity across plants; however, for $PM_{2.5}$, which constitutes over half of the monetized air pollution damages, variation in damages per ton of $PM_{2.5}$ are as important in explaining variation in $PM_{2.5}$ damages per kWh as differences in $PM_{2.5}$ emissions intensity.

TABLE 2-16 Distribution of Pounds of Criteria-Pollutant Forming Emissions per MWh by Gas-Fired Power Plants, 2005

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	0.045	0.20	0.00069	0.0044	0.0065	0.012	0.15
NO_x	2.3	9.0	0.052	0.17	0.48	1.7	5.5
$PM_{2.5}$	0.11	0.39	0.00057	0.016	0.045	0.091	0.28
PM_{10}	0.12	0.39	0.00092	0.018	0.050	0.094	0.32

Note: All plants are weighted equally, rather than by the electricity they produce.

TABLE 2-17 Distribution of Damages per Ton of Criteria-Pollutant Forming Emissions by Gas-Fired Power Plants (USD 2007)

	Mean	Std. Devn.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	13000	29000	1800	3100	5600	9800	44000
NO_x	2200	2000	460	990	1700	2800	4900
$PM_{2.5}$	32000	59000	2600	6900	12000	26000	160000
PM_{10}	1700	3400	170	330	630	1300	7800

Note: All plants are weighted equally, rather than by the fraction of electricity they produce.

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[43]Regressing $PM_{2.5}$-related damages per kWh on pounds of $PM_{2.5}$ emitted per kWh produces an R^2 of 0.26. Regressing $PM_{2.5}$ related-damages per kWh on damages per ton of $PM_{2.5}$ also produces an R^2 of 0.26.
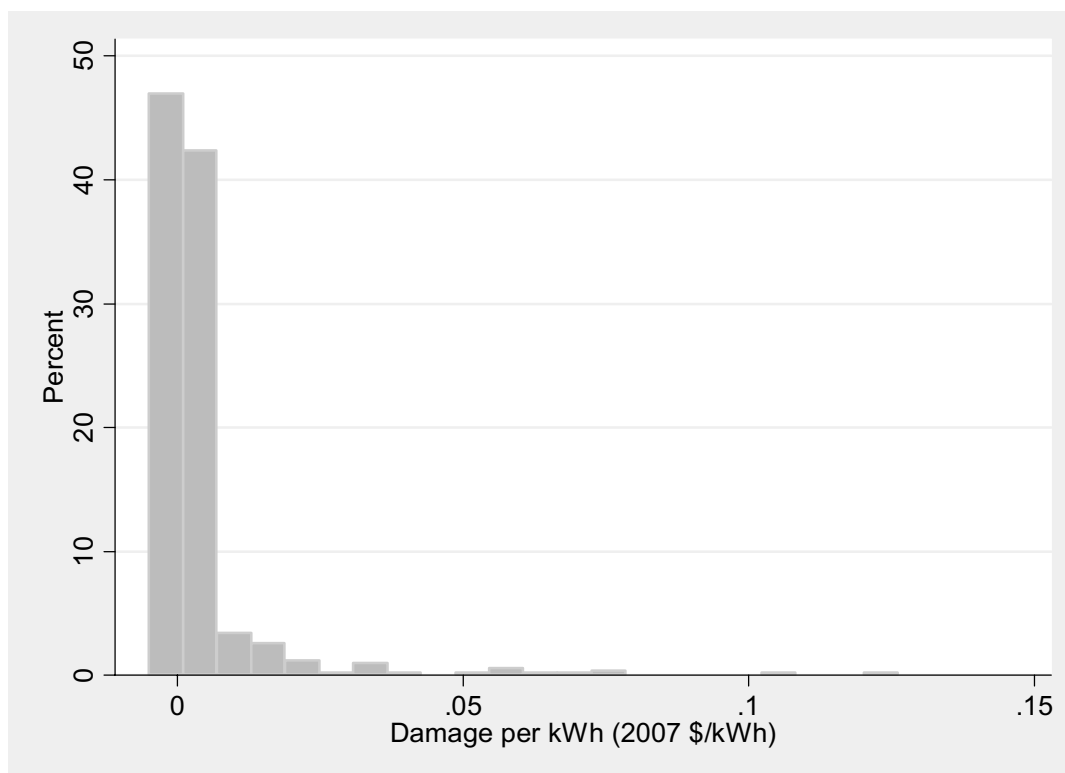
FIGURE 2-16 Distribution of criteria air pollution damages per kWh of emissions for 498 natural gas fired power plants, 2005. Damages related to climate change are not included.

Downstream CO$_2$ Emissions from Electricity Production from Natural Gas. The emissions of CO$_2$ from gas-fired power plants are significant. As the heat rate (energy of coal needed to generate 1 kWh of electricity) varies widely among coal-fired plants, so does it vary among gas-fired plants (with an average of about 0.5 ton of CO$_2$ per MWh of power generated (the 5th-95th percentile range is 0.3 to 1.1 tons per MWh).

Externalities from Natural Gas in 2030

Technology in 2030. In comparison to coal, less drastic technological change for central-station power generation by natural gas is expected. However, natural-gas powered fuel cells could become mainstream and generate significant amounts of electricity (such technology exists but is not currently at power-station scale).

Additionally, more natural gas could become available through discovery or more-aggressive development of existing sources. While domestic production has been relatively flat for years, new deposits such as the Marcellus Shale in the eastern United States hint at increasing domestic production. The prospect of this gas, however, is balanced against deeper drilling and more complicated extraction, which would increase the life-cycle energy use and associated emissions of using the resource.

Liquefied natural gas (LNG) is becoming an increasingly likely source of global natural gas-fired power. LNG has significant additional life cycle stages compared to natural gas, which leads to additional energy use and air emissions. Synthetic natural gas (SNG) from coal is also a possible pathway. LNG and SNG both have substantially higher upstream emissions than natural gas, which would need to be taken into account in assessing their effects for future natural-gas-fired power.
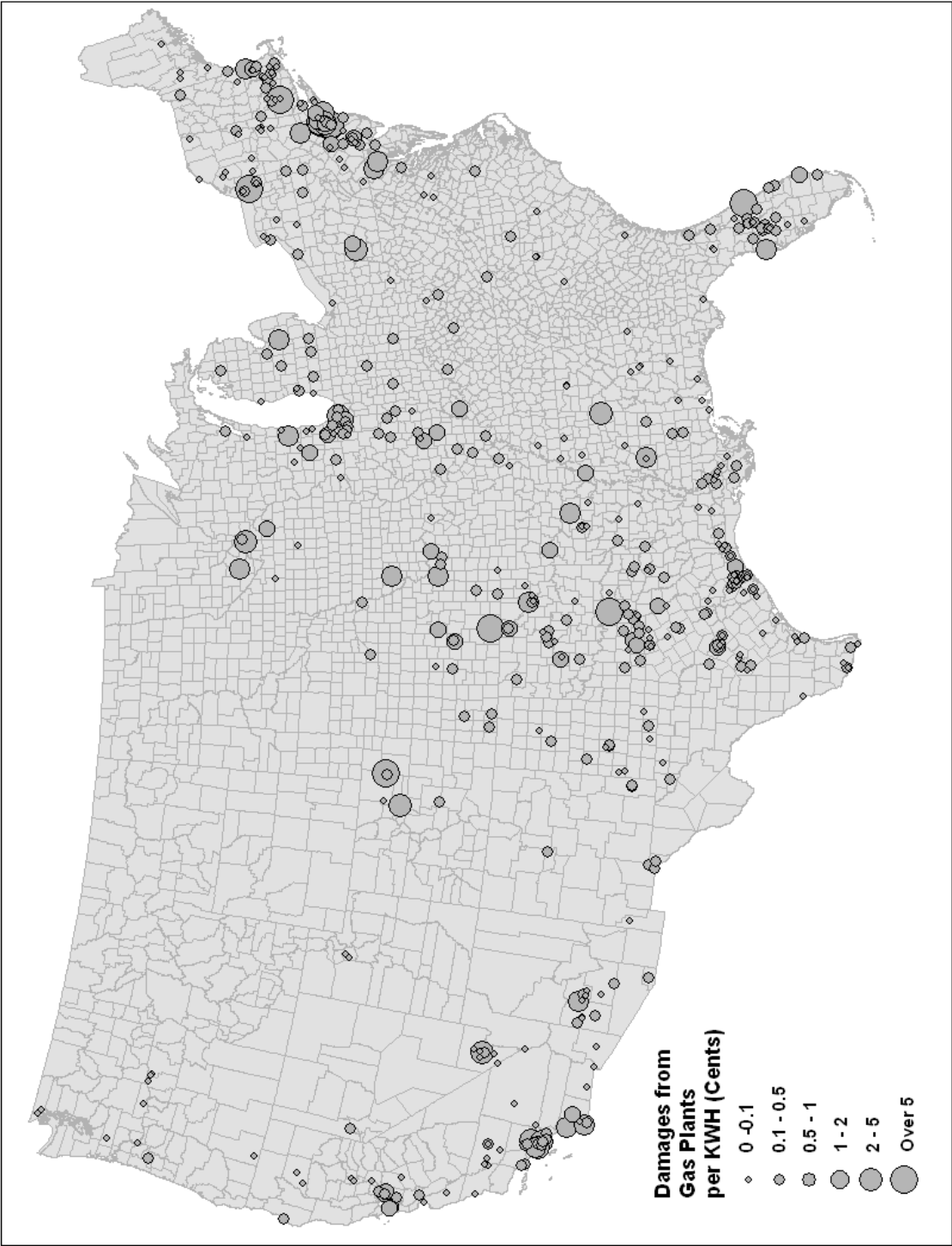
FIGURE 2-17 Regional distribution of criteria air pollution damages from gas generation per kWh (2007 USD). Damages related to climate change are not included.

Natural gas fired power plants have been discussed as candidates for carbon capture and sequestration (CCS) technology in the future. This combination is generally estimated to have smaller incremental costs (only about 1-2 cents per kWh) than for coal, but it captures less CO_2 per kWh than coal. Thus from a cost-effectiveness (and related damage avoidance) perspective, coal-fired plants will continue to be a more desirable target for CCS in the future.

A beneficial feature of natural-gas power plants is their ability to quickly increase or decrease power output as needed. Thus they can fill in power demand for intermittent renewables such as wind and solar when other fast-ramping sources such as hydropower are not available. However, today's gas turbines are not designed to be ramped up and down continuously, and emit more GHG emissions and criteria-pollutant forming emissions while ramping up and down (Katzenstein and Apt 2009). If a large percentage of renewables is installed by 2030, and natural gas is relied on for fill-in power, then considerable design improvements will be needed for those natural-gas plants.

Downstream Air Pollution Damages from Gas-Fired Power Plants in 2030. Our analysis of the criteria air pollution damages associated with electricity generation from natural gas in 2030 follows the analysis for coal-fired electricity generation described earlier in the chapter. Specifically we ask how damages at the locations of the 498 facilities examined for 2005 would change if electricity generation were to increase at the rate predicted by the EIA and if emission intensities were to decline at rates consistent with EIA projections of emissions of SO_2 and NO_x from fossil fuel. These assumptions are combined with estimates of damages per ton of the criteria-pollutant forming emissions estimated from APEEP.

EIA projections of electricity generation from natural gas were used to estimate net generation in 2030. On average, electricity production from natural gas is predicted to increase by 9% from 2005 levels; hence we assumed that generation at each facility increases by this percentage. Reductions in pollution intensity for natural gas facilities are not as dramatic as for coal plants: pounds of NO_x emitted per kWh are estimated to fall, on average, by 19%; emissions of $PM_{2.5}$ and PM_{10} per MWh are each estimated to fall by about 32%.[44] Damages per ton of pollutant will, of course, rise, as described in section on coal-fired electricity.

The net effect of these changes is to decrease the projected aggregate damages generated by the 498 gas facilities from $0.74 billion (2007 USD) in 2005 to $0.65 billion in 2030. Average damage per kWh from gas generation falls to 0.11 cents (2007 USD) from 0.16 cents in 2005.

ELECTRICITY PRODUCTION FROM NUCLEAR POWER

Current Status of Nuclear Power Production

According to the Energy Information Administration in 2009, there were 104 commercial nuclear generating units that are fully licensed by the U.S. Nuclear Regulatory Commission (U.S. NRC) to operate in the United States. They are shown in Figure 2-18. In addition, 14 nuclear power reactors are undergoing decommissioning, as shown in Figure 2-19 and listed in Table 2-18.

Of the 104 reactors in operation, 69 are pressurized light-water reactors (PWRs), totaling 65,100 net megawatts (electric[45]); and 35 units are boiling water reactors (BWR), totaling 32,300 net megawatts (electric). Other reactor technologies exist or are in development (see later discussion of new developments in nuclear technology), but as of February 2009 none of these technologies operated commercially in the United States.

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[44]Emissions of SO_2 per MWh are estimated to fall by about 51%, but little SO_2 is emitted by gas-fired power plants.

[45]The total power capacity of a thermal power plant is greater than its electric power capacity because such plants are less than 100% efficient in converting heat into electricity. The output of interest here is electric power.

There has been no recent construction of nuclear generating plants in the United States. The most recent reactor, Watts Bar No. 1, in Tennessee, was connected to the grid in February 1996. Nuclear generating capacity has been expanded by upgrading or adding capacity at existing power plants.
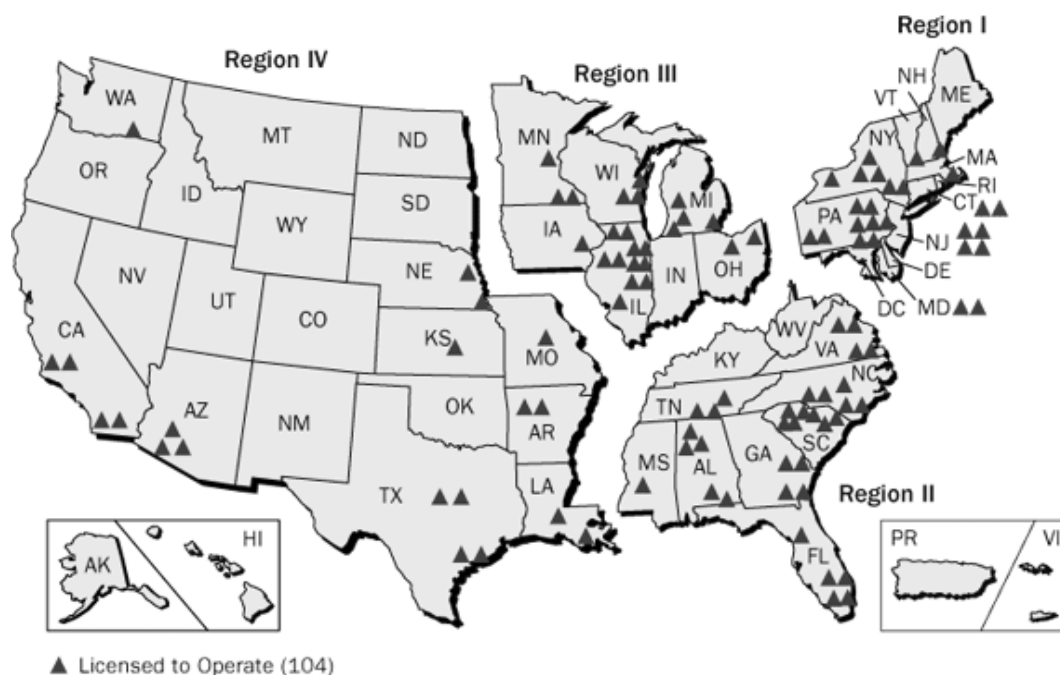
FIGURE 2-18 Locations of operating nuclear power reactors in the United States. Source: U.S. NRC 2008a.
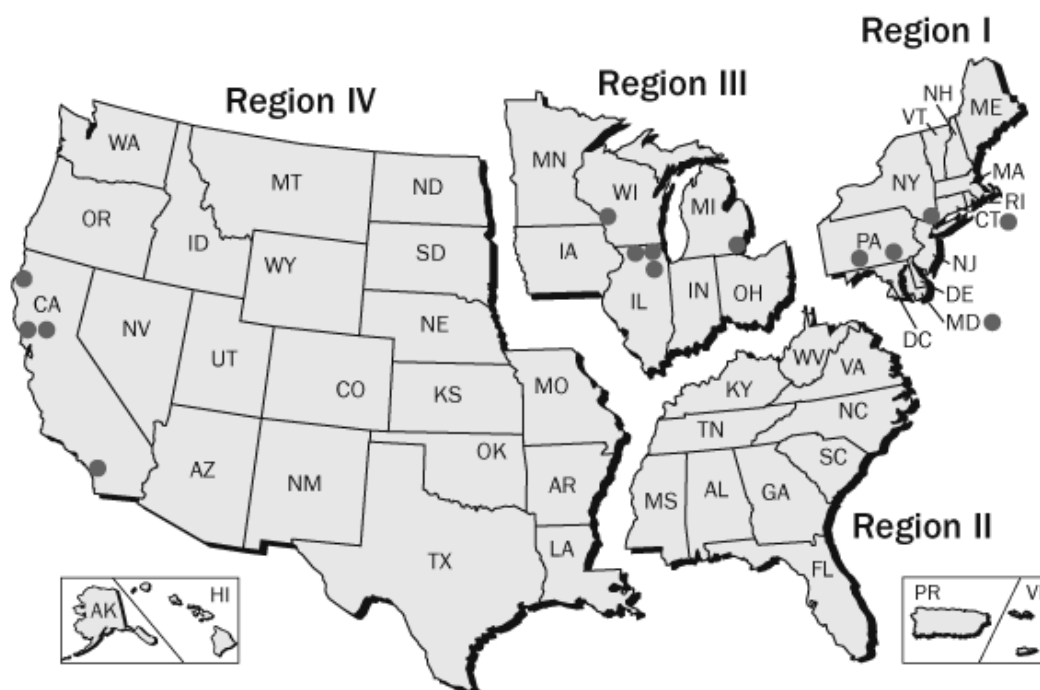
FIGURE 2-19 Locations of power reactor sites undergoing decommissioning in the United States. Source: U.S. NRC 2008b.

TABLE 2-18 U.S. Nuclear Power Reactors Undergoing Decommissioning

	Name	Location
1	Dresden – Unit 1	Dresden, IL
2	Fermi – Unit 1	Newport, MI
3	Humboldt Bay	Eureka, CA
4	Indian Point – Unit 1	Buchanan, NY
5	LaCrosse Boiling Water Reactor	Genoa, WI
6	Millstone – Unit 1	Waterford, CT
7	Nuclear Ship Savannah	Baltimore, MD
8	Peach Bottom – Unit 1	Delta, PA
9	Rancho Seco	Herald, CA
10	San Onofre – Unit 1	San Clemente, CA
11	Three Mile Island – Unit 2	Middletown, PA
12	Vallecitos Boiling Water Reactor (VBWR)	Sunol, CA
13 and 14	Zion – Units 1 & 2	Warrenville, IL

Source: U.S. NRC 2008b.

Brief History of Nuclear Power

Electricity from nuclear fission was first generated in the United States on December 20, 1951, by the U.S. Atomic Energy Commission's Experimental Breeder Reactor (DOE 2006a). The first commercial electricity generating nuclear power plant was at Shippingsport, PA, and it reached its design power production in 1957. It was shut down in 1982, when decommissioning began. The growth of nuclear-powered electricity was rapid in the 1960s, and slowed in the 1970s. In 1986, Ohio's Perry plant became the 100th U.S. commercial nuclear power reactor in operation. By 1991, the United States had 111 nuclear power units. [46] The highest number was 112, in 1990, one-fourth of the world's nuclear power units; they provided almost 20% of electricity produced in the United States (DOE 2006a, EIA 2008a). By 1998, the number of operating units was 104, as it was in 2008 (EIA 2008a). Net electricity generation grew from 1.7 GWh in 1961 to 38.1 GWh in 1971, 272.7 GWh in 1981, 612.6 GWh in 1991, 768.8 GWh in 2001, and 806.5 GWh in 2007, the highest amount during the period. The nuclear share of total electricity production reached 19.5% in 1988, and has ranged between 17.8% and 20.6% since then (EIA 2008a).

Upstream Externalities

Uranium Mining. Canada and Australia currently account for 44% of global uranium production, with 18 other countries—notably, Kazakhstan, Niger, the Russian Federation, Namibia, and Uzbekistan—accounting for the remainder (IAEA 2008). Reduction in uranium stockpiles for weapons has contributed to an abundance of uranium on the market. The United States currently accounts for 5% of global production. Much of this comes from Wyoming.

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[46]A "unit" refers to a single nuclear power-generating unit. A nuclear installation can consist of more than one unit.

Uranium is produced using open pit (surface) mining, underground mining, or in-situ leaching (ISL) techniques. Surface and underground mining for uranium is similar to mining for coal (described earlier). The ISL technique requires drilling several wells and pumping a solution into a central well to leach the uranium out of the surrounding rock. The uranium-bearing solution is then pumped from the other wells and treated on-site to produce yellowcake (uranium ore) by removing the uranium from the leaching solution. In Wyoming at present, all uranium production is from in-situ facilities in the Powder River Basin (Paydirt 1999). Other states where ISL facilities could be located include Nebraska, South Dakota, and New Mexico (U.S. NRC 2008c). In 2006, uranium mining and milling in the United States produced 4,692,000 lbs. of U_3O_8. Of this total, nearly 91% was produced at ISL facilities; the remainder was produced through underground mining (EIA 2008c, Table 2).

With uranium mining in general, radiological exposure can occur through inhalation of radioactive dust particles or of radon gas, ingestion of radionuclides in food or water, and direct irradiation from outside the body. For surface mine workers, exposure to radon exposure is generally less important than direct irradiation or dust inhalation; however, exposure to radon can be important for underground miners, though occupational radiological exposure is not an externality (see discussion and explanation in chapter 1). For members of the public, the most significant pathways from an operating mine are radon and other radionuclide ingestion following surface water transport. From a rehabilitated mine, the more significant pathways over the long term are likely to be groundwater as well as surface water transport and bioaccumulation in animals and plants located at the mine site or on associated water bodies (Australian Government 2009).

The draft *Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities* (GDEIS) released by the U.S. NRC in July 2008 assessed the impacts of four phases of ISL—construction, operation, aquifer restoration activities, and decommissioning—on land use, transportation, geology and soils, surface water and groundwater, terrestrial and aquatic ecology, air quality, noise, historical and cultural resources, visual and scenic resources, socioeconomic characteristics, public and occupational health and safety, and waste management. Impacts were qualitatively evaluated according to whether they were small ("not detectable or so minor that they will neither destabilize nor alter noticeably important attributes of the resource considered"), moderate ("sufficient to alter the resource noticeably, but not to destabilize, important attributes of the resource considered"), or large ("clearly noticeable and … sufficient to destabilize important attributes of the resource considered") (U.S.NRC 2008c, p. 4.1-1). According to the draft GDEIS, there is a potential for large impacts on historical and cultural resources, depending on local conditions; on localized ecological resources, especially on a few rare and endangered species, depending on site-specific habitat; and on groundwater. The possibility of groundwater impacts due to leaks and spills, excursions, and deep well injection of processing waste historically has been an area of particular concern with ISL. According to the draft GEIS, the magnitude of groundwater impacts will depend on such factors as contamination during construction activities, which could be mitigated by best management practices; failure of well seals or other operational conditions, which could be detected by monitoring and testing; and the potential for impacts on deep aquifers from deep well injection of processing wastes, which will depend on the state's permitting process.

Adverse environmental and human-health effects of legacy uranium mining and milling sites as well as some current operations can occur, especially in developing countries and in the former Soviet Union, and to a lesser extent elsewhere in developed countries (Waggitt 2007). In the United States, a 1978 law—the Uranium Mill Tailings Remediation Control Act (UMTRCA)—provided (as amended in 1983) for the remediation by the U.S. Department of Energy of 26 legacy uranium production facilities in the United States. U.S. laws do not classify uranium mining overburden as a radioactive waste, so its placement in radioactive waste disposal facilities is not required; however, the U.S. Environmental Protection Agency has the authority under various legal statues to protect the public and the environment from exposure to the hazardous and toxic characteristics of conventional (open pit and underground) uranium mining wastes (EPA 2009e). Nevertheless, concern continues to be expressed by some about the

negative effects of both past and current mining practices (see, e.g., WISE-Uranium 2009). A law passed by the Navajo Nation Council in 2005 has banned uranium mining and milling on sites within Navajo Indian Country (SRIC 2009).

Uranium Conversion and Enrichment. The only uranium conversion facility in the United States is at Metropolis, IL. This facility produces about 14,000 metric tons[47] of uranium per year. The process converts uranium oxide (yellowcake) into uranium hexafluoride, which is a gas. At the end of the conversion process, the amount of U-235 in the gas is about 0.7%. In order to enrich the material to that needed for reactor fuel to between 3 and 4%, the material is sent to a gaseous diffusion facility. Currently, the only facility in the United States is at Paducah, KY.

While it is anticipated that this facility will be replaced by other centrifuge facilities being constructed at Piketon, OH and Eunice, NM, the Paducah facility will remain in operation for several more years. The electricity intensity assumed for such a facility (Dones et al. 2005) is about 2600 kWh/separative work unit (SWU). When the Piketon facility is completed, the electricity use drops to approximately 40 kWh/SWU. The Piketon facility is due to come on line in 2011; uncertainties about financing made the likelihood of meeting that deadline uncertain (Mufson 2009). The Eunice facility is scheduled to begin production even sooner, but as of this writing neither facility is in production. For that reason, it is reasonable to utilize the analyses by Dones et al. that were based on life cycle assessments for pressurized water reactor facilities. While these analyses cover the entire life cycle, the majority of the atmospheric emissions come from power plants producing electricity that is needed for part of the enrichment process using centrifuge technology. Thus, the estimated emissions values (all as g/MWh) are as follows:

> Sulfur dioxide: 22.5
> Particulate matter (2.5): 5.4
> Nitrogen oxides: 33.9
> Non-methane volatile organic hydrocarbons: 7.7

Upstream Emissions of GHG Emissions and Other Pollutants. It is often mentioned that nuclear power produces no air emissions. While generally true for the generation of nuclear power, the upstream life cycle of nuclear power generation includes the mining, milling, processing of uranium; transportation of the nuclear fuel; and construction of facilities, all of which have criteria-pollutant forming emissions and greenhouse gas air emissions. In short, the non-generation impacts dominate (Dones et al. 2005, Weisser 2007).

Koch (2000) estimated the CO_2, SO_2, NO_x, and PM emissions of nuclear power to be 1-2 orders of magnitude less than coal-fired power. Sovacool (2008) summarized a range of studies on the life cycle GHG emissions of nuclear power and estimates the mean is about 66 g CO_2-equivalent/kWh. Sovacool also notes that the "frontend" of the fuel cycle (including mining and milling uranium ore, conversion and enrichment) represents 38% of the total emissions. The National Research Council (NAS/NAE/NRC 2009a, Nuclear) cited and agreed with the conclusion reached by Fthenakis and Kim (2007) that life-cycle CO_2 emissions for nuclear plants, assuming the current U.S. nuclear fuel cycle is maintained, could range from 16 to 55 g CO_2 equivalent per kilowatt-hour. For comparison, coal plants without carbon capture and sequestration produce an average of 1000 g CO_2 equivalent per kilowatt-hour.

Downstream Externalities

Damages from Routine Plant Operations and Estimated Accident Damages. The main downstream burdens from operations of nuclear power plants are related to radioactive waste, discussed

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[47]A metric ton, sometimes written tonne, is 1,000 kilograms, or 2,205 pounds.

in some detail below. Other routine burdens are related to the release of heated cooling water. There are also land-use and ecological effects associated with nuclear plants, which are similar to those experienced at other thermal power plants, for example, see Box 2-2.

There have not been significant damages associated with release of radioactive materials from an operating nuclear power plant in the United States, although such accidents have occurred elsewhere. Although the potential for such accidents is a public concern—and also a concern to industry and regulatory bodies—the committee has not attempted to monetize or even quantify such potential. Previous studies, such as ORNL/RFF (1992-98) and ExternE (EC 1995a), estimated the risk of accidents using detailed fault-tree models and found the risks and associated externalities to be small (as summarized later in this chapter). The committee did not undertake a modeling effort because such an analysis would have involved power-plant risk modeling and spent-fuel transportation modeling that would have required far greater resources and time than were available for this study. Also, apparently there were no developments since the earlier studies that would have led to any appreciable increase in the estimated probabilities of a reactor accident (a decrease in the estimate would be more likely).

Nuclear power plants generate not only electricity but also radioactive wastes, including low-level radioactive wastes (LLRW); "greater than Class C" (GTCC) wastes; and high-level radioactive waste (HLRW), mainly from spent nuclear fuel.

Nuclear power plants are a significant source of LLRW; their LLRW may include anything from clothing and rags to ion-exchange resins, filters, tank residues, and irradiated reactor components. LLRW is either stored for decay to background levels before being disposed of as conventional non-radioactive waste (a practice possible only with slightly contaminated materials), or it is disposed of in near-surface engineered landfills. An interstate compact system for the disposal of commercially-generated LLRW was established through the 1980 Low-Level Radioactive Waste Policy Act (LLRWPA) as amended in 1985. Intended to spur the development of regional LLRW disposal sites, the process mandated by the act largely has failed. As of early 2009, there were only three LLRW disposal sites in the nation: one in Barnwell, SC, which is licensed to take Classes A, B, and C LLRW but as of July 2008 was restricted to take only waste generated in the Atlantic Compact states (South Carolina, Connecticut, and New Jersey); one in Richland, WA, which takes Classes A, B, and C waste from the nine states in the Northwest and Rocky Mountain compacts; and one in Clive, Utah, which accepts waste from all states but is licensed for Class A waste only. (Class A waste, which has the lowest concentration of long-lived radionuclides, requires fewer protective measures.) In 2005, approximately 4 million cubic feet of LLRW was shipped for disposal (U.S. NRC 2009). Nuclear power plants have the means to safely store LLRW, including storage for decay to background levels if the waste is only slightly contaminated. Limited access to

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BOX 2-2 Entrainment and Impingement of Aquatic Organisms by Thermal Power Plants

Entrainment and impingement of fish and other aquatic organisms in intake structures of thermal power plants has received much attention. Impingement occurs when organisms are trapped by the force of the intake water at intake screens; entrainment occurs at power plants with once-through cooling systems when the organisms—usually eggs, larvae, and juveniles—are carried, with the water, through the plant's heat exchanger and returned to the water body with the discharged water. Mortality from impingement and entrainment can approach 100%. Despite many studies, the population effects of impingement and entrainment usually are not well known (e.g., Heimbuch et al. 2007). It appears that the most likely conditions for serious ecological impacts occur when there are many power plants in an area, or if a power plant were sited in an area with a localized population of an organism that could therefore be threatened with serious population consequences. These impacts, which are common to all thermal plants with once-through cooling systems, have not been quantified or monetized. Sovacool (2009a) has more broadly reviewed water-related impacts of thermal power plants and the effects of those plants on water resources.

LLRW disposal sites—especially for Classes B and C waste—is an inconvenience for nuclear power plants, particularly those due for rehabilitation, uprating, or decommissioning, but it is not likely to be an immediate environmental or health and safety hazard.

The GTCC wastes from nuclear power plants come mainly from highly irradiated reactor components. Under the LLRWPA as amended, the Federal government is responsible for all commercially-generated GTCC waste (as well as GTCC-like waste generated by Federal activities). In 2007, the DOE initiated a scoping process for a draft EIS to assess the environmental, social, and economic impacts of one or more facilities for GTCC and GTCC-like waste disposal. Disposal methods being considered include enhanced near-surface disposal, intermediate depth borehole disposal, and disposal at a geologic repository (GTCC LLRW EIS 2009).

According to the 1982 Nuclear Waste Policy Act (NWPA), the federal government was to develop one or more geologic repositories to store HLRW generated by commercial activities and federal defense activities. The DOE is responsible for developing the site; the NRC for licensing it and the EPA for setting radiation protection standards for humans and the environment. The NWPA was amended in 1987 to designate Yucca Mountain in Nevada as the only candidate for a geologic repository in the United States. After years of investigation and analysis by DOE, Yucca Mountain was found suitable 2002 by Energy Secretary Spencer Abraham and President George W. Bush. Nevada Governor Kenny Guinn vetoed the decision, but the veto was overturned by Congress in July 2002. An application for a license is before the Nuclear Regulatory Commission. The future of Yucca Mountain as a repository is unclear, however, because President Barack Obama's budget for FY 2010 significantly reduced funding for the program, and the Obama administration has generally voiced skepticism about it. DOE is studying alternate strategies for dealing with nuclear wastes that do not involve a repository at Yucca Mountain. With the disposal of HLRW being arguably the most contentious issue concerning nuclear energy, a detailed assessment of the externalities associated with its disposal would be a high priority for future study. Such a study would be extremely complex, given the considerable uncertainties, long timeframe, and severe impacts under certain scenarios.

As of 2002, about 45,000 tons of spent fuel from nuclear power plants were in storage—virtually all on-site. Most of the spent fuel rod assemblies are stored in water pools; less than 5% are stored in dry casks (U.S. NRC 2002). Unlike wet storage, dry cask storage is almost totally passive: It is simpler and uses few human or mechanical support systems. However, it is not suitable until the nuclear rod assemblies have been out of the reactor for a few years, allowing the heat generated by radioactive decay to decline. The NWPA limits the amount of waste to be stored at the geologic repository to 70,000 metric tons of heavy metals, of which 90% (63,000 metric tons) could be attributable to commercial spent nuclear fuel. However, one analysis suggests that Yucca Mountain would be technically capable of storing at least four and possibly nine times that amount (EPRI 2007).

Transportation of radioactive waste is jointly regulated by the U.S. NRC and the U.S. Department of Transportation (DOT). The U.S. NRC sets requirements for packaging radioactive materials; the DOT regulates shipments while they are in transit. For shipping spent fuel, casks or containers that shield and contain the radioactivity and dissipate the heat are required. Many shipments of spent fuel have been made, typically between different reactors of a utility, in order to share storage space. Lacking a geologic repository or its centralized storage equivalent, very little HLRW has been transported for long distances. Low-level waste has been transported long distances without significant incident for decades.

Reprocessing Nuclear Fuel

Since 1977, there has been a moratorium in the United States on the reprocessing of spent nuclear fuel. In limited recycling processes that are commercially available in France, Japan and the United Kingdom, uranium and plutonium are separated from spent nuclear fuel for eventual reuse as fuel, and the remaining transuranics, along with the fission products, are converted to vitrified waste for storage (Finck

2005; DOE 2006b). This process reduces the volume of waste to be stored by a factor of 4 but creates a separated pure plutonium product, which could present a proliferation and security risk.

Recently, research has been conducted in France, Japan and the United States to develop a full recycle, closed fuel process to make more efficient use of the nuclear fuel and to avoid large storage problems (Finck 2005; DOE 2006b). This recycling process makes use of advanced separation techniques that can separate out 1) long-lived fission products, such as technetium and iodine, for immobilization and eventual disposal as high-level waste; 2) short-lived fission products such as cesium and strontium, which can be prepared for decay storage until they meet the requirements for disposal as low-level waste; and 3) transuranic elements, including plutonium, neptunium, americium and curium, which can be fabricated into fuel for advanced fast reactors (DOE 2006b).

The reprocessing and recycling of spent nuclear fuel through advanced separation techniques and fast reactors increases the efficiency of fuel use and decreases the need for high-level radioactive waste disposal capacity. The DOE has stated that reprocessing offers the opportunity for significant cost reduction (Finck 2005); others, however, have argued that it would be more expensive than current "once-through" practices (von Hippel 2001). It also has been argued that no reprocessing technique is as proliferation-resistant as not reprocessing spent fuel at all and leaving the plutonium mixed with highly radioactive fission products (von Hippel 2001).

Estimates of Aggregate Damages from Nuclear Power Plants

We present here the results of two previous, studies of damages from nuclear power plants, by ExternE (EC 1995b) for France, and by Oak Ridge National Laboratory and Resources for the Future (ORNL/RFF 1995) for two sites in the United States. They are comprehensive and well documented; the range of values they produced and the reasons for the differences are informative.

ExternE (EC 1995b) estimated that the cost of damages for all stages of the nuclear fuel cycle, including reprocessing and accidents, was about 2.5 ECU mils (mECU) per kWh if no discount rate was applied. The ECU, the predecessor of the euro, was worth an average of 0.77 USD in 1995, thus the estimate was about 1.9 mils/kWh, equivalent to about 2.5 mils/kWh in 2007 USD. This is about 10% of the damage estimate in this study for criteria-pollutant forming emissions from coal. When 3% and 10% discount rates were applied, the damage cost declined to 0.1 and 0.05 mECU/kWh, respectively. The large sensitivity to discount rate results from the adoption by ExternE of a time horizon of 100,000 years for estimating the total collective radiation dose due to release of radionuclides, and the ExternE estimate suggests that over a short or medium term, the aggregate damages for nuclear power are at least 3 orders of magnitude less than the air-pollutant damages alone from coal.

The contemporaneous study by Oak Ridge National Laboratory and Resources for the Future (ORNL/RFF 1995) produced estimates of the aggregate costs of nuclear operations of an average of 0.25 mils/kWh for two sites, including accidents; and 0.2 mils/kWh without accidents. These numbers are one order of magnitude less than the ExternE values with zero discount rate, and twice and four times as large, respectively, as the ExternE values with 3% and 10% discount rates. However, the U.S. (ORNL/RFF) assessment did not include reprocessing, as that did not then (and does not now) exist in the United States; the conversion, enrichment, fuel-fabrication, and low-level waste disposal stages were considered separately in that study. The ExternE assessment also expanded the physical boundaries to 1,000 km (regional) and to global dimensions. In addition, the technologies and sites in the two assessments are different. When these factors are taken into account, the results of the two studies are directly comparable, and the estimated damage costs of nuclear power remain significantly lower than those for coal.

These results depend in part on the estimated probability of accidents and their probable consequences, and those values are a function of many factors, including reactor design, training and motivation of personnel, population density and distribution, emergency response, and so on. Additional information and experience would likely help to refine those estimates (e.g., EC 2005).

New Developments in Nuclear Technology

Nuclear power has the potential to produce large amounts of dependable electricity without emitting carbon dioxide. In recent years, nuclear reactors have produced about 20% of U.S. electricity, but this contribution will drop unless new capacity is added. This section considers both updated versions of today's light water reactors (LWRs), and possible advanced reactors for the future.

Updated Light Water Reactors. The current generation of nuclear reactors continues to function reliably, but considerable research has been conducted in recent years to improving designs. New reactors are expected to be simpler, easier to operate, and generally more resilient than current designs, and several utilities are planning on constructing them.

Next-Generation Reactors. There are plans in the United States to build several evolutionary light-water reactors (LWRs). America's Energy Future estimates that 5 to 9 such reactors could be built by 2020. If they are built on time and within budget, perhaps additional similar reactors could follow. Nonetheless, new LWRs will be very expensive. It is important to examine alternative approaches that might have advantages and cost less.

DOE's Generation IV Program (DOE 2009a) includes research on five reactor concepts. Only one, the Very-High-Temperature Reactor (VHTR) is receiving significant funding, about $70 million requested for FY 2009**.** It is a helium gas-cooled, graphite moderated reactor which is an updated re-design of the experimental high temperature gas reactors (e.g. Fort St. Vrain). The technology has significant advantages, including a low probability of a major radioactive release and the amount of heat that it produces. The VHTR is expected to operate above 1000 degrees ºC (1800 ºF) and could be used for industrial process heat and hydrogen production as well as electricity.

DOE also has a related Nuclear Hydrogen Initiative (NHI), which focuses on thermochemical splitting of water molecules. Such processes, using the VHTR as the energy source, are projected to be significantly more efficient than electrolysis.

According to a 2008 National Research Council review of DOE's Nuclear Energy programs (NRC 2008a), both Gen IV and NHI are well-designed, and funding should be kept at levels according to progress towards milestones. The result, if successful, could lead to operating reactors before 2030, but probably only a few. Major decisions have yet to be made, including the basic core design.

DOE also is supporting work on a reactor that is intended to consume long-lived components of waste LWR fuel. The reactor could also produce power, but the primary goal is to reduce the nuclear waste disposal problem from tens of thousands to hundreds of years. Given the level of R&D required, and uncertainties in economics and the licensing path, such a reactor is unlikely to be operating by 2030.

ELECTRICITY PRODUCTION FROM WIND

Current Status of Wind Energy

It is difficult to keep current with respect to the status of wind energy in the United States because it is increasing so rapidly. By the end of 2008, the total installed capacity[48] in the United States was 25,170 MW (25.17 GW), up from 16,824 MW at the end for 2007 (AWEA 2009). For the 12 months ending November 30, 2008, 44,689 GWh of electricity were generated by wind-powered turbines out of a total of 4,118,000 GWh, or 1.1% (EIA 2009a, Table 1.1a).

The American Wind Energy Association (AWEA) lists 6922 active turbines as of September 30,

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[48]Installed capacity, also called nameplate capacity, is the maximum rated electricity output in MW.

2008, ranging in nameplate capacity from less than 1 KW to 3,000KW (3 MW).[49] The number of wind-turbines per project ranges from 1 to more than one thousand. The largest project in terms of nameplate capacity is 766 MW. The smallest are many 50 KW installations consisting of single turbines. It is not possible to characterize an "average" wind plant in any meaningful way, but it is common for modern plants to have a nameplate capacity of between 40 and 300 MW and to consist of turbines ranging in individual capacity from about 1.5 to 3 MW. The earliest utility-scale projects were commissioned in California in the early 1980s; a few of those turbines, most on the order of tens of KW to about 100 KW, still are producing electricity.

Brief History of Wind Energy

The first utility-scale wind-energy plants in the United States began operation in 1981, with a total installed capacity of less than 10MW. The increase was rapid at first, reaching 1.2 GW by 1986, but then slowed, with total capacity of only 1.8 GW in 1998. Then a period of rapid increase began again; capacity reached 4.3 GW by 2001, 6.6 GW by 2003, 9 GW by 2005, and more than 25 GW by the end of 2008. Much of the increase is fueled by federal production-tax credits (PTCs), which have been sporadic. The current federal PTC extends through 2009 as of December 2008. State-mandated renewable-energy portfolios, which require the state's energy use to be based on renewable sources (mainly wind) by target dates, also have affected the penetration of wind-generated electricity, as do general economic conditions.

Future Considerations for Wind Energy

As indicated above, with the passage of time, the most-obvious change in wind-energy plants has been the reduction in total number of turbines and increase in the size (both physical size and nameplate capacity) of the individual turbines. Even some early plants had total nameplate capacities of from 40 to 80 MW, but projects exceeding 100 MW became common only in the late 1990s. These changes are largely technology-driven, resulting in larger turbines, and it seems likely that individual turbines of 5 MW will be commercially deployed in the United States soon.
A July 2008 report of the U.S. Department of Energy assessed the possibility of providing 20% of the nation's electricity from wind by 2030. The report noted that:
The 20% Wind Scenario in 2030 would require improved turbine technology to generate wind power, significant changes in transmission systems to deliver it through the electric grid, and large expanded markets to purchase and use it. In turn, these essential changes in the power generation and delivery process would involve supporting changes and capabilities in manufacturing, policy development, and environmental regulation (DOE 2008a, p. 4).
The report also noted (p. 57) that a 20% Wind Scenario would require a substantial development of offshore technology as well as improvements to land-based technology.
As of mid-2009, all U.S. wind-energy plants are on land. A number of offshore projects have been proposed, but none have yet been permitted. The Cape Wind project proposed for Nantucket Sound in Massachusetts has advanced the furthest: In January 2009, the Minerals Management Service (MMS) released a Final Environmental Impact Statement (FEIS) for the project, which is proposed to have 130 3.6 MW turbines located 4.7 miles offshore. Because the project is to be sited in federal waters, a lease with the federal government is required. (The 2005 Energy Policy Act amended the Outer Continental Shelf (OCS) Lands Act to give the U.S. Department of the Interior authority to issue leases, easements, or rights-of-way for activities supporting renewable energy production; DOI delegated this authority to one of its bureaus, the MMS.) The FEIS identifies most impacts as negligible or minor. (For the summary table of impacts in the FEIS, see MMS 2009, Table E-1.)

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[49]Because the wind does not blow all the time (it is intermittent), the actual generation capacity of a wind turbine is only about 30% of the "nameplate capacity".

In April 2009, the DOI finalized its framework for renewable energy production on the OCS. In May 2009, the Energy Facilities Siting Board of the Commonwealth of Massachusetts granted a Certificate of Environmental Impact and Public Interest for the Cape Wind project, combining nine state and local permits required into one "super permit." A Record of Decision from MMS on the Cape Wind application for construction, operation, and eventual decommissioning is expected shortly.

Upstream Impacts of Wind Energy

As noted at the beginning of this chapter, upstream effects of wind-energy generation of electricity differ substantially from those of fossil-fuel and nuclear plants in that there is no production, refinement, and transportation of fuel. As a result, the effects described below comprise all the upstream effects. Other kinds of EGUs also have such upstream effects, but because of their requirements for fuel, these effects are only a very small part of the total.

Materials and Transportation. Metal components make up nearly 90% by weight and more than 1/3 by value of a modern wind turbine. For a 150 MW project, transportation requirements have been as much as 689 truckloads, 140 railcars, and 8 ships to the United States (Ozment and Tremwell 2007). Raw materials used include copper, iron (steel), rare earths for permanent magnets in rotors. The metal parts can be cast, forged, or machined. Turbine rotors are made of composites, balsa wood, carbon fiber, and fiberglass. Blades can approach 50 meters in length (and the nacelle of a turbine can be 70-90 meters above the ground). The mining of metals, fabrication and transportation of parts, and the assembly of the components have impacts that have been qualitatively described elsewhere in this chapter.

On-site and Downstream Impacts of Wind Energy

Ecological Effects. Assessment of the ecological effects of generating electricity from wind has focused primarily on deaths of flying animals caused by interactions with turbines. Bird deaths attributable directly to wind generation of electricity probably are less than 100,000 per year in the United States (e.g., NRC 2007b; Sovacool 2009b). The only bird deaths considered to potentially reflect a population-level problem currently are of raptors, occurring mainly in older installations in California (NRC 2007b). Total anthropogenic bird deaths probably exceed 100 million per year in the United States,[50] and could be as high as 1 billion (NRC 2007b).

Bat deaths caused by wind turbines, especially in the eastern United States, have been higher than expected (NRC 2007b, Arnett et al. 2008), although they are extremely difficult to quantify, because bats are small and hard to find (Kunz et al. 2007). To date, no member of any bat species listed under the Endangered Species Act has been reported killed by a wind turbine. Bat populations of many species have been declining in the eastern United States, and because so little is known about the demography of bats, and because it is so difficult to quantify bat deaths, it is possible that the number of bats killed by wind turbines is a significant population-level threat to some species in some locations. The concern is intensified to the degree that the number of turbines continues to increase (NRC 2007b).

Although the primary focus of ecological effects of wind has been on deaths of flying animals, wind-generated electricity also can have wider ecosystem and habitat effects. Land-use changes to accommodate wind-energy installations are similar in kind to those for many other kinds of electricity-generating plants, including the need for roads and rights-of-way for transmission lines. The overall footprint of a wind-energy plant tends to be larger than for others, but the intensity of land-use change can

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[50]Estimating the number of anthropogenic bird deaths is difficult, but the largest sources of mortality include bird flying into buildings, flying into transmission lines, collisions with vehicles, toxic chemicals, and predation by domestic cats; this last factor alone could cause more than 100 million bird deaths per year (NRC 2007b and references therein).

be lower, because in many cases, the land between the turbines is not affected. On forested ridge lines in the eastern United States, the forest generally is cleared, or at least cut back, throughout the installation's footprint (NRC 2007b).

Most studies, including the NRC's 2007b report, have not identified significant ecological impacts other than those described above. However, the total installed wind-energy capacity when most recent reports were published was less than 12 GW, as compared with the more than 25 GW at the end of 2008. The rapid recent and projected future growth of wind-powered electricity generation in the United States means that ecological assessments probably will need to be repeated.

Aesthetic and Visual Effects. There have been few quantitative studies of aesthetic and visual impacts, although there are well-established methods for assessing them quantitatively (NRC 2007b).

Noise, Flicker, Radar Interference, Other: Adverse effects caused by noise—annoyance, sleep disturbance, and discomfort—have been documented and may be locally significant. Electromagnetic interference with television and radio broadcasting and radar also has been documented (NRC2007b). Flicker effects have not been documented in the United States. All the above effects appear to be relatively small compared with effects related to other energy technologies considered by the committee.

Assessment of Externalities from Wind Energy

The life-cycle damages associated with wind energy have not been fully quantified, but for those effects for which the committee has information, it is safe to say that, in aggregate for 2009, potential damages associated with wind turbines are small compared to those associated with coal and natural gas as electricity sources. Criteria-pollutant forming emissions and GHG emissions are much smaller per kWh than for coal or natural gas, and wind power produces far less electricity than do coal and natural gas, and so the aggregate emissions are very much smaller. Aggregate land-use effects considered over the entire life cycle are not significantly larger at present than those for other generation types, especially if one considers that in some cases former land uses can continue between wind turbines.

Anthropogenic causes of bird deaths include collisions with power lines, implying contributions from all sources of electric-power generation and use. Collisions with power lines likely account for the deaths of more than 130 million birds each year, dwarfing the estimated number of bird deaths caused by direct collisions with wind turbines (20,000 to 37,000 in 2005) (NRC 2007b and references therein). We do not have enough information to reliably compare the death rates of birds across all electricity-generation sources per kWh[51], but if wind power ever provides 20% of U.S. electricity supply, as some scenarios suggest it will, then its significance as a cause of bird deaths would increase.

Damages associated with bat deaths are difficult to analyze. Bat deaths appear to be largely, if not uniquely, associated with wind-generation of electricity, but no good estimate of the numbers of bats killed is available (NRC 2007b). In addition, the lack of understanding of the demography and ecology of bats makes it difficult to assess the importance of bat deaths. It appears likely to this committee that societal damages associated with the killing of bats by wind turbines are currently small by comparison with the aggregate damages associated with electricity generation by coal, natural gas, and the sum of all other sources. We agree with the NRC (2007b) that better information is needed, especially in light of the probable future increase in the number and density of wind turbines.

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[51]Such a comparison was attempted by Sovacool (2009b). He concluded that wind energy killed 0.3 birds per kWh, nuclear power killed 0.4 birds per kWh, and fossil-fuel powered electricity was responsible for 5.2 bird deaths per kWh. Most of the fossil-fuel related bird deaths were attributed to future climate change, and thus represent a projection rather than an actual estimate of current bird deaths. The non-climate-related avian mortality rate he estimated was 0.2 bird deaths per kWh.

ELECTRICITY PRODUCTION FROM SOLAR POWER

Background and Current Status

Solar power, a renewable energy source, is the capture and conversion of solar radiation (i.e., sunlight) into electricity or heat. Use of solar power to generate electricity most commonly involves photovoltaic (PV) modules (a.k.a. solar panels) that are installed in large solar power plants ("solar farms") or on the walls or roofs of buildings. However other methods exist to use heat generated by solar collectors or other technology to generate electricity from steam turbines. Passive use of solar power for heating is discussed in chapter 4. Concentrating solar power (CSP) systems use optics to concentrate direct incident solar radiation which is converted into thermal energy that can be used to generate electricity. CSP system use in the United States is limited, primarily to sites in the Southwest, which have abundant direct solar radiation.

PV- and CSP-system electricity generation by the electricity sector combined to supply 500 GWh in 2006 and 600 GWh in 2007, which constitute about 0.01% of the total U.S. electricity generation. EIA data indicate that the compounded annual growth rate in net U.S. generation from solar was 1.5% from 1997 to 2007 (NAS/NAE/NRC 2009b). However, this estimate does not account for the growth in residential and other small PV installations, which are applications that have displayed the largest growth rate for solar electricity.

U.S. solar panel and module imports increased from 45,313 peak KW in 2002 to 280,475 peak KW in 2007. EIA estimates that 90% of end-use for domestic PV shipments is grid-interactive electricity production. Approximately 3% is remote electricity production. The remaining 7% is distributed among uses in communications, consumer goods, transportation, water pumping, health, and others.

Upstream and Downstream Impacts of Photovoltaic Energy

PV systems consist of two main parts: the solar panels and the balance of system (BOS) components. Generating electricity from PV modules, which produce direct-current (DC) electricity, requires a BOS to convert the DC power to most commonly used alternate-current (AC) electricity. As such, upstream life-cycle activities involve mining of materials required for both solar panels and BOS components, panel and BOS manufacturing and construction, and finally the PV system installation.

Solar panels are made of semi-conducting materials similar to those used in the electronics industry. "Solar grade" silicon, derived from quartz sand, is the most commonly used material to make solar panels. However, emerging thin film technology, which allow use of solar panels as roof tiles and other building features, can be made of a variety of materials, including amorphous silicon, gallium arsenide (GaAs), cadmium-telluride (CdTe), and copper indium gallium selinide (CIGS). With the exception of silicon and arsenic (for arsenide), the metals required for thin-film technologies are rare, and their use may depend on foreign imports. Materials for both CdTe and CIGS can be obtained from waste streams of zinc and copper smelting (USGS 2008).

Manufacturing these panels is a very high-technology, material- and energy-intensive process. A number of the metals for thin-film PV technology are toxic (e.g., arsenic and cadmium), thus raise environmental and public health concerns about metal emissions during the extraction, material upgrading, and manufacturing activities associated with PV systems. The intense energy requirements for upstream PV activities are another concern. Various studies have considered the relevant life cycle flows of materials, energy, and resources for PV systems. Most studies have focused on the life cycle of solar photovoltaic (PV) systems, specifically on crystalline silicon systems, and on energy and greenhouse gas emissions. Fewer studies have considered life cycle material and substance use, or emerging thin-film technologies like cadmium-tellurium (CdTe) PV panels (Fthenakis and Alsema 2006).

Unlike other energy generation technologies, for which the underlying technology has not changed significantly over 30 years, the manufacture of PV panels has undergone significant efficiency

improvements and material shifts over that time (e.g., the cost/watt decreased from $6 to $2 from 1990 to 2005). Studies in Europe that focused on previous generation technology estimated that producing solar power had 30% higher health impacts than natural gas, and GHG emissions of 180 g/kWh - an order of magnitude higher than nuclear (EC 2003). Follow-on studies, including CdTe systems, showed lower but non-zero life cycle health impacts from PV of about 0.1-0.2 cents per kWh, primarily caused by GHG, lead, and particulate matter emissions (Fthenakis and Alsema 2006). The life cycle GHG emissions are estimated to be 20-60 g/kWh, comparable to those of nuclear power (Fthenakis and Kim 2007), while NO_x and SO_2 emissions are estimated at 40-180 and 50-450 mg/kWh respectively, far less than other generation methods (Fthenakis et al. 2008). Fthenakis and colleagues (2008) also evaluated heavy metal emissions (i.e., Ar, Cd, Cr, Pb, Hg, and Ni), and found that that they are greatly reduced in comparison to emissions from fossil fuels, even with PV technology that makes direct use of the emitted compounds.

Generally excluded from LCA studies are transport considerations of raw materials to panel manufacturers in the United States. Transport considerations are important depending on type of PV system. For example, the United States has very little or no domestic production of arsenic, gallium, or indium, and must rely upon imports for these materials (USGS 2008). Because of intense energy requirements for upstream activities, research has begun to evaluate the "energy payback"—the amount of time a PV system must operate in order to recover the energy used to produce a PV system (DOE 2004).

Downstream life-cycle activities include electricity generation, storage, and disposal or recycling of worn-out panels. Like wind power, the production of electricity with PV systems does not emit air pollutants, including GHGs. Externalities associated with downstream PV activities may arise due to intermittency, i.e., the need for grid electricity when sunlight is not available. Chapter 6 further discusses grid interruptions associated with renewable energy sources. Other externalities may arise from the disposal of worn-out PV systems. Worn-out solar panels have potential to create large amount of waste, a concern exacerbated by the potential for toxic chemicals in solar panels to leach into soil and water. Many components of solar panels can be recycled, but the United States currently does not have or require a solar PV recycling system.

To capture enough solar energy to produce large amounts of electricity requires a certain amount of land. Much of the United States receives enough solar energy to produce around 1 kWh per square meter of PV panel per day in the summer, less in winter, but more if the panel is tracked to follow the sun. The economic and other values of the land that would be needed to capture enough solar energy to provide substantial amounts of electricity would depend on a host of factors, including the land's location, ownership, and proximity to population centers, and other potential uses for the land. However, other factors also could affect solar-powered electricity at such a scale.

Future Considerations for Solar Energy

While solar PV and CSP are still developing technologies, they will be an increasing, but still small, part of electricity generation through 2020. Although solar power represents a very small fraction the U.S electricity generation, the energy potential of solar power is enormous. A 2009 NRC report, *Electricity from Renewable Resources: Status, Prospects, and Impediments*, notes that current domestic solar power potential is 13.9 TWh, more than 3,000 fold greater than current electricity demand (NAS/NAE/NRC 2009b, p. 4).

If solar energy for electricity were to become a significant part of the U.S. energy mix, more attention would need to be paid to damages resulting from the manufacture, recycling, and disposal of equipment. Also land-use issues would likely be a concern.

ELECTRICITY PRODUCTION FROM BIOMASS

The nature of electricity generated from biomass feedstock is difficult to quantify and, for its externalities, even more difficult to obtain reasonable numbers. This is because the production and utilization of biomass for electricity production is inherently localized, resource-specific, and small scale. In addition, the term "biomass" can refer to a variety of feedstocks. The following discussion addresses issues associated with biomass use for electricity generation; because different feedstocks often are used for ethanol production for transportation fuel, the issues associated with them are somewhat different as well (see Chapter 3).

Feedstock Production

Feedstock comes from forestry and agricultural residues and from harvesting of forest and agricultural products. Some electricity generation uses either industrial biomass residues or municipal solid waste.

In the case of energy crops, land could be used for other activities. For agricultural residues, farming practices and the viability of the land for farming could be affected. In some cases, changes in land use can increase carbon emissions. Other uses can enhance terrestrial carbon sequestration.

Sufficient water is needed to raise crops, forest products, and their residues. Non-point source run-off can impact surrounding surface-water systems. Use of pesticides can affect water quality through non-point-source runoff. Energy use can have impacts through life cycles for growing biomass feedstock and the related harvesting of crops or agricultural residues.

Use of fertilizers, particularly petroleum-based, constitutes an additional life cycle issue, since much fertilizer is produced using natural gas. Additionally, there could be an increase in greenhouse gas emissions from energy use in the treatment of the fields and emissions of nitrous oxide from the fertilizers.

Labor and related societal issues are related to changes in farming and forestry practices and in harvesting residues. Ecological effects, primarily destruction of habitat, mainly involve taking marginal lands for energy crops and forest products.

Most impacts from the use of municipal solid waste as a feedstock for electricity are expected to be positive, since the need for landfilling waste and the related potential for run-off to surface waters from landfills is minimized. However, concerns remain about atmospheric emissions from conversion facilities and land-use (siting).

Emissions from the combustion of biomass can include polychlorinated biphenyl compounds, although the focus of recent analysis has been primarily on enclosed systems, such as cook stoves (Gullet et al. 2003). While damages from biomass-generated electricity on a per-kWh basis might equal or even exceed those from other sources in some cases, the committee has not provided detailed analyses because this technology probably will have only limited market penetration in 2030.

Transportation

Similar to the harvesting of biomass feedstock, transportation of feedstocks has localized impacts. Many facilities use biomass as a feedstock, derived from processes and residues generated on site. Where energy crops or biomass residues are collected away from the location of the power plant, the cost of transportation limits how far from the power plant these low-energy-density feedstocks can be obtained. The impacts associated with transportation are similar to standard transportation impacts associated with vehicle-miles driven in terms of air quality impacts, energy penalties, and accidents.

Power Generation

In 2008, not quite 40,000 GWh were generated from wood and wood waste, about 0.9% of the total (see Table 2-1 and associated text). Biomass accounted for about 16,000 GWh (0.3%).

The National Electric Energy System data base indicates that in 2004 there was approximately 1.4 GW capacity of biomass fired power plants in the United States. This is a small amount compared to overall generating capacity.

Many of the issues facing biomass combustors are similar to issues faced by larger-scale fossil-fuel generation, although they typically are more localized, because the generators are small, which may limit the control technologies placed on the system. In addition, many of these systems have been in operation since 1937, and therefore presumably "grandfathered" in on some environmental rules.

Air quality is a local issue, particularly for particulate matter from smaller, older combustors. Facility health and safety are important for older facilities.

Siting issues, such as aesthetics, are significant for newer facilities, such as those utilizing municipal solid waste. Citizens can be concerned about aesthetics and possible odors from atmospheric emissions.

For potential new technologies such as bio-gasifiers and use of liquid fuels derived from bio-oils, other environmental issues are unlikely to be a large factor, but there could be a public perception that these facilities will use feedstock from land that has been clear cut for energy crops, such as tropical oils.

TRANSMISSION AND DISTRIBUTION OF ELECTRICITY

Here, we briefly discuss effects and damages associated with electricity transmission lines. Chapter 6 provides a discussion of security issues associated with interruptions or intermittencies in transmission/transport and distribution systems for electricity and for fuels such coal, oil, and natural gas.

Perceptions exist that high-voltage power lines and substations pose health risks (e.g., of childhood leukemias and adult cancers, as well as acute effects) through their emission of extremely low frequency (ELF) electromagnetic radiation, but despite many studies, adverse health effects of transmission lines have not been conclusively established. The World Health Organization recently assessed this issue in detail (WHO 2007), and WHO's International Agency for Cancer Research addressed it further in 2008 (IARC 2008). The reports conclude that the evidence on some impacts of ELF on human health is inconclusive, including childhood leukemias; and that on other aspects the information leads to the conclusion that there are no adverse effects. The IARC report further concludes that if there are any excess cancer cases the number is very small, and that more than 99% of people are not exposed to enough ELF radiation from transmission lines for there to be a possibility of their suffering increased incidence of cancer.

Transmission lines also have raised concerns—as have various electricity generating facilities—about loss of property values along and near them due to visual impairment and perceived or actual health risks, as well as possible land-use effects. The loss of property values is not an externality, being instead a market-mediated reflection of real or perceived physical damages. However, the visual impairment or any health risks associated with transmission lines are an externality.

Some renewable sources of energy, especially wind and solar, often need to be sited far from end users, thus requiring more new transmission lines than some other sources would need. For these reasons, proposals for new transmission lines often have been controversial, and managing the need for and building of new transmission lines is thus a significant policy issue. However, because externalities associated with them appear to be very small by comparison with other aspects of electricity generation, the committee has not considered them in detail here.

SUMMARY

This chapter has examined information on burdens, effects, and damages associated with electricity generation from coal, natural gas, nuclear power, wind energy, solar energy, and biomass. In the case of fossil fuel and nuclear power this includes consideration of the exploration, extraction and processing of fuel, and the transportation of fuel to generating facilities (upstream externalities) as well as electricity generation and distribution (downstream externalities).[52] Some burdens and effects have been discussed in qualitative terms while others have been quantified and, where possible, monetized.

Our main goal is to examine the uncompensated external costs (and benefits) associated with electricity production. Many external costs have been reduced through regulation: for example, the criteria air pollution damages associated with electricity generation from fossil fuel have been substantially reduced by federal and state regulations over the past 30 years. We examine only those damages that remain. Occupational injuries and deaths are of importance to society, but do not constitute external costs associated with coal mining and oil and gas production. We therefore do not monetize them and do not add them to external costs, such as the health costs associated with air pollution emissions.

There are at least two reasons for examining the externalities associated with electricity generation. One is to inform the choice among fuel types when increasing electricity production or replacing existing plants. This is typically done by comparing the external cost per kWh of electricity generation across fuel types. Another reason for examining externalities is to help identify situations where additional regulation may be warranted to reduce the external costs produced by current electricity generation. Identifying sources with large aggregate air pollutant damages can help identify facilities where further analysis of the costs and benefits of reducing emissions is warranted. This chapter helps to inform both issues.

Electricity from Coal and Natural Gas

In the case of electricity generation from coal and natural gas, we have described the upstream externalities associated with fuel extraction and processing and have quantified the air pollution damages associated with electricity generation at 406 coal-fired and 498 gas-fired power plants in 2005. This is based on emissions data from the 2005 National Emissions Inventory and estimates of damages per ton of pollutant from the APEEP model. Damage estimates are based on emissions of SO_2, NO_x, $PM_{2.5}$ and PM_{10} and include impacts on human health, visibility, agriculture and other sectors. The average damage associated with these emissions per kWh at coal plants, weighting plants by the electricity they generate, is 3.2 cents per kWh (2007 USD), using a Value of a Statistical Life of $6 million (2000 USD).[53] The corresponding figure for gas facilities is 0.16 cents per kWh (2007 USD). However, the distribution of damages per kWh is wide for each set of plants, reflecting variation in the emissions intensity of plants and in their location. As a result, the coal plants with the lowest damages per kWh are cleaner than the natural gas plants with the highest damages per kWh. Specifically, damages per kWh for the highest-damage, 9% of natural gas plants exceed the damages per kWh for the lowest-damage, 10% of coal plants.

The aggregate damages associated with emissions of SO_2, NO_x, $PM_{2.5}$, and PM_{10} from coal generation in 2005 were approximately $62 billion (2007 USD), or $156 million per plant on average. The 50% of plants with the lowest damages per plant, which accounted for 25% of net generation,

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[52]We have not conducted a fully comprehensive life-cycle analysis of the external costs of electricity generation. In particular, we have estimated the external costs associated with power plant construction. Those costs probably are small compared with all other life-cycle costs, because thermal power plants often last more than 50 years, so when annualized, the costs are small over the plant's life span.

[53]Premature mortality constitutes over 94% of total damages. When a VSL of $2 million is used, premature mortality constitutes 85% of total damages and the cost per kWh (electricity-weighted) falls to 1.2 cents.

produced 12% of damages, while the 10% of plants with the highest damages per plant, which also accounted for 25% of net generation, produced 43% of the damages. The situation for gas is similar, although damages per plant are lower: the 10% of natural gas facilities in our sample with the highest damages per plant produce 65% of the air pollution damages associated with the 498 facilities we examined.

What are criteria air pollution damages from coal and natural gas plants likely to be in 2030? To examine damages in 2030 we increase electricity generation at the plants analyzed in 2005 by amount consistent with EIA forecasts of electricity production from coal and natural gas. This implies, on average, a 20% increase in electricity produced from coal and a 9% increase in electricity produced from natural gas. We also assume that the emissions intensity of plants will fall in a manner consistent with EIA estimates of total emissions from fossil fuel plants. The APEEP model was used to estimate damages per ton from SO_2, NO_x, $PM_{2.5}$, and PM_{10} in 2030. In spite of increases in damages per ton of pollutant, due to population and income growth, average damages per kWh (weighted by electricity generation) at coal plants are 1.7 cents per kWh (electricity-weighted), compared to 3.2 cents per kWh in 2005 (also electricity-weighted) . The fall in damages per kWh is explained by the assumption that pounds of SO_2 per MWh hour will fall by 64% and that NO_x and PM emissions per MWh will fall by approximately 50%. Average damage per kWh from gas generation falls to 0.11 cents (2007 USD) from 0.16 cents in 2005 (weighting plants by net generation).

Electricity from Nuclear Power

The Committee did not quantify damages associated with nuclear power because the analysis would have involved power-plant risk modeling and spent-fuel transportation modeling that would have taken far greater resources and time than were available for this study. Notwithstanding that this modeling was not undertaken, previous studies suggest that the monetized value of these risks are small (ORNL/RFF 1992-98 and ExternE (EC 1995b). The upstream damages result largely from uranium mining, most of which occurs outside the United States. With uranium mining in general, radiological exposure can occur through inhalation of radioactive dust particles or radon gas, ingestion of radionuclides in food or water, and direct irradiation from outside the body. For surface mine workers, exposure to radon exposure is generally less important than direct irradiation or dust inhalation; however, exposure to radon can be important for underground miners. If radiological exposure is taken into account in the miners' wages, it would not be considered an externality. For members of the public, the most significant pathways from an operating mine are radon or other radionuclide ingestion following surface water transport; from a rehabilitated mine, the more significant pathways over the long term are likely to be groundwater as well as surface water transport and bioaccumulation in animals and plants located at the mine site or on associated water bodies. Upstream impacts also include air emissions, including greenhouse gas emissions, but they are one or two orders of magnitude smaller than the emissions from coal-fired plants.

Downstream burdens are largely confined to the release of heated water used for cooling—such releases occur at any type of thermal plant—and the production of low-level radioactive wastes (LLRW) and high-level radioactive wastes (HLRW) from spent fuel; release of highly radioactive materials has not occurred on a large scale in the United States (but obviously has occurred elsewhere). Either LLRW is stored for decay to background levels and then disposed of as non-radioactive waste (a practice possible with slightly contaminated materials) or it is disposed of in near-surface landfills designed for radioactive wastes.

For spent nuclear fuel that is not reprocessed and recycled, HLRW is usually stored at the plant site. No agreement has been reached on a geologic repository for HLRW in the United States, and therefore little HLRW is transported for long distances. LLRW has been transported for decades without serious incident. The issue of having a permanent repository is perhaps the most contentious nuclear-energy issue, and considerably more study on the externalities of such a repository is warranted.

Electricity from Wind

Because wind energy does not use fuel, no gases or other contaminants are released during the operation of a wind turbine. Upstream effects are related to the mining, processing, fabrication, and transportation of raw materials and parts; those parts are normally transported to the wind-energy plant's site for final assembly. The committee concludes that these life-cycle damages are small compared with the life-cycle damages from coal and natural gas. Downstream effects of wind energy include visual and noise effects, the same kinds of land-use effects that accompany the construction of any electricity-generating plant and transportation of electricity, and the killing of birds and bats that collide with the turbines.

Far more birds—by at least three orders of magnitude—are estimated to be killed by collisions with transmission lines, which are associated with all forms of electricity generation, than by collision with wind turbines. Therefore, although the detailed attribution of transmission-line-caused bird deaths by electricity source would be difficult, the committee concludes that bird deaths caused by wind-powered electricity generation are small compared with deaths from all other sources.

Wind-energy installations often have larger footprints than nuclear or coal plants, but the land use within the footprint often is less intensive than within the smaller footprints of thermal plants. In most cases, wind-energy plants do not currently kill enough birds to cause population-level problems except perhaps locally, mainly affecting raptors. The numbers of bats killed and the population consequences of those deaths have not been quantified, but could be significant. If wind-powered energy generation continues to grow as fast as it has recently, bat and perhaps bird deaths could become more important.

The committee has not quantified any effects of solar or biomass generation of electricity, but has not seen evidence that, at current generation capacity, there are effects that are comparable to those from larger sources of electricity generation. However as technology and penetration into the U.S. energy market improves, the externalities from these sources will need to be re-evaluated.

Research Recommendations

Many of the significant externalities associated with electricity generation can be estimated quantitatively, but there are several important areas where additional research is needed:

- Although it appears that upstream and downstream (i.e., pre- and post-generation) activities are generally responsible for a smaller portion of the life-cycle externalities than the generation activities themselves for some sources, it would be useful to perform a systematic estimation and compilation of the externalities from these other activities, comparable in completeness to the externality estimates for the generation part of the life cycle. In this compilation, damages from activities that are locally or regionally significant (e.g., the storage and disposal of coal combustion byproducts, in-situ leaching techniques for uranium mining) need to be taken into account.
- The "reduced form" modeling of pollutant dispersion and transformation is a key aspect in estimating externalities from airborne emissions, which constitute most of the estimated externalities for fossil-fuel fired power plants. These models should continue to be improved and tested and compared with the results of more complex models, such as CMAQ.
- The health effects associated with toxic air pollutants, including specific components of particulate matter, from electricity generation should be quantified and monetized. Due to the importance of VSL in determining the size of air pollution damages, further exploration is needed of how willingness to pay varies with mortality-risk changes and with population characteristics such as age and health status.
- For fossil fuel options, the ecological and socioeconomic impacts of coal mining, e.g., of mountaintop removal and valley fill, are a major type of impact in need of further research in order to quantify their damages.

- For nuclear power, the most significant challenges in estimating externalities are appropriately estimating and valuing risks when the probabilities of accidents and of radionuclide migration (e.g., at a high-level waste repository) are very low but the consequences potentially extreme, and whether the cost to utilities of meeting their regulatory requirements fully reflects these externalities.
- The analysis of risks associated with nuclear power in the RFF/ORNL study should be updated to reflect advances in technology and science.
- For wind technologies, the major issues are in quantifying bird, and especially bat deaths; disturbances to both the local animal populations and landscape; and valuing them in terms comparable to economic damages.
- For solar, an important need is a life-cycle analysis of the upstream activities that quantifies the possible releases of toxic materials and their damages; another is a better understanding of the externalities that would accompany dedicating tracts of land to solar panels.
- For transmission lines needed in a transition to a national grid system, better estimates are needed of both the magnitude and the spatial distribution of negative and positive externalities that would accompany this transition.

3

Energy for Transportation

BACKGROUND

The Current Mix of Energy Sources for Transportation

According to the U.S. Energy Information Agency, approximately 28% of all U.S. energy use is consumed in the transportation sector currently (NAS/NAE/NRC 2009 in press). Of this use, approximately 96% is in the form of petroleum, 2.6% is natural gas, and less than 1% is biomass, electricity, or other fuels. Overall, transportation is responsible for approximately 70% of all U.S. petroleum consumption.

In its recent report, the NRC Committee on America's Energy Future reports that as of 2003, the transportation sector used approximately 28.4 quadrillion Btu of energy, of which more than 75% was expended in highway transportation, 17% in non-highway transportation (e.g. air, rail, pipeline), and 8% in other off-highway use (e.g., agriculture, construction) (NAS/NAE/NRC 2009 in press).[1] Figure 3-1 from their report below illustrates that of the highway sector, cars account for 43% of highway energy use (~34% of all transportation energy use), light trucks for 32% (~26% of the total), and medium and heavy trucks for 24% (~19% of the total).

Of the fuels consumed, AEF reports that gasoline accounted for approximately 62% of the energy used (measured in Btu; EIA 2006b) and diesel (primarily in medium- and heavy-duty vehicles) accounted for approximately 17% of energy used.

Regulation of Transportation Air Quality Emissions

The past four decades have seen a substantial national effort to regulate the emissions from transportation, starting with light-duty vehicles in the 1970s, and moving to heavy-duty on-road vehicle, and most recently to a range of other transportation sources including construction and agricultural equipment, locomotives, boats and ships, and others (NRC 2004c). These efforts have been driven in part by even stricter standards adopted by California, which have in turn been adopted by a number of states. The result has been substantial reductions in emissions and ambient levels of a number of pollutants, even as vehicle miles have increased. For example, there have been substantial reductions of ambient levels of carbon monoxide, in most cases to levels below[2] the current National Ambient Air Quality Standards (NRC 2003b).

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[1] The 2009 edition of the *Transportation Energy Data Book* indicates that highway transportation expended 80% of the energy used by the entire transportation sector in 2007.

[2] As of July 31, 2009, Clark County, Nevada is the only U.S. county in nonattainment for carbon monoxide. (See EPA 2009f)
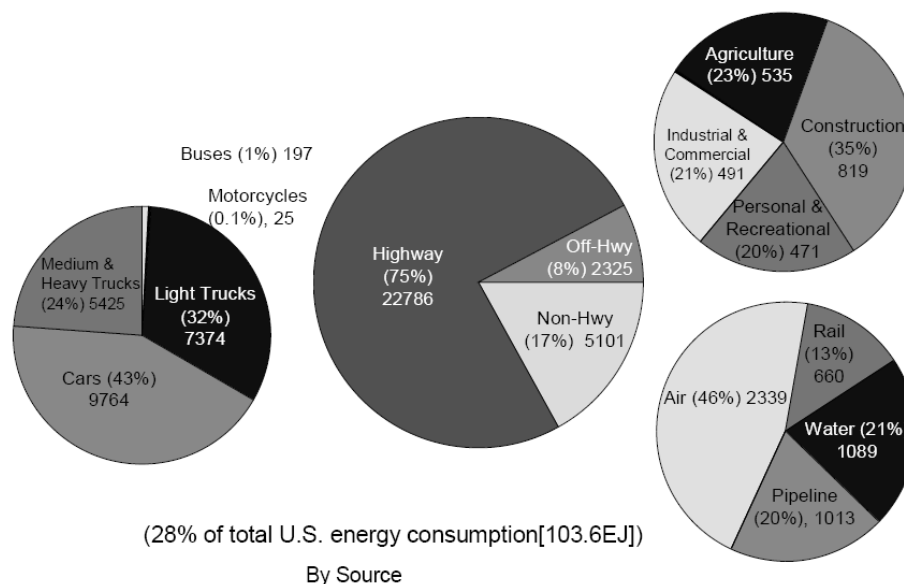
FIGURE 3-1 U.S. transportation energy consumption by mode and vehicle in 2003. Source: Based on the Transportation Energy Data Book (Bodek 2006) in NAS/NAE/NRC (in press). Reprinted with permission; copyright 2006, Massachusetts Institute of Technology.

Starting in the late 1980s in the states, and in 1990 on the national level, there have also been a number of rules aimed at changing the formulation of fuels to reduce a variety of emissions (e.g. benzene and other volatile organic compounds) and to facilitate the introduction of new emission control technologies (e.g. ultra low sulfur diesel fuel) (NRC 2004c). There have also been substantial requirements enacted in the current decade requiring enhanced use of biofuels (more detail is provided later in this chapter).

Improving Vehicle Efficiency

In addition to regulation to reduce emissions in the transportation sector, the United States has seen substantial efforts, beginning in the 1970s and renewed recently, to improve vehicle efficiency (NRC 2002c). The recent AEF Efficiency Panel Report (NAS/NAE/NRC 2009 in press) assessed the opportunities for reducing energy consumption in the transportation sector through advances in efficiency.

That report notes that energy usage in transportation has grown rapidly in the United States over the past decades, except for brief pauses during economic recessions in 1974, 1979-1982, 1990-1991, and 2001. The present economic decline, along with the 2008 spike in petroleum prices, is also likely to slow the demand for transportation fuels. Globally, the major drivers for energy efficiency are: the price of fuel (influenced by taxes), regulations, personal choice, and the personal environmental values movement. In Europe, where high fuel and vehicle taxes raise owner costs, and where diesel fuel is taxed less than gasoline, new vehicle fuel economy is approaching 40 miles per gallon (mpg). In 1999, Japan instituted a fuel economy program to encourage vehicle efficiency per mile travelled, and their present new vehicle fuel economy is similar to Europe's. In 2006, Japan revised its fuel economy standard to 47 mpg by 2015 (Ann et al. 2007).

In the United States, technologic efficiency improvements are available at fairly modest costs. With present market structures, vehicle drive train efficiency has been improving at a rate of about 1% per year. However, rather than reducing their fuel expenses as a result of these improvements, most U.S.

consumers have opted to purchase larger vehicles with more acceleration and accessories that consume even more energy. So in spite of technological improvements in the efficiency of vehicle components, the fuel demand has continued to rise, and the U.S. light-duty vehicle fleet now has an average new vehicle fuel efficiency of about 25 mpg.

Recently, California has adopted so-called greenhouse gas emission standards which would require substantial reductions in greenhouse gas emissions, primarily through enhancements in fuel economy, by 2016; 13 additional states have indicated that they would adopt the standards once the U.S. Environmental Protection Agency (EPA) approved a waiver of the Clean Air Act to allow them to move forward. Although EPA had originally rejected California's application for a waiver, in January 2009 EPA began a process to formally reconsider the waiver, and in May 2009, after detailed discussions among California, EPA, and the auto makers, President Obama announced an approval of the waiver and a new unified approach to both federal Corporate Average Fuel Efficiency (CAFE) and greenhouse gas emissions standards that will result in a national standard comparable to the California standards. This is expected to result in achievement of the former 35.5 miles per gallon CAFE goal by 2016, several years sooner than originally envisioned.

A wide variety of technologies are available to improve fuel economy, in particular those to improve drive train efficiency, vehicle aerodynamics, rolling resistance, and weight reduction (NRC 2008b). Many of these will be widely deployed by 2020, but further gains will be possible. Diesel engines and hybrid-electric vehicles such as the Toyota Prius are currently available and can reduce fuel consumption by more than 25 percent relative to today's gasoline vehicles. A shift to these technologies, coupled with other improvements, could result in a new vehicle fleet with substantially improved fuel efficiency.

APPROACH TO ANALYZING EFFECTS AND EXTERNALITIES OF TRANSPORTATION ENERGY USE

Rationale for the Selection of Vehicle Fuels and Technologies

In considering its task, the Committee recognized that it would not be possible to estimate quantitative externalities for every possible energy use in the transportation sphere. The Committee therefore attempted to prioritize its work based on two key factors: (1) the degree to which a current transportation energy use is a significant part of the energy use, and (2) the degree to which an emerging fuel and/or technology is likely to become a significant part of transportation energy use in the future. In applying these criteria, and assessing the degree to which the data would support quantitative analysis, the Committee focused on two key areas:

- A quantitative analysis of current and 2030 energy use, emissions, and externalities, for highway transportation for both petroleum-based fuels and conventional bio-fuels (e.g. corn ethanol) using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model for primary analysis and tied to the APEEP model to estimate physical effects and monetary damages. This analysis applies to more than 75% of all current U.S. energy use in the transportation sector.
- A qualitative and quantitative synthesis of what is currently known on several other key fuels/technologies: including: emerging biofuels (e.g. corn stover, grasses); hybrid, plug-in hybrid, and electric vehicles; and other fuels: (natural gas, hydrogen fuel cells).

Transportation Life-Cycle Analysis

Our goal is to develop and apply an LCA framework that can provide more detailed quantitative assessments of the comparative health and environmental benefits, risks, and costs of existing fossil fuels

(petroleum), as well as future mixes of transportation technologies and fuels. To meet this goal, we build on state of the art Life-Cycle-Impact-Assessment (LCIA) methods that have been developed for evaluating and allocating the health, resource, and environmental impacts of industrial, agricultural, and energy technology systems (Guinée and Heijungs 1993; Horvath et al 1995; Hoffstetter 1998; IAEA 1999; Hertwich et al. 2001; Bare et al. 2002; EC 2008). This effort and its resulting framework provide quantitative estimates of impacts that can be considered "external" in the context of Chapter 1.

One can take either a top-down or bottom up approach when allocating health and environmental costs to transportation technologies. The top-down approach considers morbidity and mortality statistics for a specific population, such as the inhabitants of a country or of a large urban region, and attempts to allocate these impacts to a specific source such as transportation emissions or power-plant emissions. The bottom-up approach provides a list of hazard sources (such as pollutant releases) and tracks these hazards from the source to exposure and damage. Top-down assessments for air pollution have been carried out for many regions such that it is possible to provide a disease burden estimate for air pollution. But allocation to specific energy systems cannot be resolved, because the top-down approach lacks the spatial and temporal resolution needed to track impacts to specific technologies. In contrast, the impact pathway assessment used in the ExternE study (EC 2003, p. 3) and the more recent analysis by Hill et al. (2009) of air-emissions impacts from transportation fuels both engage a bottom-up-approach in which environmental benefits and costs are estimated by following the pathway from source emissions through pollutant level changes in air, soil and water to health and environmental impacts.

The life cycle of effects associated with using energy for transportation includes upstream effects such as extracting and processing the fuels, building the infrastructure needed to use transportation systems (e.g., roads), building the infrastructure needed to deliver energy for vehicles (e.g., pipelines and tankers); and manufacturing the vehicles themselves. The life cycle also includes the use of energy in vehicles, i.e., effects associated with emissions from vehicle tailpipes.

With respect to the categories of interest of this study we summarize some of the key pathways by which energy sources for transportation lead to impacts. In general, most of the emissions occur as a result of burning fossil fuels in the life cycle of transportation fuels. Such energy use occurs across the supply chain, including fuel use for drilling oil wells or farming biomass fields, to transporting feedstocks and/or fuels to and from refineries, the refining process, transporting fuel to/from consumers, and the use of the fuels by consumers.

The movement of feedstocks and fuels in the supply chain of transportation fuels is different than for electricity. Petroleum and petroleum products (e.g., gasoline or diesel fuel) are generally transported by pipeline or truck; whereas coal, the primary energy source for electricity, predominantly transported by rail. A significant share of the petroleum used to make fuels is from foreign sources (i.e., where it is extracted in a foreign country and delivered to the U.S. market via ocean tanker).

Various studies have been conducted of externalities with energy use in transportation. Before the phrase "life cycle" became popular, studies of this scope in the energy domain were referred to as "fuel cycle" studies, intended to represent the entire cycle of effects associated with using fuels. Nowadays such studies are often called "well to wheel" analyses since their scope goes from the oil well to powering the wheels of the car. In general, these terms all refer to the holistic study of impacts from extraction through combustion of the fuel for transportation. Other scopes exist too, e.g., "well to tank" which involves all steps needed to get a fuel to the vehicle, but not using the fuel.

Prior studies around the world have assessed the relative contribution of environmental burdens from producing and using fuels for transportation (e.g., Delucchi 1993, MacLean and Lave 2003a,b, Ogden et al. 2004, Brinkman et al. 2005, EC-JRC 2008, Ruether et al. 2005). Different from the case of electricity, those studies present a mixed view of the relative upstream phase versus use effects. In prior studies, for petroleum-based fuels, the largest amount of emissions generally occurred when burning fossil fuels in vehicles while driving them, with upstream emissions being relatively modest (although they did not, in general, include vehicle manufacturing in those upstream effects).

Scope of the Analysis

Because this study is about externalities associated with *energy* production, distribution and use, this chapter considers the externalities from transportation technologies that use different forms of energy and fuels. The externalities of transportation, per se, are not within the scope of the study. Thus, the Committee generally did not consider vehicle safety issues and traffic accidents, damage to road pavement from heavy trucks, or traffic congestion. These are not related to energy options. We considered them only to the extent that there are significant damages from the transport of *fuels*. For instance, Chapter 2 considered rail accidents associated with the transport of coal, but not all rail accidents. Similarly, our study considers oil tanker accidents, but not all transportation accidents.

The Committee's goal was to estimate the external damages, in dollars per additional mile traveled, of different types of vehicle-fuel technologies, both current (2005) and future (2030). To do this properly, the committee recognized that it would be necessary to keep track of each type of pollutant and its source location and other factors that would vary spatially and over time. The Committee also wanted to track the life-cycle stage of the damage and the end-point category (e.g., mortality, morbidity).

To obtain the estimates of emissions per vehicle mile traveled (VMT) by vehicle-fuel technology and life-cycle stage, the Committee relied primarily on the GREET model. Sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Argonne National Laboratory has developed a full life-cycle model called GREET. It allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. The GREET model and analyses using the model have been published in a large number of peer-reviewed journals. The model has been widely used by Argonne and other organizations have used GREET for their evaluation of advanced vehicle technologies and new transportation fuels. GREET users include government agencies, the auto industry, the energy industry, research institutions, universities, and public interest groups. GREET users are spread in North America, Europe, and Asia.[3]

GREET includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems. Fuels include Conventional and oil sands based petroleum fuel, natural gas, coal-based liquid fuels, biofuels derived from soybeans, corn, sugarcane, and cellulosic biomass, grid independent hybrids, grid dependent hybrids and all electrics and hydrogen fuel cells. Unfortunately, while GREET covers light-duty autos and two types of light-duty trucks,[4] it does not contain information on heavy-duty trucks, which represent almost the entire consumption of the U.S. fleet's diesel fuel and even is sizable compared to the consumption of all transportation fuels. Accordingly, the Committee made separate estimates of direct emissions from heavy-duty trucks based on the EPA's Mobile 6.2 model and then used GREET to calculate the upstream emissions for the given fuel cycle. The committee decided in the interest of time, and given their relatively smaller overall contribution to transportation energy use (i.e. less than 25% of total transportation energy use), to omit from consideration in the modeling analysis emissions from rail, sea and air transport, as well as off-road vehicles.

Table 3-1 provides the full list of vehicle-fuel technologies that the Committee modeled with GREET[5] and the heavy-duty vehicles modeled by the Committee outside of GREET.

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[3]A comparison of GREET 1.8b and Mobile 6.2 emissions factors for gasoline vehicles reveals that the latter are generally higher. See Appendix F for details.

[4]Class 1 trucks are under 6,000 lbs Gross Vehicle Weight Rating (GVWR) and less than 3,750 lbs Loaded Vehicle Weight (LVW) while class 2 trucks have the same GVWR and greater than 3,750 LVW.

[5]We used Version 1.8b for estimating fuel-related emissions and Version 2.7a for estimating vehicle manufacturing emissions

TABLE 3-1 Vehicle-Fuel Technologies in the Committee's Analysis

Light-Duty Autos and Class 1 and 2 Trucks	Heavy-Duty Vehicles
RFG SI Autos (Convent. Oil)	HDGV2B
RFG SI Autos (Tar Sands)	HDGV3
CG SI Autos (Convent. Oil)	HDDV2B
CG SI Autos (Tar Sands)	HDDV3
RFG SIDI Autos (Convent. Oil)	HDDV4
RFG SIDI Autos (Tar Sands)	HDDV5
CNG	HDDV6
E85 - Dry Corn	HDDV7
E85 - Wet Corn	HDDV8A
E85 - Herbaceous	HDDV8B
E85 - Corn Stover	
E10 - Dry Corn	
E10 - Wet Corn	
E10 - Herbaceous	
E10 - Corn Stover	
Electric	
Hydrogen (Gaseous)	
Grid Independent SI HEV	
Grid Dependent SI HEV	
Diesel (Low Sulfur)	
Diesel (Fischer Tropsch)	
Diesel (Soy BD20)	

Notes: The modeling analysis included 33 different vehicle fuel technologies (23 light-duty vehicle fuels and 10 heavy-duty vehicles). BD20 = 20% biodiesel blend; CG = conventional gas; CNG-compressed natural gas; E10 = 10% ethanol blend; E85 = 85% ethanol blend; HEV = hybrid electric vehicle; HDDV = heavy-duty diesel vehicle; RFG = reformulate gasoline; SI = spark ignition; SIDI = spark ignition, direct injection.

To address technology improvements over time, GREET simulates fuel production pathways and vehicle systems over a period from 1990 to 2020, in five-year intervals with the results for any given year reflecting GREET's estimates from five years before (i.e., reflecting the average fleet on the road in the year being analyzed). Thus the committee, which was interested in external damages for 2005 (the base-year for our analysis), used the 2000 GREET results for 2005. For its 2030 estimates, the committee used the 2020 results (i.e., those vehicles on the road in 2020) with one major adjustment, replacing the default vehicle fuel efficiency for light-duty autos in GREET with the 35.5 mpg which will be required by 2016 under the recently announced new efficiency and greenhouse gas emission standards. For heavy-duty diesels (HDDs), the Committee captured emissions improvements expected as dirtier trucks are retired from 2021 to 2030 and are replaced by HDDs meeting the 2007 and 2010 tailpipe standards. This approach will probably overestimate emissions in these years if emissions continue to fall with efficiency improvements (as GREET assumes until 2020).

For a given vehicle and fuel system, GREET separately calculates the following:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal and natural gas.
- Emissions of carbon dioxide (CO_2)-equivalent greenhouse gases—primarily CO_2, methane (CH_4), and nitrous oxide (N_2O). (The committee recognizes the potential importance of other climate-change agents, such as black carbon and ozone. Although our estimates of damages that are not related to

climate change included particulate matter and ozone, it was not feasible to obtain climate-change related estimates through GREET.)

- Emissions of six substances that form criteria air pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter with size smaller than 10 microns (PM_{10}), particulate matter with size smaller than 2.5 microns ($PM_{2.5}$),and sulfur oxides (SO_x).

GREET represents "well-to-wheel" life-cycle emissions in four stages: feedstock, fuel, vehicle manufacturing, and operations. For gasoline vehicles, these stages translate to the following:

- Feedstock: Extraction of oil and its transportation to the refinery
- Fuel: Refining of the oil and its transportation to the pump
- Vehicle: All emissions associated with production of the vehicle, which itself, since it involves energy use, accounts for all life-cycle stages
- Operations: Tailpipe and evaporative emissions

For other types of vehicles, the stages are analogous. Note that for grid-dependent hybrids, as a more complicated example, several energy types are involved. First, is the above gasoline life cycle for that portion of driving that uses gasoline. Second is the electricity life cycle. In this case, the feedstock emissions are those involving the extraction of coal, natural gas, etc., weighted to reflect a default mix of generating technologies. (The Committee uses a national electricity generation mix of fuel types taken from the National Energy Modeling System (NEMS) model for estimating 2030 electricity emissions). The fuel emissions are those from the power sector's smokestacks. Emissions estimates for vehicle manufacturing are adjusted to reflect differences between energy and materials requirements for hybrids versus conventional vehicles, say regarding battery manufacturing.

The GREET model is fully assumption-driven, but comes with a series of default values representing various assumptions. The Committee set these values primarily at their default values, but tested alternative values when it appeared warranted. See Appendix D for details on settings chosen by the committee.

The level of spatial detail in GREET is limited to whether the emissions are from urban or rural use. This choice appears to be primarily related to considerations of how direct grams/mile emissions from vehicles are dependent on vehicle speeds, which, in turn, are different in an urban vs. rural setting. To estimate damages, however, particularly by air pollutants, a finer degree of spatial detail is necessary.

The Committee's strategy was to define U.S. counties in the 48 contiguous states as either urban or rural and then assign urban or rural emission factors to counties. This approach probably works well for direct vehicle emissions, since every county has vehicle emissions. However, decisions had to be made as to where to locate sources of upstream emissions such as refineries for petroleum and ethanol.

In general, such sources (except for emissions from electricity produced for electric and grid-dependent electric vehicles) were assumed to be located in every county, although some adjustments were made for oil refineries, ethanol production, and vehicle manufacturing). The Committee located refineries by petroleum administration for defense districts (PADD), calculated damages per unit emissions by PADD from the APEEP Model, assigned counties to PADDs and from there assigned the PADD-specific unit damages to each county. Clearly these assumptions simplify a complex situation where fuels can be imported as well as domestically produced. But the purpose of the analysis is to examine damages from sources in the United States. Thus, one should interpret the GREET results as what the damages would be *if* the county featured all the stages of the life cycle, e.g., a refinery. See Appendix D for details.

Once GREET produces estimates of the emissions per mile associated with various vehicles and fuel types, this information (with the exception of emissions associated with vehicle operation and electricity production for electric vehicles and grid-dependent hybrids) was paired with results from the APEEP model, which provides estimates of the physical health and other non-GHG effects and monetary

damages per ton of emissions that form criteria air pollutants.[6] For electric and grid-dependent hybrid vehicles, a similar approach was used to estimate damages for the feedstock and vehicle manufacturing components of the life cycle; however, the allocation of electric utility-related damages to the operations and electricity production components of the life cycle, were better approximated by applying a GREET-generated kWh/VMT and applying that to the estimated average national damages per kWh from the electricity analysis presented in Chapter 2 (details of this approach can be found in Appendix D).

Damages are estimated for mortality, morbidity and "other," which include recreational damages related to visibility and crop damage related to ozone.   These estimates are delivered for every U.S. county and for four "stack heights," including tall stacks (appropriate for modeling source-receptor relationships (SRRs) associated with electric utility emissions), medium stacks (appropriate for modeling SRRs for industrial emissions, low stacks (appropriate for modeling SRRs for commercial emissions) and ground level emissions, appropriate for modeling mobile source SRRs. Thus, one can think of there being four matrices of physical and dollar per ton estimates, one matrix for each stack height, with each matrix covering counties and effects/damages. Because we have life-cycle emissions information, emissions/mile estimates at various stages of the life cycle were paired with the appropriate stack height estimates.

Presentation of Results

Results are provided by light-duty autos, two classes of light-duty trucks and 8 classes of heavy-duty diesel trucks, covering 2005 and 2030, for all the vehicle-fuel technologies, all the pollutants, and all the life-cycle stages, as well as for alternative assumptions about the value of statistical life (VSL). All damages are expressed in dollar (2007 USD) per VMT terms, unless specified otherwise. With damages estimated at the county level for the 48 contiguous U.S. states, a distribution of damages over all counties was obtained. Thus, for all life-cycle stages, the 5th and 95th percentile range and median county damages are presented for each pollutant, type of effect, year (2005, 2030) and vehicle-fuel technology combination. For the operation stage, damage estimates are presented averaged over all counties, both un-weighted and weighted by population. The latter is more realistic as more populated counties are doing more damage.

The Committee also made estimates of these health and other non GHG damages on a per gallon basis, although interpretation of these is complicated by the fact that those fuel/technology combinations with higher inherent fuel efficiency would appear to have markedly higher damages per gallon than those with lower efficiency, solely due to the higher number of miles driven per gallon. Also, GHG-related life-cycle emissions/mile are presented in this chapter, but damages are not discussed here (that occurs in chapter 5). Information on energy use per mile was also calculated.

Finally, the Committee did attempt to estimate aggregate annual damages for light-duty vehicles and heavy-duty vehicles in 2005—by multiplying per mile damages for each of the fuel/technology combinations in use in 2005 by the best estimates available of total vehicle miles travelled. The former are somewhat conservative as, given limitations on separating vehicle miles traveled among light-duty autos and light-duty trucks, we estimated aggregate damages using the per VMT damages we estimated for autos only. Similar estimates could not be made for 2030 given the substantial uncertainty in what fuels and technology market shares will be at that time.

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[6]More detailed description of the APEEP model is given in Chapter 2 and Appendix D. In estimating monetary damages, APEEP uses a Value of a Statistical Life of $6 million/year (in 2007 dollars) as discussed further in Chapter 2.

PRODUCTION AND USE OF PETROLEUM-BASED FUELS

Current Status and Brief History of Petroleum

Crude oil, a non-renewable energy source, comprises the largest fraction of energy consumed in the United States (Figures 1-3 and 1-4 in Chapter 1). In 2007 the United States consumed 7.5 billion barrels of crude oil and petroleum products, of which nearly seventy percent was used by the transportation sector. U.S. consumption declined briefly in 1973 due to Arab OPEC oil embargo (Figure 3-2). In response to the embargo, the U.S. government created the Strategic Petroleum Reserve (SPR). As of 2007, the SPR holds 697 million barrels of crude oil. Once the Arab OPEC embargo was lifted, U.S. consumption dramatically increased until rising oil prices in early 1980s caused a steep decline in consumption. Since mid 1980s, U.S. oil consumption has steadily risen. In 2007, motor gasoline consumption reached record high of 9.29 million barrels per day (390 million gallons/day).

Since the mid-20th century, U.S oil consumption has exceeded domestic oil production. , thus nearly 60% of crude oil and petroleum products are imported. In 2007, seventy-one percent of net crude oil imports came from five countries: Nigeria (11%), Venezuela (12%), Mexico (14%), Saudi Arabia (15%), and Canada (19%). Domestic and imported crude oil are transported to U.S. refineries primarily by pipeline, barge, and ocean tankers (EIA 2008d).

The United States currently has 150 operable oil refineries capable of processing 17.6 millions barrels of crude oil per day. Refineries are located in urban and rural areas across the United States. A map of current refineries is provided in Figure 3-3.
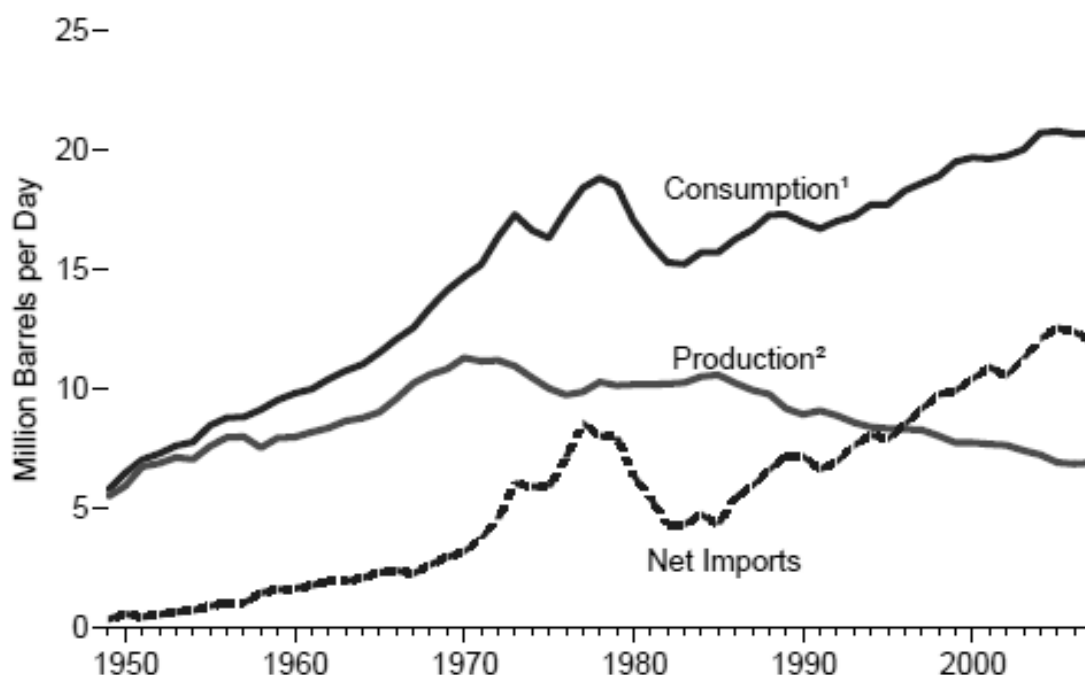
1. Petroleum products supplies is used as an approximation for consumption
2. Crude oil and natural gas plant liquids production

FIGURE 3-2 Overview of petroleum consumption, production, and imports from 1949 to 2007. Source: EIA 2008a, p. 124, Figure 5.1.
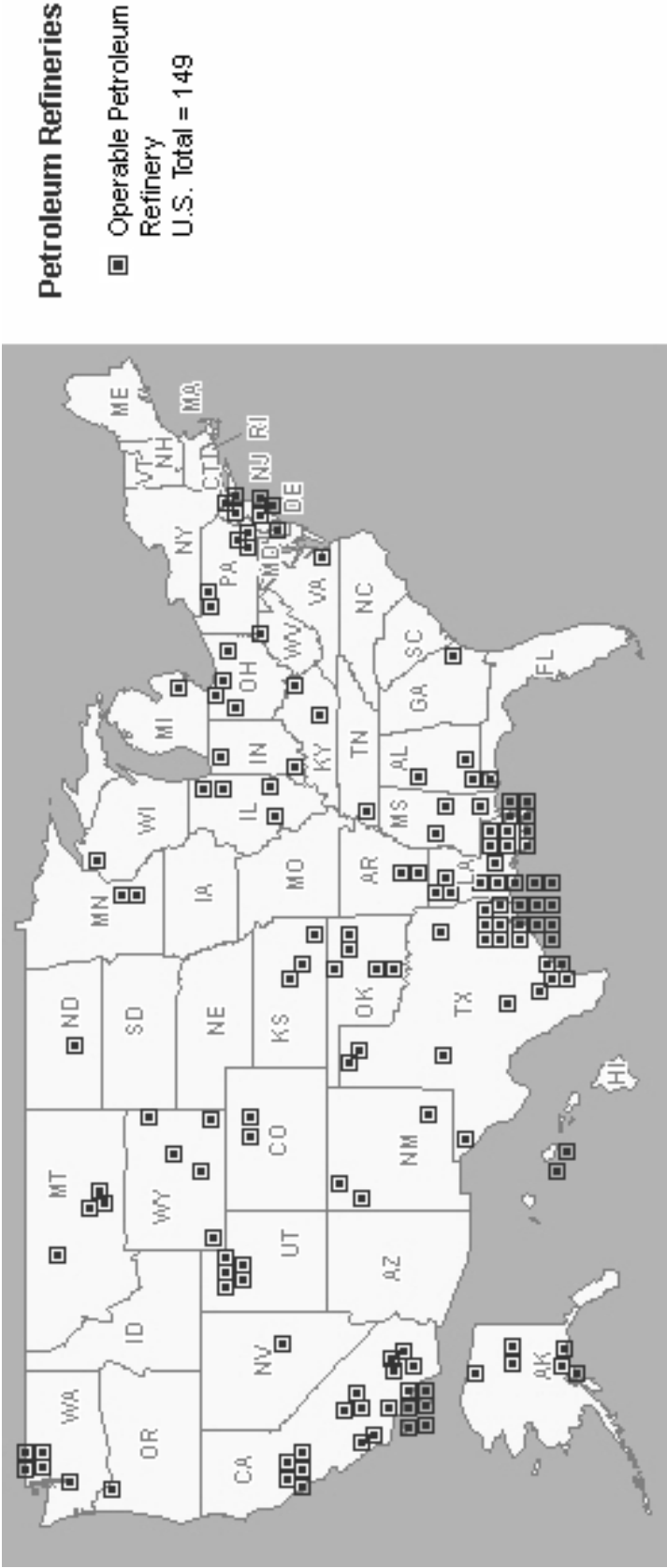
FIGURE 3-3 Location of U.S. oil refineries. Texas and Alaska each account for large shares of U.S. crude oil production, but the Federal offshore areas in the Gulf of Mexico and California produce roughly a one-fourth share of the U.S. total, which surpasses the individual shares of Texas and Alaska. Source: EIA 2009g.

Approximately one barrel of crude oil produces 44 gallons of finished petroleum products, including jet fuel, diesel, and gasoline (Figure 3-4). More than 40% of crude oil is refined to finished motor gasoline (Figure 3-5).

U.S. Vehicle Fleet

The U.S. Department of Transportation maintains an on-line report entitled "National Transportation Statistics". The report is updated quarterly, and includes data beginning in 1960. Table 3-2 provides a summary of the most recent transportation statistics.
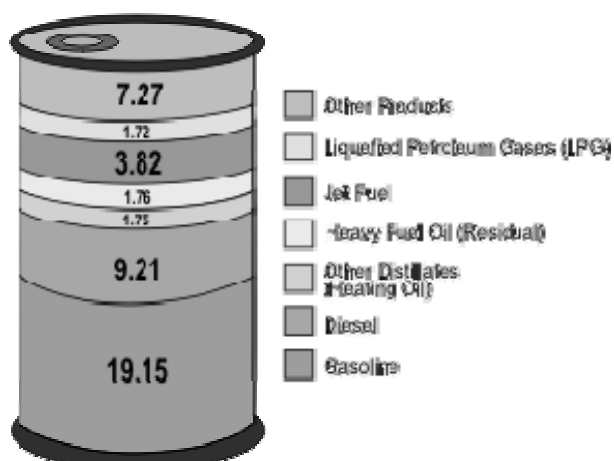
FIGURE 3-4 Products made from one barrel of crude oil (gallons). One barrel of crude oil is approximately equal to 45 gallons. Source: EIA 2009h
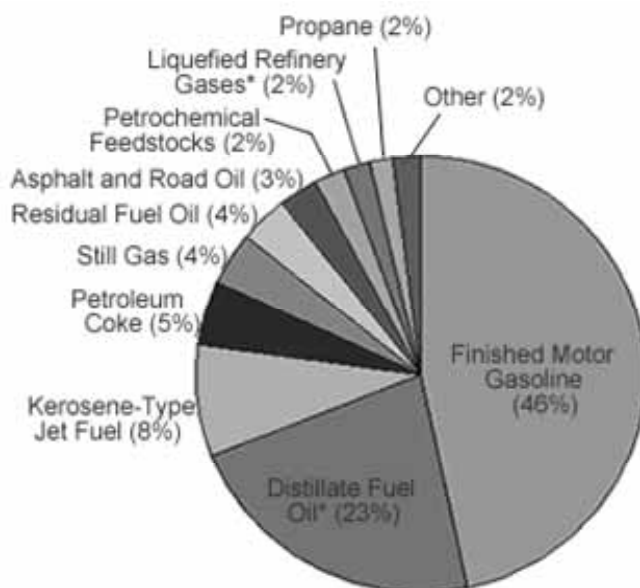
* Distillate Fuel Oil includes heating oil and diesel fuel. Liquid Refinery Gases include
ethane/ethylene, propylene, butane/butylene, and isobutane/isobutylene.

FIGURE 3-5 U.S. refinery and blender net production of refined petroleum products in 2007 (Total = 6.57 billion barrels). Source: EIA 2008d.

TABLE 3-2 Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances

	1960	1990	2000	2006
Air				
Air carrier[a]	2,135	6,083	8,055	U
General aviation[b] (active fleet)	76,549	198,000	217,533	221,943
Highway, total (registered vehicles)	*74,431,800*	*193,057,376*	*225,821,241*	*250,851,833*
Passenger car	61,671,390	133,700,496	133,621,420	135,399,945
Motorcycle	574,032	4,259,462	4,346,068	6,686,147
Other 2-axle 4-tire vehicle	N	48,274,555	79,084,979	99,124,775
Truck, single-unit 2-axle 6-tire or more	N	4,486,981	5,926,030	6,649,337
Truck, combination[c]	11,914,249	1,708,895	2,096,619	2,169,670
Bus	272,129	626,987	746,125	821,959
Transit[d]				
Motor bus	49,600	58,714	75,013	(P) 83,080
Light rail cars	2,856	910	1,327	(P) 1,801
Heavy rail cars	9,010	10,567	10,311	(P) 11,052
Trolley bus	3,826	610	652	(P) 609
Commuter rail cars and locomotives	N	4,982	5,498	(P) 6,403
Demand response	N	16,471	33,080	(P) 43,509
Other[e]	N	1,197	5,208	(P) 8,741
Rail				
Class I, Freight cars	1,658,292	658,902	560,154	475,415
Class I, Locomotive	29,031	18,835	20,028	23,732
Nonclass I freight cars	32,104	103,527	132,448	120,688
Car companies and shippers freight cars	275,090	449,832	688,194	750,404
Amtrak, Passenger train car	N	1,863	1,894	1,191
Amtrak, Locomotive	N	318	378	319
Water				
Nonself-propelled vessels[f]	16,777	31,209	33,152	32,211
Self-propelled vessels[g]	6,543	8,236	8,202	8,898
Oceangoing steam and motor ships (1,000 gross tons and over)[h]	2,914	635	461	286
Recreational boats[i]	2,450,484	10,996,253	12,782,143	12,746,126

Note: N = data do not exist; R = revised; U = data are not available.

[a]Air carrier aircraft are those carrying passengers or cargo for hire under 14 CFR 121 and 14 CFR 135. Beginning in 1990, the number of aircraft is the monthly average of the number of aircraft reported in use for the last 3 months of the year.

[b]1991-94 data revised to reflect changes in adjustment for nonresponse bias with 1996 telephone survey factors; 1995-97 data may not be comparable to 1994 and earlier years due to changes in methodology. Includes air taxi aircraft.

[c]In 1960, this category includes all trucks and other 2-axle 4-tire vehicles.

[d]Prior to 1984, excludes most rural and smaller systems funded via Sections 18 and 16(b)(2), Urban Mass Transportation Act of 1964, as amended. Also prior to 1984, includes total vehicles owned and leased.

[e]Other includes aerial tramway, automated guideway transit, cablecar, ferry boat, inclined plane, monorail, and vanpool.

[f]Nonself-propelled vessels include dry-cargo barges, tank barges, and railroad-car floats.

[g]Self-propelled vessels include dry-cargo and/or passenger, offshore supply vessels, railroad-car ferries, tankers, and towboats.

[h]Beginning in 2006, vessels are reported if they are greater than 10,000 deadweight tons and prior to 2006 boats of greater than 1000 deadweight tons were reported.

[i]Recreational vessels that are required to be numbered in accordance with Chapter 123 of Title 46 U.S.C.

Source: BTS 2009, Table 1-11.

Technology and Fuel Pathways

Hydrocarbon fuels (gasoline, diesel fuel, and their potential substitutes) have a complex web of production and transport processes that include resource extraction, transport, refining storage, transfers, and combustion. So to understand externalities one has to develop a map of the life-cycle of fuel. Different populations are impacted at different stages of the life cycle. Despite the complexity, there are a few components of the fuel life-cycle that tend to dominate with respect to overall health and environmental damage associated with the full life-cycle of a transportation fuel. Figure 3-6 illustrates how we conceive the different stages of the fuel life cycle in several key phases: extraction and transport of petroleum feedstock; production and transport of refined product; transport, retail storage, and distribution; fuel use; and waste generation and management in order to carry out a life-cycle impact assessment. The potential effects of each of these phases are described briefly below.

In general, each phase of the cycle can contribute to deleterious effects stemming from components of the hydrocarbon mixture itself; activities and materials associated with a particular phase in the fuel cycle (e.g. road development for oil production); and generated wastes or by-products that pollute air, water, and soil, or that contribute to climate change effects.

This section describes pollutant releases and other stressors that can lead to effects described above. It does not attempt to quantify effects and does not attempt to assess the efficacy of the various approaches used to manage risks of those effects.

Each phase of the petroleum cycle involves the use of electricity. Because Chapter 2 discusses life cycle effects associated with electricity production, they are not included here.

Extraction of Crude Oil

Conventional Oil Reserve. The major oil producing areas in the United States are in the Gulf of Mexico region (onshore and offshore), California, and Alaska. As of 2007, there were about 500,000 active oil wells in the United States (onshore and offshore) *(*EIA 2008a, p. 127, Table 5.2). Much of U.S. extraction activities take place near sensitive coastal and estuarine habits.
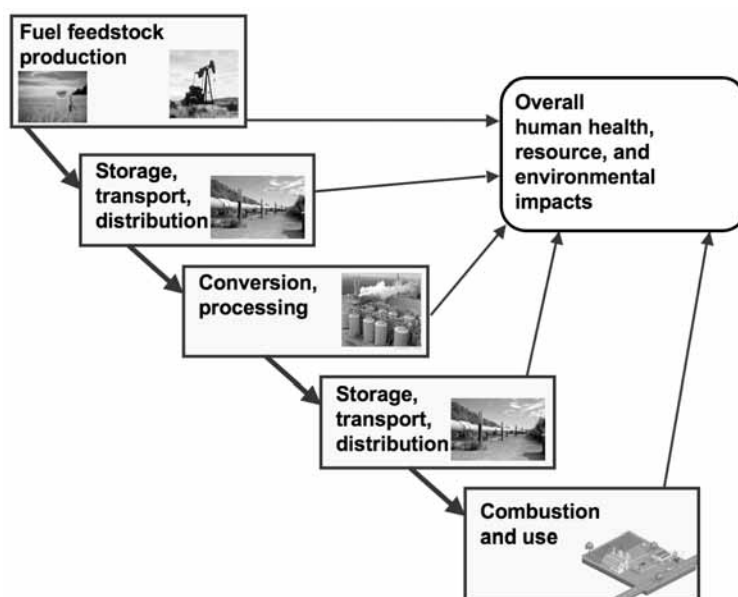
FIGURE 3-6 Conceptual stages of fuel life cycle. Source: Adapted from Energy Biosciences Institute, University of California.

When a potential oil reservoir is discovered, exploratory drilling is conducted to confirm the presence of oil. For on-shore drilling, the land is cleared and leveled to construct a drill platform and install ancillary equipment. Depending on the location, roads, air strips, and buildings may also be constructed. Offshore, floating barges, semi-submersible vessels, or specially designed floating oil rigs are used to support exploratory drilling (API 2009). Inland water and wetland drilling and transportation can have significant effects on wetlands and estuarine habitats, requiring additional techniques to reduce disruption of those ecologic habitats.

Land is also excavated to form a reserve pit where wastes from drilling are placed. When drilling wastes are disposed from offshore operations, a rapid build-up of a debris layer onto the ocean floor can degrade benthic communities. Drilling wastes may contain trace amounts of mercury, cadmium, arsenic and hydrocarbons.

Drilling operations also produce combustion-related emissions, such as exhaust from diesel engines and turbines that power the drilling equipment. Additionally, hydrogen sulfide may be released.

When the presence of oil is confirmed, oil wells are constructed to extract the crude oil. Initially oil may rise by "natural lift". Over time, mechanical pumps or injection methods, using steam for example, are needed to bring the oil to the surface. Storage tanks, pipelines, and processing plants are also built.

The crude oil is prepared for shipment to storage facilities and then to offsite refineries. Natural gas can be separated from the oil at the well site and processed for sale, or the gas can be flared as a waste (usually at onshore operations) releasing carbon monoxide, nitrogen oxides, and possible sulfur dioxide if the gas is sour. Triethylene glycol is commonly used as a desiccant to remove water from the gas.

Waste water generated at the production facility may contain organic compounds (e.g., benzene and naphthalene), inorganics (e.g., lead and arsenic) and radionuclides.

Volatile organic compounds (VOCs) may be emitted via leaks from the production process equipment. Emissions also occur from combustion of fuel to operate machinery.

Oil spills may come from storage tanks, during transfers, or from pipes, valves, joints, or gauges. For onshore spills, concern is for surface water contamination via runoff and for seepage into groundwater. Effects of offshore spills can vary substantially depending on factors such as coastal proximity and degree of turbulence.

Accidents known as well blowouts can result in large releases of contaminated water, oil, methane or other fluids. The mixture can be spread in a wide area around the rig possibly leaching through the soil to a fresh water aquifer or running off into nearby surface waters. The blowout may also result in a well fire.

Nonconventional Oil Reserve: Oil Sands. Oil sands (also called tar sands or bituminous sands) contain a viscous oil referred to as bitumen that serves as a nonconventional source of synthetic crude oil. Oil sands can be extracted by surface mining using methods similar to those used for coal. The sands are transported to an extraction plant, where bitumen is separated from the sands using hot water and agitation. Once separated, the bitumen is upgraded to synthetic crude oil, which can then be refined into fuels. Approximately 2 tons of tars sands generates 1 barrel of synthetic crude oil In situ extraction is generally used for deep oil sand deposits. Heat is applied underground, and bitumen is pumped to the surface for subsequent refining.

Currently there is no production of synthetic crude oil from tar sands in the United States. The largest commercial oils sands industry is located in Alberta, Canada. Oil sands currently contribute more than 40% of total crude oil production in Canada. Approximately 20% of crude oil imported into the United States is from Canada.

Impacts of oil sand extraction and processing generally arise from degradation of ecologic habitats, water and consumption, and waste (tailings) disposal. Canada's National Energy Board reports surface and in situ mining operations require 2-4.5 barrels of water to produce 1 barrel of synthetic crude oil (NEB 2006). Tar sand extraction and upgrading also requires high-level of energy input. Natural gas is used to heat steam and generate electricity required for in situ recovery, as well as for bitumen upgrading.

The government of Alberta reports that oil sand production is responsible for 5% of Canada's GHG emissions (Alberta 2008).

Nonconventional Oil Reserve: Oil Shale. Oil shale is a sedimentary rock that contains kerogen, a solid bituminous material that can be processed to create synthetic crude oil. The United States contains the world's largest deposit of oil shale. The Green River Formation of Colorado, Utah, and Wyoming contains an estimated 800 billion barrels of recoverable oil (BLM 2008). Although technological methods exist to extract crude oil from oil shale, commercial extraction and processing is not economically or environmentally viable in the United States.

Potential impacts from oil shale extraction arise from changes in land use, habitat disturbance, mining waste production, water consumption, and energy consumption. Oil shale development is expected to consume between 2 and 5 barrels of water per barrel of oil produced (Bartis et al 2005).

From among this wide range of potential impacts at different stages of resource extraction, the Committee was constrained—by the limitations of the GREET model and the scarcity of available national databases on many ecosystem and other impacts—to quantify only those impacts which result directly or indirectly from energy use and the air quality emissions produced during these operations

Refining Crude Oil. Refineries separate conventional and synthetic crude oil into different petroleum products that can be used as fuels, lubricants, chemical feedstocks, and other oil-based products. Fuels make up the vast majority of the output (see Figure 3-5). Pollutants generated during crude oil refining typically include VOCs, carbon monoxide (CO), sulfur oxides (SO$_x$), nitrogen oxides (NO$_x$), particulates, ammonia (NH$_3$), hydrogen sulfide (H$_2$S), metals, spent acids, and numerous toxic organic compounds. Emissions occur throughout refineries and arise from the thousands of potential sources such as valves, pumps, tanks, pressure relief valves, flanges. Emissions also originate from the loading and unloading of materials (such as VOCs released during charging of tanks and loading of barges), as well as from wastewater-treatment processes (such as aeration and holding ponds).

Relatively large volumes of wastewater are generated by the petroleum refining industry, including contaminated surface water runoff and process water. Accidental releases of liquid hydrocarbons have the potential to contaminate large volumes of ground water and surface water possibly posing a substantial risk to human health and the environment.

Storage tanks are used throughout the refining process to store crude oil, intermediate products, finished products, and other materials. The tanks are a considerable source of VOC emissions. Hazardous and non-hazardous wastes are generated from many of the refining processes, petroleum handling operations, as well as wastewater treatment.

Transport and Distribution of Crude Oil and Refined Products. Oil imported to the United States from outside of North America is transported predominantly by ocean tanker. Imports from Canada flow through several pipelines that connect with U.S. pipeline infrastructure in Illinois, Oklahoma, Wyoming, and Washington (EIA – Canada). Crude oil is transported from production operations to refineries by tankers, barges, rail tank cars, tank trucks, and pipelines. Refined petroleum products are conveyed to fuel marketing terminals and petrochemical industries by these same modes. From the fuel marketing terminals, the fuels are delivered by tank trucks to service stations, other commercial facilities, and local bulk storage plants. The final destination for gasoline is usually a motor vehicle gasoline tank.

The United States has an extensive oil pipeline network used to transport oil from wells and ocean tankers to refineries. There are about 30,000-40,000 gathering pipelines and 55,0000 trunk pipelines to transport oil in the United States (API/AOPL 2007). Pipelines also carry refined petroleum products from oil refineries to bulk terminal storage sites. There is an estimated 95,000 miles of pipelines carrying refined petroleum products (API/AOPL 2007). Airports often have dedicated pipelines to carry fuel directly to them (API/AOPL 2007).

Transport and distribution of oil is a source of air pollution. Each of the transport and distribution activities is a potential source of evaporation loss. Transport of crude oil and refined petroleum products

also present risks of oil leaks, spills, and large scale accidents (i.e. 1989 Exxon Valdez oil spill). Environmental releases of crude oil or refined petroleum products can pollute terrestrial and aquatic habitats as well as drinking water. The NRC report *Oil in the Sea III: Inputs, Fates, and Effects* (NRC 2003c) assessed data gathered between 1990 and 1999 and estimated that 9,100 tons of petroleum are released in North American waters as a result of transportation of crude oil and refined products. Pipeline leaks and other accidents related to petroleum fuel are discussed in Chapter 6.

Distribution and Storage of Refined Product. Crude oil and refined petroleum products are stored in large volumes throughout the fuel cycle. In 2008, more than 338 million barrels of crude oil and refined products were held in storage at refineries. Bulk terminal storage facilities held more than 320 million barrels of refined petroleum products, including distillate fuel oils (i.e. diesel fuel), gasoline, and aviation fuels. Finished gasoline and diesel fuel are also stored in underground storage tanks (USTs) at gasoline stations. EPA regulates more than 623,000 USTs at approximately 235,000 locations (EPA 2009g).

The primary concern surrounding storage tanks is the potential for leaks, spills, and explosions. Similar to pipelines, crude oil and refined petroleum products leaking from storage tanks can accumulate into soils and seep into surface and ground water, contaminating terrestrial and aquatic habitats as well as drinking water resources. Since 1988, there have been about 479,800 confirmed releases from USTs and about 377,000 completed clean-ups (EPA 2008b). Storage tanks are also a source of evaporative emissions.

Use of Fuel for Light-Duty and Heavy-Duty Transportation. The category of on-road or highway mobile sources includes vehicles used on roads for transportation of passengers or freight. On-road vehicles are further divided in categories such as light-duty vehicles, light-duty trucks, heavy-duty vehicles, and motorcycles. The vehicles may be fueled with gasoline, diesel fuel, or alternative fuels such as alcohol or natural gas. Nonroad sources include vehicles, aircraft, marine vessels, and locomotives, and other vehicles and equipment used for construction, agriculture, and recreation.

Cars, trucks, and buses consumed about 80% of the transportation energy used in the United States in 2005. Portions used by other transport modes are air (9%), water (5.3%), pipeline (3%), and rail (2.4%).

The AEF report on energy efficiency indicates that incremental improvements in vehicle technology could reduce the fuel consumption of gasoline internal-combustion engine vehicles by up to 35% over the next 25 years. Diesel-fueled trucks are expected to continue dominating the freight transportation sector for at least the next 25 years. The report estimates 10-20% reductions in fuel use by heavy-duty and medium-duty vehicles by 2020, resulting mostly from technological and design improvements. Advances in jet engine and aircraft technology have the potential to improve the efficiency of new aircraft (for passenger and freight) by up to 35% over the next two decades. The AEF report indicates that it is feasible to reduce energy consumption in marine shipping by 20-30% by 2020, through a combination of technology innovations (e.g., improved hull design) and systems improvements (e.g., speed reduction). Technology improvements could reduce carbon dioxide emissions by 5% to 30% in new vessels and 4% to 20% in existing ones.

Combustion of petroleum-based fuels by motor vehicles results in exhaust emissions which include VOCs, nitrogen oxides, particulate matter, carbon monoxide, and carbon dioxide. Evaporative emissions from the on-board reservoir of unburned fuel can occur while the vehicle is in use or when the engine is turned off.

Vehicle emissions include a class of pollutants referred to as air toxics. These include known carcinogens, such as benzene, and probable human carcinogens, such as formaldehyde or diesel particulate matter. EPA estimates that mobile sources of air toxics account for about half of all cancers attributed to outdoor sources of air toxics. Some toxic compounds occur naturally in petroleum and become more concentrated when petroleum is refined. Others are not present in fuel but are formed as by-products in the vehicle exhaust or formed from reactions of vehicle emissions in the atmosphere.

Lead emissions occur from piston-engine aircraft that use a commonly available aviation gas 100LL (one hundred octane low lead). Lead is added to 100LL in the form of tetraethyl lead to improve engine performance. Lead is not added to jet fuel that is used in commercial aircraft, military aircraft, or other turbine-engine powered aircraft (EPA 2008c).

Modeled Estimates of Life-cycle Emissions, and Damages from Petroleum Use in Light-Duty and Heavy-Duty Highway Transportation

The Committee selected VMT as the primary unit for characterizing external damages for highway transportation. Rather than a gallon of fuel, which is difficult to compare because of large variations in energy content, or a joule of delivered energy, which depends strongly on vehicle efficiency, the VMT best characterizes the type of service associated with transportation vehicles. The use of VMT as the functional-unit for comparison makes it possible to address the life-cycle impacts of fuel-vehicle combinations, which was a key goal for comparing current and future damages for transportation options. There is also the option of using person-VMT, but this requires assumptions about vehicle passenger loads the confuse the goal.

Modeling damages from the life-cycle emissions attributable to petroleum requires characterization of emissions factors for both the life-cycle of the fuel and the production and operation of the vehicle. Both greenhouse-gas emissions expressed as CO_2-equivalent and local-air pollution emissions are included. For air pollution emissions, not only the magnitude of the emissions (per VMT) but also the geographic distribution of the emissions is important. The committee modeled the monetized damages associated with pollutant emissions using the APEEP model. For greenhouse gas emissions, for which damages do not depend on the geographic location of release, only the life-cycle CO_2-equivalent emissions for the petroleum/vehicle life cycle are reported. Damages for CO_2-equivalent emissions are discussed in Chapter 5.

Emissions Characterization. Emissions characterization included life-cycle emissions for light-duty gasoline- and diesel-fueled vehicles and for heavy-duty diesel vehicles for 2005 and 2030 fuel/vehicle combinations. Life-cycle emissions for gasoline- and diesel-fueled light-duty vehicles are obtained primarily from GREET (Argonne National Laboratory 2009) and include emissions of greenhouse gases, VOCs, NO_x, SO_x direct $PM_{2.5}$, secondarily-formed $PM_{2.5}$ (from VOCs, NO_x, and SO_x emissions) and secondarily-formed ozone (from VOC and NO_x emissions). The committee carried out its own analysis to obtain (a) life-cycle NH3 emissions related to PM2.5 formation for both 2005 and 2030, (b) emissions from gasoline- and diesel-fueled heavy-duty vehicles in both 2005 and 2030 (which are not covered in GREET), and (c) estimated emissions for those substances covered in GREET for the year 2030 based on using the most current 2020 data in GREET, further updated to incorporate the expect 35.5 mpg required fuel efficiency after 2016 (see discussion in Scope of the Analysis above and in Appendix D on how this was accomplished). For each pollutant/vehicle mix, emissions per VMT include emissions from (a) feedstock production, (b) fuel production, (c) vehicle operation and (d) vehicle production (except heavy-duty vehicles). To assess health and other monetized damages, emissions for vehicle operation are allocated to U.S. counties based on the estimated fraction of aggregate U.S. VMT that occur within that county. Emissions for other stages are allocated to regions based on the geographic distribution of the economic activity associated with each specific life stage, for example the distribution for refineries.

Results. Table 3-3 contains a summary of the results from the GREET/APEEP modeling effort related to gasoline and diesel fuels in light-duty autos. Calculations were also carried out for light-duty trucks, but these did not very significantly from the results for light-duty autos. Each row of Table 3-3 contains the range and population adjusted mean for health damages in 2005 and 2030, reported on a VMT basis. There is also a column showing the health costs per gasoline gallon equivalents (gge). It can

TABLE 3-3 Health and Other Non-GHG Damages from a Series of Gasoline and Diesel Fuels Used in Light-Duty Autos[a]

	2005			2030	
	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)	Population Adjusted Mean (Cents/gge)[c]	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)
Conventional Gasoline (SI, petroleum)	0.34-5.07	*1.34*	29.02	0.43-4.87	*1.35*
Conventional Gasoline (SI, tar sands)	0.35-5.36	*1.35*	29.26	0.45-4.99	*1.36*
Reformulated Gasoline (SI, petroleum)	0.35-5.12	*1.38*	29.83	0.45-4.87	*1.35*
Reformulated Gasoline (SI, tar sands)	0.35-5.40	*1.39*	30.07	0.45-4.99	*1.36*
Reformulated Gasoline (SIDI, petroleum)	0.33-4.89	*1.32*	32.68	0.45-4.96	*1.37*
Reformulated Gasoline (SIDI, tar sands)	0.33-5.14	*1.33*	32.92	0.45-5.09	*1.38*
CIDI using Low-sulfur Diesel	0.30-7.57	*1.49*	38.65	0.40-4.22	*1.19*
CIDI using Fischer Tropsch Diesel	0.41-7.77	*1.80*	46.65	0.58-5.48	*1.61*

[a]Costs are in 2007 USD.
[b]From the distribution of results for all counties in the 48 contiguous states in the United States.
[c]Cents/gallon of gasoline equivalent, calculated by multiplying average miles per gallon by per VMT damages. This will therefore show highest damages for the most fuel efficient vehicles. Costs are in 2007 USD.
Abbreviations: VMT = vehicle mile traveled; gge = gasoline gallon equivalent; SI = spark ignition; SIDI = spark ignition, direct injection; CIDI = compression ignition, direct injection.

be seen from this table that year 2005 health impacts do not vary significantly among the various fuel/vehicle technology options. Only compression ignition direct injection using Fischer-Tropsch diesel shows a significant difference from other options, largely due to the more-intense energy use needed to process that type of fuel. Although there would be an expected increase of damages from 2005 to 2030 due to population growth, that is largely offset in these analyses by the substantial increase in fuel economy to 35.5 mpg by 2016.

Table 3-4 provides a summary of the modeling results from the GREET/APEEP modeling effort related to gasoline and diesel fuels in heavy-duty vehicles. Each row of Table 3-4 lists the range and population adjusted mean for health and other non-GHG damages in 2005 and 2030, reported on a VMT basis. As for light-duty vehicles, there is also a column showing the health and other non-GHG damages per gge. Here we see that, within the heavy-duty class, larger vehicles have a greater impact per VMT, as is expected. We also see a significant decrease in impacts from 2005 to 2030 in spite of rising populations. This is attributable to lower PM and SO_2 emissions from heavy-duty vehicles in 2030 relative to 2005. Negative cost estimates represent conditions for which NO_x emissions from vehicles would contribute to a decrease in ambient ozone concentration, when PM emissions are limited. For the pollutants considered and for these few cases, the negative results reflect benefits within this analytic framework.

Table 3-5 shows how emissions of CO_2-equivalent vary among the different fuel types and between the years 2005 and 2030 on a VMT basis. Although there is a significant difference between CO_2-equivalent emissions from light-duty and heavy- duty vehicles (as illustrated later in this chapter, there is not a significant difference among light-duty vehicles in the CO_2-equivalent emissions, with the exception that the vehicles fueled with petroleum derived from oil shale had notably higher life-cycle emissions.

TABLE 3-4 Health and Other Damages Not Related to Climate Change from a Series of Gasoline and Diesel Fuels Used in Heavy-Duty Vehicles (cents/VMT)[a]

	2005			2030	
	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)	Population Adjusted Mean (Cents/gge)	5th and 95th Percentile Range (Cents/VMT)	Population Adjusted Mean (Cents/VMT)
HDGV2B Heavy-duty gasoline vehicles class 2B	1.01-31.89	*6.14*	61.39	0.36-11.43	*1.87*
HDGV3 Heavy-duty gasoline vehicles class 3	1.15-38.82	*7.23*	66.47	0.41-13.86	*2.41*
HDDV2B Heavy-duty diesel vehicles class 2B	0.46-18.79	*3.23*	41.34	0.24-8.63	*1.23*
HDDV3 Heavy-duty diesel vehicles class 3	0.51-20.76	*3.58*	41.50	0.27-9.87	*1.39*
HDDV4 Heavy-duty diesel vehicles class 4	0.20-22.83	*3.90*	39.40	0.29-10.26	*1.53*
HDDV5 Heavy-duty diesel vehicles class 5	0.68-31.87	*5.29*	51.87	0.33-13.47	*1.76*
HDDV6 Heavy-duty diesel vehicles class 6	0.88-38.38	*6.49*	56.48	0.38-15.92	*1.97*
HDDV7 Heavy-duty diesel vehicles class 7	1.08-47.53	*8.01*	60.08	0.45-15.92	*2.39*
HDDV8A Heavy-duty diesel vehicles class 8A	-0.50-56.61	*9.47*	61.52	0.47-16.77	*2.53*
HDDV8B Heavy-duty diesel vehicles class 8B	-2.20-62.65	*10.41*	64.53	0.49-16.94	*2.63*

[a]Costs are in 2007 USD.
[b]From the distribution of results for all counties in the 48 contiguous states in the United States.

TABLE 3-5 Carbon Dioxide Equivalent (CO_2-eq) Emissions of Greenhouse Gases from a Series of Gasoline and Diesel Fuels

Fuel/Vehicle Combination	CO_2-eq 2005 g/VMT	CO_2-eq 2030 g/VMT
RFG SI Autos (Convent. Oil)	552	365
RFG SI Autos (Tar Sands)	599	399
CG SI Autos (Convent. Oil)	564	365
CG SI Autos (Tar Sands)	611	399
RFG SIDI Autos (Convent. Oil)	487	366
RFG SIDI Autos (Tar Sands)	527	399
Diesel (Low Sulfur)	476	372
Diesel (Fischer Tropsch)	537	401

Note: 2030 estimates assume 35.5 mpg for all light-duty vehicles. Costs are in 2007 USD.

GHG emissions. Moreover, there is also not a significant reduction in CO_2-equivalent releases per VMT between 2005 and 2030.

PRODUCTION AND USE OF BIOFUELS

History and Current Status

It has been long known that alcohols, which are produced from the fermentation of sugars, can be used as a fuel in internal combustion engines. Serious and recent interest in the production of biofuels for transportation was spurred by the oil embargo and petroleum supply disruptions that occurred in the 1970s. This interest in producing biofuels from biomass was of interest because biomass could be grown domestically and serve as a possible substitution for petroleum. Also, if the crops growing the biomass feedstock were managed properly, it could serve as a renewable fuel, that is, each year, or on some appropriate crops rotation bases, fuels could be continually produced. In recent years, the potential benefit of biofuels to reduce the amount of greenhouse gases per unit energy content of fuel compared to petroleum and other fossil-fuel-based sources of transportation fuels has become another important factor in developing production and vehicle technologies for the use of biofuels.

Ethanol produced from corn is currently the largest and most economically viable biofuel being produced in the United States (biodiesel from soy is the second largest). Ethanol's production has grown over the years stimulated by federal subsidies and has risen to a level of about 8 billion gallons per year in 2008. Corn is the primary feedstock in the United States and is converted to EtOH through either dry milling or wet milling production processes (NRC 2008c). One bushel of corn produces about 2.8 gal of EtOH. In Brazil sugar cane is the primary crop used and an extensive EtOH industry has evolved, producing about 4½ billion gal per year to fuel vehicles that can use mixtures of gasoline and EtOH.

Regulations and Technologies Current and Anticipated in 2030

The Energy Independence and Security Act (EISA) of 2007 stipulates that 36 billion gal/yr of biofuels should be produced and used by 2022, with 21 billion gal/yr produced from cellulose-based technologies beyond an expected corn-based ethanol target for 2015 of 15 billion gal/yr. Both the legislation and energy analysts see cellulosic-based biofuels as the most important long-term feedstock for producing EtOH, with the underlying assumption that in the long term, breakthroughs and bio-engineering of organisms might lead to processes that convert cellulose through more advanced production technologies to produce other fuels such as gasoline, biobutanol, or possibly hydrogen.) Whether these targets stipulated in EISA will be realized depend on how quickly the technology for production of biofuels evolves, the cost of such fuels, federal policies, and the economics of the fuel market.

Biofuel Supply. The "Liquid Transportation Fuels from Coal and Biomass" (NAS/NAE/NRC 2009c) report from America's Energy Future (AEF) Panel on Alternative Transportation Fuels provides summaries of the likely technologies and growth in the use of coal and biomass liquid transportation fuels until 2020. They identify the primary technologies for converting cellulosic feedstocks (biochemical and thermochemical), discussing many of the technological challenges associated with each.

Table 3-6 lists the main feedstocks that the AEF panel discussed, the timeframe in which these feedstocks are expected to be technologically and economically viable, the region of the United States in which they are most likely to be of significant magnitude and a qualitative list of the externalities that may be associated with the production of this feedstock.

Of the feedstocks identified in Table 3-6, only corn grain ethanol is in production at a scale that can be viewed as currently significant and with a technology that is mature. Thus, the technologies that

will ultimately develop, market location and the associated set and magnitude of externalities associated with the other feedstocks can only be reasonably speculated on. Overall, the recently completed analysis of the prospects for these sources by the America's Energy Future Committee on liquid transportation fuels estimated that approximately 420 million tons of a variety of such fuels could be produced using technologies available today, and 550 million tons could be produced using technologies expected by 2020 (NAS/NAE/NRC 2009c, Table S-1). It is difficult to accurately project what that will mean in terms of actual fuel produced; indeed, the rapidity with which the corn ethanol market has grown and the volatility of prices means that neither the technology nor the set of externalities generated by its presence are particularly well understood or appraised.

Given the uncertainties associated with these feedstocks, we have identified three that we believe are among the most likely to be relied upon and for which some data are available from which we can produce educated guesses concerning the likely externalities associated with them. The feedstock we focus on for further analysis include: corn grain, corn stover, and a perennial grass to produce transportation fuels. These feedstocks represent the current technology (corn grain), a likely mid-term technology (corn stover) and a likely long-term, so-called "second generation" technology (perennial grasses).

Another biofuel under consideration and in some use is so-called biodiesel, that is, fuels derived from biomass that can replace diesel fuels for use in diesel engines. Typically, biodiesel refers to fuels produced from crops that contain oils, such as soy beans, which can be converted quite efficiently with well know processes into diesel fuel. NRC (2008c) estimates that because of limitations on soy bean production, only about 1.5 billion gal/yr of soy-based diesel fuel could be produced without significant impacts on the food and agricultural markets. Demand for biodiesel greater than that would probably have to be satisfied with imports. Other investigators are pursuing R&D on the production of biodiesel through the growth of algae in algal farms but there is disagreement on how far from commercial readiness this technology might be. Its potential role probably lies in the 2020-2035 time frame and beyond.

TABLE 3-6 Feedstocks Identified in AEF Report and Partial List of Their Externalities

Feedstock	Timeframe	Likely Location	Potential Externalities
Corn, grain	Current	Cornbelt	Water quality (nutrients, sediment, pesticides), wildlife habitat, GHG
Corn stover	[a]	Cornbelt	Soil erosion and water quality, carbon sequestration in soils, GHG
Traditional hay crops (alfalfa and clover)	[a]	Pacific Northwest, Great Plains	Wildlife habitat

Perennial grasses
  Switchgrass
  Miscanthus
  Diverse mixes
	[a]	Existing CRP land (spread throughout the U.S.), marginal lands, existing crop land	Water quantity, Water quality (nutrients, sediment, pesticides), wildlife habitat, GHG

Woody biomass (hybrid polar and willow, forest industry residues, fuel treatment residues, forest product residues, and urban wood residues)	[a]	[a]	Forest fires
Animal manure	[a]	[a]	Water quality (positive externality if diverted from excess agricultural application or storage spills)
Waste paper and paperboard	[a]	[a]	
Municipal solid wastes	[a]	[a]	

[a]An analysis of the potential for these fuels can be found in the Liquid Transportation Fuels Report of the America's Energy Future committee (NAS/NAE/NRC 2009c).

Fuel Cycle and Externalities

The upstream production externalities of feedstock effects will be quite location specific as different feedstocks will be economically viable in different locations (e.g., corn stover and switchgrass in the corn belt, miscanthus in warmer climates, and trees and forestry in the southeast). In addition, the externalities associated with any given feedstock are also likely to vary by specific field/watershed within a region (such as depending on climate, land use history, soils, slope of the land, and proximity to water bodies) and can be attenuated by farming practices (such as the use of conservation tillage, nutrient management of both fertilizer and manure applications, and placement of buffers or wetlands).

Finally, transportation of feedstocks to processing facilities is expected to remain expensive, even after technological improvements so that numerous, small processing facilities located throughout the landscape is a likely configuration of the industry. This means that externalities associated with production and transportation of the feedstock and liquid fuels will be both site specific and widespread (the AEF reports that "hundreds of conversion plants, and associated fuel transportation and delivery infrastructure" (NAS/NAE/NRC 2009c, p. 5) will be needed. Note that the AEF report also calls for watershed specific studies to address the suite of externalities and technology challenges associated with alternative feedstocks.

In characterizing the externalities associated with liquid transportation fuels from biomass, we need to consider the externalities generated at each of the following stages:

1. Production of the feedstock (farm or forest externalities),
2. Transportation of the feedstock to the processing facility,
3. Processing of the feedstock into liquid fuels,
4. Transportation of the fuel to distribution endpoints, and
5. Downstream effects of using the fuel.

There may be different external effects and different magnitudes of those externalities along each of these steps associated with each type of feedstock. A complete externality accounting would need to include those occurring at each step. The externalities listed in Table 3-6 are those associated primarily with the first step, the production of the feedstock.

The technology associated with transforming alternative feedstocks into fuel is developing for the cellulosic feedstocks and include biochemical and thermochemical conversion processes. In both cases, a large quantity of water is required for processing which, in water constrained areas, will likely constitute an externality (measured in terms of increased water scarcity via quicker drawdown of reservoirs and increased pumping costs). Water and air emissions are likely to be externalities as well.

The Sources of Externalities in Production of Feedstocks. The three feedstocks we target for analysis all require land for their growth and production. Eventually, all three feedstocks as well as a mixture of others may be used to produce biofuels and may compete with each other for land and profitability or may be located in quite different regions of the country. Briefly the externalities we investigate and the way in which feedstock can generate the externality are described next.

Greenhouse Gas Emissions. The production and harvesting of corn generates greenhouse gas emissions in a number of ways including the use of fuel for tillage, planting, applying inputs (nutrients, pesticides), harvesting, and shipping of the product. By tilling the soil in preparation for planting, carbon that is stored in soil is released into the atmosphere. Farmers that practice conservation tillage (one of many forms of reduced or no tillage) generally increase the carbon stored in the soil (carbon is sequestered), but this tillage practice is not profitable for all farmers and depends on the characteristics of the land, climate, and crop grown. Currently, regardless of tillage practice, corn stover is left to decompose and rebuild carbon and other nutrients in the soil.

If corn stover were to be used for ethanol production, it would be removed from the soil and therefore not left to decompose and rebuild the soil. Agronomists and others debate about how much stover can be removed to maintain soil productivity, but there is no reason to believe that soil carbon storage does not decline immediately as stover is removed (although the magnitude could be quite small). Thus, on any given field, biofuel production using corn stover can be expected to have the same greenhouse gas emission consequences associated with planting and harvesting corn as just described, with additional losses of carbon sequestration. There may be additional fuel usage needs for the stover to be harvested and almost certainly there will be high fuel needs for the transportation of stover from the field to the processing facility.

Switchgrass or other perennial grass will not need annual planting or tilling, once established. Hence, should have lower fuel usage and corresponding GHG emissions than corn production. The degree to which switchgrass or other perennial will be fertilized is unclear. Large scale commercial production of switchgrass is not currently viable so the amount of inputs that farmers will use to maximize their profitability of growing this crop is unclear. Heggenstaller et al. (2009) provides estimates of fertilization that maximizes profitability.

A number of studies have looked at the life cycle emissions of greenhouse gases associated with ethanol produced from various feedstocks. Delucchi (2006) provides such an analysis and a review of earlier analyses. Estimates by NAS/NAE/NRC (2009c) of well-to-wheels CO_2-equivalent emissions in tonnes per bbl gasoline equivalent[7] are the following: for petroleum-based gasoline, 0.40; for corn EtOH, 0.22; for biochemical cellulosic EtOH, -0.02; for thermo-chemical coal/biomass conversion, 0.5, and with CCS, -0.19; and for thermo-chemical biomass conversion, -0.12, and with CCS, -0.95. Thus, there could be significant greenhouse gas benefits for biomass fuels as well as a reduced dependence on imports although the projections by NAS/NAE/NRC (2009c) indicated that biofuels could replace only a proportion of what is consumed in the transportation sector. The impacts on reducing CO_2 emissions could be significant, especially if CCS technology is developed in the period between now and 2020, becomes ready for commercial deployment, and can be coupled to some of the technologies, such as gasification-based systems.

Additionally, the GREET model provides estimates of these. We use estimates from GREET to generate estimates of the GHG emissions from alternative feedstocks.

Water Quality and Soil Erosion. Corn is a heavily fertilized crop with large water demands. The major water quality issues related to corn production include the runoff of nitrogen, phosphorous, and sediment. The amount of nutrients and sediment that leave a field can vary greatly depending on the slope of the land, the climate (particularly heavy rains), whether the field is tiled, the cropping history, the soil type, the tillage practice, and a variety of other factors. Thus to undertake a careful analysis of the water quality consequences of corn production, one must know where the additional corn that would be used for feedstocks would be produced as well as how the field is managed, whether any conservation practices are in place, etc. To further complicate the issue, the amount of pollutant that enters a waterway and how far it moves within a waterway depend on a variety of geologic and hydrologic factors.

Additional corn to produce biofuels can come from producing more corn on land that is already in corn production. This can occur by the use of more inputs or by changing rotation practices, for example by moving from a 2 year corn-soybean rotation to the continuous planting of corn. While continuous corn has lower yields than rotated corn, if price differentials are high enough, it will be profitable for farmers to grow corn more often in their rotations. The second way that additional corn can be produced is to grow it on land that was previously not in agricultural production or that was used for a lower valued crop. A major potential source of such land is land that has been placed in the Conservation Reserve Program (CRP), a federal program that pays farmers to idle land. About 5% of agricultural land nationwide is enrolled in the CRP; this land tends to be of lower value and higher environmental

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[7]One tonne is equal to 2,200 pounds.

sensitivity than average. The water quality affects of additional corn production will depend on how the additional corn is generated and where, which in turn will depend on the profitability of corn production for biofuel usage. There is evidence that the higher corn pries experienced in the past two years or so has resulted in increased conversion of CRP to working land (Secchi et al. 2009).

If corn stover is used to produce to biofuels, the same set of water quality externalities just described will apply, but will be magnified for two reasons. First, when stover is left on the land, it acts to reduce soil erosion and helps to retain nutrients on the land (especially phosphorous). Second, when stover can be sold for biofuels, the overall profitability of corn production will rise (since the ears can still be sold for biofuels or feed) thus making corn a more profitable plant and therefore increased production is likely.

The water quality effects associated with perennial grasses will also depend on the location in which they are grown, but their perennial nature and likely lower input use (though again without evidence of how these crops will be commercially grown, this is difficult to gauge) should translate into lower water quality impacts than corn production.

Wildlife Habitat and Biodiversity. The effect on wildlife and biodiversity from using more land for corn or perennial grass production will depend on how the land was used prior to production (i.e., whether it was planted to a different row crop, left idle in CRP, or used as pasture, etc.). Perennial grasses are likely to be suitable habitat for more wildlife than corn, but it may be less suitable than the land use prior to biofuels production.

A number of other externalities related to biofuels production and industry expansion should be noted. First, a significant expansion of the industry will require a major increase in production facilities which will generate externalities associated with the building and maintaining of these facilities. Depending upon the technology used to convert feedstocks to ethanol, there may be solid waste or other pollution externalities associated with the ongoing production of ethanol in these facilities. Also, there are potentially significant concerns related to water consumption for ethanol production. For an extensive discussion of implications across the United States, see the recent National Academies report on water quantity and biofuels production (NRC 2008d).

Indirect Land Use and Externalities

The role of "indirect land use"—changes occurring indirectly as a result of biofuels policy in the United States and the effect of such changes on greenhouse gases—has been a major source of discussion since a paper by Searchinger and colleagues was published in Science in 2008. The argument put forth by Searchinger et al.(2008) is that when demand for corn or farmland in general increases, crop prices increase which makes it profitable for farmers to increase their acreage. If this increased acreage comes from plowing up land that has not been in agricultural production and/or is particularly environmental sensitive (e.g., rainforests in Brazil, pristine ecosystems in the United States), this could actually increase GHG emissions (since burning rainforests would release lots of carbon) and have other detrimental environmental concerns. The loss of Brazillian rainforests due to these market pressures is particularly cogent, but the issue applies to a variety of land use changes as long as the land that is brought into production to grow biofuel feedstocks results in lower carbon storage as a result.

Under the requirements of EISA, EPA recently released their revised Renewable Fuels Standards (RFS2). As mandated, they performed their life-cycle computation of GHG contributions of corn ethanol, two types of biodiesel and three cellulosic ethanol feedstocks (sugarcane, switchgrass, and corn stover) using indirect land use effects as a component of the GHG contribution. In recognition of the uncertainty associated with measuring indirect land use effects, they present their emission estimates both with, and without, the indirect effects. (See EPA 2009h for a summary of EPAs life-cycle analysis). The effect of indirect land uses can be quite large, in some cases their analysis suggests that significant positive gains in

GHG of a fuel relative to gasoline could be largely offset by indirect land use changes. The state of California has also adopted the approach of including indirect land use effects in its fuel standards.

Our task in this report is to identify and monetize the externalities associated with energy production and consumption. The committee discussed whether these externalities should include both the direct land use effects and the indirect effects and have chosen to report only the direct land use effects (as captured in GREET). In doing so, we by no means dismiss the potential importance of indirect land use effects in policy design, but we do not wish to treat externalities associated with the production of biofuels any differently than the externalities associated with the production of other fuels.

Why did we come to this choice? First, there is an important distinction between the externalities associated with the direct use of land to grow crops for biofuels and the externalities associated with the indirect effects. The indirect effects are induced by price changes and are associated with the production of a second product. To avoid double counting, it is important that the externalities associated with the indirect effects be associated with the second production activity, not both be assigned to the first product.

For example, when a crop is planted and grown to produce a gallon of ethanol, there are externalities associated with its production (greenhouse gases, water quality, etc.); these externalities of course are appropriately counted against the production of that gallon of ethanol. These externalities include the direct land use effects. In contrast, the indirect effects occur from a market response due to some price changes: when the price of a biofuel crop increases due to a policy that promotes biofuels, farmers elsewhere will find it profitable to plant those crops, which will then be used to produce a *second* product (perhaps another gallon of biofuels or a food product). This "indirect effect" will generate externalities, but these externalities should be associated with the second product not the first.

In the specific context of the biofuels landuse debate, the lost carbon and ecosystem services from indirect land use changes are appropriately viewed as an externality from growing crops elsewhere, say Brazil, not from production of biofuels in the United States. Or if these indirect land uses occur within the United States, they would already be counted as the direct land use effects of growing biofuels for carbon in that second location. Thus, when estimating the externalities associated with U.S. biofuel production, we would want to include the externalities associated with direct land use change to produce the feedstocks, but not the market induced indirect effects.

The second reason we do not attempt to incorporate indirect land use effects is that if were we to do so, for consistency we would need to include all market induced changes in externalities that could be linked to any other energy source. For example, an increase in the price of electricity generated by an expanded electric vehicle requirement could result in more people using wood burning stoves in lieu of electric heaters, more usage of gas powered lawn mowers, and earlier turning out of lights in the evening. The first two changes would increase the negative externalities of smog, green house gases, and noise, whereas the third would reduce light pollution. The accounting of the "indirect effects" argument would be to add all of these externalities affects on to electric vehicles. And, these are just a few of the externalities that could be induced by price changes.

The fact that there are two separate externalities associated with production at two different locations is not merely an academic distinction; it is critical to keep them separate to avoid double counting and therefore to appropriately inform policy as this second set of externalities may still be policy irrelevant. As an example, were greenhouse gases worldwide subject to a tax, then it would be appropriate to tax agricultural crops in the United States based on their greenhouse gas emissions and separately to tax agricultural crops grown elsewhere based on their emissions. In this case, it would be inefficient to tax U.S. agricultural crops for the sum of their own emissions plus those associated with land use change elsewhere—this would be double counting. Ideally, the U.S. policy would correct the market distortion for the production of externalities for crops grown in the United States and other governments would do the same. On the other hand, if policymakers in the United States wish to set policy recognizing that greenhouse gases are not optimally regulated elsewhere then it may be appropriate to tax or regulate U.S. biofuels crops based on more than just the direct externalities, taking into account some or all of the indirect externalities induced by market prices. In economics parlance, this would be policy design in a second-best setting.

We note, however, that if one is interested in policy design in a second best setting, it will not generally be appropriate to simply sum the damages from the indirect externalities to the direct externalities to form a basis for a tax. For purposes of our report, we do not attempt to explicitly inform decision making in a second best setting despite the fact that many existing distortionary taxes elements are present in the U.S. economy (labor taxes, imperfect competitive sectors, etc.).

Our goal throughout this report is to define and estimate the externalities associated with the production of energy sources. By providing estimates of the direct effects of land use (as reported in GREET) we are providing an estimate of externalities that are consistent with those presented elsewhere. We well recognize the important issue of indirect land uses, but do not evaluate or incorporate them in our analysis.

Land Use Externalities from Biofuels: A Case Study of the Boone River Watershed

Given the relatively recent expansive interest in biofuels, studies that assess the magnitude and value of externalities related to direct land use changes and soil carbon provide incomplete coverage of the issues, particularly at the local landscape level where these effects may vary considerably across locations. A number of studies provide information on components of the externalities related to water quality. For example, Donner and Kucharik (2008), Simpson et al. (2008), and Secchi et al. (2009) examine the consequences of expanded corn production to produce ethanol for the amount of nitrogen and phosphorous entering the Gulf of Mexico, and therefore potentially contributing to the recurrent hypoxic zone there. Other work addresses the consequences of higher corn prices on conservation reserve lands) and concerns have been expressed about the loss of habitat and local water quality. There is still much unknown however about the set of externalities that a particular region or watershed might be expected to experience with expanded ethanol production.

To demonstrate one approach for estimating some of the externalities that are location-specific, we use an existing set of data and models for the Boone River Watershed in central Iowa to perform a case study. The estimates for the externalities described here relate to water quality (nutrients and sediment). We stress that this exercise is meant to shed light on the process and approach needed to estimate these externalities associated with ethanol production rather than to provide firm estimates. Further, the estimates are unlikely to be transferable to other regions where biofuels may be produced and/or to other feedstocks grown for biofuel production.

To evaluate the water quality and carbon sequestration externalities associated with biofuels production in the Boone, we analyze three possible feedstocks: corn grain, corn stover, and switchgrass. To do so, we use a biophysical model, EPIC, to estimate the nitrogen, phosphorous and erosion changes associated with different agricultural land uses and management at the field scale, then aggregate these to the watershed level. The EPIC model (Williams 1990; 1995; Williams et al., 1984; 1996; 2008) was designed with this purpose in mind; specifically to estimate the impacts of different cropping and management systems on a variety of environmental indicators including soil erosion, nutrient losses, and soil carbon levels. EPIC is a field-scale model that functions on a daily time step and can simulate a wide range of crop rotations, tillage systems, and other management practices. More detailed discussion on modeling analysis is provided in Appendix E.

EPIC Results. Table 3-7 provides estimates of the average amounts of erosion, nitrogen, and phosphorous, and the amount of soil carbon sequestered for the baseline and each of the scenarios run. Recall that carbon sequestration is a positive externality where the nutrients(nitrogen and phosphorous) and sediment are negative externalities. It is also important to recall that EPIC is an "edge-of-field" model in that it predicts the amount of nutrients and sediment that leave each field under each scenario, but this does not necessarily mean that the pollutants will enter the waterways (a fate-and-transport model that incorporate the hydrology of the region would be needed to estimate the waterway loadings). For conciseness and ease of interpretation, several of the environmental indicators generated by EPIC have

been combined. Specifically, the column entitled "Erosion" represents the sum of water and wind erosion predicted by EPIC. Likewise, "Nitrogen" represents the sum of soluble N loss, N leaching and N loss via sediment. While the pathways that the nitrogen leaves the field differs in each of these cases, most of the N losses that ultimately escape the crop fields and drainage ways will enter surface water due to the subsurface tile drains that capture the majority of leached N, so the aggregated N amounts are reasonable representations of the overall system losses. Finally, the numbers indicated in the "Phosphorous" column represent the sum of sediment-bound and soluble phosphorous that is transported in surface runoff.

As expected, the water quality externalities increase relative to the baseline when continuous corn becomes the predominant cropping system. This reflects the fact that corn has high input requirements and is relatively "leaky."

In each of the first three "stover" scenarios, it is assumed that the baseline crop rotation is maintained, but that some or all of the above ground biomass is harvested for biomass to be used in ethanol production. Since the removal of stover (biomass) will generally increase erosion, three different levels of removal are simulated for comparison: 50%, 80% and 100%. As can be seen, model results predict that the average erosion per acre will increase from just under 1/3 ton/acre in the baseline to .45 tons/acre under a 50% removal and well over 1 ton under 100% removal. The changes in nitrogen export are much less dramatic which is expected, but larger for phosphorous. This is expected, given that the majority of nitrogen is transported in the soluble phase while the phosphorous moves mainly with sediment.

Since stover removal could also occur under continuous corn, we evaluate the same three scenarios under the continuous corn rotation. The combination of continuous corn and stover removal at any of the three rates has fairly dramatic effects on the magnitude of both erosion levels and phosphorous loss with nitrogen again having lesser impacts.

The final four scenarios all relate to switchgrass produced as a feedstock. In this case, we evaluate four alternative levels of switchgrass planting in the watershed: 25%, 50%, 75%, and 100% of the acreage converted to the switchgrass production. The substitution of this perennial has notable effects on the erosion rates as well as on nutrient loss.

It is worth reiterating that the edge-of-field sediment loss indicators reported here cannot capture the complex watershed-scale and in-stream sediment movement dynamics that have been reported in previous studies such as Trimble (1999), Simon and Rinaldi et al. (2006), and Schilling et al. (unpublished, 2009). Similar caution is stressed for the edge-of-field nutrient indicators.

TABLE 3-7 Water Quality and Externalities Estimated for Ethanol Scenarios[a]

	Erosion (tons/ acre)[b]	Nitrogen (kg/acre)[c]	Phosphorous (kg/acre)[d]
Baseline	0.31	20.11	0.29
Stover: 50%	0.44	19.62	0.35
Stover: 80%	0.69	21.09	0.48
Stover: 100%	1.23	24.53	0.72
Continuous Corn	0.45	30.68	0.29
CC Stover: 50%	0.78	29.12	0.43
CC Stover: 80%	1.16	30.46	0.61
CC Stover: 100%	1.55	32.19	0.79
Switchgrass: 25%	0.23	26.11	0.24
Switchgrass: 50%	0.16	31.93	0.18
Switchgrass: 75%	0.08	37.93	0.13
Switchgrass: 100%	0.01	43.79	0.08

[a]All values are annual averages.
[b]Erosion reports the sum of wind and water erosion.
[c]Nitrogen reports the sum of N loss with sediment, nitrate loss with runoff and nitrate leached.
[d]Phosphorous reports the sum of the loss with sediment and runoff (Labile P).

Ethanol Production and Monetization. Each of the scenarios presented are associated with different amounts of potential ethanol production. In Table 3-8, we present estimates of the amount of ethanol that the feedstocks grown in the Boone watershed could produce so that the magnitude of the externalities reported can be compared to the fuel production they are associated with. In the first column of the table we provide estimates of the total amount of ethanol that the identified scenario could produce, including the baseline. In each case, the predicted yield of corn grain is assumed to be convertible to ethanol at a rate of 105 gallons/metric ton. The predicted stover removed for biomass in the stover scenarios is assumed to be converted to ethanol at a rate of 100 gallons/metric ton. This is the same rate used for the switchgrass scenarios. These are the same values assumed in the GREET model transportation runs used in the rest of this report and are chosen for internal consistency.

The second column of the table shows the incremental amount of ethanol the scenario is predicted to produce above and beyond the production in the baseline. When the land use is changed to produce additional ethanol, it creates additional externalities. By computing the additional ethanol produced we can compare those incremental externalities (a cost to society) with the incremental ethanol (a gain).

To demonstrate the monetization of land use externalities, we focus on the erosion estimates reported in Table 3-7. We choose to monetize erosion only for several reasons. First, more information about the costs of erosion is available relative to the damages from nitrogen and phosphorous. Further, since phosphorous and sediment tend to move together, it is likely that the estimates of damages from erosion already include some of the costs associated with phosphorous. Likewise, the water quality damages from all three, nitrogen, phosphorous, and erosion/sediment, are likely to be interrelated and if separate values were added together for all three, we would risk double counting.

In a recent report, Hansen and Ribaudo (2008) provide a summary of studies that have valued erosion damages (or benefits from erosion reduction) from agricultural sources for numerous categories. They provide dollar per ton estimates of erosion reductions by 8-digit watershed (The Boone River Watershed represents HUC #07100005) for the following categories: sedimentation in reservoirs, navigation, water-based recreation, irrigation ditches, road drainage, municipal water treatment, flood

TABLE 3-8 Estimated Ethanol Production from Feedstocks in the Boone River Watershed

Scenarios	Potential[a,b] Including Baseline Corn (gals/year)	Potential[c] Increment Over Baseline (gals/year)
Baseline	112	
Stover: 50%	167	55
Stover: 80%	196	85
Stover: 100%	214	103
Continuous Corn	217	105
CC Stover: 50%	325	213
CC Stover: 80%	384	272
CC Stover: 100%	421	309
Switchgrass: 25%	150	39
Switchgrass: 50%	187	75
Switchgrass: 75%	226	115
Switchgrass: 100%	264	152

[a]These values assume that 105gal of ethanol can be produced per dry metric tonne of grain and 100gal/metric tonne of stover or switchgrass (GREET default values). Values in this column report all of the corn in the baseline is used to produce ethanol as well as the addition stover, corn, or switchgrass assumed in the scenario
[b]Multiply the number of ethanol gallons by 0.6575 to convert to gasoline-equivalent gallon (geg). That is the conversion factor used in the GREET model.
[c]Values in this column report the additional ethanol produced by the scenario, above and beyond the baseline. 0.6575.

damages, marine and freshwater fisheries, marine recreational fishing, municipal and industrial water use and steam power plants. Estimates appropriate for the Boone River Watershed indicate that the value of a 1 ton reduction in erosion is $4.43 (2007 USD). Hansen and Ribaudo note that these values omit some potentially important categories of benefits including effects on wetlands, endangered species, coastal recreation and existence values and they suggest that the numbers may best be viewed as a lower bound.

Table 3-9 uses this value to monetize the erosion reductions on a per acre basis, and, in the final column, on a per gallon of ethanol basis. The scenarios that remove stover for ethanol production have fairly high costs when aggregated to the watershed level, particularly when stover removal is combined with continuous corn. However, even in these cases, the costs on a per gallon of ethanol basis are quite small: averaging less than one cent per gallon in all cases except for 100% stover removal. It is worth bearing in mind that these represent the externality costs associated with erosion only and are likely an underestimate. We also note the need for enhanced capabilities for simulation of N_2O and other greenhouse gas (GHG) emissions in EPIC; such capabilities are now being tested and will be included in future releases of EPIC (Izaurralde et al. 2006). Nonetheless, the health effects damages considered elsewhere in this report are significantly greater.

The scenarios that introduce switchgrass into the landscape yield gains in erosion. That is, total erosion is reduced relative to the baseline cropping pattern and therefore the costs are negative, i.e., they are a benefit. While at a watershed level, the value of the benefits appears relatively large, on a per gallon basis these gains are again quite small.

Modeled Estimates of Life-Cycle Emissions, and Damages from Biofuel Use in Light-Duty Highway Transportation

Table 3-10 contains a brief summary of the modeling results from the GREET/APEEP modeling effort related to biofuels. The first row of the table contains the range and population adjusted mean for conventional gasoline vehicles for 2005 and 2030, reported on a VMT basis. The remaining rows contain the same information for the three feedstocks, dry corn, herbaceous crops, and corn stover used in production of E10 and E85, respectively.

TABLE 3-9 Monetized Land-Use Damages of the Boone-River Case Study [a]

	Erosion Loss/Acre	$/Acre	$/Watershed	Damages $/gal Ethanol	Damages $/gge[b]
Stover: 50%	0.13	$0.49	$261,427	$0.005	$0.003
Stover: 80%	0.38	$1.41	$752,857	$0.009	$0.006
Stover: 100%	0.93	$3.43	$1,828,204	$0.018	$0.012
Continuous Corn	0.14	$0.52	$278,084	$0.003	$0.002
CC Stover: 50%	0.47	$1.74	$929,355	$0.004	$0.003
CC Stover: 80%	0.86	$3.17	$1,690,837	$0.006	$0.004
CC Stover: 100%	1.25	$4.61	$2,459,075	$0.008	$0.005
Switchgrass: 25%	-0.08	-$0.28	-$149,076	-$0.004	-$0.003
Switchgrass: 50%	-0.14	-$0.53	-$284,211	-$0.004	-$0.003
Switchgrass: 75%	-0.23	-$0.83	-$444,829	-$0.004	-$0.003
Switchgrass: 100%	-0.30	-$1.09	-$581,777	-$0.004	-$0.003

[a] Erosion monetized at $3.70 (2000 dollars). See Hansen and Ribaudo 2008, Appendix 1.
[b] gge = gallon of gasoline equivalent.

TABLE 3-10 Comparison of Health and Other Non-GHG Damages from Conventional Gasoline to Three Ethanol Feedstocks[a]

	2005			2030	
	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)	Population Adjusted Mean (Cents/gge)[c]	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)
Conventional Gasoline	0.34-5.07	1.34	29.20	0.45-4.87	1.35
E10 (Dry Corn)	0.35-5.26	1.35	29.18	0.44-4.87	1.32
E10 (Herbaceous)	0.33-5.06	1.30	28.09	0.43-4.66	1.30
E10 (Corn Stover)	0.33-5.08	1.30	28.10	0.43-4.71	1.30
E85 (Dry Corn)	0.57-7.31	1.52	32.90	0.56-5.84	1.39
E85 (Herbaceous)	0.40-5.45	1.20	25.89	0.47-4.06	1.22
E85 (Corn Stover)	0.39-5.78	1.21	26.13	0.47-4.63	1.22

[a]Costs are in 2007 USD.
[b]From the distribution of results for all counties in the 48 contiguous states in the United States.
[c]Cents/gallon of gasoline equivalent, calculated by multiplying average miles per gallon by per VMT damages. This will therefore show highest damages for the most fuel efficient vehicles. Costs are in 2007 USD.

The estimates do not differ significantly across the feedstock types, nor do the ethanol blends differ significantly from conventional gasoline. Given that only dry corn as a feedstock is truly a proven technology, we believe the small differences in either the range across counties or the population adjusted mean should not be given much attention. Even the somewhat higher estimate for dry corn E85 of 1.52 cents is likely to contain enough error that it should not be viewed as distinctly different from the other feedstocks of conventional gasoline.

Several factors contribute to the aggregate damage estimates being similar for ethanol blends and gasoline in Table 3-10. The GREET model calculated similar estimates of vehicles emissions for all fuels shown in the table, thus the operational component of the aggregate damages are the same. Because the E10 fuel is only 10% ethanol and 90% gasoline, similar damage estimates were obtained across the entire life cycles for E10 and gasoline. The damage costs for E85 (herbaceous and corn stover) are the lowest for any of the fuel-vehicle life cycles when looking at the population adjusted means. A main reason is higher vehicle/fuel damages attributable to the feedstock and fuel components of the other vehicle-fuel life cycles.

To aid in comparisons with other studies and policy uses, we converted these costs/VMT into an equivalent costs per gallon. The mean adjusted population costs computed in cents per gallon of gasoline equivalent (gge) are reported for the 2005 results in the table. These are the same units that Hill et al. (2009) use to summarize their findings and a comparison of these results with theirs is instructive. Hill et al. (2009) also use the GREET model to estimate the health effects associated with conventional gasoline and various forms of ethanol. They report estimates of health costs from gasoline averaging $0.34/gallon. They contrast this with estimates of ethanol ranging from $0.16 for ethanol produced from prairie grasses to $0.93 for ethanol produced from corn using coal as the process heat. As can be see via comparison with the results in our table, their estimates are generally higher, and somewhat more discouraging for corn ethanol than ours.

One difference is that their results correspond to 2010 rather than our 2005 baseline. More importantly, the results we report include emissions from feedstock production, fuel production, vehicle operation and vehicle production. In contrast, Hill et al (2009) focus only on fuel production and use and do not consider vehicle production.

ELECTRIC VEHICLES

History and Current Status

The late 1990s saw the emergence—in large measure in response to so-called Zero Emission Vehicle requirements of the California Air Resources Board—of both a small number of all electric vehicles and the first gasoline hybrid vehicles. Though the all-electric vehicles did not continue in production, gasoline hybrid vehicles have continued to develop and spread in the market place, more recently due to higher gasoline prices, and substantial tax incentives. Currently, such vehicles constitute approximately 1-2% of the U.S. light-duty vehicle fleet. Recently, there has been increased interest in developing different versions of "plug-in" hybrid vehicles (which some are calling "extended range electric vehicles"), though other than aftermarket conversions, there are few such vehicles on the market currently.

There are two primary advantages that are usually cited for PHEVs. First, they will use electricity to power a portion a vehicle's energy requirements and thus avoid some fraction of petroleum that would otherwise be consumed. This would presumably lead to reductions in petroleum imports. Second, although there would be some impact on emissions from electric power plants, vehicle emissions would be reduced especially in metropolitan and urban areas.

Regulations and Technologies: Current and Anticipated in 2030

Although there are no formal national requirements for increased use of such vehicles (a la the Renewable Fuel Standards that require increased use of biofuels), there are a number of regulatory and incentive programs that have the potential to affect the use of such vehicles. These have been put in place to address multiple objectives including energy efficiency, reduced dependence on imported petroleum, and reduced greenhouse gas emissions. They include

- Continued regulation by CARB (and other states) requiring some number of so called Partial Zero Emission Vehicles (PZEV) as well as the pending CARB regulations for greenhouse gas emissions (which many other states have proposed to adopt as well)
- Substantial tax credits for purchase of such vehicles which, although they have been exhausted for some manufacturers (e.g. Toyota) are still available for others (and could be revised and extended
- Substantial government supported research and development of advanced battery technologies.

The recent report of the AEF Panel on Energy Efficiency in Transportation estimates that Gasoline Hybrids and Plug-In Hybrids are likely to play a significant role in the 2035 time frame we are considering. (15-40% and 7-15% respectively; see Table 3-11). Strictly speaking, the gasoline hybrids are more a fuel efficiency improvement rather than a new technology placing new demands on the

TABLE 3-11 Plausible LDV Market Shares of Advanced Vehicles by 2020 and 2035

Propulsion System	Plausible LDV Market Share by	
	2020	2035
Turbocharged Gasoline SI	10-15%	25-35%
Diesels	8-12%	15-30%
Gasoline Hybrids	10-14%	15-40%
Plug-in Hybrids	1-3%	7-15%
Hydrogen Fuel Cell Vehicles	0-1%	3-6%
Battery Electric Vehicles	0-2%	3-10%

Source: NAS/NAE/NRC in press.

electricity grid. However, several important parts of the pathway described below concerning batteries are also relevant to this technology, especially if it expands dramatically.

Based on the AEF analysis, it appears that there will not likely be significant penetration of either fuel cell or full electric battery vehicles within the 2030 timeframe.

Technology and Fuel Pathways

Facilities involved with manufacture and assembly of motor vehicles are located throughout the United States, but many are clustered in the Great Lakes states, California, and Texas. Manufacturing and assembling the thousands of different parts that comprise motor vehicles includes the following processes: raw material recovery and extraction, material processing and fabrication, vehicle component production, finishing or electroplating metal surfaces, painting the vehicle body, vehicle assembly, and vehicle disposal and recycling. These processes are energy and material intensive involving components made out of metal (e.g., steel, aluminum, or copper), glass, rubber, plastics, and fluids. Energy is required to transport the raw and processed materials along each process step. Some of the material production and transport takes place outside of the United States.

Waste streams are generated by manufacturing and assembly facilities as a result of fuel combustion, materials used in processes that are not shipped out in product streams, and chemical reactions occurring within specific processes. Air pollutants include particulate matter, volatile organic compounds, sulfur dioxide, nitrogen oxides, and carbon monoxide. Greenhouse gas emissions are also produced. In addition, various manufacturing processes generate sludge or wastewater that contains toxic metals (e.g. cadmium, lead, or chromium), oils, acids, and solvents.

The fuel cycle and potential effects pathways for electric vehicles are similar to other vehicles in a few respects (e.g. manufacture of the vehicle) but substantially different in nearly all other respects. Major components of those pathways are (e.g., see Axen et al. 2008; Samaras and Meisterling 2008) are the following:

- *Natural Resource Extraction*. The expanded use of electric batteries is likely to significantly increase demand for certain metals that come from relatively limited sites (some in unstable regions). This includes lithium (major stocks in the Congo and Russia) and cobalt (major stocks in Bolivia). This may pose national security costs (although they may not be per se, an externality). It also would involve significant increases in worker exposure and emissions associated with transport.

- *Displacement of Imported Oil*. At the same time, increased use of hybrids could reduce dependence on imported petroleum. For example, a study by PNNL (Box 3.1) made aggressive projections for introduction of Plug-in Hybrid Electric Vehicles and estimated that "A shift from gasoline to PHEVs could reduce the gasoline consumption by 6.5 MMBpd, which is equivalent to 52% of the U.S. petroleum imports."

- *Battery Manufacture* poses issues of worker exposure to metals as well as potential for both conventional and greenhouse gas emissions from the manufacturing process. The AEF report has used the GREET model to estimate energy use from manufacture of these and other technologies (see Table 3-12 from NAS/NAE/NRC (in press, Table 2.4).

- *Electric Power Grid Implications* PNNL conducted a study of the current capabilities of the electric power system in the United States, analyzing 12 regions, estimating how many PHEV-33 vehicles could be supported and what impact they might have, e.g., on emissions (Kintner-Meyer et al. 2007 summarized in Text Box 3.1). This was not a dynamic analysis and there was no estimate of the market penetration of such vehicles into the market. Basically, it was in some ways a maximum estimate of what could be. There conclusions were the following:

- "The existing electricity infrastructure as a national resource has sufficient available capacity to fuel 84% of the nation's cars, pickup trucks, and SUVs (198 million) or 73% of the light-duty fleet (about 217 million vehicles) for a daily drive of 33 miles on average..

- Several other grid-related impacts are likely to emerge when adding significant new load for charging PHEVs. Higher system loading could impact the overall system reliability as the entire infrastructure is utilized near its maximum capability for long periods. "Smart" PHEV charging systems that recognize grid emergencies could mitigate the extent and severity of grid emergencies. Near maximum utilization of the nation's power plants is likely to impact wholesale electricity markets. The mix of future power plant types and technologies may change as a result of the flatter load-duration curve favoring more base-load power plants and intermittent renewable energy resources.

- *Vehicle Use*—The use of these vehicles is likely to involve three major externalities:

    Conventional Pollutant and Greenhouse Gas Emissions from use of HEVs and PHEVs—impact on potential reductions in urban emissions and exposures (i.e. a positive externality) vs. increased emissions from grid electricity. The AEF report (and other analyses reported below) estimate that that the gradual expansion of use of these technologies would result in likely emissions being representative of the average grid emissions (i.e. rather than peak) though there assessment does note the likely unequal geographic distribution of these emissions.

    Safety has been raised as a concern with a number of the battery formulations. This includes possible malfunction (with inappropriate chemical reactions, heat and fire) and, probably most relevant for vehicles, potential exposures and impacts in vehicle accidents. Given the wide range of potential mixtures and significant uncertainty about which of these might become most prevalent, it is difficult to quantify these externalities at this time.

    Battery Recycling and Disposal—With substantially increase use of batteries containing unusual metals a key question will be where battery recycling and disposal will take place. If in the United States and under U.S. regulatory requirements improper emissions and worker exposures are likely to be minimized (though at a minimum there is a need for a review of current requirements to ensure their adequacy). If any significant portion of this activity takes place in the developing world, however, past experience suggests there could be significant worker and even population exposures.

Estimates of Effects and Monetized Damages for Electric Light-Duty Highway Vehicles

Not surprisingly, the analysis of damages attributable to the operation of different electric technologies is highly dependent on the assumptions made about the energy mix and emissions from the electric utility system. The damage estimates for operation of hybrid and electric vehicles show significant lower damages than for conventional gasoline (even when accounting for the uncertainty in the

TABLE 3-12 Energy Use During Vehicle Manufacturing and Disposal from AEF Report

Propulsion System	Energy (GJ/Vehicle)
Current Gasoline	90-125
Current Diesel	95-130
Current Gasoline Hybrid	110-150
2035 Gasoline	110-160
2035 Diesel	110-160
2035 Plug-In Hybrid (PHEV)	135-180
2035 Battery Electric Vehicle (BEV)[a]	
2035 Hydrogen Fuel Cell Vehicle (FCV)	155-210

[a]GREET 2.7 does not have the capability to estimate the BEV vehicle cycle impact accurately. The future versions of this model may include this capability.
Source: Bandivadekar et al. 2008.

analysis). This is especially true for the all electric vehicles, but even the grid independent hybrid vehicle is approximately 20% lower.

However, emissions from electricity generation are included in the full life cycle damages of the grid-dependent vehicles, specifically the emissions from the power plants as well as emissions from activities to produce the fossil fuels used in these plants. As shown in Table 3-13, when the damages attributable to other parts of the lifecycle were included, especially the emissions from the feedstock and the fuel (emissions from electricity production), the aggregate damages for the grid dependent and all-electric vehicles became comparable to, or somewhat higher than, those from gasoline.

The EIA AEO projections were used both in this analysis and in Chapter 2 to estimate the electricity damages. Although very large decreases in emissions from fossil fuel plants were projected for 2030 compared to current emissions (on a per kWh basis), electricity from coal- and natural gas-fired power plants would still account for 66% of total generation. This percentage is only a slight decrease from the 70% in 2005. Thus, although we estimate that the damages associated with electricity generated for use by the vehicle will decrease, the total life cycle damages of the electric vehicle technology are still estimated to be slightly greater than those of the conventional gasoline vehicle [i.e., by 1.49-1.35 = 0.14 cents/VMT (see Table 3-13)].

One or two significant transformations would be needed for the (non-climate change related) life cycle damages of electric vehicles to be equal to or less than those of conventional vehicles. One of these transformations would be a dramatic shift to much greater non-fossil fuel electricity generation—from renewable energy sources as well as nuclear power plants (for example, see Samaras and Meisterling, 2008). Instead of fossil fuels accounting for 66% of total generation in 2030, they would need to be lowered to about 37%. This estimated decrease is based on assuming that there is no improvement in manufacturing efficiency (see below) and the "fuel" component of the damages would need to decrease by the 0.14 cents/VMT difference between gasoline and electric vehicles.

The other technological transformation would have to be in great improvement in energy efficiency in vehicle manufacture. As noted in Table 3-12, energy use in manufacturing a plug-in hybrid vehicle is about 13%-23% greater than for a gasoline vehicle in 2035, and both are greater than energy use to manufacture current gasoline hybrid and gasoline vehicles. Damages from the emissions associated with vehicle manufacture account for a large percentage of the overall lifecycle damages. Thus, even with the large decreases in emissions from generating electricity at fossil fuel plants, the large damages from the vehicle-manufacture component mean that life cycle damages for electric vehicles would likely be somewhat greater than those for conventional vehicles, unless there is significant reduction in energy use in manufacturing batteries and other electric vehicle components.

In addition, the aggregate damages also reflect approximately 20% higher energy use and emissions from the manufacture of the vehicles, based on higher estimated energy inputs in GREET for battery manufacture.

TABLE 3-13 Comparison of health and Other Non-GHG Damage Estimates for Hybrid and Electric Vehicle Types with Conventional Gasoline 2005 and 2030[a]

	2005			2030	
	5th and 95th Percentile Range Aggregate Damages[b] (Cents/VMT)	Population Adjusted Mean Aggregate Damages (Cents/VMT)	Population Adjusted Mean Operations Only (Cents/VMT)	5th & 95th Percentile Range Aggregate Damages[b] (Cents/VMT)	Population Adjusted Mean Aggregate Damages (Cents/VMT)
Conventional Gasoline	0.34-5.07	1.34	0.38	0.45-4.87	1.35
Grid Independent HEV	0.31-4.12	1.22	0.31	0.49-5.57	1.50
Grid-dependent HEV	0.27-8.90	1.46	0.22	0.45-9.20	1.62
Electric	0.20-15.0	1.72	0.05	0.35-12.2	1.49

[a]Costs are in 2007 USD.
[b]From the distribution of results for all counties in the 48 contiguous states in the United States.

NATURAL GAS

Current Status

Natural gas vehicles (NGVs) are very similar to gasoline vehicles; the major difference is in fuel storage. Light-duty NGVs, and some heavy-duty vehicles like urban transit buses, use compressed natural gas (CNG). Heavy-duty vehicles can also use liquefied natural gas (LNG), which is denser but must be maintained below -260 degrees F in very well insulated tanks (NGV America 2009; DOE 2009b).

In 2008, there were more than 150,000 NGVs in the United States. The main markets for NGVs are new transit buses and corporate fleet cars that are used mainly for short trips. That demand is due mainly to EPA's Clean-Fuel Fleet Program. NGVs are more expensive than hybrid vehicles or gasoline vehicles. For example, the Honda Civic GX NGV has a MSRP of $24,590 compared to $22,600 for the hybrid sedan, and $15,010 for the regular sedan (Rock 2008).

About 1,500 NGV fueling stations are in the United States as of 2008; a substantial portion is part of private company facilities and is not available to the general public. Natural gas is sold in units of gasoline gallon equivalents (GGEs). One GGE represents the same energy content (124,800 BTUs) as a gallon of gasoline. Natural gas for CNG is obtained directly from a distribution line. Stations require large, high-pressure compressors and storage tanks to fill a vehicle quickly. Alternatively, a small compressor can work overnight. Natural gas for LNG can also be taken from a gas pipeline and then liquefied onsite, but it is also can be transported in liquid form to a refueling facility via tanker truck.

Technology Development and Barriers

The main benefit of CNG has been its relatively low price (about 80% that of gasoline on the GGE basis). Also, transport and distribution can rely on an existing infrastructure for both industrial and household use (Yborra 2006). According to the AEF report (NAS/NAE/NRC 2009c), if natural gas were to be used for transportation instead of for electricity production, North American natural gas reserves could supply about 20-25% of transportation fuel needs by 2020, but only with investment in distribution infrastructure. To supply more would require importing natural gas and LNG to meet that increased demand. (Chapter 6 discusses hazards related to infrastructure for distribution ion of LNG in the United States.)

The AEF report indicates that the main challenges to increased use of NGVs include an insufficient number of refueling stations and inconvenient on-board CNG tanks that take up most of the trunk space. Another key disadvantage is a limited range. While the average range of a gasoline or diesel vehicle is 400 miles, the range of an NGV is only 100 to 150 miles depending on the NG compression. The AEF report suggests that the most important barrier for NGVs could be a public perception that using CNG as a fuel would involve carrying a dangerous 'explosive' on board a vehicle and that self-service refueling with a high pressure gas may be too risky to offer to the general public.

Fuel Cycle Effects and Externalities

Natural gas has several significant advantages as a fuel for vehicles when compared to gasoline or diesel. Dedicated NGVs have the least exhaust emissions of CO, non-methane VOCs, NO_x, and CO_2. NGVs emit unburned methane (which has a higher climate forcing potential than CO_2), but this might be compensated by the substantial reduction in CO_2 emissions.

The choice of fuel pathway for CNG can have a large impact on GHG emissions over the fuel life cycle. If non-North American natural gas is imported as LNG via ocean tanker and then regasified and compressed to produce CNG, for example, CNG reduces life-cycle GHG emissions by only 5% compared

to gasoline. If domestic gas is used, life-cycle GHG emissions are reduced by 15%. If gas that otherwise would be flared or landfill gas is used as the feedstock, net GHG emissions can actually be negative.

Modeled Estimates of Damages from Light-Duty CNG Vehicles

Table 3-14 contains a summary of the modeling results from the GREET/APEEP modeling effort related to natural gas light-duty autos and trucks (with a row for reformulated gasoline autos for comparison purposes). Each row of Table 3-14 contains the range and population adjusted mean for health damages in 2005 and 2030, reported on a VMT basis. There is also a column showing the health costs per gasoline gallon equivalents (gge). Because of population growth, other things equal, damages would tend to increase from 2005 to 2030. So, decreases in damages mean that for a variety of reasons, emissions per VMT are diminishing over time faster than the population is growing.

In fact, damages for CNG autos are 1.2 cents per VMT or about 23 cents per gallon gasoline equivalent. Emissions for trucks are much larger, reaching 28 cents a gallon for LDT2 in 2005. Emissions per VMT are increasing over time for all CNG vehicle types, except for LDT2 where the population adjusted means are 12% lower in 2030 than 2005. Interestingly, CNG autos outperform gasoline autos, with only 87% of the damages in both 2005 and 2030, implying that the emissions per VMT of the former over the life cycle are that much lower than the latter. On a per gallon equivalent basis, CNG autos do even better, with only 78% of the damages of gasoline vehicles.

By life-cycle stage, the difference in damages from CHG vehicles compared to gasoline vehicles is accounted for by lower operations emissions (particularly of NO_x and VOCs) and lower emissions from the fuel stage for CNG, offset only somewhat by higher feedstock emissions (with identical emissions from the vehicle manufacturing stage).

Table 3-15 shows how the CO_2-equivalent emissions vary for CNG autos and reformulated gasoline autos for the years 2005 and 2030 on a VMT basis. From this table we see that CO_2-equivalent emissions for CNG autos are about 89% of those for gasoline vehicles in 2005 but this advantage is greater in 2030, CNG emissions being only 79% of gasoline vehicle emissions in 2030. As expected, methane emissions for CNG vehicles are greater than those for gasoline, but CO_2 emissions are much lower, yielding a net decrease in CO_2-equivalent emissions for CNG vehicles.

One caveat with these estimates is that they take, as given, GREET default assumptions with respect to LNG imports. If LNG imports grow by more than assumed between 2005 and 2030, much if not all the gains from CNG vehicles relative to gasoline vehicles (at least from the perspective of GHG emissions) would be eroded.

TABLE 3-14 Health and Other Non-GHG Damages from CNG Light-Duty Autos and Trucks (Values Reported in Cents/VMT)[a]

	2005			2030	
	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)	Population Adjusted Mean (Cents/gge)[c]	5th & 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)
Conventional Gasoline SI Autos	0.35-5.12	1.32	29.83	0.45-4.87	1.35
CNG autos	0.30-4.54	1.20	23.35	0.38-4.41	1.16

Notes: This will therefore show highest damages for the most fuel efficient vehicles. Costs are in 2007 USD.
[a]Costs are in 2007 USD
[b]From the distribution of results for all counties in the 48 contiguous states in the United States.
[c]Cents/gallon of gasoline equivalent, calculated by multiplying average miles per gallon by per VMT damages.
Abbreviation: SI = spark ignition.

TABLE 3-15 Carbon Dioxide Equivalent (CO_2-eq) Emissions of Greenhouse Gases from CNG Autos and Light-Duty Trucks Compared to Reformulated Gasoline Vehicles (Grams/VMT)

Fuel/vehicle combination	CO_2-eq 2005 g/VMT	CO_2-eq 2030 g/VMT
RFG SI Autos (Convent. Oil)	552	365
CNG Autos	492	280

Note: Costs are in 2007 USD.

HYDROGEN FUEL CELL VEHICLES

Current Status

According to the AEF report (NAS/NAE/NRC 2009c), hydrogen fuel cell vehicles HFCVs can yield large and sustained reductions in U.S. oil consumption and GHG emissions, but several decades will be needed to realize these potential long-term benefits. The NRC report *Transitions to Alternative Transportation Technologies a Focus on Hydrogen* (NRC 2008c) estimates that the maximum practical number of HFCVs that could be operating in 2020 would be approximately 2 million in a fleet of 280 million light-duty vehicles. The number of HFCVs could grow rapidly to about 25 million by 2030, and account for more than 80 percent of new vehicles entering the fleet by 2050. Those estimates assume that technical goals are met, consumers readily accept HFCVs, and policy instruments are in place to facilitate the introduction of hydrogen fuel and fuel cell vehicles through the market transition period.

Modeled Estimates of Damages from Hydrogen Fuel Cell Vehicles

Table 3-16 contains a summary of the modeling results from the GREET/APEEP modeling effort related to hydrogen fuel cell autos relative to gasoline light-duty autos. GREET covers two technologies for fuel cells—one which assumes the vehicle uses hydrogen gas directly and another that assumes the vehicle carries a liquid fuel on the vehicle that is converted to hydrogen gas in a reformer. Because of the substantial uncertainties associated with the likely types and amounts of energy use for liquid hydrogen fuel, only results for hydrogen gas are included here. Each row of Table 3-16 contains the range and population adjusted mean for health damages in 2005 and 2030, reported on a VMT basis. There is also a column showing the health costs per gasoline gallon equivalents (gge).

TABLE 3-16 Health and Other Non-GHG Damages from Hydrogen Fuel Cell Autos Compared to Reformulated Gasoline Autos[a]

	2005			2030	
	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)	Population Adjusted Mean (Cents/gge)[c]	5th and 95th Percentile Range[b] (Cents/VMT)	Population Adjusted Mean (Cents/VMT)
Conventional Gasoline SI Autos	0.35-5.12	1.32	29.83	0.45-4.87	1.35
Hydrogen (gaseous) autos	0.38-4.17	1.34	66.68	0.61-5.61	1.64

[a]Costs are in 2007 USD.
[b]From the distribution of results for all counties in the 48 contiguous states in the United States.
[c]Cents/gallon of gasoline equivalent, calculated by multiplying average miles per gallon by per VMT damages.
Notes. This will therefore show highest damages for the most fuel efficient vehicles.
Abbreviation: SI = spark ignition.

It can be seen from this table that estimated damages for hydrogen (gaseous) and reformulated gasoline are similar in 2005. Yet, there are large differences in emissions over the life cycle. Hydrogen fuel cells have far larger emissions from the fuel stage and the vehicle manufacturing stage than gasoline vehicles, which is about fully offset by lower emissions in the operation stage and to a lesser extent in the feedstock stage. By 2030, however, reformulated gasoline is less damaging than hydrogen (gaseous), owing to a bigger increase in emissions per VMT in the vehicle manufacturing stage. Note that it is misleading to compare damages on a per gallon gasoline equivalent basis since hydrogen fuel cells use such a different means of propulsion and get such "high" mileage per damage unit.

Table 3-17 shows how the CO_2-equivalent emissions vary among the different fuel vehicle types and between the years 2005 and 2030 on a VMT basis. From this table we see that the hydrogen (gaseous) vehicle-fuel significantly outperforms gasoline vehicles for CO_2-equivalent, with only about 60% of the latter's emissions.

SUMMARY AND CONCLUSIONS

We have presented here a detailed summary of the wide range of potential emissions and damages from the use of energy in transportation. Our discussion and analysis focused on the components of transportation energy use—for light- and heavy-duty on-road transportation—that account for the great majority of annual transportation energy use. Other transportation energy uses—e.g., for nonroad vehicles, aircraft, locomotives, and ships—are not inconsequential, but they account for a smaller portion of transportation energy use and were beyond the scope of this analysis.

Results of the Analysis: Health and Other Damages

Given these limitations, our analysis does provide some useful insight into the relative levels of damages from different fuel/technology mixes. Overall, we estimate that the aggregate national damages to health and other non-GWP effects would have been approximately $36.4 billion per year for the light-duty vehicle fleet in 2005; the addition of medium-duty and heavy-duty trucks and buses raises the aggregate estimate to approximately $56 billion. These estimates are likely conservative, as they do not fully account for the contribution of light-duty trucks to the aggregate damages, and of course should be viewed with caution, given the significant uncertainties described above in any such analysis.

Health and other Non-GWP Damages on a per VMT Basis: Although the uncertainties in the analysis preclude precise ranking of different technologies, Table 3-18 below illustrates that on a cents per vehicle mile traveled basis there are some differences that provide useful insight into the levels of damages attributable to different fuel/technology combinations in 2005 and 2030. Overall, the damage levels illustrate several things:

TABLE 3-17 Carbon Dioxide Equivalent (CO_2-eq) Emissions of Greenhouse Gases from Hydrogen Fuel Cell Autos Compared to Reformulated Gasoline Autos

	CO_2-eq 2005	CO_2-eq 2030
Fuel/vehicle combination	g/VMT	g/VMT
RFG SI Autos (Convent. Oil)	552	365
Hydrogen (gaseous) Autos	341	294

Note: Costs are in 2007 USD.

- Among the fuel/technology choices, there are some differences in damages although overall, especially in 2030, the different fuel/technology combinations have remarkably similar damage estimates.
  - Some fuels—E85 from herbaceous and corn stover, and CNG—have relatively lower damages than all other options in both 2005 and 2030
  - Diesel, which has relatively high damages in 2005, has one of the lowest levels of damage in 2030. This is due to the substantial reductions in both PM and NO_x emissions that a 2030 diesel vehicle is required to attain.
  - Corn-based ethanol, especially E85 has relatively higher damages than most other fuels; this is in large measure due to the higher level of emissions from the energy required to produce the feedstock and the fuel.
  - Grid-dependent HEVs and electric vehicles have relatively higher damages in 2005. As noted above, these vehicles actually have significant advantages over all other fuel/technology combinations when considering only damages from operations. However, the damages associated with the current and projected mixes of electric generation (with the latter still being dominated by coal and natural gas in 2030 albeit at significantly lower rates of emissions) add substantial damages to these totals. In addition, the increased energy associated with battery manufacture adds approximately 20% to the damages from vehicle manufacture. However, further legislative and economic initiatives to reduce emissions from the electricity grid could be expected to improve the relative damages from electric vehicles substantially.

- Although the underlying level of aggregate damages in the United States could be expected to rise between 2005 and 2030, due to projected increases in population and to increases in the value of a statistical life, the results in our analysis for most fuel/technology examples are very similar in 2030 to those in 2005, in large measure because of the expected improvement in many technology/fuel combinations (including conventional gasoline) as a result of enhanced fuel efficiency (i.e. 35.5 mpg) expected by 2030 from the recently announced new national standards for fuel efficiency. (It is possible however that these improvements are overstated somewhat, since there is evidence that improved fuel efficiency can also lead to increased travel, likely resulting in higher aggregate damages than would otherwise be seen.)

TABLE 3-18 Relative Categories of Damages 2005 and 2030 for Major Categories of Light-Duty Fuels and Technologies[a]

Category of Aggregate Damage Estimates (Cents/VMT)	2005	2030
1.10-1.19		CNG Diesel with low sulfur and biodiesel
1.20-1.29	E85 Herbaceous E85 Corn Stover CNG Grid-independent HEV	E85 Corn Stover E85 Herbaceous
1.30-1.39	Conventional Gasoline and RFG E10 Hydrogen gaseous	Conventional Gasoline and RFG E10 E85 Corn
1.40-1.49	Diesel with low sulfur and biodiesel Grid-dependent HEV	Electric Vehicle
1.50-1.59	E85 Corn	Grid-independent HEV Grid-dependent HEV
>1.60	Electric Vehicle	Hydrogen gaseous

[a]Costs are in 2007 USD.

- As shown in Figure 3-7 (a and b), these aggregate damages are not spread equally among the different life-cycle components. For example, in most cases the actual operation of the vehicle is one-quarter to one-third of the aggregate damages, while the emissions incurred in creating the feedstock, refining the fuel, and making the vehicle, are responsible for the larger part of aggregate damages.
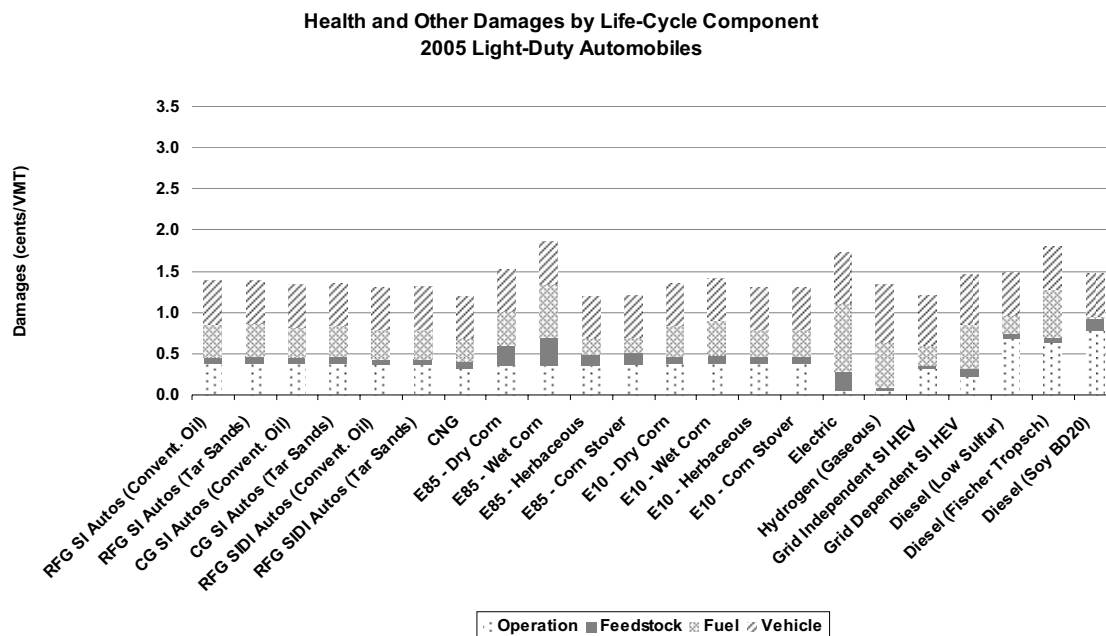
FIGURE 3-7a Aggregate 2005 life-cycle damages of light-duty vehicles from air pollutant, excluding GHGs emissions (cents/VMT). Costs are in 2007 USD.
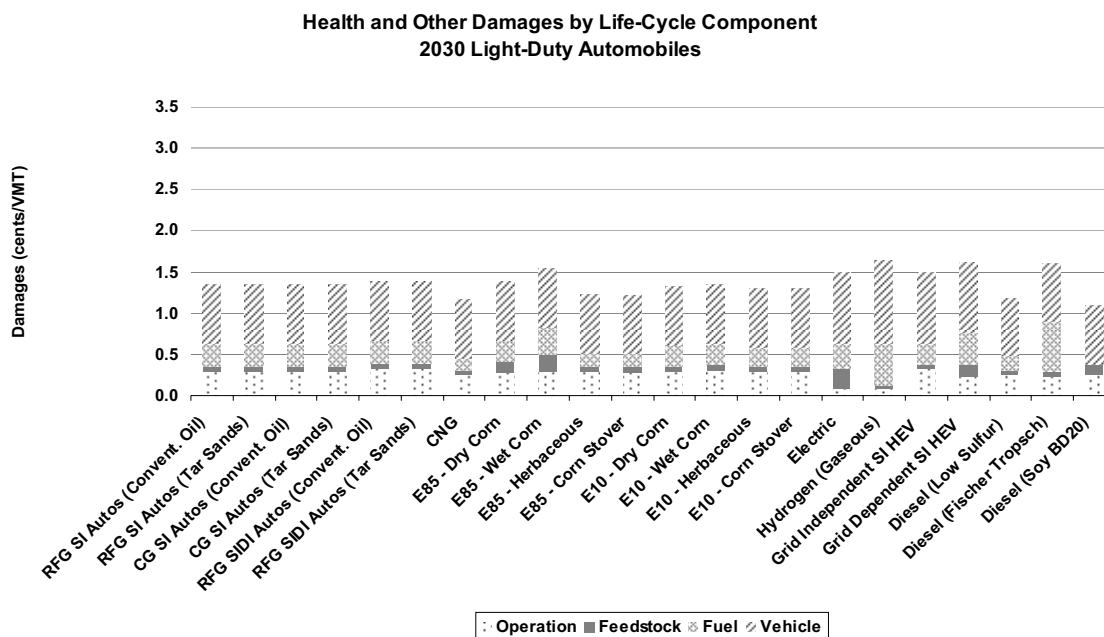
FIGURE 3-7b Aggregate 2030 life-cycle damages of light-duty vehicles from air pollutant, excluding GHGs emissions (cents/VMT). Costs are in 2007 USD.

Health and Other Non-GHG Damages on a per Gallon Basis: As illustrated in Table 3-3, 3-10, and 3-14 above, the Committee also attempted to estimate the health and non-GHG damages on a per gallon basis. This is made somewhat more complicated by the fact that simply multiplying expected miles per gallon for each fuel/vehicle type by the damages per mile will tend to make the most fuel efficient vehicles, which travel the most miles on a gallon, appear to have higher damages per gallon than a less fuel efficient vehicle. With that caveat in mind, the committee's analysis estimated that in 2005, the mean damages per gallon for most fuels ranged from 23 cents/gallon to 38 cents/gallon, with the damages for conventional gasoline engines being in approximately the middle of that range at approximately 29 cents per gallon.

Estimates of Aggregate National Health and Other Non-GHG Damages. Overall, and scaling up the per VMT damages reported here to reflect national vehicle miles traveled in 2005, we estimate that the aggregate national damages to health and other non-climate-change-related effects would have been approximately $36 billion per year (2007 USD) for the light-duty vehicle fleet in 2005; the addition of medium-duty and heavy-duty trucks and buses raises the aggregate estimate to approximately $56 billion (2007 USD). These estimates are likely conservative, as they include but do not fully account for the contribution of light-duty trucks to the aggregate damages, and of course should be viewed with caution, given the significant uncertainties in any such analysis.

Limitations in the Health and Other Non-GHG Damages Analysis It is important in interpreting these results to consider two major limitations in the analysis:

- *Emissions and Damages that were not quantifiable.* Although our analysis was able to consider and quantify a wide range of emissions and damages throughout the life cycle, and included what arguably could be considered the most significant contributors to estimates of such damages (e.g. premature mortality resulting from exposure to air pollution), there are many potential damages which could not be quantified at this time. These include, among others:
  - *Overall:* estimates of impacts of hazardous air pollutants, and estimates of damages to ecosystems (e.g. from deposition), the full range of agricultural crops, and others
  - *For biofuels:* Impacts on water use and water contamination, as well as any formal consideration of potential indirect land use effects (see however our discussion of the latter in 3.4 above)
  - *For battery electric vehicles:* Potential exposures to air toxics in battery manufacture, battery disposal, and during accidents.

- *Uncertainty* Any such analysis includes a wide set of assumptions and decisions about analytic techniques that can introduce uncertainty in the results. Although we did not attempt to conduct a formal uncertainty analysis, we have been cautious throughout our discussion of results—and urge the reader to be cautious—to not over-interpret small differences in results among the wide range of fuels and technologies we assessed. Moreover, we engaged in limited sensitivity analyses to check the impacts of key assumptions.

Results of the Analysis: Greenhouse Gas Emissions

- Similar to the damages estimates, the greenhouse gas emission estimates from each fuel/technology combination can provide relative estimates of greenhouse gas performance in 2005 and 2030. Although caution should be exercised in interpreting these results and comparing among fuel/technology combinations, some instructive observations from Table 3-19 are possible:
  - Overall, the substantial improvements in fuel efficiency in 2030 (to a minimum of 35 mpg for light-duty vehicles) result in most technologies becoming much closer to each other in per VMT life-cycle greenhouse gas emissions. There are however some differences:

TABLE 3-19 Relative Categories of GHG Emissions in 2005 and 2030 for Major Categories of Light-Duty Fuels and Technologies

Category of Aggregate CO$_2$-eq Equivalent Emission Estimates (g/VMT)	2005	2030
150-250	E85 Herbaceous E85 Corn Stover	E85 Herbaceous E85 Corn Stover
250-350	Hydrogen Gaseous	E85 Corn Diesel with biodiesel Hydrogen Gaseous CNG
350-500	E85 Corn Diesel with biodiesel Grid-independent HEV Grid-dependent HEV Electric Vehicle CNG	Grid-independent HEV SI Conventional Gasoline, RFG Grid-dependent HEV Electric Vehicle Diesel with low sulfur E10 Herbaceous, Corn Stover SIDI Conventional Gasoline E10 Corn SI Tar Sands
500-599	Conventional Gasoline and RFG E10 Low sulfur diesel	
>600	Tar Sands	

Costs are in 2007 USD.

o   As with the damages reported above, the herbaceous and corn stover E85 have relatively low emissions; in terms of aggregate g/VMT of CO$_2$-equivalent emissions, E85 from corn also has relatively low emissions

o   The tar sands based fuels have the highest GHG emissions of any of the fuels.

o   As shown in Figure 3-8, and in contrast to the damages analysis above, the operation of the vehicle is in most cases a substantial relative contributor to total life-cycle emissions. This is not the case, however, with either the grid-dependent technologies (e.g., electric or grid-dependent hybrid) or the hydrogen fuel cell vehicles, where the dominant contributor to life-cycle emissions is the processing of the fuel in the grid or in the production of hydrogen.

Results of the Analysis: Heavy-duty Vehicles

The Committee also undertook a more limited analysis of the damages and greenhouse gas emissions associated with heavy-duty vehicles. Although this analysis included operations, feedstock, and fuel components of the life cycle, it could not, due to the wide range of vehicle types and configurations, include a vehicle manufacturing component. In sum, and as illustrated in Figures 3-9 and 3-10, there are several conclusions that can be drawn:

•   The damages per VMT in 2005 are significantly higher than those shown for light-duty vehicles above, although they of course accrue to a much higher weight of cargo and/or number of passengers being carried per mile as well.

•   Damages drop significantly in 2030, due to the full implementation of the 2007-2010 Highway Diesel Rule which requires substantial reductions in PM and NO$_x$ emissions.

Greenhouse gas emissions are driven primarily in these analyses by the operations component of the life-cycle, and do not change substantially between 2005 and 2030 (except for a modest improvement in fuel economy). EPA and others are currently actively investigating possible future enhanced requirements for fuel economy among heavy-duty vehicles.

Results of the Analysis: Damage and GHG Emission Comparisons

Although energy use and emissions generally track one another quite closely, the comparisons above indicate that they do not uniformly distinguish among the fuel/technology combinations. In general, there are few fuel/technology combinations that have significantly lower damages than gasoline in 2005 (Table 3-10), although several combinations have significant advantages in global warming potential (GWP) (the former is in part due to the GREET model, which assumes all fuel/vehicle combinations must at least meet similar emissions standards). The electric and fuel cell options have somewhat higher life-cycle damages than gasoline even though in most cases they have significantly lower GWP.

The conclusions to be drawn from the 2030 analysis are similar, although some diesel options begin to exhibit improvements in damages over gasoline due to the substantial mandated reduction in emissions, and the overall difference in damages is somewhat smaller as fuel efficiency among the fuel/technologies converge.

Overall Implications of the Results

Perhaps the most important conclusion to be taken from these analyses is that, when viewed from a full life-cycle perspective, the results are remarkably similar across fuel/technology combinations. One key factor contributing to this is the relatively high contribution to health and other non-GHG damages from emissions in life-cycle phases *other* than the operation of the vehicle (i.e., the development of the feedstock, processing of the fuel, and manufacturing of the vehicle).

There some differences though, and from these some conclusions can be drawn:

- The gasoline-driven technologies have somewhat higher damages and GHG emissions in 2005 than a number of other fuel/technology combinations. The grid-dependent electric options have somewhat higher damages and GWP than other technologies, even in our 2030 analysis, in large measure due to the continued conventional and greenhouse gas emissions from the existing and likely future grid at least as of 2030. (See below for mention of possible pathways for reducing those emissions.)
- In 2030, with the move to meet the enhanced 35 mpg requirements now being put in place, those differences among technologies tend to converge somewhat, although the fact that operation of the vehicle is generally less than a third of overall life-cycle emissions and damages tends to dampen the magnitude of that improvement. Further enhancements in fuel efficiency—the likely push for an extension beyond 2016 to further improvements—would improve the GHG emissions estimates for all liquid-fuel driven technologies.
- The choice of feedstock for biofuels can significantly affect the relative level of life-cycle damages, with herbaceous and corn stover having some advantage in this analysis.
- Additional regulatory actions and/or changes in the mix of electricity generation can significantly affect levels of damages and GHG emissions. This was illustrated in this analysis by the substantial reduction in diesel damages from 2005 to 2030. Similarly, major regulatory initiatives to reduce electricity generation emissions and/or legislation to reduce carbon emissions would significantly improve the relative damages and emissions from the grid-dependent electric options. Similarly a shift to

Greenhouse Gas Emissions by Life-Cycle Component
2005 Light-Duty Automobiles

Greenhouse Gas Emissions
(gCO2-eq/VMT)

Legend: Operation ■ Feedstock ▨ Fuel ▨ Vehicle
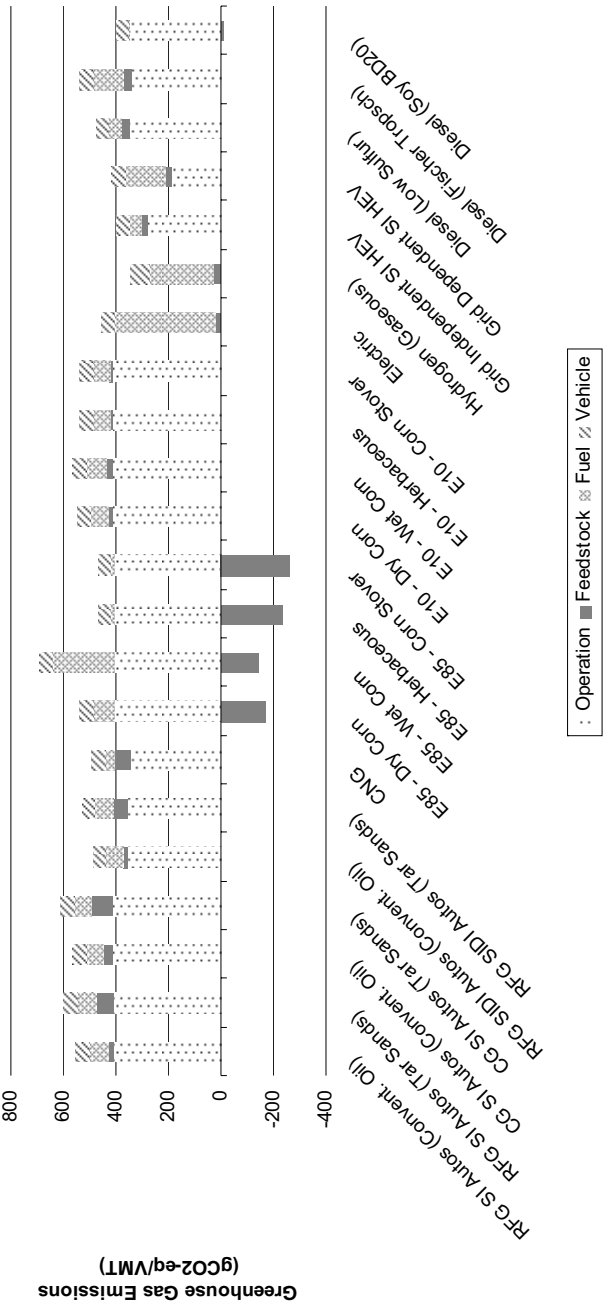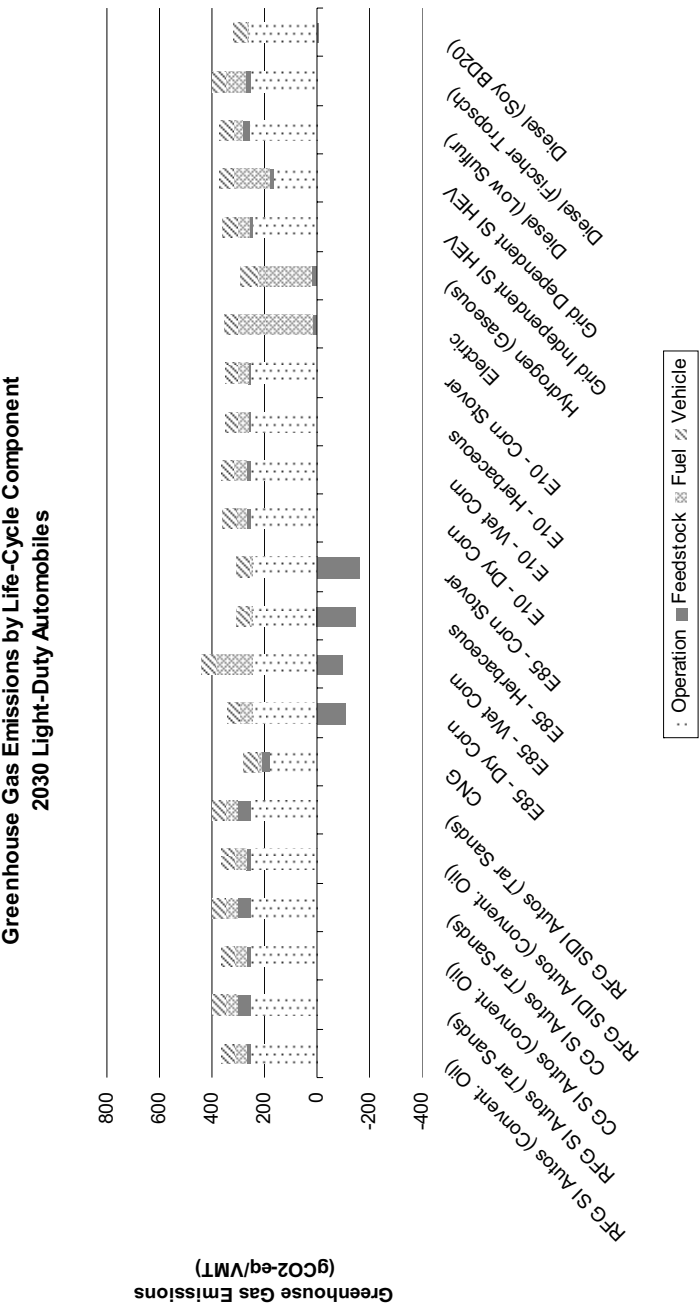
FIGURE 3-8 GHG emissions (grams CO_2 equivalent)/VMT by life-cycle component for light-duty automobiles in (Top) 2005 and (Bottom) 2030. Blue refers to vehicle operation, red to feedstock for fuels, green to fuel refining, and purple to vehicle manufacture (from bottom to top of each bar). One exception is ethanol fuels for which feedstock production exhibits negative values due to CO_2 uptake. The amount of CO_2 consumed should be subtracted from the positive value to arrive at a net value.

**Health and Other Damages by Life Cycle Component
2005 Heavy Duty Vehicles**

**Health and Other Damages by Life Cycle Component
2030 Heavy Duty Vehicles**
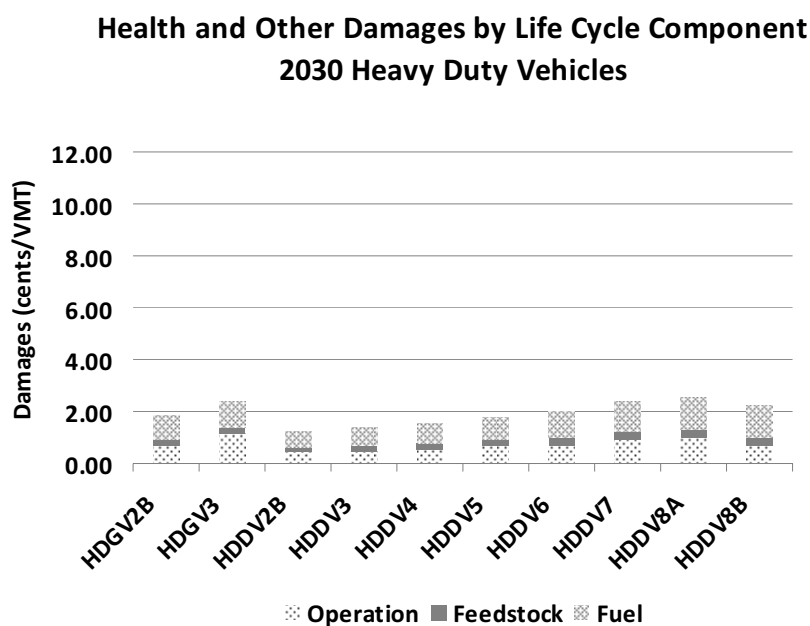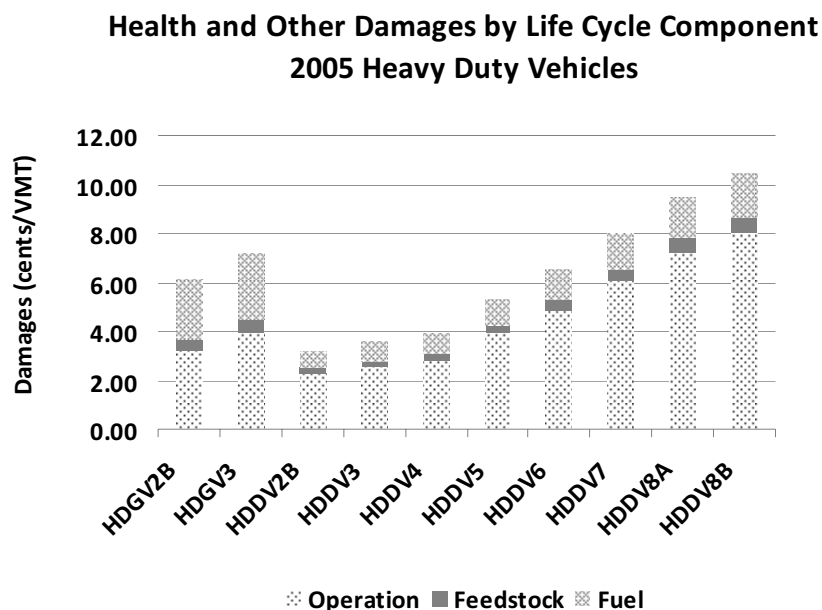
FIGURE 3-9 Aggregate operation, feedstock, and fuel damages of heavy-duty vehicles from air pollutant emissions (excluding GHGs) (cents/VMT). (Top) Estimated damages in 2005; (Bottom) estimated damages in 2030.

GHG Emissions by Life Cycle Component
2005 Heavy Duty Vehicles

GHG Emissions by Life Cycle Component
2030 Heavy Duty Vehicles
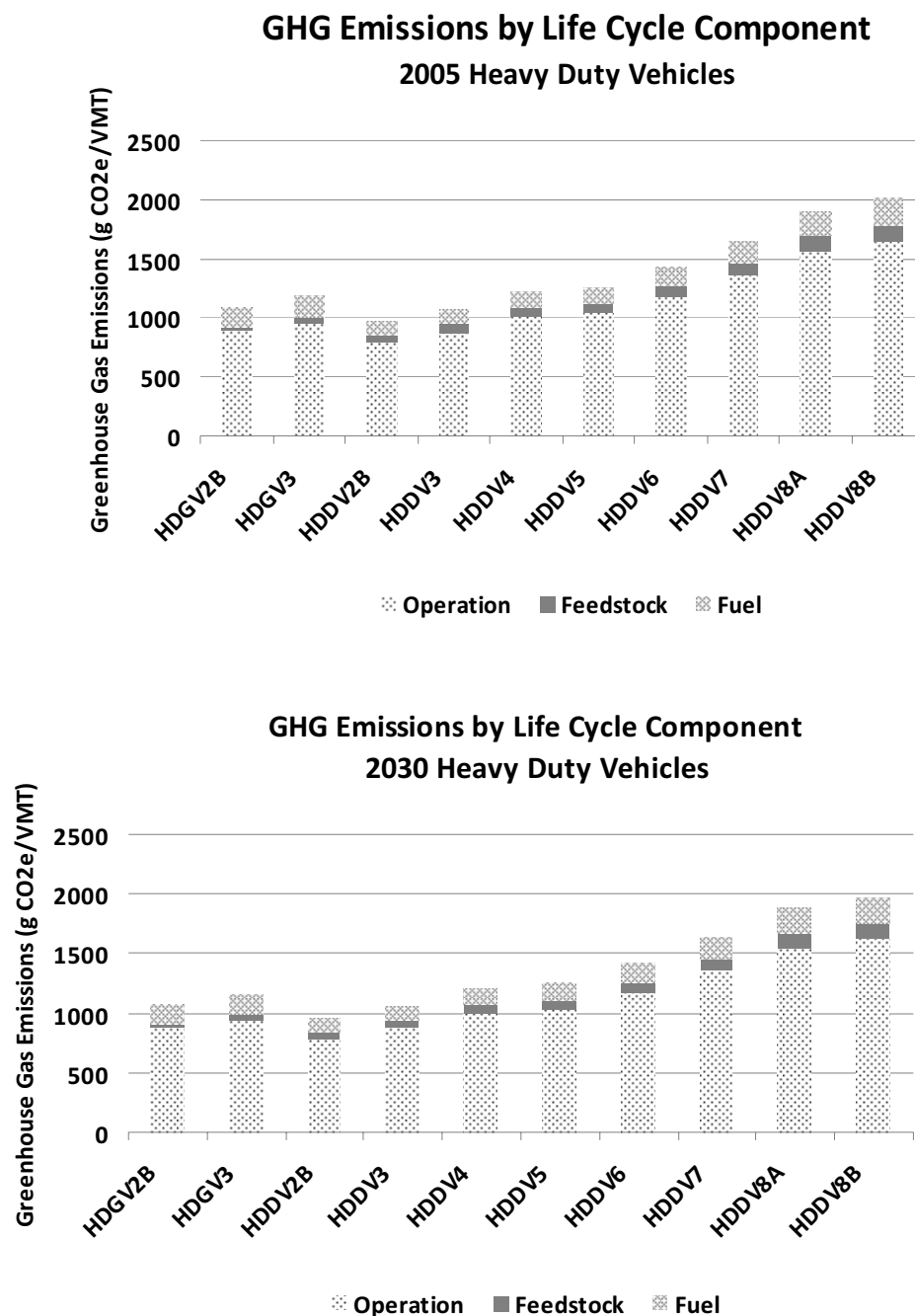
FIGURE 3-10 Aggregate operation, feedstock, and fuel damages of heavy-duty vehicles from GHG emissions (cents/VMT). (Top) estimated damages in 2005; (Bottom) estimated damages in 2030.

electricity generation with lower emissions (e.g. natural gas, renewables, and nuclear) would further reduce the life-cycle emissions and damages of the grid-dependent technologies

- Overall, there are somewhat modest differences among different types of vehicle technologies and fuels, even under the likely 2030 scenarios although some technologies (e.g. grid-dependent electric) had somewhat higher life-cycle emissions. It appears therefore that some breakthrough technologies (e.g. cost-efficient conversion of advanced biofuels; cost-efficient carbon capture and storage and/or much greater use of renewable resources for electricity generation) will be needed to dramatically reduce transportation-related externalities.

These results must be viewed in the context of a significant number of potential damages noted above that cannot at this time be quantified, and substantial continued uncertainties. There is a need for substantial additional research to

1. Better understand potential negative externalities at the earliest possible stage in the research and development process for new fuels and technologies so as to avoid these externalities as the fuels and technologies are being developed.

2. Improve understanding of the currently unquantifiable effects and potential damages, especially as they relate to biofuels (e.g. effects on water resources and ecosystems) and battery technology (e.g. effects throughout the battery life cycle of extraction through disposal);

3. Obtain more accurate emissions factors for each stage of the fuel/vehicle life stages. In particular there is a need, in the context of enhancing even further EPA's recent shift to the Motor Vehicle Emission Simulator (MOVES) model for mobile source emissions, to make measurements to confirm or refute the assumption that all vehicles will only meet but not exceed emissions standards. In actual practice, there can be significant differences between on-road performance relative to emissions requirements and some alternative-fuel vehicles may do better or worse than expected.

4. The issue of indirect land use change is central to current debates about the merit of biofuels. Regardless of whether this impact is regarded as an externality associated with U.S. or foreign biofuels production, it is important to obtain more empirical evidence about its magnitude and causes, as well as to improve the current suite of land use change models.

5. Because a significant fraction of life-cycle health impacts comes from both vehicle manufacture and fuel production, it is important to improve and expand the information and databases used to construct emissions factors for these life stages. In particular, there is a need to understand whether and how energy-efficiency improvements in these industrial components might change the overall estimates of life-cycle health damages.

6. As better data becomes available, future studies should also focus on other transportation modes—both those that are alternatives to automobiles and light trucks (transit) as well as air, rail and marine, which are alternatives for longer-distance travel and for freight.

4

Energy for Heat

BACKGROUND

An evaluation of the externalities of energy used to produce heat as an end use is important since this comprises about 30% of U.S. primary energy usage.[1] Unlike the chapters on the electricity production and transportation sectors, this chapter will not present a detailed, assessment of externalities associated with all uses of all energy sources for heat. Rather, this chapter will assess air pollution damages from the present uses (and uses expected in 2030) of natural gas for heat by residential and commercial sector buildings (see Box 4-1 for sector definitions) and also make some comparisons with the use of electricity for heat. The industrial sector is discussed only qualitatively, because published statistics do not differentiate clearly between fuel used for heating and fuel used for process feedstocks. Figures 4-1 and 4-2 show the overall energy use in the United States by sector, the details of building and industrial energy consumption by source, and the consumption by sector of electricity and natural gas (EIA 2008b). Natural gas is the major fuel use for heat in buildings. However, buildings also consumed about 5% of the 39.7 quadrillion British thermal units (Quads) of petroleum used in 2008; industry consumed about 25%. Industrial consumption of petroleum includes the petroleum refining industry which in turn provides the 70% of petroleum used as fuel in transportation.

Approximately 20% of total energy consumed in the United States is attributed to non-electric use in the industrial sector (for both heating and feedstock); about 10% is attributed to non-electric use in commercial and residential buildings. Building sector energy is predominantly used for heating. The industrial sector and buildings are also the consumers of almost all electricity generation, about 40% of the U.S. primary energy usage. Damages associated with electricity production were evaluated in Chapter 2. Damages that are of the types considered by this committee and associated with end uses of electricity are relatively small compared to those associated with electricity generation.

This chapter will provide approximate estimates of damages associated with the use of natural gas for heating applications in the industrial and buildings sectors. The technologies used in these sectors vary in type, size and age and are widely distributed, but mainly burn natural gas, with some use of petroleum in the industrial sector and small amounts of other primary fuels. The magnitude of associated externalities is strongly influenced by the amount of a particular fuel used and the locations of use.

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[1]"The energy that powers our civilization is obtained from a number of primary energy sources that exist in nature. These sources fall into two categories: flows of energy and stored energy. Examples of energy flows include sunlight, wind, and waves. Stored energy includes fossil energy (petroleum, natural gas, and coal), bioenergy (contained in biomass), and nuclear energy (stored in atomic nuclei in radioactive elements such as uranium) and the heat stored in Earth's upper crust. Primary energy sources can be converted into *useful* energy that, for example, powers a vehicle, lights a building, or supplies heat for an industrial process, although the conversion process inevitably involves energy losses (which can be quite considerable) and often entails substantial costs" (NAS/NAE/NRC, 2009a).

BOX 4-1 Definition of Residential, Commercial, and Industrial Sectors

Residential sector: An energy-consuming sector that consists of living quarters for private households. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a variety of other appliances. The residential sector excludes institutional living quarters. Note: Various programs of the U.S. Energy Information Administration differ in sectoral coverage.

Commercial sector: An energy-consuming sector that consists of service-providing facilities and equipment of: businesses; Federal, State, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. The commercial sector includes institutional living quarters. It also includes sewage treatment facilities. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a wide variety of other equipment. Note: This sector includes generators that produce electricity and/or useful thermal output primarily to support the activities of the above-mentioned commercial establishments.

Industrial sector: An energy-consuming sector that consists of all facilities and equipment used for producing, processing, or assembling goods. The industrial sector encompasses the following types of activity: manufacturing (NAICS codes 31-33); agriculture, forestry, fishing and hunting (NAICS code 11); mining, including oil and gas extraction (NAICS code 21); and construction (NAICS code 23). Overall energy use in this sector is largely for process heat and cooling and powering machinery, with lesser amounts used for facility heating, air conditioning, and lighting. Fossil fuels are also used as raw material inputs to manufactured products. Note: This sector includes generators that produce electricity and/or useful thermal output primarily to support the above-mentioned industrial activities.

Source: Glossary accessed at EIA website http://www.eia.doe.gov/.
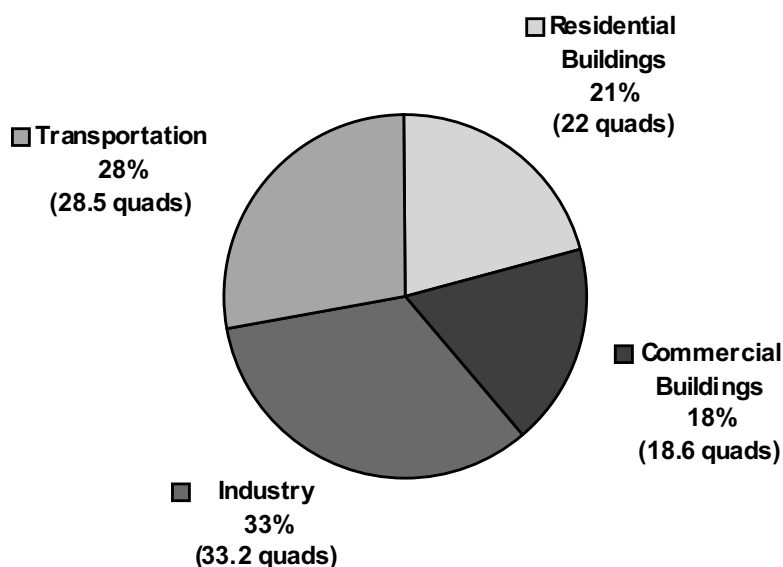
Notes:

- For each sector, "Total Energy Use" is direct (primary) fuel use plus apportioned purchased electricity and electricity system losses

- Economy-wide, total US primary energy use in 2008 was 102.3 quadrillion BTU (quads)

- Source: US Department of Energy, Energy Information Administration, *Annual Energy Outlook 2008*

FIGURE 4-1 Total U.S. energy use by sector, 2008. Source: EIA 2008b.
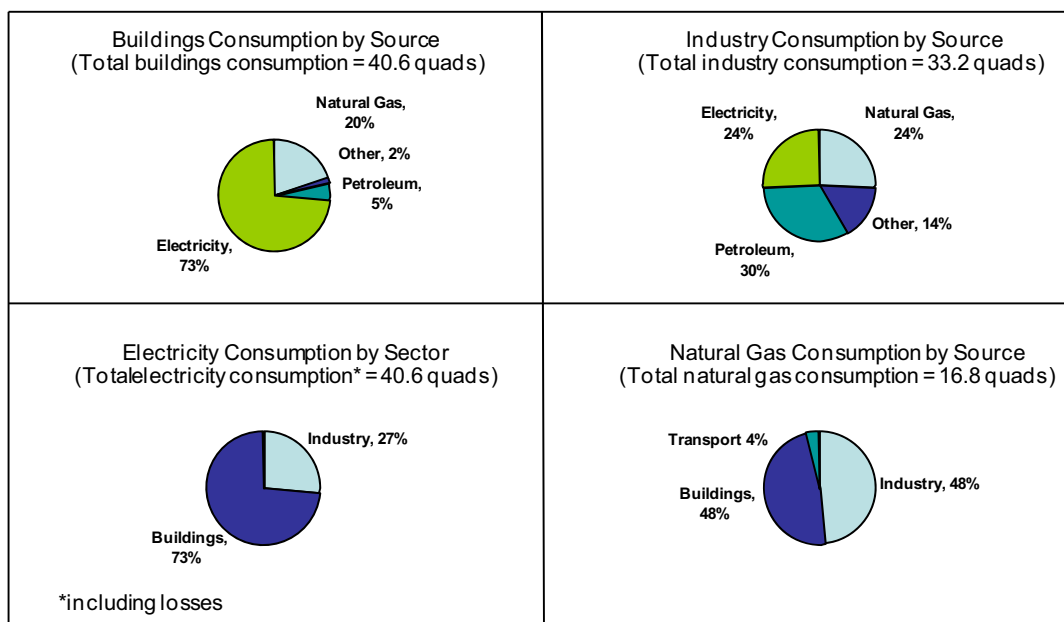
FIGURE 4-2 U.S. Energy consumption by source and sector, 2008 (quadrillion Btu). Source: EIA 2008b.

Most industrial processes and buildings have operating lives of three or more decades, so, in addition to new installations to meet growth in demand, only a few percent of the existing stock is replaced each year. Much of the existing building and industrial plant stock is thirty or more years old and employs older technologies. Therefore assessing externalities associated with future energy use needs to consider the upgrading of existing systems ("retrofits") as well as the introduction of new technologies. The AEF Panel Report, *Real Prospects for Energy Efficiency in the United States (*NAS/NAE/NRC 2009 in press), has been used as a major resource for the materials presented in this chapter.

Residential building sector emissions are generally distributed in the same manner that population is distributed. Commercial buildings are located in urban areas and suburban towns and villages. Industrial fuel use is more concentrated in industrial areas, and varies by industry. Because of differences in scale and characteristics of the combustion processes, local health effects and other effects will be somewhat different, and these are identified and discussed in general. Greenhouse gas emissions enter a common atmosphere and are not sensitive to location of the emission. Other externalities may exist, but are not quantified in this chapter.

The committee used the same APEEP methodology, with all the caveats described in detail in prior chapters and in Appendix C, to assess damages related to energy use for heat in the buildings and industrial sectors. The primary fuel, natural gas, is estimated to have relatively low non-climate change damages per kWh as compared to coal or wood, for example. We have not estimated damages associated with home heating by coal or biomass fuels because these are a relatively small part of the total energy mix for that use and because recent trends in increased use of natural gas fireplaces are expected to reduce damages related to coal or biomass use for space heating. Only about 12% of U.S. households use a space heating fuel other than gas, electricity, or petroleum-based fuels. At present, there is no other primary energy source that can be readily substituted for natural gas on a wide scale to provide further reduction of such damages. Therefore, opportunities for future reductions of non-climate-change damages from energy use for heat in the buildings sectors, in particular, are likely to occur mainly through the incorporation of energy efficiency in the building structures and heat energy systems, as well as the inclusion of localized energy technologies, such as solar thermal water heating or geothermal heat pumps.

HEAT IN RESIDENTIAL AND COMMERCIAL BUILDINGS

Buildings in the United States consume about 39% of U.S. primary energy, although 73% of this energy is delivered in the form of electricity. The remaining 27% of the energy is primarily used for heating purposes. The AEF Efficiency Panel Report provides a detailed description of buildings in the residential and commercial sectors in the United States and describes present status and a portfolio of future opportunities for reducing energy consumption in both these sectors. In the past, energy for heating was a modest and affordable portion of annual building operating expenses. As energy prices have risen, more attention is now being given to energy conservation through investments in efficiency and in behavioral changes. Building codes are just starting to reflect this trend, but the construction industry employs many standardized building components and construction methods that it is reluctant to change because a move toward building more innovative structures would require new investments and training and also increase costs. However, many "green" buildings are emerging from forward-thinking architects and design firms for wealthier clients, and the public is becoming more aware of these possibilities.

The *residential* building stock in the United States consists of 101 million single family homes, 32 million multifamily housing units, and nearly 7 million mobile homes (EIA 2008). Homes typically last 100 years or more; household electrical appliances usually last for 10-20 years; and furnaces and water heaters last around 10 years.

There are about 5 million *commercial* buildings in the United States (2003), with about 75 billion square feet of floor space (EIA 2008e, Table A1). Commercial buildings have life spans of 50 years or longer. This section will look separately at energy use for heat in residential and commercial buildings for estimation of present externalities and implications for 2030 externalities. For each of these sectors, because of the large existing building stock, options for retrofit of older buildings need to be considered in addition to possibilities for improved new technologies and designs.

The National Research Council (NRC) report, *America's Energy Future: Technologies and Transformation (*NAS/NAE/NRC 2009a*),* finds:

- "Studies taking several different approaches are consistent in finding the potential for large, cost-effective energy savings in buildings…amounting to a 25-30% energy savings for the buildings sector as a whole over 20-25 years. If these savings were to be achieved, it would hold energy use in this sector about constant, in contrast to the current trend of continuing growth."

- "There are substantial barriers to widespread energy efficiency improvements in buildings. But a number of factors are counteracting these barriers. Drivers of increased energy efficiency include rising energy prices, growing concern about global climate change and the resulting willingness of consumers and businesses to take action to reduce emissions, the movement towards 'green buildings,' and growing recognition of the significant non-energy benefits offered by energy efficiency measures."

Residential Buildings

The major uses of energy for heating in residential buildings are water heating and space heating. The U.S. Energy Information Administration (EIA) (EIA 2009i) data show that in 2005, for 111 million households, energy use for space heating was 4.3 Quads and for water heating was 2.1 Quads. Since 40% of water heaters are electric, roughly 1.2 Quads can be attributed to use of *natural gas* for water heating. This total "energy for heat" estimate for 2005 of about 5.5 Quads is consistent with the 2007 sector use numbers for liquid fuels and natural gas of 6.2 Quads, allowing for some growth in the number and size of residential buildings. Renewable sources of energy provide a small part of the total and would be expected to produce smaller externalities than the fossil fuels in generating heat.

Commercial Buildings

The major uses of energy for heat in commercial buildings are for space heating and water heating. In 2003, EIA reported that 2.37 Quads of energy were used for space heating. About 0.5 Quads were reported for water heating and 0.2 Quads for cooking. Since some of these uses are provided by electricity, an estimate for non-electric heating for water heating and cooking is about 0.4 Quads. This results in an "energy-for-heat estimate" for commercial buildings of about 2.8 Quads total in 2003 (for 58.5 billion square feet of floor space). A 2005 survey of industrial and commercial boilers in the United States (EEAI 2005) reports that there were almost 163,000 industrial and commercial boilers in the United States that consumed about 8.1 Quads of fuel energy per year. The report stated that the total rated capacities for the 120,000 smaller commercial facility boilers were 1.1 million Btu/h and estimated that these commercial boilers consumed about 3 Quads of the 8.1 Quads reported for total boiler usage. This can be compared with the 2007 commercial buildings estimate in Table 4-1 of 3.9 Quads (for 75 billion square feet of floor space), indicating that the 2007 increase mostly reflects the expansion in total floor space.

It is also noted that much of the expansion in floor area is due to construction of strip malls. Looking forward, the DOE Annual Energy Outlook estimates that commercial building energy use will increase 32% (1.1% per year) by 2030.

HEAT IN THE INDUSTRIAL SECTOR

The U.S. industrial sector (see Box 4-2) consumes about one-third of the U.S. energy supply, but only about 21% of the total supply comes from non-electric energy use. Of the 21 Quads of non-electric energy consumed in the industrial sector in 2007, around 8 Quads of this may be attributable to "non-fuel" purposes, such as the use of petroleum refining byproducts in asphalt, feedstock for petrochemical products, and coal in the production of coke for steelmaking (EIA 2007, Table 1.5).[2] However, although asphalt, plastics and similar products sequester some carbon from the feedstock, most of the industrial uses generate carbon dioxide emissions as a result of processing operations—in some cases more than would be generated from direct fuel combustion, if the process itself generates carbon dioxide. In addition, as more industrial production has moved offshore, energy embodied in imported goods is not counted in the EIA statistics. Ultimately, some petrochemical products may end up in waste streams that are used as an energy feedstock.

TABLE 4-1 U.S. Non-Electric Energy Consumption by Source and End Use Sector: Years 2007 and 2030 (EIA estimates) (quadrillion Btu)

Energy Source	Industrial Sector	Residential Sector	Commercial Sector
Liquid fuels[a]	9.96/8.35	1.35/1.10	0.63/0.59
Natural gas	8.02/8.47	4.86/5.06	3.10/3.53
Coal	1.83/2.23	0.01/0.01	0.07/0.06
Renewables[b]	2.07/3.89	0.43/0.50	0.12/0.12
Total	21.88/22.94	6.65/6.67	3.92/4.30

[a]Liquefied petroleum gases, kerosene, distillate fuel oil, residual fuel oil, gasoline.
[b]Hydropower, wood and wood waste, municipal solid waste.
Note: Total U.S. primary energy consumption in 2007 was 101.92 Quads; in 2030, total U.S. energy use is projected to be 112.35 Quads.
Source: EIA 2009e.

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[2]See: EIA 2009j These are the latest data available.

BOX 4-2 Energy for Heat in Steel Manufacture

Iron ores are mined as minerals in oxidized form. After cleaning and separation, the iron ore is reduced to pig iron in a coke-fueled blast furnace. Coke is the char material produced by heating bituminous coal in a sealed oven for 10 or more hours to drive off volatile "coal gases" resulting in a char material called coke. Without proper effluent treatment, coke ovens can emit substantial amounts of dust and a wide range of emissions that from various criteria pollutants. In a blast furnace, iron ore is reduced to pig iron by reaction with the coke and the formation of carbon dioxide. Energy was needed to produce the coke; but the coke reactions add some energy to the blast furnace. Further heat is required in additional refining steps in a basic oxygen furnace or an electric arc furnace.

When iron products are recycled, a much smaller amount of heat energy is needed to re-melt them in an electric arc furnace (EAF) than is needed in producing pig iron from mineral ores, partly since the reducing agents are not needed. While it is difficult to compare "virgin" and "recycled" steel since nearly all steel is comprised of some mix of recycled steel, the underlying processes are somewhat indicative of the difference. Worrell et al. (2008, Table 1.1) give a "best practice" of 14.8-17.8 GJ/tonne for a BOF and 2.6 GJ/tonne for a 100% scrap EAF.

Estimation of Industrial Use of Energy for Heating

Table 4-1 presents EIA industrial energy use estimates, by primary fuel type, for 2007 and their use projections out to 2030. DOE's Annual Energy Review suggests facility heating in the industrial sector consumes about 10% of electricity and natural gas (EIA 2008a). Figure 4-3 presents energy use, energy intensity, output and structural effects in the industrial sector from 1985 to 2004. Table 4-1 indicates that the major industry sector fuel sources generating externalities are about 10 Quads of liquid fuels (liquefied petroleum gases, kerosene, distillate fuel oil, residual fuel oil, and gasoline), 8 Quads of natural gas, and about 2 Quads of coal. The mix includes about 2 Quads of energy use from "renewables" (primarily hydropower, wood, and wood waste) and municipal solid waste. The two largest industrial sectors in terms of fossil fuel consumption are the petroleum refining industry and the chemical industry. The petroleum industry in 2002 used about half of its 6 Quads of liquid fuels for feedstock (not associated with producing energy products such as gasoline and jet fuel); the chemical industry used about half of its 5 Quads of fuel use (primarily natural gas) for feedstock.[3] Coal is mostly used to make coke and carbon black, but a portion of the coke ends up as heat energy in steelmaking. Therefore, it is only possible to make fairly crude estimates of energy use for heat in the industrial sector; estimating externalities associated with such uses is subject to even more uncertainty.

Industrial boilers are used to generate steam for a wide variety of industries and industrial processes. The 2005 survey of industrial and commercial boilers in the United States (EEAI 2005) cited earlier in the commercial sector discussion, reports that there are almost 163,000 industrial and commercial boilers in the United States that consume about 8.1 Quads of fuel energy per year. Of that about 5 Quads is accounted for by industrial boilers, with about 60% (3 Quads) of this energy supplied by natural gas. The industrial manufacturing sector accounts for 43,000 of the boilers, but these are of larger capacity than those used in commercial heating applications. The report presents total rated capacities for these industrial boilers at 1.6 million Btu/h. Non-manufacturing industrial boilers include those used in agriculture, mining, and construction. These 16,000 units have a nameplate capacity of 0.26 million Btu/h. The remaining boilers use a diversity of fuels, often byproducts of the industry involved. For example, the paper industry uses biomass waste streams to fuel 48% of its boilers (rated capacity 0.4 million Btu/h); primary metals utilize process heat for 42% of their boilers (rated capacity 0.1 million Btu/h); and the refining industry uses refinery byproducts to fuel 49% of their boilers (rated at 0.2 million Btu/h).

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[3]NAS/NAE/NRC 2009. Energy Efficiency Panel Report.
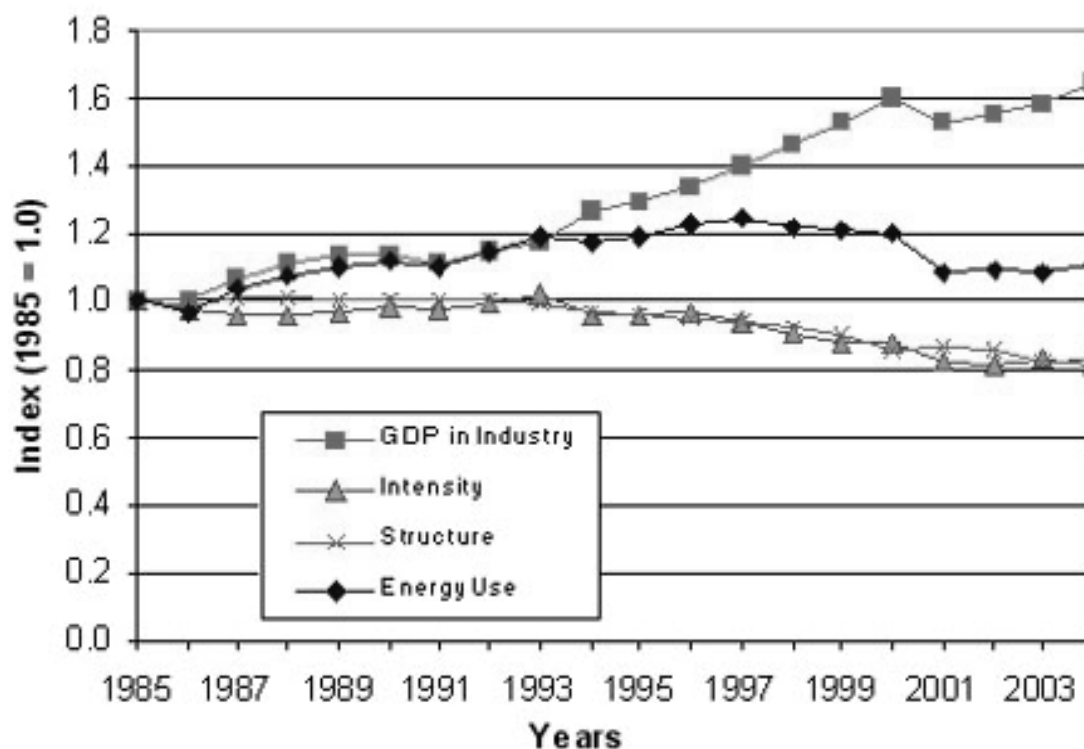
FIGURE 4-3 Energy use, energy intensity, output, and structural effects in the industrial sector, 1985-2004. DOE uses input/output analyses to assess energy use across all U.S. industrial activities. Intensity is energy consumption per unit of demand for energy services (e.g., per kWh or VMT or, nationally, GDP); structural effects attempt to account for variability across the spectrum of industry operations (see EIA 2003). Source: DOE 2008b, Figure I1.

Because the U.S. industrial sector is so diverse and EIA energy statistics do not necessarily correspond to energy use for heat in this sector, the externalities attributable to industrial energy use for heat are difficult to separate from externalities associated with energy use for other industrial processes involved (Box 4-2).

Natural gas is the major fuel used for heating in the industrial sector. Figure 4-4 shows how its use was distributed among manufacturing sectors in 2002. Total industrial sector natural gas consumption in 2002 was reported as 6.47 Quads with 5.8 Quads used for heating and 0.67 Quads used for feedstock purposes (e.g., chemicals and fertilizer). Consumption in 2007 is reported as 8.02 Quads, but the general distribution by industry sector is probably still representative.

The economic downturn in progress as this report is being written is likely to reduce industrial activities in the United States to some extent. Nevertheless, the following adjusted 2007 EIA data for the industrial sector are taken as the baseline for making rough estimates of externalities associated with heating uses in industry in our report.

- Petroleum: 10 Quads – 3 Quads used as feedstock   = 7 Quads net
- Natural Gas: 8 Quads – 2 Quads used as feedstock   = 6 Quads net
- Coal: 1.8 Quads   = 1.8 Quads net
- Renewables (treat as biomass) 2.1 Quads   =2.1 Quads net
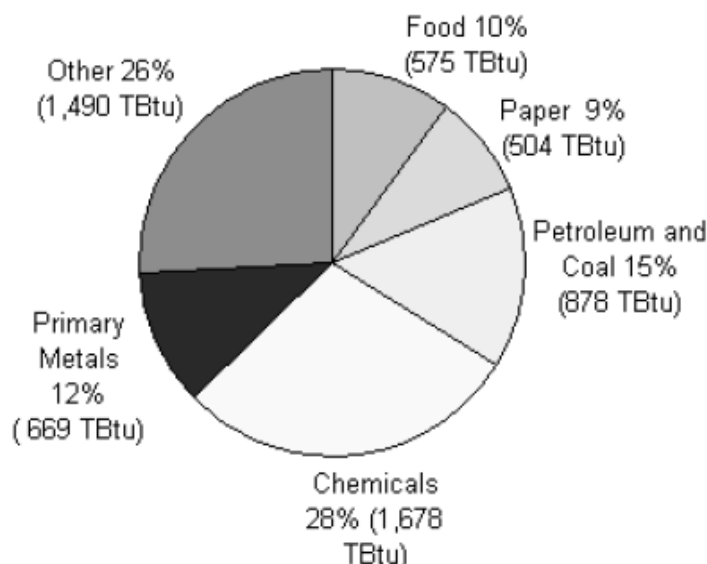
FIGURE 4-4 Manufacturing sector consumption of natural gas as a fuel by industry, 2002. Source: EIA 2006c, Figure 5.

ESTIMATES OF EXTERNALITIES
ASSOCIATED WITH ENERGY USE FOR HEAT

It is much more difficult to make reliable estimates of the unpriced damages associated with energy use for heating in the buildings and industrial sectors, than to evaluate such impacts for electricity generation or for transportation. However, since about 30% of U.S. primary energy is used for heating purposes, it is important to attempt a quantification of associated damages even if detailed estimates are not possible. The residential and commercial sector estimates are somewhat more tractable than those for the industrial sectors where some of the energy use reported by DOE statistics does not sufficiently delineate fuels used as feedstocks.

Table 4-1 shows that the dominant fuel used in the residential and commercial building sectors is natural gas, comprising about 75% of their energy use. About 19% comes from liquid fuels, with somewhat higher health impacts; about 5% comes from renewables; and less than 1% comes from coal. Detailed data were not available on county-level consumption of wood for heating and so a comparable damage estimation method for wood was not possible in this study. The industrial sector impacts involve more fuels and more diverse activities.

The focus of externalities considered in this chapter are health effects associated with criteria-pollutant forming emissions from fuel combustion. Greenhouse gas emission externalities that are linked to present and future changes in climate and the associated impacts are discussed in Chapter 5.

Residential Buildings: Damage Estimates for Criteria Air Pollutants

As shown in Table 4-1, the liquid fuels and natural gas predominate because of the relatively large volumes consumed, with a small amount of coal use: those associated with "renewables" are not included because they are of a diverse and smaller magnitude. For these reasons we focus on natural gas directly burned for heating purposes and make some comparisons with the use of electricity for heating in buildings.

As noted previously, potential externalities from consuming natural gas for heat could arise not only from the on-site combustion but also from the upstream supply chain of extraction and distribution of the gas. We estimate damages attributable to criteria-pollutant forming emissions from combustion on site, but we were not able to estimate damages from such emissions from upstream activities due to data and modeling issues. Few studies have estimates these upstream emissions (e.g., Jaramillo et al. 2007), and these estimates were limited to only NO_x and SO_x emissions, and showed large uncertainty ranges. Since modeling the upstream extraction and distribution damages from criteria-pollutant forming emissions would need to be allocated to more than 300,000 wells and associated pipelines across the United States (compared to the existing database of power plants for electricity production in Chapter 2 and the roughly 100 plants for automobile production in Chapter 3), we elected not to estimate them. This is not to say the externalities would be negligible; Jaramillo et al. (2007) estimated significant upstream emissions of NO_x and SO_x (ranges of 0.009-0.3 and 0.006-0.03 lb/MMBtu, respectively) associated with North American natural gas compared to the combustion emissions (0.094 and 0.0006 lb/MMBtu); however, the process of allocating natural gas use to the thousands of potential point and area sources, given such large uncertainty ranges in the literature, was deemed intractable given the time and resources available. Thus, we focused on criteria pollutant forming emissions from on site combustion.

Our estimates of combustion externalities come from multiplying county level consumption with county level damages. The county level consumption and criteria-pollutant forming emissions of residential natural gas are taken from the EPA National Emissions Inventory (NEI) for 2002. These emissions by county at grade are multiplied by estimated county-level health and other damages per ton of criteria-pollutant forming emissions from the APEEP model, and are subject to the model's assumptions and limitations (see Chapters 1, 2, and 3).

The results are county-level health and ecosystem externality estimates, which are then normalized by the 2002 NEI's consumption of natural gas by county to estimate damages per thousand cubic feet (MCF) of gas.

Table 4-2 shows the national range across more than 3,000 U.S. counties of estimated damages from air pollutants (excluding CO_2, which is considered later), assuming the value of a statistical life (VSL) is $6 million ($7.2 million in 2007 USD). Variability is a result of county differences. The median damage estimate is approximately 11 cents/MCF (the mean is approximately 35 cents/MCF). Those estimates are unweighted; weigthting the damages by county population of the source emissions would lead to an average of about 30 cents/MCF. As previously indicated, we do not include the upstream life-cycle SO_2 emissions related to natural gas—such emissions are low. With the residential price of natural

TABLE 4-2 Residential Sector Natural Gas Use for Heat: National Damage Estimates from Air Pollutants (Excluding Greenhouse Gases) (cents/MCF) (2007 USD) (Damage Estimated from 2002 NEI Data for 3,100 Counties)

	Mean	Std. Dev.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO_2	0.37	2.4	0	.06	0.16	0.27	.9
NO_x	26	180	1.7	4.9	8.3	13	48
$PM_{2.5}$	0.8	5	.05	.12	.23	.50	2.1
VOC	1.4	8.7	0.02	0.12	0.25	0.54	2.9
NH_3	0.37	2.4	0	0	0	0	1.6
Total (unweighted)	35	230	3	7	11	18	72

Note: 200 counties, for which relatively little emissions data were available, were excluded so as not to skew the distribution in an unrealistic way.

gas at about $10/MCF,[4] the mean health-related externalities from criteria-pollutant forming emissions are about 1% of the price. Aggregate damages (unrelated to climate change) were approximately $500 million (2007 USD).

As done in the Chapter 2 on electricity, it is relevant to consider the regional variation within the United States for the externalities from heating. Table 4-3 illustrates the damage estimates on a census region basis). The median estimates of damages related to criteria- pollutant forming emissions from different regions are similar to the national level, ranging from 6 cents/MCF to 14 cents/MCF (2007 USD). The regional breakdown highlights the large range of externalities in the South compared to other regions, but these outliers occur due to rounding errors in estimating externalities of counties with very low consumption of natural gas. Regardless, the 90th percentile values in the South still represent damages at only 5% of the price of natural gas.

We can use these results to compare the damages from natural gas combustion for heating with damages associated with using electricity for heat. From Chapter 2, production of coal-fired electricity has mean damages weighted by net generation from criteria-pollutant forming emissions of $0.032/kWh and gas-fired electricity has a mean externality of at least $.0016/kWh (excluding CO_2). Scaling these

TABLE 4-3 Residential Sector Natural Gas Use for Heat: Regional Damage Estimates (Excluding GHGs) (cents/MCF) (2007 USD). Damage Estimates Based Upon 2002 NEI Data for 3100 Counties

	Mean	Std. Dev.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
MIDWEST							
SO_2	0.4	2	0	.05	.15	.22	.49
NO_x	35	290	4	7	11	15	36
$PM_{2.5}$	0.8	7	.05	.1	.18	.34	1.1
VOC	1	9	.06	.13	.25	.44	1.4
NH_3	0.4	2	0	0	0	.03	2.6
Total (unweighted)	46	370	5	9	14	19	47
NORTHEAST							
SO_2	0.38	0.34	0	.19	.3	.47	1.0
NO_x	10	12	0	3.5	6.3	11	34
$PM_{2.5}$	0.8	1.1	0	0.23	0.5	1	2.8
VOC	1.1	1.3	0	0.35	0.71	1.5	3.4
NH_3	0	0	0	0	0	0	0
Total (unweighted)	16	17	2	6	11	18	51
SOUTH							
SO_2	0.4	1.1	.03	.09	0.2	0.34	1.1
NO_x	24	79	2.1	4.8	7.8	13	64
$PM_{2.5}$	0.92	3.1	.09	.17	0.31	0.64	2.5
VOC	2	10	0	0.15	0.3	0.72	4.2
NH_3	0.5	3	0	0	0	0	1.3
Total (unweighted)	33	107	3.4	6.8	11	18	93
WEST							
SO_2	.27	1.7	0	.06	.08	.13	.41
NO_x	12	66	.18	2.9	4.4	6.5	16
$PM_{2.5}$	0.5	2.7	0.02	0.05	.09	.21	1.8
VOC	.32	1.6	.02	.06	.09	.18	.83
NH_3	.03	.3	0	0	0	0	.05
Total (unweighted)	16	88	1.7	4	6	8.8	22

Note: This table reports the same data as in Table 4-2, aggregated by Census region. 200 counties, for which relatively little emissions data were available, were excluded so as not to skew the distribution in an unrealistic way.

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[4]A 2007 price for natural gas is used for consistency with the 2007 data on which the estimates of damages are based. Natural gas prices fluctuate and in 2009 are well below this price.

numbers using the weighted average national grid in Table 2-1 of Chapter 2 (48.5% coal and 21.3% gas) results in average damages near $0.016/kWh (excluding CO_2; 2007 USD). Likewise the median damages from electricity would be estimated as 0.485*1.8+0.213*.036 = 0.87 + $0.0088/ kWh (excluding GHGs; 2007 USD).

The obvious comparison to show is heating a house with natural gas versus heating a house with electricity at the national level (grid average). The average amount of electricity used to heat a house in the US is 2,100 kWh (EIA 2009i, Table SH7). The average amount of natural gas used to heat a house is 49,000 cf. (49 Mcf). Using the numbers above we would say the estimated mean damages of electricity for heating, excluding GHGs, would be calculated as $0.016 * 2100 = $34 per year (2007 USD), and the estimated mean damages for natural gas would be $0.35*49 = $17 per year (2007 USD). The estimated median damages of electricity and natural gas use for heat would be $19/year and $5/year respectively. Thus the non-climate damages from heating with gas instead of electricity are almost an order of magnitude less. Using the range of natural gas non-climate-change damages would lead to results three times lower than electricity for heating at the 5th percentile, but at the 95th percentile would be about the same as non-climate damages from using electricity for heating.

Commercial Buildings: Damage Estimates for Criteria Air Pollutants

Following a similar method, commercial sector heating externalities from burning natural gas were estimated. Unlike for the residential case, the 2002 NEI emissions inventory did not include corresponding estimates of natural gas consumption for the commercial sector in each county. Thus the consumption of commercial sector natural gas was estimated by using AP-42 emissions factors for carbon monoxide (CO) of 84 lbs/MCF, which do not vary drastically across combustion technologies (but adds some uncertainty to our estimated consumption by county). When using this proxy, the total estimated consumption of natural gas in the commercial sector was 2.2 million MCF, somewhat lower than the EIA estimate for 2002 of 3.1 million MCF. Table 4-4 shows the national level range of externalities from commercial combustion of natural gas, with results very similar to the residential case. The median externality excluding GHG emissions, 11 cents/MCF, is plausible given its similarity to the residential damage estimate. Given the similarity, the externality estimates by census region for the commercial sector are not shown. Aggregate damages are about $300 million (excluding damages related to climate change) (2007 USD).

TABLE 4-4 Commercial Sector Natural Gas Use for Heat: National Damage Estimates from Air Pollutants (Excluding GHGs) (cents/MCF in 2007 USD) (Damages Estimates Are Based upon 2002 NEI Emission Data for 3,100 Counties.)

	Mean	Std. Dev.	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
SO2	0.3	1.3	.06	0.1	0.2	0.3	0.8
NOx	13	35	3.5	5.9	9.0	14	27
PM2.5	1.1	19	.07	.14	.26	.53	1.7
VOC	.65	2.7	.08	.16	.28	.53	1.7
NH3	.68	2.6	0	.03	.13	.44	2.7
Total (unweighted)	15	56	3.7	6.7	10	16	32

Note: 200 counties, for which relatively little emissions data were available, were excluded so as not to skew the distribution in an unrealistic way.

Externalities Associated with Industrial Energy Use for Heating

Unfortunately a parallel analysis could not be undertaken for externalities from heating in the industrial sector due to several challenges. The level of detail for the residential and commercial sectors in the NEI, including fuel consumption by county, was not available for the industrial sector. While the NEI has estimates of emissions from industrial activities by county, disaggregating the emissions to include only estimates from the use of fuels for heating, and from industrial activities that would not be included elsewhere in this report, proved too problematic to overcome. We are thus only able to make qualitative assessments of these externalities.

Externalities associated with present energy uses for heat in the industrial sector might be approximated by using estimates of the externalities that are associated with the use of the particular energy source in electricity generation. These are the externalities caused by the production, processing, transportation, and combustion of the particular fuel (petroleum, natural gas, biomass, and coal) in electric power plants, scaled by the annual use factors for the industrial sector and the electrical sector. This method gives approximate results for greenhouse gas emissions, but is very crude for estimates of local health and environmental impacts, because of large difference in emissions from power plants, and those associated with a wide range of industrial facilities that use energy for heat as a part of wider manufacturing activities. Specific local health and environmental effects will be different for industrial locations, so the estimates will be subject to considerable uncertainty. The EIA provides national and regional (Northeast, Midwest, South and West) data for energy use by industry according to the North American Industry Classification System (NAICS) codes (EIA 2007, Table 3.2). Unfortunately many of the details are missing in regional summaries because errors are too high or because specific plants might be identified. Therefore it was not possible to identify the locations of large emitters that might have more significant local health and environmental effects.

Table 4-1 shows that natural gas use in the industrial sector, less use for feedstock, was about 6 Quads in 2007. This usage is actually smaller than the 8 Quads of natural gas used in the residential and commercial buildings sectors. Therefore, in the absence of more detailed information, it may be assumed that the health and environmental externalities of this usage are probably of the same order or less than the impacts associated with natural gas use for heat in buildings. A very rough order of magnitude estimate of average externalities associated with the industrial sector usage of natural gas is therefore 11 cents/MCF, excluding GHG damages. Thus, the 6 Quads of natural gas used for industrial heat would generate about $600 million in damages.

The other large usage of fuel for industrial energy is associated with liquid fuels (about 7 Quads). Half of this usage is associated with just three sectors—paper, chemicals, and petroleum refining—the last of which has already been included as part of the lifecycle upstream externality estimates made for the transportation sector usage of petroleum fuels.

We can infer from Table 4-1 that the non-electric use of energy in the industrial sector is almost double that of the residential and commercial sectors combined. However, when feedstock use is taken out of the fuel mix, the remaining use of energy for heat is probably about equivalent to the buildings sectors. Figure 4-5 also shows that the greenhouse gas emissions from the industrial sector have been declining since 2000, while the buildings sectors show only small increases.

The EIA energy use projections for 2030 incorporate some consideration for the incorporation of energy efficiency improvements to offset energy demand from growth in industrial capacity. These are based on present energy policies and could vary considerably if new policies are adopted. The estimates for non-electric usage show a very small growth in energy use between now and 2030. The three efficiency studies cited in the previous section indicate that there is a good potential for achieving about 10-15% overall improvement in efficiency in the use of energy to produce heat in the industrial sector if more aggressive energy policies are adopted in the future. Therefore, non-climate externalities in 2030 might be about the same as those associated with the fuel uses that exist today—or they might be reduced by 10-15%. The most likely source of reducing externalities per unit of heat would be from changes in the electricity sector, as emissions from natural gas are relatively small and already well controlled.

Considering externalities from heat in 2030 should consider potential changes in energy sources. Over such a short timeframe it is unlikely that significant infrastructure replacements or changes could occur (e.g., by moving from electricity or gas to an alternative). Instead, it is more likely that alternative sources of natural gas become more prevalent, such as from shale deposits or from increased imports of LNG. Our analysis has presumed domestically sourced natural gas for estimating externalities, both because LNG imports are currently small and because estimating the health damages from global operations was not possible. However the upstream emissions of LNG have been estimated to be somewhat higher. Thus the externalities estimated here are low because they do not consider these upstream extraction emissions from any sources of natural gas.

EMISSIONS OF GREENHOUSE GASES

Figure 4-5 shows the greenhouse gas emissions (in million of metric tonnes[5] of carbon dioxide per year) for each of the end use sectors. The sector estimates also include electricity use apportioned to use within the sector. To estimate the greenhouse gas emissions associated with heating uses, it is necessary to deduct the electricity component (also shown in Figure 4-5).

- 2007 residential and commercial sector emissions = $1,250 + 1,087 - (0.73)(2,433) = 561$ million tonnes of CO_2 (618 tons). This is roughly equivalent to about 10 Quads of natural gas.
- 2007 industrial sector emissions = $1,640 - (0.27)(2,433) = 983$ million tonnes of CO_2 (1,084 tons).

For natural gas, each MCF generates about 1,000 million Btu on average and generates about 120 pounds of CO_2 (about 0.05 tonnes or 0.06 tons of CO_2). Methane, the major component of natural gas, is a greenhouse gas itself if it enters the atmosphere through leakage. It has a warming potential about 25 times that of CO_2.[6] However, EIA estimates that such leakage amounts to less than 3% of total U.S. CO_2-equivalent emissions (excluding water vapor) in 2007. Nitrous oxide (N_2O) is also a greenhouse gas, but the emissions from its use are a very small share of total GHG emissions.

In the sections above we estimated externalities from criteria-pollutant forming emissions from the residential and commercial building sectors. Aggregate damages from combustion of natural gas for direct heat are estimated to be about $1.4 billion per year (2007 USD), assuming the magnitude of effects resulting from heat production in industrial activities is comparable to those of residential and commercial. These estimates did not include emissions of GHGs. Emissions of GHGs associated with burning natural gas can be estimated in a fairly straightforward manner, about 120 lb (0.06 tons) of CO_2-eq/MCF (EPA AP-42). While we did not estimate damages related to criteria-pollution forming emissions from upstream activities due to spatial and geographical modeling concerns, we can estimate the emissions of upstream GHGs from natural gas from literature sources. Jaramillo (2007) summarizes estimates of upstream natural gas emissions of 15-20 lb CO_2-eq/MCF for North American sources or 30-70 lb CO_2-eq /MCF for LNG, adding about 15% and 40% to the emissions, respectively.

Thus in the near term where domestic natural gas remains the dominant source, the emissions factor is likely to be approximately 140 lb CO_2/MCF (including upstream methane emissions), while in the longer term with increasing levels of LNG or shale gas as part of the mix, the average emissions factor could be 150 lb CO_2-eq/MCF.

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[5]One tonne equals 2,200 pounds.
[6]Based on 100-year GWP values.
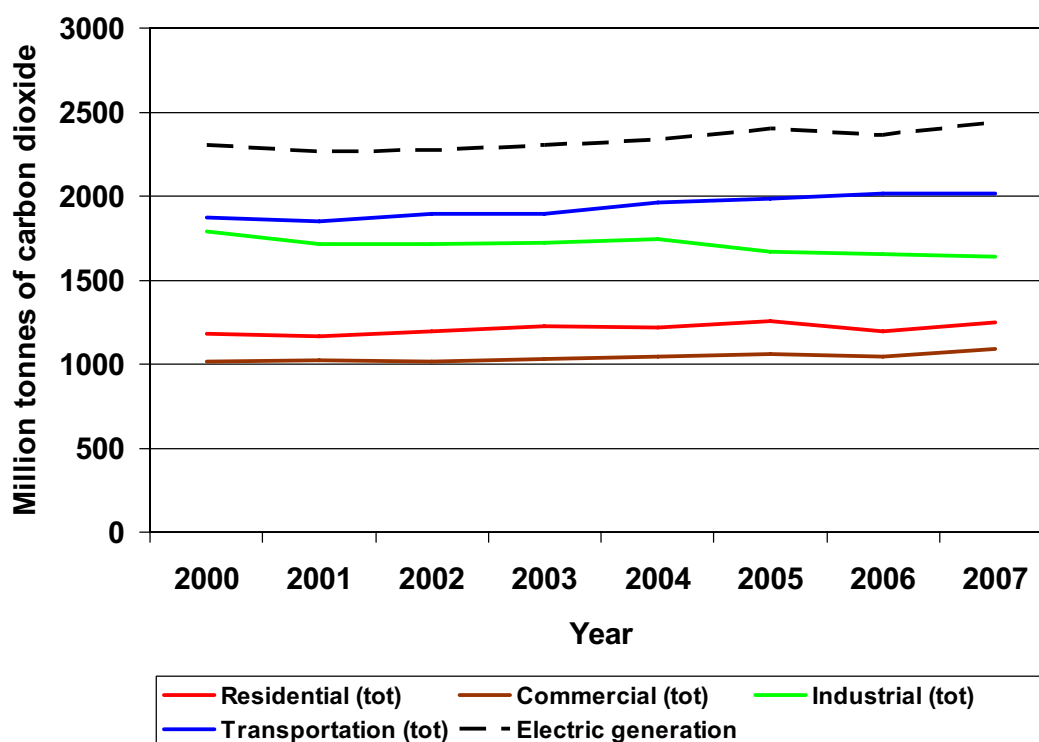
FIGURE 4-5 GHG emissions in the United States by sector. Totals include electric power use distributed across the end use sectors. Source: EIA 2008f.

POTENTIAL DAMAGES REDUCTIONS IN 2030

Residential Buildings

The major options for reducing heating energy demand in the future are presented in more detail in the AEF report Real Prospects for Energy Efficiency in the United States (NAS/NAE/NRC 2009 in press). The report focuses on the potential for reducing total energy consumption in the residential sector, where primary energy used to provide electricity is much greater than the consumption of non-electric primary energy for heat. The ways to reduce energy use for heating mainly focus on better insulation of the building envelope and use of higher efficiency methods for water heating. The main possibilities include:

- For existing buildings:
  - Addition of insulation to exterior walls and under roofs
  - Replacement of old windows with high performance windows
  - Replacement of old furnaces with higher efficiency devices
  - Use of control systems to minimize heating of unoccupied spaces (except to prevent freezing of water pipes) and to lower temperatures at night
  - Addition of solar thermal water heating
  - Behavioral changes such as reducing thermostat settings, sensible opening and closing of windows and shades, wearing warmer clothing to lower indoor set temperatures during the heating season (and cooler clothing to higher set temperatures during the cooling season)

o   Reducing air leakage from the building (with care to assuring that indoor air quality is not compromised—some heat exchangers are available to preheat inlet air with warm exhaust air)
- New construction:
    o   Energy efficient design for site location—using passive solar heating, shading, installation of geothermal heat pump systems, combined heat and power systems, high efficiency walls and windows, natural ventilation for warm climates, smart control systems, and many other techniques (see Box 4-3).
    o   Behavioral changes to accommodate to smaller living spaces per capita or more desirable multiple dwelling units designed for energy efficiency.

Projecting how improvements in the heating demand for residences might evolve to a 2030 time period seems highly uncertain although some improvements to at least offset sector growth appear feasible. As of 2008, the DOE's Annual Energy Outlook forecasted energy use in the residential sector to otherwise increase by 16% (0.4% per year) by 2030. The trends resulting from current financial issues are also likely to keep the 2030 energy use in this sector stable or reduced relative to 2007. This potential is discussed in the AEF Main Report cited earlier.

Commercial Buildings

Because space heating requirements are largely determined by the building envelope characteristics, there are limited opportunities for reducing the heating energy requirements for existing buildings. Replacement of windows, upgrading of furnaces, boilers, and heat distribution systems may offer some improvement, but such investments may have limited cost-effectiveness except for much older or larger buildings. The AEF report Real Prospects for Energy Efficiency in the United States (NAS/NAE/NRC 2009 in press) focuses primarily on larger efficiency gains that can be achieved through improvements in the use of electricity. Ironically, large amounts of waste energy from electrical devices, e.g., from inefficient electronic power supplies that give off heat, may actually reduce the heating load required for a commercial building (but increase the cooling load in warm weather).

New commercial buildings offer many more opportunities for investing in new designs to reduce heating energy requirements. Since commercial floor space has been expanding rapidly over the past

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BOX 4-3   Zero-Energy Concept Home

Architects and engineers currently discuss the prospects of residences that have zero net demand for energy. This "zero net" demand does not imply that the buildings have no energy demand; rather the buildings have technologies integrated into them (such as solar panels or geothermal wells) such that they do not demand energy from beyond what the home is able to supply itself. Achieving such a goal depends on several innovative design changes in the residential housing industry. First, technologies need to be cost-effectively scaled to what can fit within the space and budget available for a house. Second, to be able to generate enough of its own energy needs, a house needs to be designed to achieve much lower energy use regardless of energy source. This means using advanced lighting (e.g., solid state lighting (aka LED lighting), orienting the house to take advantage of sunlight and improving insulation. Design for efficient utilization of space is also important to eliminate the need for heating and cooling of rarely used floor area. These measures reduce the demand for energy, and allow the onsite energy generating technologies to better supply this needed level of demand, making the "zero energy" goal possible.

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decade, this may be an area for innovative new buildings that greatly reduce their thermal energy footprints. The U.S. Green Business Council has developed The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ which uses third party experts to evaluate new commercial buildings (or renovations of existing facilities) for their overall environmental and community performance and award ratings based on criteria that include energy efficiency of design and construction as well as ease of maintenance, quality of working environment, waste minimization, etc.(U.S. GBC 2008). The highest LEED rating is "platinum," followed by "gold," "silver," and "certified." The DOE has expanded its Energy Star program to include green building design and makes available a variety of resources for the improved design, construction, and operation of commercial buildings (DOE 2009c). Investment in improved efficiency reduces energy use and eliminates any externalities that would be associated with the energy use avoided.

Case Study of Passive Solar Design

One of the approaches listed in Box 4-3 for a hypothetical "zero energy home" is the incorporation of passive solar design principles. Unlike most of the other technologies listed in this report (and the AEF reports), passive solar is not an energy generation technology.

Passive solar design uses the light and heat of the sun to offset what would otherwise be energy or fuel use in a building. For example, using more skylights in the ceiling and arranging the layout so that the light is able to permeate wide areas of the living space reduces the amount of electricity needed for lighting. Similarly, creating south-facing windows allows the heat of the sun to enter the building and reduce other heating needs.

There are multiple considerations for incorporating passive solar design, and various cost tradeoffs. It was not feasible for the committee to assess how the impacts of a passive solar house might compare to a traditional, fossil energy-fueled building, and no significant literature was found to have quantified the relevant tradeoffs. For direct heat, south-facing windows with special glazing are used that then allow sunlight to enter and reflect off dark masonry floors which absorb heat. This stored heat then is slowly released while the home otherwise cools later in the day (reducing the heating load). Heavier walls can be designed to store and release heat to even out variations between day and night outdoor temperatures. Solar heating can also drive natural circulations within buildings and provide more comfort without circulating devices requiring purchased energy. Case studies have shown massive energy reductions (up to 90%) for comparable new buildings; retrofits are more limited in their ability to reduce impacts and externalities due to various fixed design choices in the existing structures.

While the use phase of the building may require significantly less energy (and thus result in far lower externalities from heat production), the initial construction or renovation of the building along passive solar design principles may lead to significant externalities from manufacturing new insulation, windows, or other intensive construction materials. These initial impacts can be apportioned over the total operating life of the building to provide life cycle annual impacts. A full comparison of these externalities is outside the scope of this study but should be considered before viewing a passive solar house as being externality-free.

Integrated Planning Opportunities

Construction and retrofit of residential and commercial buildings can use integrated design principles with a goal of improving the buildings' environmental and economic performance over their operating lifetimes. Integrated planning is more effective when initiated early in the design/construction process (e.g., subsurface geothermal systems or siting for incorporation of PV or passive solar systems), but can also have benefits for retrofits. Combined heat and power (CHP) systems are now available that generate electricity and utilize the waste energy for heating purposes. When building designs reflect the

extremes of local climate, operation of the building reduces both heating and cooling loads. Commercial buildings generate waste streams that can be utilized for energy on-site or offsite. Incorporation of recycled components into building materials is another way to reduce the lifecycle impacts of buildings. Construction debris represents a substantial component of the waste stream, and much of this can be recycled or converted to thermal energy and/or electricity with proper environmental control. Like energy, water conservation and reuse is another important component—as is indoor air quality and its associated health and productivity impacts.

Industrial Facilities

The AEF report Real Prospects for Energy Efficiency in the United States (NAS/NAE/NRC 2009 in press) devotes a chapter to the potential for energy efficiency improvements in the industrial sector and provides specific examples of how individual industry sectors can reduce energy demand through efficiency improvements, use of waste heat, and more efficient new technologies. That report looks at total energy use, including both electricity and thermal energy (energy for heating) use. It notes that the most energy-intensive industries (e.g., petroleum refining, aluminum, iron and steel, and chemicals) have already placed high emphasis on efficiency of use, especially in domestic facilities.

While some improvements in these industries are possible, larger improvements seem available in the pulp and paper industry and through waste energy utilization and use of combined heat and power systems. When energy costs are a smaller fraction of total costs, companies may pay less attention to investing in efficiency. However, as energy prices increase, industry is geared to respond with innovations in efficiency, more utilization of waste heat, and new processes to reduce its energy consumption. Nevertheless, industry becomes more reluctant to invest of its own initiative in energy efficiency when future energy prices are uncertain and/or volatile. Likewise, under poor market conditions, expenditures for process improvements are likely to be deferred.

Several recent studies cited in the AEF Real Prospects for Energy Efficiency in the United States (NAS/NAE/NRC 2009 in press) estimate the potential for further energy efficiency savings in the U.S. industrial sector as a whole:

- Savings potential of 18-26% (IEA 2007).
- Savings potential of 3.9 Quads of energy reduction (about 12%) in 2020 (McKinsey 2007).
- Savings potential of 16.6% from 2000-2020 with advanced policies (Interlaboratory Working Group 2000).

With continuing emphasis on energy efficiency in industry and likely increases in the cost of energy, it seems likely that energy use for industrial heating in 2030 will be somewhat lower than levels in 2007. The NRC report America's Energy Futures: Technology and Transformation (NAS/NAE/NRC 2009a) finds

- "Independent studies using different approaches agree that the potential for improved energy efficiency in industry is large. Of the 34.3 Quads of energy forecast to be consumed by U.S. industry in 2020 (EIA 2008b), 14 to 22% could be saved through cost-effective energy-efficiency improvements (those with an internal rate of return of at least 10 percent or that exceed a company's cost of capital by a risk premium). These innovations would save 4.9 to 7.7 Quads annually."
- "Additional efficiency investments could become attractive through accelerated energy research, development, and demonstration. Enabling and crosscutting technologies—such as advanced sensors and controls, … and high temperature membrane separation—could provide efficiency gains in many industries as well as throughout the energy system.…"

SUMMARY

Externalities associated with heat production come from all sectors of the economy – residential and commercial buildings, and industry. The vast majority of heat is generated from combustion of natural gas or use of electricity. Combustion of natural gas results in relatively lower emissions compared to emissions from coal combustion, which is the main energy source for electricity generation. Therefore, damages related to providing heat directly from natural gas combustion are much less than damages related to use of electricity for heat. The better emissions performance of natural gas for direct heat also is reflected in the externality estimates of 11 cents/MCF (2007 USD) for residential use and 11 cents/MCF for commercial use, excluding GHGs. These results do not vary much regionally, although some counties have much higher externalities than others. Assuming industrial externality is 11 cents/MCF aggregate damages from combustion of natural gas for direct heat is approximately $1.4 billion per year. The industrial sector contribution to this estimate reflects only natural gas use for heat generation. Including externalities from petroleum combustion, which is on the same scale of energy use as natural gas for industrial heat generation, would lead to a higher estimate of aggregate damages from energy use for heat Insufficient data are available to conduct a parallel analysis of industrial activities that generate useful heat. This situation could be improved with greater attention by EIA to collecting fuel consumption data by county and to provide additional resolution to emissions from disaggregated industrial activities.

The results represented here are the result of an end-use assessment, i.e., that in terms of providing heat, natural gas has lower externalities than electricity. It is not an assessment of how or where to use natural gas, which can be used for direct combustion or indirectly as a fuel for generating electric power.

Overall Implications of the Results

1. Aggregate damages associated with criteria-pollutant forming emissions from the use of energy (primarily natural gas) for heating in the buildings and industrial sectors are low relative to damages from energy use in the electricity generation and the transportation sectors.

2. GHG emissions associated with the use of energy (primarily natural gas) for heating in the buildings and industrial sectors are low relative to GHG emission associated with transportation and electricity production because natural gas carbon intensity is lower than that of coal and of gasoline.

3. The largest potential for reducing damages associated with the use of energy for heat lies in greater attention to improving the efficiency of energy use. The AEF report suggests a potential for improving efficiency in the buildings and industrial sectors by 25% or more—with likelihood that emissions damages in these sectors could be held constant in spite of sectoral growth between now and 2030.

Future Research Needs

1. Assessment of energy use and its impacts in the industrial sector, in particular (but in all sectors to some extent), could be improved by more extensive databases that contain details about specific forms of energy use and associated waste streams. Such databases should be designed so that life cycle analysis of alternatives can be made without inadvertent double counting.

2. A more quantitative assessment of industrial sector externalities, done collaboratively between the government and industry, would be valuable in informing priorities for future initiatives to reduce the externalities associated with industrial operations. Such an assessment was not possible in this study, largely because of data limitations.

5

Climate Change

OVERVIEW OF QUANTIFYING AND VALUING CLIMATE CHANGE IMPACTS

Burning fossil fuels creates externalities through its impact on the stock of greenhouse gases (GHGs) in the atmosphere and the subsequent effects of GHG concentrations on climate. This chapter provides a general overview of these effects and various attempts that have been made to quantify and monetize the damages associated with GHG emissions. The chapter begins by summarizing information on trends in the earth's temperature over the past century, the relationship between greenhouse gas concentrations and climate, and predictions of future changes in climate associated with various emissions trajectories. This is followed by an overview of the approach that economists have taken to quantifying the damages associated with GHG emissions, including a discussion of three Integrated Assessment Models (IAMs) which provide estimates of the monetary impacts of GHG emissions. Given its resource constraints, it was not feasible for the committee to conduct a detailed critical review of the IAMs.

Estimates of the damages associated with GHG emissions in (IAMs) rest on estimates of the physical and monetary impacts of temperature changes in various market and non-market sectors. The next section of the chapter describes the physical impacts of climate change on weather, snow and ice formations and water systems. This is followed by estimates of the physical and monetary impacts of climate change on individual market and non-market sectors, including water, agriculture, coastal infrastructure, health and ecosystems. The next section discusses how monetary impacts reported in the literature are aggregated across sectors and countries and presents estimates of the marginal damage of a ton of carbon dioxide equivalent[1] (CO_2-eq) from various IAMs. The committee did not conduct its own modeling analyses of damages related to climate change. We determined that attempting to estimate single values would be inconsistent with the rapidly changing nature of knowledge about climate change and the extremely large uncertainties associated with estimation of climate change effects and damages.

Climate Change Observations, Drivers, and Future Projections

According to the Intergovernmental Panel on Climate Change (IPCC), scientists have documented that Earth's climate system is warming, the last decade was the warmest on record, global average temperatures have increased about 1.3 F since 1990, and sea levels at the end of the 20th century were rising almost twice as fast as over the century as a whole (IPCC 2007a,b).[2] Also, Arctic sea ice and

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[1] CO_2-equivalent (CO_2-eq) expresses the global warming potential of a greenhouse gas, such as methane, in terms of CO_2 quantities.

[2] The IPCC is an intergovernmental scientific body given to the assessment of climate change. It does not conduct research. IPCC estimations are derived from literature reviews and assessments, not from their independent predictions or projections.

glaciers are rapidly shrinking. Economic losses from extreme weather events, such as tropical cyclones, heavy rain storms, flooding, severe heat waves, and droughts, are increasing rapidly (CCSC 2008).

The IPCC states that "most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC 2007a, p.5). With high and increasing confidence, a range of "fingerprinting" techniques attribute a substantial fraction of recent warming to anthropogenic causes (IPCC 2007a).

Although the greenhouse effect is a natural process necessary for life on Earth, humans have inadvertently intervened in this process such that the greenhouse effect is now trapping additional heat in the Earth's atmosphere which is driving climate change. Specifically, human activities have led to a significant increase in the amount of CO_2 and methane (CH_4) in the atmosphere. These additional GHGs absorb more energy and let less heat escape to space. Therefore, the Earth's climate is warming.[3]

GHG emissions have steadily grown since the Industrial Revolution, with a 70% increase between 1970 and 2004. Burning fossil fuels, agriculture, and deforestation are the primary anthropogenic sources of these GHG emissions. In 2004, the burning of fossil fuels accounted for 56.6% of the GHGs emitted. Of the total anthropogenic emissions released in 2004, energy supply produced 25.9%, the transportation sector produced 13.1%, and industry produced 19.4% (Figure 5-1) (IPCC 2007a).

Future Projections

Using global climate models, scientists predict that, in the absence of concerted action to reduce GHG emissions, climate will warm substantially over the next century. The IPCC has developed
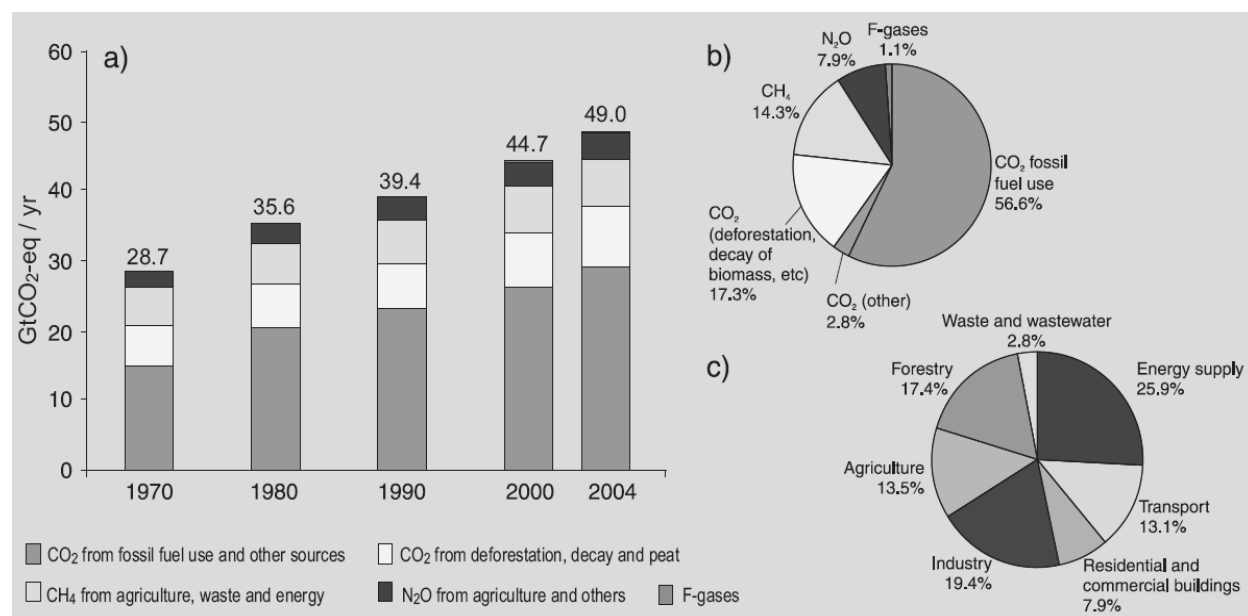
FIGURE 5-1 Global anthropogenic GHG emissions. (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) share of different sectors in total anthropogenic GHG emissions in terms of CO_2-eq. (Forestry includes deforestation.). Source: IPCC 2007a, p.5, Fig. SPM.3. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.

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[3]Airborne particles may have either a warming or cooling effect. Sulfate particles reflect incoming sunlight and cause a cooling effect at the surface. Other types of particles, referred to as carbon black, absorb incoming sunlight and trap heat in the atmosphere.

scenarios that characterize a wide range of internally consistent, feasible alternative futures, characterized by trajectories in population, industrialization, governance, gross domestic product, and GHG emissions (IPCC 2000). By inputting these emission scenarios into global climate models, scientists have developed sophisticated estimates of what atmospheric temperatures could look like in 2100 (Figure 5-2).

If carbon concentrations were kept constant at the level produced in 2000, these models predict that the Earth's climate would continue to keep warming (see Figure 5-2). Scenario A2 describes a heterogeneous world with a focus on self-reliance and regional identity, with relatively slow economic and technology growth. This scenario ends the 21st century with very high emissions and dramatic warming. Scenario A1B describes a future with rapid economic growth and human population that peaks around 2050 and then starts to decline. This scenario assumes significant interregional cooperation and a balanced portfolio of energy sources. A1B predicts continued warming that starts to slow by 2100. Scenario B1 describes the same population and economic trends as in Scenario A1B. However, B1 incorporates a rapid shift toward a service and information economy, reduced material intensity, and the wide spread adoption of efficient low-carbon energy technologies. B1 predicts a less dramatic increase in global average temperatures.

Since 2000, industrial carbon-emissions have increased more rapidly than in any of the scenarios (Raupach et al 2007). Moreover, natural feedback processes, such as melting permafrost and more extensive wild fires, are releasing carbon into the atmosphere more quickly than anticipated (IPCC 2007b). On the other hand, as of mid-2009, the carbon budget data have not yet been updated to reflect changes resulting from the global economic crisis of 2008-2009.

The U.S. Global Change Research Program (GCRP) concluded that climate-related changes are already underway in the United States and surrounding coastal waters, and the quantity and growth rate of these changes are dependent upon human choices in the present day (Karl et al. 2009).

IPCC Mitigation Findings

The IPCC concludes that the impacts of climate change can be reduced, delayed, or avoided through mitigation strategies designed to stabilize atmospheric carbon concentrations. These concentrations can be stabilized primarily by reducing anthropogenic carbon emissions and, secondarily, by increasing carbon sinks (see Table 5-1). Figure 5-3 depicts the future carbon emission profiles needed to achieve the various stabilization concentrations and the global mean temperature associated with each stabilization concentration. The IPCC strongly suggests that the technology needed to achieve the needed stabilization levels is already or will very soon be available. They also claim that 60 to 80% of the needed emission reductions would have to come from the energy sector, via a shift to non-carbon based energy sources and energy efficiency (IPCC 2007a)

In response to a request from Congress, the National Academies has launched America's Climate Choices (ACC), a suite of studies designed to inform and guide responses to climate change across the nation . A final ACC report, addressing strategies to reduce or adapt to the impacts of climate change is expected to be complete in 2010.

Overview of Quantification Methods, Key Uncertainties, and Sensitivities

Defining the Marginal Damage of GHG Emissions. The combustion of fossil fuels is a major source of GHG emissions, which create externalities through their impact on the stock of greenhouse gases in the atmosphere and subsequent effects of GHG concentrations on climate. Evaluating the external costs of energy due to climate change is a daunting task. The principal difficulty is the complexity arising from the fundamental dimensionality of the climate problem. The relevant dimensions are time (indexed by *t*),
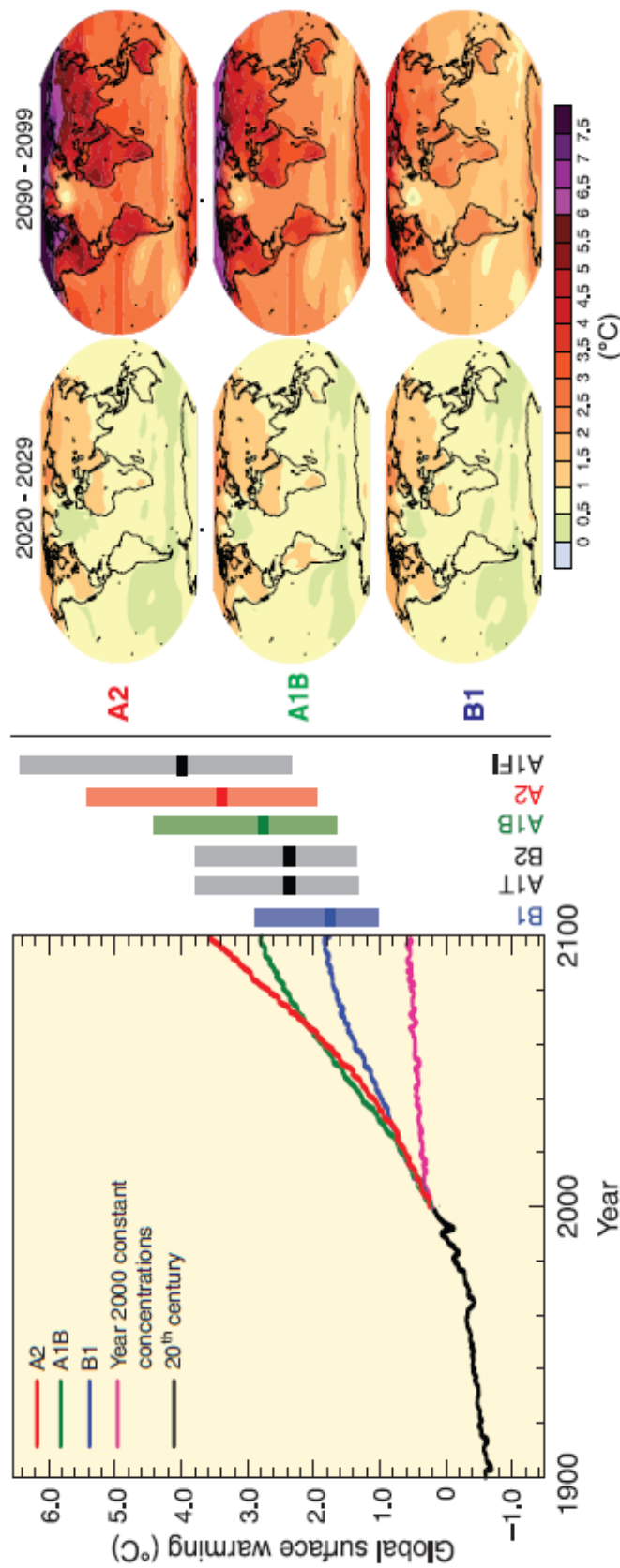
FIGURE 5-2 Atmosphere-Ocean General Circulation Model projections of surface warming. Left panel: Solid lines are multi-model global averages of surface (relative to 1980-1999) for the SRES scenarios A2, A1B and A1, shown as continuations of the 20th century simulations. The orange line is for the experiment where concentrations were held constant at year 2000 values. The bars in the middle of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999. The assessment of the best estimate and likely ranges in the bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from hierarchy of independent models and observational constraints. Right panels: Projected temperature changes for the early and late 21st century relative to the period 1980-1999. The panels show the multi-AOGCM average projections for the A2 *(top)*, A1B *(middle)*, and B1 *(bottom)* SRES scenarios averaged over decades 2020-2029 *(left)* and 2090-2099 *(right)*. Source: Source: IPCC 2007b, p. 14, Figure SPM.5; Right Panel: IPCC 2007b, p. 15, SPM.6. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.

TABLE 5-1 Characteristics of Post-TAR Stabilization Scenarios and Resulting Long-term Equilibrium Global Average Temperature and the Sea-Level Rise Component from Thermal Expansion Only

Category	CO_2 Concentration at Stabilization (2005 = 379 ppm)[b]	CO_2-Equivalent Concentration at Stabilization Including GHGs and Aerosols (2005=375 ppm)[b]	Peaking Year for CO_2 Emissions[a,c]	Change in Global CO_2 Emissions in 2050 (percent of 2000 emissions)[a,c]	Global Average Temperature Increase above Preindustrial at Equilibrium, Using "Best Estimate" Climate Sensitivity[d,e]	Global Average Sea Level Rise above Preindustrial at Equilibrium from Thermal Expansion Only[f]	Number of Assessed Scenarios
	ppm	*ppm*	*Year*	*Percent*	*°C*	*Meters*	
I	350-400	445-490	2000-2015	-85 to -50	2.0-2.4	0.4-1.4	6
II	400-440	490-535	2000-2020	-60 to -30	2.4-2.8	0.5-1.7	18
III	440-485	535-590	2010-2030	-30 to +5	2.8-3.2	0.6-1.9	21
IV	485-570	590-710	2020-2060	+10 to +60	3.2-4.0	0.6-2.4	118
V	570-660	710-855	2050-2080	+25 to +85	4.0-4.9	0.8-2.9	9
VI	660-790	855-1130	2060-2090	+90 to +140	4.9-6.1	1.0-3.7	5

[a]The emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated due to missing carbon cycle feedbacks.

[b]Atmosphere CO_2 concentrations were 379ppm in 2005. The estimate of total CO_2-eq concentration in 2005 for all long-lived GHGs is about 455ppm, while the corresponding value including the net effect of all anthropogenic forcing agents is 375ppm CO_2-eq.

[c]Ranges correspond to the 15th to 85th percentile of the post-TAR scenarios distribution. CO_2 emissions are shown so multi-gas scenarios can be compared with CO_2-only scenarios.

[d]The best estimate of climate sensitivity is 3°C.

[e]Note that global average temperature at equilibrium is different from expected global average temperature at the time of stabilization of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilization of GHG concentrations occurs between 2100 and 2150.

[f]Equilibrium sea level rise is for the contribution from ocean thermal expansion only and does not reach equilibrium for at least many centuries. These values have been estimated using relatively simple climate models (one low-resolution AOGCM [Atmosphere-Ocean General Circulation Model] and several EMICs [Earth System Models of Intermediate Complexity] based on the best estimate of 3°C climate sensitivity) and do not include contributions from melting ice sheets, glaciers and ice caps. Long-term thermal expansion is projected to result in 0.2 to 0.6m per degree Celsius of global average warming above pre-industrial.

Source: IPCC 2007a, p. 20, Table SPM.6. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.
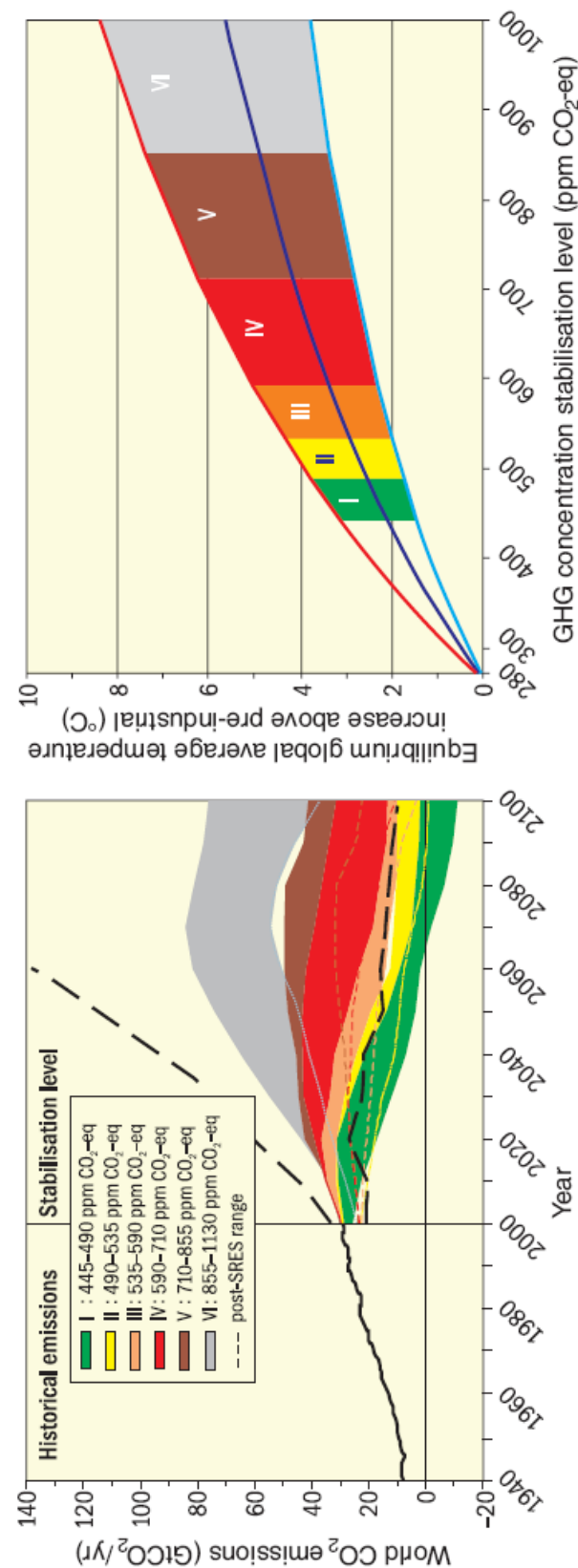
FIGURE 5-3 Global CO$_2$ emissions for 1940 to 2000 and emissions ranges for categories of stabilization scenarios from 2000 to 2100 (*left-hand panel*); and the corresponding relationship between the stabilization target and the likely equilibrium global average temperature increase above pre-industrial (*right-hand panel*). Approaching equilibrium can take several centuries, especially for scenarios with higher levels of stabilization. Colored shadings show stabilization scenarios grouped according to different targets (stabilization category I to VI). The right-hand panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of likely range of climate sensitivity of 4.5°C (red line at top of shaded area) (iii) lower bound of likely range of climate sensitivity of 2°C (blue line at bottom of shaded area). Black dashed lines in the left panel give the emissions range of recent baseline scenarios published since the SRES (2000). Emissions ranges of the stabilization scenarios comprise CO$_2$-only and multigas scenarios and correspond to the 10th to 90th percentile of the full scenario distribution. Note: CO$_2$ emissions in most models do not include emissions from decay of above ground biomass that remains after logging and deforestation, and from peat fires and drained peat soils.
Source: IPCC 2007a, p. 21, Figure SPM.11. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.

location (indexed by *l*), the set of relevant climatic variables (indicated by the index *c*), the categories of physical impacts as a result of climatic changes (indexed by *i*), and the categories of damage incurred by these impacts (indexed by *d*). The external cost of an additional ton of greenhouse gases, E_0, emitted at time *t* = 0 depends on:

(a) The effect of emissions on earth system processes, and, in turn, climatic variables in candidate locations over future time periods, $C_{c,l,t}$;

(b) The contemporaneous effect of climatic changes in each location on various categories of physical impacts, $I_{i,l,t}$;

(c) The contemporaneous effect of impacts in each location on various categories of damage, $D_{d,l,t}$.

The dependence can be summarized in Equation 5-1, which is the analogue of the impact pathway approach used in the analysis in Chapters 2 and 3:

$$MD_0 = \sum_t \sum_l \sum_c \sum_i \sum_d \left[\underbrace{\left(\frac{\partial C_{c,l,t}}{\partial E_0}\right)}_{\Delta EC} \underbrace{\left(\frac{\partial I_{i,l,t}}{\partial C_{c,l,t}}\right)}_{\Delta CI} \underbrace{\left(\frac{\partial D_{d,l,t}}{\partial I_{i,l,t}}\right)}_{\Delta ID} \right] \delta_t$$

Equation 5-1

where $\delta_t = (1 + r)^{-t}$ is a factor that discounts damages in future year *t* back to the present, and *r* is the rate of discount. Effect b is captured by the term Δ*CI* which summarizes the results of physical impact models. These models suggest how changes in temperature and precipitation may affect agricultural yields or how changes in climate will affect biodiversity. Effect c is captured by the term Δ*ID*, which captures the monetary damages associated with changes in agricultural yields or loss of species diversity. Attempts to measure these damages are reviewed briefly later in this section. In many cases the relationships between climate impacts and damages are based on judgment, assumptions or analogy because data are lacking.

This last point highlights the second difficulty facing any assessment of the costs of climate change: lack of information and uncertainty regarding effects a-c. The terms represented by Δ*EC,* which include the extent of ice sheet melting and shifts in regional distribution of precipitation are still subject to considerable uncertainty. A vast amount of effort is actively being dedicated to elaborating the elements of Δ*CI*. However, while natural scientists mostly agree on the climatic variables whose impacts should be studied, there is less consensus on what are significant impacts that should be examined. Moreover, even those impacts thought to be significant (e.g., species loss) respond to changes in climate in ways that are poorly understood. The difficulties in estimating monetary damages are described in more detail below.

The climate equivalent of the APEEP model would embody estimates of Δ*EC,* Δ*CI,* and Δ*ID* and combine them according to Eq. 5-1 to produce a summary measure of marginal damage. The committee did not have at access to an integrated assessment model (IAM) of this kind. Indeed, such a model does not exist—the IAMs used for climate studies are designed not to produce descriptively realistic, spatially disaggregate responses of climatic, impact and damage variables, but rather to bring together key stylized facts about these responses within the framework of Eq. 5-1 as a means of elucidating their joint implications. But the benefits of such integration are often gained at the expense of introducing substantial theoretical and empirical weaknesses into IAMs. While each element of Δ*EC,* Δ*CI,* and Δ*ID* can be thought of as a model in its own right, IAMs adopt reduced-form approaches which reduce these complex relationships into simplified response surfaces, in the process oversimplifying of the complexities of the underlying science. In addition, IAMs typically cope with the curse of dimensionality by consider only relatively narrow sets of impacts or types of damage. IAMs also tend to trade off coarse regional coverage in favor of broad global scope, so that relationships validated for restricted geographic domains are implicitly scaled up to broader spatial scales. The remainder of this section describes in general terms how Integrated Assessment Models (IAMs), such as RICE/DICE, FUND and PAGE,

evaluate marginal damages. In a typical IAM the marginal damages from a ton of CO_2-equivalent emissions (E) emitted today (year 0) can be expressed as

$$MD_0 = \sum_{t=0}^{t_f} \frac{dT_t'}{dE_0} \frac{dD_t}{dT_t'} \delta_t$$

Equation 5-2

where $t = $ year of impact,

$MD_0 = $ marginal damage from GHG emissions in year 0 (\$/ton CO_2-eq),

$T_t = $ mean global temperature in year t relative to pre-industrial levels (°C),

$E_0 = $ GHG emissions in year 0 (ton CO_2-eq),

$D_t = $ total climate damages in year t (\$),

$\delta_t = $ discount factor from year t to $0 = (1+r)^{-t}$, where r is the discount rate

$t_f = $ final year for which climate damages are included.

The expression indicates that the marginal damages from GHG emissions (MD) depend on how much temperatures increase in response to a unit increase in emissions (dT/dE), how much additional climate damage results from this temperature increase (dD/dT), how one values future damages relative to the present (δ), and how far into the future one aggregates impacts (t_f). In terms of the preceding discussion, climate effects have been reduced to temperature, and the link between climate and impacts and impacts and damages has been condensed into a single step.

The relationship between a ton of CO_2-eq emitted today and future temperature depends on the effects of GHG emissions on the concentration of GHGs in the atmosphere, and on the effects of GHG concentrations on temperature. Spatially detailed predictions of the impact of GHG concentrations on temperature and precipitation are provided by general circulation models. Integrated Assessment Models (IAMs) typically simplify these relationships and describe changes in mean global temperature corresponding to a ton of CO_2-eq emissions.

In the most disaggregated IAMs the monetary damages associated with a change in temperature are calculated by estimating damages by sector (e.g., energy, health, agriculture) and geographic region. Damages are expressed as a percent of GDP using methods described in the next subsection. dD_t/dT_t represents the aggregation of impacts across sectors and regions. How change in GDP are aggregated across regions—whether using equity weights or by summing the monetary changes in GDP—is discussed below.

Future monetary damages are discounted either at the market rate of interest (the revealed preference approach), or using the Ramsey formula (the prescriptive approach), which describes how the discount rate, r, varies along an optimal growth path. These two approaches are discussed in detail later in the chapter. Marginal damages are extremely sensitive to the choice of discount rate, given the fact that the climate impacts of a ton of CO_2-eq emissions will be felt for centuries (t_f is typically 100 to 300 years).

The marginal damage formula in Equation 5-2 assumes that the effect of a ton of CO_2-eq emissions on temperature and the effects of temperature on the economy are certain—which is clearly not the case. Indeed, a major difference between quantifying the local air pollution effects of fossil fuels and the impacts of GHG emissions is that the two differ significantly in their time dimension, their spatial scale, the variety of impacts, and, hence, in the certainty with which they can be estimated. In contrast to SO_2 or NO_x, CO_2 is a pollutant that resides in the atmosphere for centuries.[4] This implies that the effects

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[4]The atmospheric lifetime of CO_2 is complex. About half disappears in 40 years but about 20% remains in the atmosphere for many centuries, essentially indefinitely..

of a ton emitted today must be estimated on a time scale (centuries) in which the state of the world is inherently more uncertain than the period during which effects of local air pollutants are estimated (months or years). Key sensitivities in Equation 5-2 include the impact of a change in atmospheric concentrations of CO_2 on temperature (termed climate sensitivity) and how dD/dT varies with T. There is, in reality, a distribution of damages associated with any given temperature change.

IAMs typically handle this uncertainty in two ways. One is to calculate marginal damages using Monte Carlo analysis: the parameters used to parameterize the dT/dE and dD/dT are drawn from probability distributions and used to calculate the corresponding distribution of marginal damages. A second approach is to acknowledge that, corresponding to each change in mean global temperature from pre-industrial levels, there is a probability of abrupt, catastrophic events such as the melting of the West Antarctic ice sheets or melting of permafrost—events that could result in huge declines in world GDP. Some models attempt to estimate what individuals would pay to avoid such events. The next section provides an overview of how the damages associated with various temperature changes are modeled in three prominent IAMs.

Approach to Measuring Marginal Damages in Integrated Assessment Models

Integrated Assessment Models combine simplified global climate models with economic models in an effort to estimate the economic impacts of climate change and to identify emission paths that balance these economic impacts against the costs of reducing GHG emissions. Three of the most widely used IAMs are William Nordaus' RICE and DICE models, Richard Tol's FUND model, and Chris Hope's PAGE model. The goal of this section is to provide overviews of how each of these IAMs monetizes the impact of changes in mean global temperature.

RICE and DICE Model. *T*he Regional Integrated Model of Climate and the Economy (RICE) and the Dynamic Integrated Model of Climate and the Economy (DICE) examine the linkages between economic growth, CO_2 emissions, the carbon cycle, the economic damages associated with climate change, and climate-change policies. These models incorporate the climate system's 'natural capital' into a model based on traditional economic growth theory. They treat as exogenous global population, global stock of fossil fuels, and the pace of technological change, and calculate world output and capital stock, CO_2 emissions and concentrations, global temperature change, and climatic damages. RICE distinguishes various regions of the world (8 in some versions; 13 in others) while DICE has a single, aggregated global economy. The models are typically run from the year 1990 until 2100.

The approach to quantifying climate change damages in each sector in RICE is as follows. (1) The percentage reduction in GDP associated with a mean global temperature increase of *T* is calculated for the year 1995 for each sector (*i*) and region (*j*). (Call this $Q_{ij}(T)$.) (2) The impact of the *T* °C temperature change in calculated for a future year, *t*, by multiplying $Q_{ij}(T)$ by the ratio of per capita GDP in year *t* to per capita GDP in 1995 raised to a power η, where η is the income elasticity of the impact index. The percentage change in GDP in year *t* for temperature change T is thus,

$Q_{ij}(T) \; [y_j(t)/y_j(1995)]^{\eta}$ **Equation 5-3**

In practice $Q_{ij}(T)$ is calculated for benchmark warming—a 2.5°C increase in mean global temperature—based on a review of the literature. η is determined from a literature review or expert opinion. $Q_{ij}(T)$ changes as a function of T according to a quadratic function. The sectors for which impacts are monetized in RICE/DICE are agriculture, sea-level rise, other market sectors, health, non-market amenities, human settlements and ecosystems and catastrophic damages. The magnitudes of damages in these sectors are discussed in sections below.

FUND Model. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model examines how a set of exogenous scenarios, concerning economic growth, population growth, energy efficiency improvements, decarbonization of energy use, and GHG emissions, affect the concentration of atmospheric CO_2, global mean temperature, and the impacts of temperature change. FUND models these linkages for nine regions[5] over 250 years, from 1950 to 2200.

The sectors for which impacts are monetized in FUND are agriculture, forestry, water resources, energy consumption, sea-level rise, ecosystems and human health. Monetization of impacts in FUND is slightly different for each sector and more detailed than the reduced-form approach used in RICE/DICE. For example, the impact of a temperature change on agricultural revenues consists of three components: one reflects the difference between future temperature and ideal growing temperature for the region, a second reflects the rate of increase in temperature, which captures opportunities for adaptation, and the third component reflects the carbon fertilization effect. To map the percentage change in agricultural revenues implied by these three effects into a change in GDP requires estimates of the share of agriculture in GDP. This, in turn, is modeled as a function of per capita GDP and assumptions about the income elasticity of agriculture.

FUND differs from RICE/DICE in that the base year impacts in agriculture and ecosystems depend not only on the magnitude of temperature change but also on the rate of temperature change. It is also the case in FUND that the effect of a change in mean global temperature on marginal damages varies by sector

PAGE Model. The Policy Analysis of the Greenhouse Effect (PAGE) model is a multi-region model that models the impacts of climate change in three sectors—economic impacts, non-economic impacts and discontinuity impacts, i.e., impacts associated with abrupt changes to the climate system.[6] Functions that describe the economic and non-economic impacts of a given temperature change (T) in region r are of the form:

$$I(r) = A(r)T^{n(r)} \qquad\qquad \textbf{Equation 5-4}$$

where $I(r)$ is the percentage change in GDP associated with the impact, $A(r)$ is a scaling factor and $n(r)$ lies between 1 and 3. The weights $A(r)$ represent the percent of GDP lost in region r relative to losses in the European Union. For a description of the modeling of discontinuity impacts see Hope (2006).

IMPACTS ON PHYSICAL AND BIOLOGICAL SYSTEMS

The Earth's climate system is integrally intertwined with many other global biological, chemical, and physical systems. Impacts on the weather, cryosphere, hydrosphere, coastal zones, and the biosphere are briefly discussed below. Impacts on human systems resulting from impacts on these physical systems are discussed in more detail in a subsequent section. This discussion is intended to provide a brief summary of recent knowledge. Another effort is underway within the National Academies to study issues relating to global climate change. [7] Also, it is important to keep in mind that none of the individual impacts described in this section have been monetized.

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[5] OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and South-East Asia, Centrally Planned Asia, and Africa.

[6] Economic and non-economic impacts are not disaggregated by sector, as in RICE/DICE and FUND.

[7] In response to a request from Congress, the National Academies has launched America's Climate Choices, a suite of studies designed to inform and guide responses to climate change across the nation.

Changes in the Weather

The most literal effect of climate warming is an increase in ambient air temperatures, particularly at night over land in the Northern Hemisphere (Figure 5-2). Global climate models predict an increase in the frequency of heat waves, heavy precipitation events, and the intensity of tropical cyclones (IPCC 2007b). The IPCC also predicts that precipitation will likely decrease in the subtropics and will very likely increase near the poles (Figure 5-4).

Changes in the Cryosphere

The cryosphere, comprising all the permanent and seasonal snow and ice formations found on Earth, including the polar ice caps, sea ice, permafrost, glaciers, and seasonal snow and ice on land and water, is particularly sensitive to climate change, with dramatic decrease predicted in the amount of snow and ice on Earth as climate changes progresses. In fact, scientists have already documented the following changes (Rosenzweig et al. 2007):

- Arctic sea-ice extent has declined by about 10 to 15% since the 1950s, with the 2007 summer minimum more than 35% smaller than the 1950-1980 average.
- Mountain glaciers have receded on all continents.
- Northern Hemisphere permafrost is thawing.
- Snowmelt and runoff have occurred increasingly earlier in Europe and western North America since the late 1940s.
- The annual duration of lake- and river-ice cover in Northern Hemisphere mid- and high latitudes has been reduced by about 2 weeks and become more variable.

The IPCC also predicts the compete disappearance of late-summer Arctic sea ice by the end of the 21st century (IPCC 2007b).

Changes in the Hydrosphere

The hydrosphere comprises all the liquid water systems on Earth, including the oceans, lakes, rivers, streams, and aquifers. The hydrosphere is tightly integrated with the climate system and the cryosphere. Climate change and consequent warming are linked to changes in the hydrologic cycle with increased evaporation from land and seas, changing precipitation patterns, and reduced snow cover. Specific, observed changes in the hydrosphere include the following (Rosenzweig et al. 2007):

- The salinity of the North Atlantic is decreasing, most likely due to melting glaciers.
- Annual runoff is increasing in higher latitudes and decreasing in some parts of West Africa, southern Europe, and southern Latin America.
- Peak spring river flows are occurring earlier in areas with a seasonal snow pack. This causes less water to be available during the late summer and autumn when human and ecological demand tends to be the greatest.
- The temperature, chemistry, and ultimately the structure of lakes and rivers are changing.
- 'Large' floods are occurring with more frequency around the globe.
- Very dry areas have more than doubled since 1970, causing desertification and droughts.
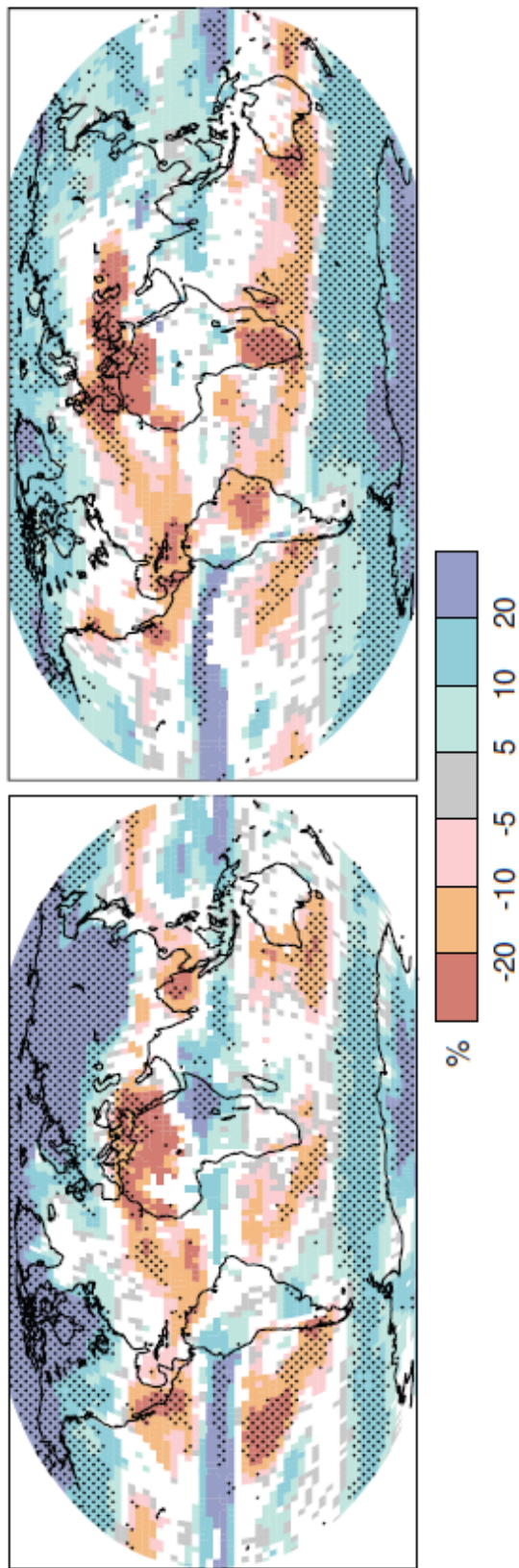
FIGURE 5-4 Multi-model projected patterns of precipitation changes. Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999. Values are multi-model averages based on the SRES A1B scenario for December to February (*left*) and June to August (*right*). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. Source: IPCC 2007b, P.16, Figure SPM.7. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.

Ultimately, between the changes in weather patterns and changes in the cryo- and hydrospheres, scientists predict that the earth will become dryer in the subtropics, especially in the Northern Hemisphere, and much wetter and less frozen near the poles. In other words, climate change is likely to manifest in ways, with consequent impacts, that will not occur evenly across the globe. Global climate models (GCMs) predict increasing global precipitation, with important regional variation, including increases in high latitudes and parts of the tropics but decreases throughout the subtropics (Bates et al. 2008).   The western United States, for example, is vulnerable to reduced water availability. Table 5-2 lists climate-related changes in the freshwater system presented in the Fourth Assessment Report of the IPCC.

The physical impacts on water availability vary considerably geographically with some regions benefitting from warming while other areas suffer. For example the Warren et al. (2006a) analysis shows water scarcity increasing on a global scale from 29% in 1995 to 39% in 2085 under the A1 and B1

TABLE 5-2 Climate-related Observed Trends of Various Components of the Global Freshwater Systems

	Observed Climate-Related Trends
Precipitation	Increasing over land north of 30°N over the period of 1901-2005. Decreasing over land between 10°S and 30°N after the 1970s (WGI AR4, Chapter 3, Executive Summary). Increasing intensity of precipitation (WGI AR4, Chapter 3, Executive Summary
Cryosphere	
Snow cover	Decreasing in most regions, especially in spring (WGI AR4, Chapter 4, Executive summary).
Glaciers	Decreasing almost everywhere (WGI AR4, Chapter 4, Section 4.5).
Permafrost	Thawing between 0.02 m/yr (Alaska) and 0.4 m/yr (Tibetan Plateau) (WGI AR4 Charter 4, Executive summary; this report, Chapter 15, Section 15.2).
Surface Waters	
Streamflow	Increasing in Eurasian Arctic, significant increases or decreases in some river basins (this report, Chapter 1, Section 1.3.2).
	Earlier spring peak flows and increased winter base flows in Northern America and Eurasia (this report, Chapter 1, Section 1.3.2).
Evapotranspiration	Increased actual evapotranspiration in some areas (WGI AR4, Chapter 3, Section 3.3.3).
Lakes	Warming, significant increases or decreases of some lake levels, and reduction in ice cover (this report, Chapter 1, Section 1.3.2).
Groundwater	No evidence for ubiquitous climate-related trend (this report, Chapter 1, Section 1.3.2
Floods and Droughts	
Floods	No evidence for climate-related trend (this report, Chapter 1, Section 1.3.2), but flood damages are increasing (this section).
Droughts	Intensified droughts in some drier regions since the 1970s (this report, Chapter 1, Section 1.3.2; WGI AR4, Chapter 3, Executive summary).
Water quality	No evidence for climate-related trend (this report, Chapter 1, Section 1.3.2)
Erosion and sediment transport	No evidence for climate-related trend (this section).
Irrigation water demand	No evidence for climate-related trend (this section).

Source: Kundzewicz et al. 2007, p.177, Table 3.1. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.

scenarios, respectively (Figure 5-2). Some areas see sharper increases in water scarcity under their analysis (South Asia more than doubles from 26% to 59%) while other areas see a decline in water scarcity (Europe falls from 38% to 26%). The United States and Canada see a modest increase in scarcity from 16% to 20% in their analysis.

Changes in the Coastal Zones

Rising sea levels—among the best-documented impacts of climate change—are another consequence of the melting cryosphere. Sea level has been rising at the rate of 1.7 to 1.8 mm/yr over the past century. This rate increased to approximately 3 mm/yr over the past decade (IPCC 2007a). Rising sea levels and increased storm intensities are rapidly eroding coastlines around the globe. Seventy-five percent of the east coast of the United States and 67% of the east coast of the United Kingdom are thus affected (Rosenzweig et al. 2007). However, there is scientific consensus that over many centuries thermal expansion of the ocean due to global warming is very likely to cause much larger rises in sea levels than those observed over the 20th century. In the latest IPCC projections thermal expansion contributes 70-75% of the best estimate of sea-level rise for each of the six SRES marker scenarios, in the most extreme case exhibiting a 5-95% confidence interval of 0.26-0.59 meters by the year 2100 (IPCC 2007b, p. 820, Table 10.7 and IPCC 2007b, p. 821, Figure 10.33). This is cause for concern, given that relative sea-level rises have exceeded 8 inches in some areas along the Atlantic and Gulf coasts (see Karl et al. 2009, p. 37, figure) Although the contributions to sea-level rise made by thermal expansion and melting glaciers are well understood, uncertainty remains about the magnitude of ice sheets' effects, so much so that their impact was left unquantified in the most recent IPCC report. Based upon several recent studies on sea-level rise, Karl et al. (2009) conclude that the IPCC predictions are likely to underestimate the impact, and cite estimates by century's end of 0.9-1.2 m under higher emissions scenarios, with an upper bound of 2 m.

Changes in the Biosphere

Many plants and animals have relatively specific environmental conditions that they can survive in. Even small environmental changes, in extremes of ambient temperature or the availability of water for example, can make a region inhospitable to members of the existing flora and fauna. Ecologists are already documenting important shifts in ecosystem structures and functioning, such as the following (Rosenzweig et al. 2007):

- Plant and animal ranges have shifted to cooler higher latitudes and altitudes. Therefore, as overall temperatures rise, plants and animals with very narrow temperature requirements will shift their ranges accordingly or become extirpated.
- The timing of many life-cycle events, such as flowering, migration, and emergence, has shifted earlier in the spring and often later in the autumn.
- Different species change at different speeds and in different directions, causing a changing of species interactions (e.g., predator-prey relationships).

IMPACTS ON HUMAN SYSTEMS

Observed (and predicted) changes in the Earth's global systems have significant ramifications for humans. The redistribution of water availability across the globe, for example, will amplify water conflicts, particularly in regions that are getting drier. Changes in the availability of water and in the length of growing seasons will affect which crops farmers can plant and how much those crops yield.

Tropical diseases will start to affect more people as the ranges of disease vectors, such as mosquitoes, shift poleward. Table 5-3 describes some of the many ways in which climate change may affect important human systems.

The impacts of climate change on humans will not be uniform throughout the world. Different regions will experience climate change somewhat differently. Southern Africa, for example, is predicted to become drier and will therefore need to cope with water scarcity. Northern Europe, on the other hand, is predicted to become wetter. Figure 5-5 summarizes some of the key regional impacts humans will experience. The rest of this section systematically explores the impacts of climate change on a variety of aspects of human life, including water resources, ecosystem services, food production and forest products, sea-level rise and coastal populations, and human health, industry, society, and security.

Water Availability

A critical challenge facing the growing world population is access to water, which could be significantly affected by climate change. Warren et al. (2006a) note that a country experiences water scarcity when available supply falls below 1000 cubic meters per person per year and absolute scarcity when supply falls below 500 cubic meters per person per year. Globally they estimate that roughly 30% of the world's population was water stressed in 1995, where water stress was defined as experiencing water scarcity (see Table A2 of Warren et al. 2006a). By 2085 they project that 39 to 59% of the world's population could be water stressed, depending on economic and population growth. However, all analyses and predictions of physical impacts must be qualified by the great uncertainties we face about hydrologic cycles and their responses to warming. Additional caveats to estimates of impacts are the possibilities of adaptation and mitigation. For example, exposure to water scarcity will change as populations migrate for reasons related or unrelated to global warming.

Changes in water availability can lead to losses in crop production, premature deaths and greater disease prevalence from water shortages in the short run and adjustment costs of population movements as people abandon areas that have become too dry and/or engineer new water transfers. However, measuring the impacts of increasing water scarcity is difficult. Among other issues, the value of losses is exacerbated by increasing demand for irrigation in agriculture (Mendelsohn and Williams 2007). Aldy et al. (2009) provide summaries of damages from climate change as measured in a number of studies. Table 5-4 reports estimates of damages arising from changes in water availability. These damages are reported as percentages of GDP at the end of this century. For the United States damages range from a low of .01 to .03% for warming between 4.6 and 7.1 degrees Celsius to a high of .29% for 2.5 degrees Celsius.

World damages are modestly higher, with Tol (2002a) reporting the highest damages of .43% for 1 degree Celsius warming. The range of estimates for the United States and for the world is large, especially when taking into account the different assumptions about global warming. This speaks to the difficulties in making sharp impact predictions.

Regarding the three IAMs described earlier in the chapter, PAGE does not provide sector-specific estimates of damages, and RICE/DICE does not provide separate estimates for water resources. Indeed, Nordhaus and Boyer (1999) argue that the damages from water availability can be essentially set to zero (p. 4-13), based on their survey of previous studies. The FUND model 3.0 measures water availability impacts for each of 16 regions using the following formula.

$$W_{t,r} = \min\left\{ \alpha_r Y_{1990,r}(1-\tau)^{t-2000}\left(\frac{Y_{t,r}}{Y_{1990,r}}\right)^{\beta} T_t^{\gamma}, \frac{Y_{t,r}}{10} \right\}$$

Equation 5-5

TABLE 5-3 Examples of Possible Impacts of Climate Change Due to Changes in Extreme Weather and Climate Events, Based on Projections to the Mid- to Late 21st Century

Phenomenon[a] and Direction of Trend	Likelihood of Future Trends Based on Projections for 21st Century Using SRES Scenarios	Examples of Major Projected Impacts by Sectors			
		Agriculture, Forestry and Ecosystems (WGII 4.4, 5.4)	Water Resources (WGII 3.4)	Human Health (WGII 8.2, 8.4)	Industry, Settlement, and Society (WGII 7.4)
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	*Virtually certain*[b]	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snowmelt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land areas	*Very likely*	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g. algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas	*Very likely*	Damage to crops; soil erosion, inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	*Likely*	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortage for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	*Likely*	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers; potential for population migrations; loss of property
Increased incidence of extreme high sea level (excludes tsunamis[c])	*Likely*[d]	Salinization of irrigation water, estuaries and fresh-water systems	Decreased fresh-water availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

[a]See WGI Table 3.7 for further details regarding definitions.
[b]Warming of the most extreme days and nights each year.
[c]Extreme high sea level depends on average sea level and on regional weather systems. It is defined as the highest 1% of hourly values of observed sea level at a station for a given reference period.
[d]In all scenarios, the projected global average sea level at 2100 is higher than in the reference period. The effect of changes in regional weather systems on sea level extremes has not been assessed. (WGI 10.6)
Source: IPCC 2007d, p.18, Table SPM.1. Reprinted with permission; copyright 2007, Intergovernmental Panel on Climate Change.
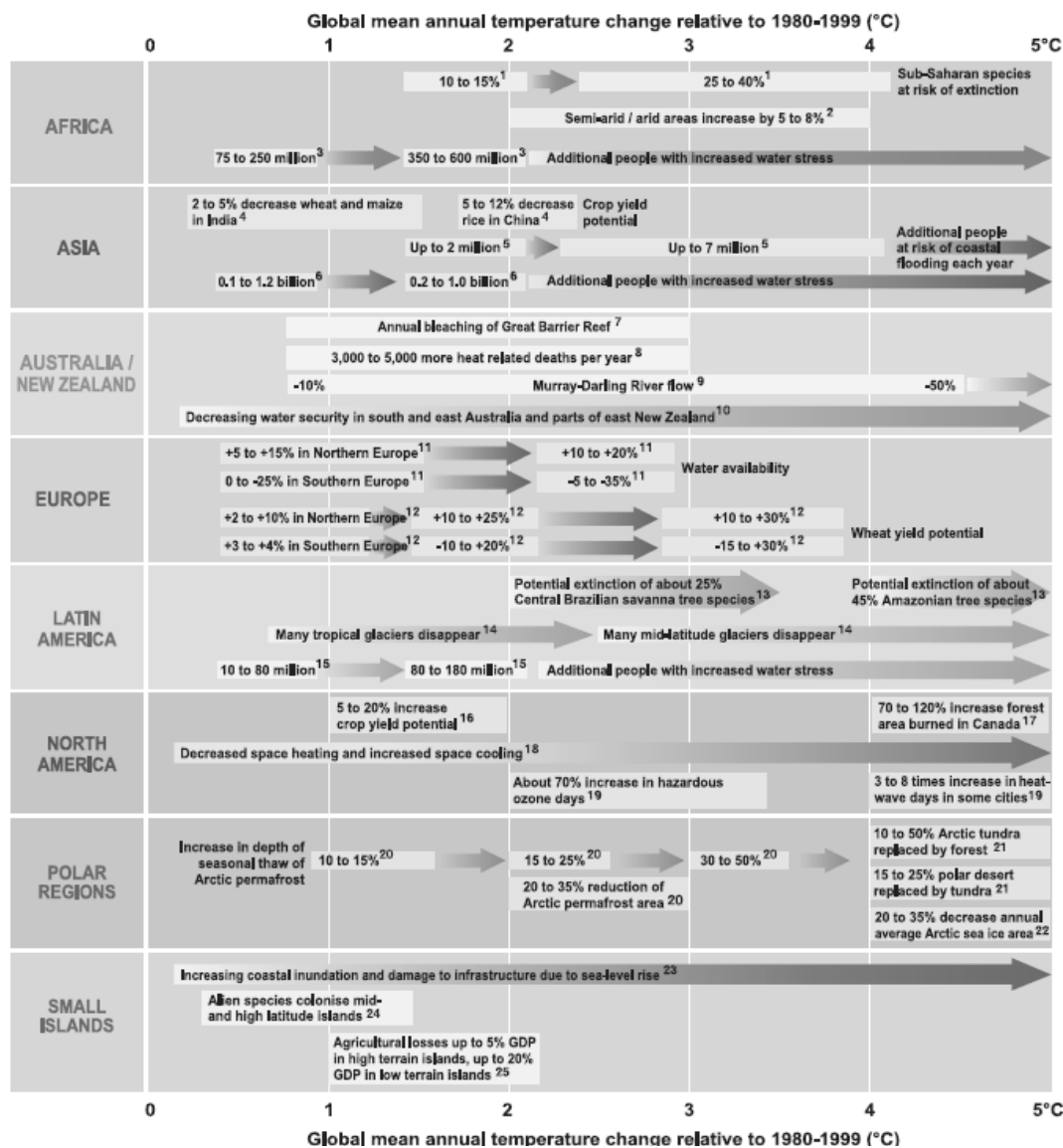
FIGURE 5-5 Examples of regional impacts of climate change. Source: Yohe et al. 2007, p. 829, Table 20.9.

TABLE 5-4 Water Availability Effects from Climate Change for Selected Studies (Percent of Contemporaneous GDP Around 2100)

Primary Author	Cline	Fankhauser	Mendelsohn			Titus	Tol	
Year of study	1992	1995a	1999	2004	2007	1992	1995	2002a
Co-author			Neumann	Williams	Williams			
Warming, C^b	2.5	2.5	2.5	4.6 - 7.1	2.5 - 5.2	4.0	2.5	1.0
United States World	.12	.29	.07	.01-.03		.20	n/a	.07
	n/a	.24	n/a	.01-.03	.00 -.02	n/a	n/a	.43

[a]Stern (2007) does not separate out individual categories within market and non-market impacts.
[b]Warming is relative to pre-industrial (as opposed to current) temperatures.
Notes: n/a = values not available or not estimated. In some cases estimates for the United States also include Canada.
Source: Aldy et al. 2009. Reprinted with permission from authors; 2009.

where

W	denotes the change in water resources in 1995 dollars in region *r* in year *t*
Y	denotes income (in 1995 dollars)
T	global mean temperature
α	benchmarking parameter
τ	parameter measuring technological progress in water supply and demand (ranges from 0 to .01 with a preferred estimate of .005
β	elasticity of impact with respect to income growth (ranging from .7 to 1 with a preferred estimate of .85)
γ	elasticity of impact with respect to temperature change (ranging from .5 to 1.5 with a preferred estimate of 1).

The parameter choices are made by calibrating the FUND model to results from Downing et al (1995, 1996a). The estimated impact of a 1 degree Celsius increase in global temperature is -0.065% of GDP for the United States (FUND 2008, p. 33, Table EFW). A negative estimate indicates benefits to the United States from warming. This estimate is imprecisely estimated with a coefficient of variation equal to 1.0. The impact on other regions is small with a few exceptions. The former Soviet Union sees benefits as large as 2.75% of GDP while China has losses of 0.57% of GDP. Overall, however, losses are quite small and in all cases the estimates have very large standard errors.

Coastal Zone Impact of Climate Change

As previously mentioned, the coastal sector is one of best-documented areas of the impacts of climate change. However, it is difficult to assess with any confidence what the monetary damages of elevated seas might be for the United States, let alone globally. The only comprehensive assessment of the vulnerability of the U.S. coastline to sea-level rise (Thieler and Hammar-Klose 1999; 2000a,b) predates the latest IPCC estimates. Notwithstanding this, the fact that its methodology of assigning to segments of coastline an index of vulnerability calculated based on rank-ordered attributes would seem to suggest that updated data on sea-level rise will preserve coastlines' relative position in the vulnerability hierarchy, at least over broad geographic scales.[8] Recent analyses at the regional scale indicate that sandy-shore environments such as the Mid-Atlantic coastline have a high likelihood of seeing more rapid erosion and segmentation of barrier islands, as well as wetland loss. For example, Figure 5-6 illustrates that for the Mid-Atlantic region an acceleration in sea-level rise of 2 mm/year over current rates will cause many wetlands to become stressed, while under a 7 mm/year acceleration (consistent with IPCC's upper-bound estimate, above) it is likely that most wetlands will not survive. The value of these kinds of losses has not been rigorously quantified. Depending on the increase in sea level, the adaptation options confronting human populations in the coastal zone are to protect the shore, relocate inland, or a combination of both, each of which is associated with forgone income and well-being—i.e., damage. How much of each option is to be chosen is an essentially economic decision, which is simulated within IAMs in the process of arriving at aggregate estimates of climate damages. The remainder of this section sheds light on the methodological details of this process, as a way of illustrating the large extent to which it is driven by assumptions on the part of IA modelers.

There is a sizeable literature on the damages associated with sea-level rise. The differences in model results stem from different ways of representing the processes by which damages arise, including the level of detail in climate and physical impact modeling and the choice between a "process-based" and "reduced form" approaches to representing impacts. The RICE/DICE model (Nordhaus and Boyer 2000)

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[8]The variables are geomorphology, shoreline erosion and accretion rates, coastal slope, rate of relative sea-level rise, mean tidal range, and mean wave height.
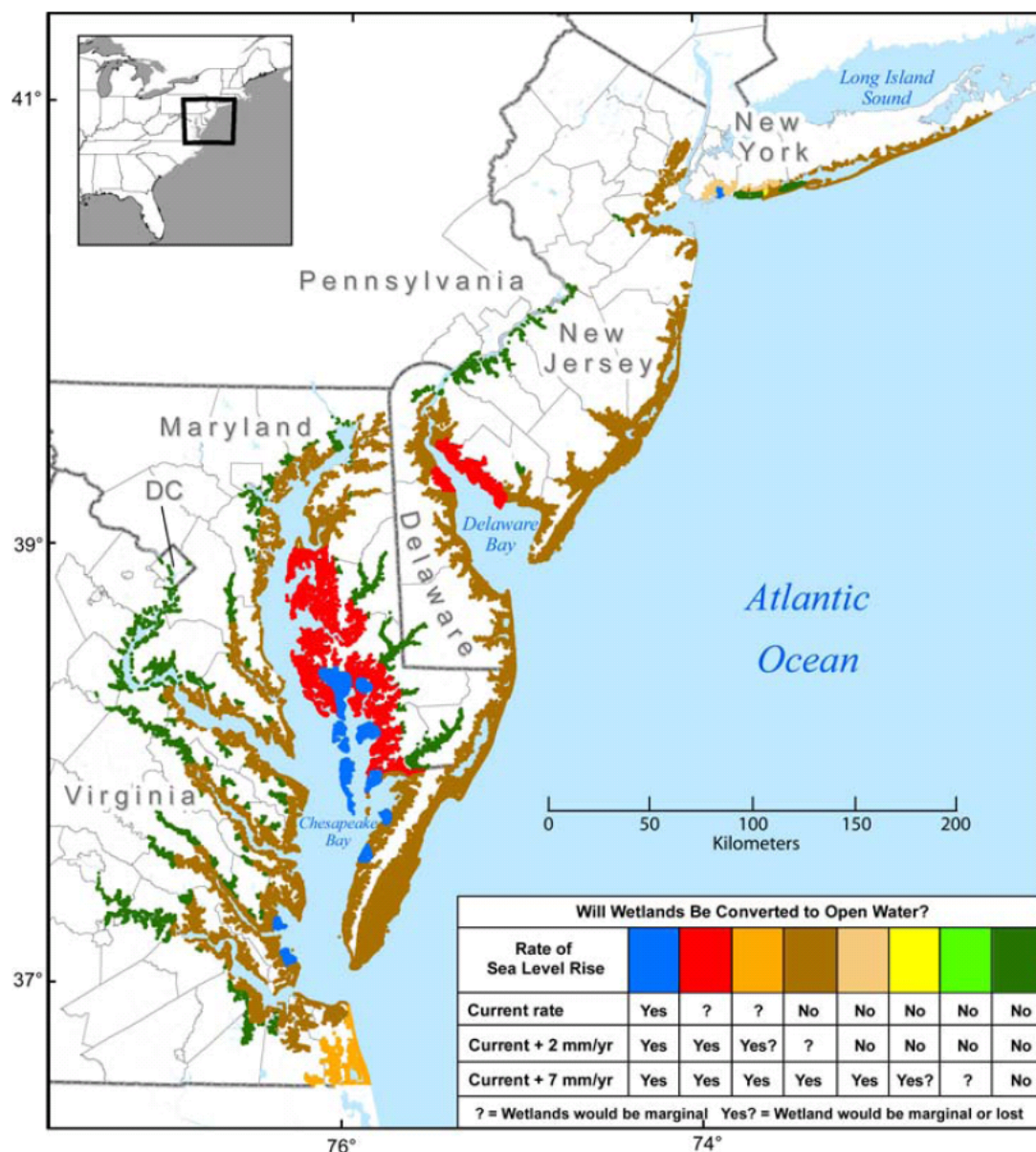
FIGURE 5-6 Mid-Atlantic wetland marginalization and loss as a consequence of sea-level rise. Source: CCSP 2009, Fig. ES.2.

is typical of the reduced-form approach, while the detailed representations of damages in the FUND model (Tol 2002a,b) exemplify the process-based approach. Both authors develop damage estimates on a regional basis by extrapolating from studies of the United States and other countries, but to implement the process-based approach requires many more assumptions about the detailed impacts of sea-level rise and the character of affected individuals' adaptation responses.

Damages in the RICE model are constructed by developing a benchmark estimate of the cost of the sea level increase arising from 2°C warming in the United States (0.1% of GDP) and then applying this to other regions using an index of coastal sensitivity. The benchmark estimate for the United States includes damages to developed and undeveloped land and damages from storms. The index of coastal sensitivity is constructed by dividing the ratio of coastal area to total area for a given region by the ratio for the United States (see Table 5-5). The income elasticity of coastal damages is assumed to be 0.2.

For the FUND model, Tol (2002a,b) follows the method pioneered by Fankhauser (1995a,b) in estimating the costs of sea-level rise as the sum of the capital cost of structures for coastal protection, and the cost of foregone services from "dry" and "wet" coastal land that is inundated. This entails determining the optimal level of coastal protection, which determines the first component of cost and also the amount of coastal land that is inundated, for a given rise in sea level.

The cost of inundation of unprotected land depends on the extent of land loss and population displacement from the inundation. Tol estimates population displacement as the product of projected loss of drylands and average population density, and makes several assumptions about the destinations of the resulting migrants.[9] The next step is to monetize these impacts. The unit values of lost dry and wet land in OECD counties are assumed to be \$4 million/km^2 and \$5 million/km^2, respectively, and are extrapolated to other regions by adjusting them according to the inundation probability-weighted population density in the coastal zone and per capita income. For population displacement Tol assumes a cost of emigration from an affected zone equal to three times per capita income, and an immigration cost equal to 40% of the per capita income in the host country.[10] The results are shown in Table 5-5.

The amount of land (percent of the coast) that is protected is determined by comparing the costs and benefits of protection. Table 5-6 presents the optimal fraction of the coast protected, by region, as well as the costs of that protection.

Impacts on Ecosystems and Ecosystem Services

Without a solid, broadly accepted set of standards for the value of ecosystems, the external costs of climate change assigned to ecosystem effects tend to get categorized in one of two ways. Based on the IAMs that do incomplete and preliminary accounting, the damages are generally quite low, sometimes barely enough to register in the overall cost accounting for climate change impacts. Other studies based on ecosystem services often start from the proposition that ecosystem services are critical for the maintenance of healthy people, communities, and people. As a consequence, they tend to assign large but rarely quantified amounts to the external impacts of climate change. The general inclination of stakeholders who take this position to assign zero or even negative discount rates creates the foundation for extraordinarily large damages. The steps to quantitatively test or reconcile these perspectives will likely be numerous and challenging.

Four widely used IAMs (RICE/DICE, MERGE, FUND, PAGE) all estimate damage from climate change based on willingness to pay. An alternative approach, calculating the economic value lost from the ecosystem services degraded by climate change, is addressed in the Millennium Ecosystem Assessment, though these results are not quantitative in the sense that the output is damage per ton of CO_2. All of the published representations of ecological damages from climate change are highly simplified. Willingness to pay is typically based on data from one or a few countries, often the United States, and then scaled to other countries on the basis of an assumed relationship with GDP.

In the RICE/DICE models, human settlements and ecosystems are treated together. It assumed that the capital value of climate-sensitive human settlements and ecosystems ranges from 5 to 25% of regional output. For the United States the number is 10%; for island countries and countries with sensitive ecosystems, the number is higher. Willingness to pay to avoid a 2.5°C temperature change is

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[9]Displaced persons in countries of the OCED, Central and Eastern Europe and the former Soviet Union stay entirely within their own regions, while only 10% displaced persons in poorer regions emigrate outside their own regions. A variety of assumptions about where the latter go are made.

[10]Compare Cline's (1992) rough estimate of \$4,500 per migrant for the United States.

TABLE 5-5 Values of the Benchmarking Parameter (α)

	Coastal Impact[a]	Coastal Index (% of GDP, 1990)	α † (2.5°C impact)
United States	1.00	0.10	0.11
China	0.71	0.07	0.07
Japan	4.69	0.47	0.56
Western Europe	5.16	0.52	0.60
Russia	0.94	0.09	0.09
India	1.00	0.10	0.09
Other high income	1.41	0.14	0.16
High-income OPEC	0.52	0.05	0.06
Eastern Europe	0.14	0.01	0.01
Middle income	0.41	0.04	0.04
Lower-middle income	0.94	0.09	0.09
Africa	0.23	0.02	0.02
Low income	0.94	0.09	0.09
Global			
Output weighted‡			0.32
Population weighted§			0.12

[a]Ratio of fraction of area in coastal zone in country to that fraction in the United States. "Coastal zone" is defined as that part of the region that lies within 10 kilometers of an ocean.

†Calibrated to impacts in the year 2100.

‡Output projections in 2100 from RICE model base case.

§ 1995 population.

Source: Nordhaus and Boyer (2000: Tables 4-5 and 4-10). Reprinted with permission; copyright 2008, MIT Press.

TABLE 5-6 Benchmark Sea-Level Rise Estimates in FUND

	Cost Length (10³ km)	Level Prot. (%)	Dryland Loss (10³ km²)	Dryland Value (10⁶ km²)	Wetland Loss (10³ km²)	Wetland Value (10⁶ km²)	Protection Costs (10⁹$)	Emigrants 10⁶	Value 10⁹$	Immigrants 10⁶	Value 10⁹$	Total Costs 10⁹$/year
OECD-A	33	0.77	4.8 (2.4)	1.3 (0.6)	12.0 (8.6)	5.4 (2.7)	83 (74)	0.13 (0.07)	7.5 (5.3)	0.0 (0.20)	2.9 (2.1)	1.6 (0.9)
OECD-E	59	0.86	0.7 (0.4)	13.1 (6.6)	4.0 (2.3)	4.3 (2.2)	136 (45)	0.22 (0.10)	8.2 (5.4)	0.64 (0.32)	3.1 (2.2)	1.7 (0.5)
OECD-P	23	0.95	0.3 (0.4)	13.7 (6.7)	1.0 (1.1)	5.9 (2.9)	63 (38)	0.04 (0.02)	2.8 (2.0)	0.18 (0.10)	1.6 (1.2)	0.8 (0.4)
CEE&dSU	25	0.93	1.2 (2.7)	0.9 (0.5)	0.0 (0.0)	2.9 (1.5)	53 (50)	0.03 (0.03)	0.7 (0.7)	0.03 (0.03)	0.0 (0.0)	0.5 (0.5)
ME	6	0.30	0.6 (1.2)	0.5 (0.3)	0.0 (0.0)	1.3 (0.7)	5 (3)	0.05 (0.08)	0.4 (0.6)	0.04 (0.07)	0.0 (0.0)	0.0 (0.0)
LA	39	0.86	7.8 (7.1)	0.3 (0.2)	50.2 (36.4)	0.9 (0.5)	147 (74)	0.71 (1.27)	3.9 (7.2)	0.64 (1.14)	0.5 (0.9)	2.0 (0.9)
S&SEA	95	0.93	9.3 (9.6)	0.5 (0.3)	54.9 (48.0)	0.3 (0.2)	305 (158)	2.30 (1.40)	3.7 (2.9)	2.07 (1.26)	0.5 (0.4)	3.3 (1.6)
CPA	33	0.93	8.4 (15.1)	0.3 (0.2)	15.6 (17.1)	0.2 (0.1)	171 (126)	2.39 (3.06)	2.5 (3.4)	2.15 (2.75)	0.3 (0.4)	1.8 (1.30)
AFR	35	0.89	15.4 (18.4)	0.4 (0.2)	30.8 (14.8)	0.4 (0.2)	92 (35)	2.74 (2.85)	5.4 (6.3)	2.47 (2.56)	0.7 (0.8)	1.1 (0.4)

Notes: Definitions of the regions (which correspond to the regions of FUND) are as follows: OECD-America (excl. Mexico) (OECD-A), OECD-Europe (OECD-E), OECD-Pacific (excl. South Korea) (OECD-P), Central and Eastern Europe and the former Soviet Union (CEE&fSU), Middle East (ME), Latin America (LA), South and Southeast Asia (S&SEA), Centrally Planned Asia (CPA), and Africa (AFR).

Source: Tol 2002a. Reprinted with permission; copyright 2008, *Environmental and Resource Economics*.

assumed equal to 1% of the capital value of the vulnerable system (Nordhaus and Boyer 1999). The elasticity of willingness to pay with respect to income is assumed equal to 0.1.

FUND does a separate calculation for 16 regions. The impact of warming on ecosystems in fund is calculated as a "warm-glow" effect in which people are assumed to assign value to biodiversity and other ecosystem services, independent of whether they receive any concrete benefits from those services (Tol 1999). The value of the damage function rises with the fraction of biodiversity lost, with the amount of warming, and with per capita income in each region (Warren et al. 2006b).

Approaches based on the valuation of ecosystem services typically calculate the cost of replacing natural services with human or industrial alternatives. Many studies of the value of ecosystem services (e.g., USEPA 1999), however, do not explicitly assess the vulnerability of the ecosystem services to climate change. Schröter et al (Schröter et al. 2005) look at the vulnerability of ecosystem services to climate change in Europe, but they don't calculate an explicit cost impact. Naidoo et al. (2008) concluded that, for a large set of ecosystem services, they could reliably estimate values for only four and that the values of these four ecosystem services do not align well with areas targeted for biodiversity conservation. Brauman et al. (2007) review a number of approaches to assessing ecosystem services and conclude that, whether or not the services are monetized, trade-offs among them can provide a useful set of tools for evaluating policy options. This is the approach utilized by the Millennium Ecosystem Assessment, which assessed the impacts of four future scenarios (including climate change) based on the number of ecosystem services, in each of four categories, expected to increase or decrease.

Overall, estimates of the impacts of economic damage to ecosystems from climate change are more conceptual and heuristic than quantitatively meaningful. The approaches that generate explicit numbers are simple and non-mechanistic approaches, starting with willingness to pay studies of a small number of ecosystem services for one region or country at one level of economic development.   Even if the willingness to pay studies were accurate, they should not be assumed to cover the full suite of climate-sensitive ecosystem services or to effectively capture the extrapolation of willingness to pay to other services, regions, or levels of economic activity. Finally, the sensitivity of the ecosystem services to climate is not well known. These factors combine to define an approach that can be very useful for understanding aspects of the way the system works but that are unlikely to provide values that can be robustly used for studies that address multiple sectors of the economy. Approaches based on valuing ecosystem services sometimes generate numerical values, but sometimes they do not. The approaches based on valuing ecosystem services are not yet integrated in any of the main IAMs. Realizing such integration would represent an important conceptual advance in the credibility of the modeling, but it might not yield dramatic improvements in model accuracy or utility.

Impacts on Agriculture

The welfare effects of climate change on agriculture depend on the impacts of climate on crop yields and on how farmers adapt to them. In many areas of sub-Saharan Africa it is predicted that temperatures will exceed optimal temperatures for many crops currently grown, and even for crops that could be substituted for current crops. Yield losses will, however, be less when irrigation is possible. Farmers may also be able to reduce income losses from crops by raising cattle and thus diversifying their agricultural portfolios. In northern latitudes yields are actually predicted to increase for many crops, and the latitude at which field crops, such as winter wheat, can be grown is likely to increase. The magnitude of physical impacts, in addition to depending on adaptation to climate in the form of crop substitution and irrigation, will depend on the magnitude of the CO_2 fertilization effect: increased carbon in the atmosphere will increase yields by promoting photosynthesis and reducing plant water loss.[11]

To estimate the GDP impacts of the effects of climate change on agriculture, economists predict the impact of temperature and precipitation on agricultural revenues. These estimates are based primarily

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[11]This raises yields approximately 15% for crops such as rice, wheat and soybeans (Cline 2007).

on cross sectional studies—often referred to as the Ricardian approach (Mendelsohn et al. 1994; Kurukulasuriya et al. 2006) or on crop models (Parry et al. 2004). The Ricardian approach looks at variation in net revenues across different geographic areas that vary in climate. For example, in Dinar et al.'s (1998) study of Indian agriculture, variation in the net revenue per hectare across districts in India is explained as a quadratic function of temperature and precipitation, measured during different seasons of the year. In principle this captures adaptation to climate—farmers in North India, for example, are more likely to irrigate their crops than farmers in South India—which is reflected both in revenues and costs. Crop models examine the impact of changes in temperature and precipitation on yields in a controlled setting. The results can be used as inputs into models that simulate farmer adaptation changes in climate (e.g., by changing crop mix). With assumptions about food prices and input costs, crop models can also predict the impact of climate change on agricultural revenues (see Box 5-1.).

To estimate the GDP impacts of a particular climate scenario—for example, an increase in mean global temperature of 2.5 degrees Celsius in the year 2100—researchers must predict the impact of a temperature change on agricultural revenues in the year 2100, as well as the share of agriculture in GDP in 2100. In practice, the percentage change in agricultural revenues associated with a climate scenario is multiplied by the share of agriculture in GDP to estimate the GDP impacts of the scenario. When percentage changes in agricultural revenues are predicted from Ricardian models, it is implicitly assumed that prices will remain the same in the future as when the models were estimated. Yield changes predicted by crop models can, in principle, serve as inputs to world models of food trade that will predict future agricultural prices and, hence, revenue impacts in a future year. Models that produce country-level estimates of GDP impacts such as FUND and RICE/DICE assume that the share of agriculture in GDP declines as per capita income rises.

What is the magnitude of estimates of the impact of climate on agriculture and how do they vary across countries? A recent study by Cline (2007) estimates the impact on agricultural yields of a 4.4˚C increase in mean global temperature and a 2.9% mean increase in precipitation occurring during the period 2070-2099. As Figure 5-7 shows, the largest losses are predicted to occur in parts of Africa, in South Asia and in parts of Latin America. In contrast, the United States and Canada, Europe and China will, in general, benefit from an increase in mean global temperature. These are estimates of impacts on yields and do not represent impacts on GDP.

Nordhaus and Boyer's (1999) estimates of the impact of agriculture on GDP corresponding to a doubling of CO_2 concentrations (estimated to occur in 2100) suggest increases in GDP of over 0.5% in China, Japan and Russia but losses of over 1.5% of GDP in India. However, when weighted by GDP, the losses associated with a doubling of CO_2 concentrations, are less than 0.2% of world output (Warren et al. 2006b). Tol finds aggregate net benefits to agriculture from a doubling of CO_2 concentrations, although Warren et al. (2006b) criticize this finding as overly optimistic.

Impacts on Human Health

Theoretical analyses of the health consequences of rising average temperatures, and the associated changes in average precipitation, have led to research in the following five areas:

1. *Heat(and cold)-associated health conditions*, including the excess morbidity and mortality attributable to infectious, respiratory and cardiovascular diseases and over-exposure that occur after intense or prolonged cold weather, and in heat-stress related morbidity and mortality, especially excess cardiovascular disease mortality after intense or prolonged hot weather. Included in this category could be the potential impacts on occupational health from working in hot and cold climates. These are typically derived by looking at patterns of mortality either by day or season as a function of temperature for major cities, then using regression techniques to estimate temperature associated effects. Investigators differ in choice of daily changes, e.g., heat waves, or average seasonal temperatures, the former providing higher estimates but with excess deaths typically limited to more vulnerable sub-populations.

BOX 5-1 Estimating the Impacts of Climate Change on Agriculture

Estimates of the impacts of climate change on agriculture are based primarily on cross sectional studies of land values or net revenues (the Ricardian approach, see Kurukulasuriya et al., 2006) or on crop models (Parry et al., 2004).

Crop models examine the impact of changes in temperature and precipitation on yields in a controlled setting, which can also control for the effects of CO_2 fertilization. The advantage of these models over statistical studies is that they allow for a much richer set of parameters that influence yields. Plant growth is modeled as a dynamic process of nutrient application, water balance, as well as many other factors. The potential pitfalls are that the sheer number of parameters makes it impossible to estimate them jointly in a regression model and hence these models rely on calibration instead. Some authors are concerned about misspecification and omitted variables biases (Sinclair and Seligman 1996, 2000). The results can be used as inputs into models that simulate farmer adaptation changes in climate (e.g., by changing crop mix). Changes in yields predicted by these models are often used as inputs to world food trade models to calculate the impacts of yield changes on prices and welfare. The effect of yield changes on world prices are not captured in the Ricardian framework and are ignored in Cline (2007).

The Ricardian approach looks at variation in land values or net revenues across different geographic areas that vary in climate. For example, in Dinar et al.'s (1998) study of Indian agriculture, variation in the net revenue per hectare across districts in India is explained as a quadratic function of temperature and precipitation, measured during different seasons of the year. The Ricardian approach in principle captures adaptation to climate—farmers in North India, for example, are more likely to irrigate their crops than farmers in South India. This impact is reflected both in revenues and in costs: Farmers who irrigate have higher yields as well as higher costs. The Ricardian approach thus measures the impact of higher temperatures on net revenues allowing for adaptation. The models also allow for crop substitution across different climate zones. If the results from models such as these are used to examine climate impacts it is implicitly assumed that prices will remain the same in the future as when the model was estimated. Without additional adjustment, the predictions of Ricardian models will not capture CO_2 fertilization effects or the impact of international trade in food on welfare.

Other criticisms of the cross sectional approach include the fact that climate variables may pick up other effects—for example, knowledge of farm practices—that also vary geographically. Any variable that is correlated with climate and itself influences farmland values has to be accounted for in the analysis. For example, access to subsidized irrigation water in the United States is correlated with warmer temperatures and capitalizes into farmland values. Omitting irrigation from a hedonic analysis will wrongfully attribute these subsidies as a benefit of a warming climate (Schlenker et al. 2005). For example, an analysis that pools the entire United States in a regression analysis assumes that if Iowa were to become warmer, it would become like California, where farmers enjoy access to highly subsidized irrigation water. In reality, Iowa would likely become more like Arkansas, which is also warmer and more irrigated (72% of the corn acreage is irrigated), but doesn't have access to subsidized irrigation water. While the decision to irrigate is endogenous, the access to water and its cost vary greatly in space. Irrigation is just one example of a potential variable that varies with climate and influences farmland values. Soil quality, access to markets, etc, might be others. It is difficult to account for all of them correctly.

Some authors have therefore suggested using year-to-year weather fluctuations and examining how they impact yields or profits (Auffhammer et al., 2006, Deschenes and Greenstone, 2007). The advantage is that a panel (a data set with repeated observations for each spatial unit like a county) allows for the use of fixed effects to capture all time-invariant factors like soil quality and access to irrigation. The potential problem is that year-to-year weather fluctuations are something fundamentally different from climate change. The former are inherently short-term, examining how yields or profits change in response to weather fluctuations after the crop is planted. The latter are long-term responses to a permanent shift in climate, which include switching to other crops or production methods that are not available in the short term.

Both the Ricardian analysis and panel studies have distinct advantages and disadvantages. Research for the United States suggests that both approaches agree that primarily extremely warm temperatures have a negative influence on yields and farmland values. Yields of corn, soybeans, and cotton gradually increase with increasing temperature until a crop-specific threshold between 29°C and 32°C is reached (Schlenker and Roberts, 2009). Further temperature increases quickly become very harmful. Hotter regions exhibit the same sensitivity to these high temperatures as cooler regions, suggesting that they were not able to adapt to the higher frequency of these warm temperature events. Similarly, a Ricardian model of farmland models that separates temperature into beneficial moderate temperatures and damaging extreme temperatures finds that the land values are most sensitive to extremely warm temperatures (Schlenker et al. 2006).

With carbon fertilization

If some crops benefit from increased carbon dioxide, the global impact is less dire and those areas farther from the equator may see some increases in agricultural productivity.

(climate-induced percent change in agricultural productivity between 2003 and the 2080s)

NA
<-25
-25 to -15
-15 to -5
-5 to 0
0 to 5
5 to 15
15 to 25
>25

Source: Cline (2007).
Note: NA refers to "not applicable" for Alaska and northern Canada, and to "not available" elsewhere.

FIGURE 5-7 Impact of increased temperature and precipitation on agricultural productivity. Percent increases and decreases were calculated assuming additional carbon fertilization. Negative values indicate percent decreases in productivity. For example, the agricultural productivity in Mexico and the southwestern United States is predicted to decline by 25% of more. Source: Cline 2007. Reprinted with permission; copyright 2008, Peterson Institute for International Economics.

2. *Vector-borne diseases*, especially malaria (mosquitoes), but also including dengue and yellow fever (mosquitoes), hanta and related viruses (rodents), Lyme and rickettsial diseases (ticks) and bird-borne viruses such as West Nile and possibly influenza.

3. *Sanitation-related disorders*, including diarrheal diseases such as cholera and others that occur with increased frequency in the setting of storms and prolonged droughts.

4. *Climate-associated changes in air-pollution health effects*. While climate is not the source of air pollutants, atmospheric conversion of NO_x and hydrocarbons to ozone, and of SO_2 to its acid forms may be related to climate.

5. *Aeroallergen load* associated with altered ecosystems resulting from temperature and rainfall changes. As a consequence, potential increases in rates of upper and lower respiratory track allergies including asthma.

Substantial efforts have been made to model impacts in each category for the US and other regions of the world based on the study of morbidity and mortality patterns in relation to climate patterns historically

Accurate prediction of future impacts is substantially limited by the complexity of underlying assumptions about the populations at risk over time. The following factors complicate current efforts to estimate, based on various climate change scenarios, what the impact on human health will be in the distant future:

1. *Demographics and development.* All the categories listed above affect different populations differentially, depending on such features as age, underlying health status and stage of socio-economic

development. For example, the sanitation-related disorders are relevant only in the context of under-development; populations in advanced countries rarely suffer from these impacts under any climate conditions except in a hurricane Katrina-like disaster. Similarly, heat and cold associated disorders affect disproportionately the very young and very old, those with chronic health conditions, and those with resource limitations; any predictions of impact of a given climate change scenario demands that explicit assumptions be made regarding the distribution of at-risk people in a given population, introducing more uncertainty.

2. *Adaptation.* The impact of many purported climate-associated health effects depends on the degree to which the affected population has become adapted to particular conditions. For example, heat-related morbidity and mortality are far more salient in populations living in temperate climates with large seasonal fluctuations in temperature than in those with year-round hot weather because of acclimatization; the *rate* of change may be a larger determinant than the extent of change in some of these estimates.

3. *Technology.* Separate from the impact of development on the underlying condition of populations is the potential impact of specific technological changes. For example, a successful malaria vaccine could neutralize the projected impact of increased malaria mortality even in the absence of underlying developmental change in regions of the world with endemic malaria. Likewise, advances in sanitation science, development of new anti-microbial techniques of agents, or vector control technologies, could substantially alter modeled impacts on sanitation-related effects.

4. *Mitigation.* Projected effects for each climate change scenario could be substantially modified by efforts to anticipate the effects, with an eye to mitigating them. Above and beyond the societal changes anticipated by societal development following its natural path, specific interventions could, in theory, reduce or eliminate effects due to any of the above categories. This could include such things as climate-surveillance, with institution of remedial steps under conditions of anticipated high risk, or introduction of societal counter-measures, such as more stringent air quality controls, or provision of climate-controlled public shelters.

While the importance of each of these factors is widely acknowledged by investigators attempting multi-sector estimates of the (external) costs of damages related to human health under various scenarios (e.g., RICE/DICE and FUND), the cost-estimates for damages in each category have been developed generally under the default assumptions that development and demographic change over time would occur *unrelated* to intentional efforts to modify or mitigate the impacts of GCC. In other words, it is assumed that technologies and GDP will advance in parallel, and the underlying health-status related to development will improve based on projections of regional GDP and GWP, without taking into consideration specific efforts (nor their costs) which might specifically offset or modify possible climate-related health effects.

The FUND model and the RICE//DICE model estimates for health damages as percent lost GDP, for the United States and total/global, reflect two somewhat divergent approaches. Tol (FUND model), building on previous efforts, approaches the damages for the United States (and also other developed economies) restricting attention to a single category of effects, namely "heat-associated health conditions." FUND incorporates Martens (1998) meta-analysis of data from 17 European and American countries (20 cities)—a model based on seasonal averages—to calculate the impact of temperature under several different climate scenarios. Notably, none of the other categories of potential health effects are added beyond this, possibly a source of underestimate (see below). Nordhaus (RICE/DICE), on the other hand, does not use this approach for a U.S. estimate and relies instead on deriving a temperature-associated estimate based on the WHO Global Burden of Disease (Murray and Lopez 1996) estimates for the region; this results in a very small figure, more than 10-fold lower than Tol.

It is noteworthy that both methods may have underestimated effects attributable to other categories. Most notably on the United States side is the possibility that pollution, interacting with climate, may have greater impact on ozone-related morbidity and mortality than estimates of temperature or pollution separately (e.g., Knowlton et al. 2004). Globally, Kjellstrom et al. (2008) recently published a model suggesting substantial impact of climate in developing countries on the ability to work because of

heat-stress. The magnitude of this health effect has not been incorporated into either model, nor has either addressed the potential importance of allergy-related disease despite the global epidemic of asthma, still unexplained, already underway. It should also be commented that while Tol offers a range of estimates based on differing assumptions about the composition of the at-risk populations, neither model has tested divergent assumptions about the effects of mitigation, adaptation or specific technology change.

Other Impacts: Energy Production and Consumption, Socioeconomics, National Security

Climate change will likely lead to many impacts that are poorly measured or difficult to quantify. In this section we focus on impacts to industry, population movements, energy supply and consumption, and national security. The greatest risks from climate change are likely to increased instability in vulnerable areas of the world with a consequent potential for increased risk of terrorism and political instability.

Impacts on Energy Production and Consumption. Global warming will likely lead to modest decreases in heating demand and modest increases in cooling demand in the United States with the former felt predominantly in the northern area of the country and the latter in the southern area (CCSP 2007). Impacts on energy consumption primarily affect demand for electricity.

The CCSP study reports decreases in energy used in residential, commercial, and industrial space heating as possible effects of climate change. Estimates are quite imprecise. One study (Mansur et al. 2005) finds a 2.8% decline in energy use for electricity-only customers, a 2% decline for gas customers and a 5.7% decline for oil customers corresponding to a 1 degree Celsius increase in January temperature in 2050. The variation in heating reduction is driven in part by regional variation in heating. Oil accounts for over one-third of heating in the Northeast whereas customers with electricity-only are likely to be located in the South or Southwest. Scott et al. (2005) find a stronger response.

Residential cooling impacts are stronger with Mansur et al. (2005) finding a 4% increase in demand for electricity only customers for a 1 degree Celsius increase in July temperature in 2050. Increases for gas and fuel oil customers are 6% and 15% respectively.

Annual energy consumption is affected by decreased heating and increased cooling costs. Mansur et al. find a 2% increase in residential expenditure and no impact on commercial expenditures at the national level. Others studies find similar impacts though there exists potentially significant regional variation.

Global impacts mirror regional impacts in the United States with higher latitude regions benefiting from reductions in heating while lower latitude regions face higher costs of cooling (Stern 2007).

Beyond heating and cooling, the CCSP report finds little impact on industrial energy demand (see studies by Amato et al. 2005; Ruth and Lin 2006). Industry may be affected in other ways. In particular electrical outages arising from extreme weather events would have significant impacts on energy-sensitive industries.

Similarly, impacts on energy production are likely to be modest in the aggregate. Regionally, certain areas may experience impacts. Reductions in water in the Northwest could reduce supply of hydroelectricity appreciably. Weather disruptions and extreme events could impact oil and gas supply and refining activities in the Gulf of Mexico. Similar impacts arise globally. Stern (2007) reports reductions in nuclear power production in France during the 2003 European heat wave due to overly warm river water that the plants rely on for cooling (pp. 142-143 of the cited report).

Socioeconomic Impacts. It is difficult to predict the full range of potential socioeconomic impacts from global climate change. Stern (2007) reports that some 7 million people in sub-Saharan Africa have migrated to new regions in order to obtain food due to environmental stresses on agriculture (p. 128-9). In addition to migration, climate change has the potential to create disruptions that impact

education and gains in gender equality (Chew and Ramdas 2005). Coastal erosion, rising oceans, and extreme weather all disproportionately impact the most vulnerable members of society. (See a catalog of impacts in Leary et al. (2006.)

National Security Impacts. The socioeconomic instabilities described in the previous sub-section all have implications for national security of the United States as well as global security. A recent report by the CNA Corporation (CNA Corporation 2007) finds that climate change will add to instability in already volatile parts of the world (e.g. Somalia and Darfur). In addition, the impacts will be felt globally and so create greater strains for the U.S. military as it stretches itself to cover conflicts in various parts of the world (acting either unilaterally or multilaterally).

Population migration will also impact currently stable countries and regions. The United States and Europe, for example, will face increased pressure from immigrant populations. Moreover while underdeveloped regions of the world are disproportionately impacted by extreme weather (or are especially vulnerable), stable regions are not immune. It is estimated that the European heat wave of 2003 killed more than 50,000 people (Larsen (2006).

The CNA report highlights especially important regional impacts. Two-thirds of the Arab world currently relies on imported sources of water (CNA 2007, p. 30). Decreased precipitation exacerbates this problem and raises the specter of increased out-migration and land tension with neighbors. Nearly 40% of Asia's population lives no more than 45 miles from the coast. Sea-level rise could put millions of people at risk for inundation and increased risk of infectious disease (CNA 2007, p. 24).

The military implications of these impacts are two-fold. First, U.S. military systems and bases will be stressed. Diego Garcia in the Indian Ocean serves as a major logistics hub for U.S. and British forces in that region of the world. The island at its highest point is only a few feet above sea level (CNA 2007, p. 37). In the event of significant sea-level rise, it may be possible to adapt by building dikes or other capital infrastructure but this comes at an economic cost and may affect the ability to use the base to its current capabilities. In addition to impacts on military bases, climate change and severe weather make military missions that much more challenging. Extreme weather also creates vulnerabilities for military energy supplies. Electricity systems are subject to outages in extreme weather. This is an issue for the military since the Department of Defense relies on electricity from the national grid to power critical infrastructure at installations (CNA 2007, p. 38).

A second concern identified by the CNA report is the Arctic. With global warming retreat of the Arctic ice pack means that the U.S. Navy will have to expand its scope of operations to cover this area. In addition, increased access to the Arctic is likely to bring about increased competition for previously inaccessible resources including potentially large reserves of oil.

Estimates of Other Impacts. It is extremely difficult to monetize the external costs of political instability, population displacement, national security, and military costs arising from climate change. We can, on the other hand, provide estimates of the external costs arising from increased demand for electricity due to climate change. We briefly discuss below the treatment of these costs in the FUND and DICE models.

The FUND model 3.0 does not provide estimates of most of the socioeconomic costs discussed above, although resettlement costs are included in the costs of sea-level rise (see above). FUND does provide estimates of increased heating and cooling costs based on an equation relating heating (or cooling) to increases in temperature, per capita income, population, and technology improvements. The elasticity of heating with respect to global mean temperature (relative to 1990 levels) is 0.5 in their base case for heating and 1.5 for cooling. The income elasticity of space heating and cooling demand is 0.8 in the base case (taken from Hodgson and Miller, 1995, cited in Downing et al., 1996b). Tol (2009) reports that globally the increased costs of electricity for cooling are the single largest component of the marginal damages from a ton of CO_2-eq emissions, while global reductions in heating costs reduce the marginal damages from a ton of CO_2-eq emissions.

Nordhaus and Boyer 1999) estimates that a 2.5 degree Celsius increase in temperature would have negligible costs on energy and modest costs on human settlements ($6 billion in 1990 dollars; see Table 4-11 on p. 4-45 of the cited document) . These costs include costs of migration and adaptation as well as losses that occur due to difficulties in responding to sea-level rise or extreme weather. These costs are computed by estimating the capital value of vulnerable areas and assuming a willingness to pay to avoid damages equal to 1% of the value of at-risk capital (see section on coastal zone impacts). The authors acknowledge that the methodology "is at this stage speculative and requires a detailed inventory and valuation of climatically-sensitive regions for validation" (pp. 4-21 to 4-22). The authors note, however, that this is likely to be an area of high impact and cost that will factor in to climate change policy in important ways.

ECONOMIC DAMAGE FROM IRREVERSIBLE AND ABRUPT CLIMATE CHANGE

"The term "abrupt climate change" has several definitions (e.g., Clarke et al. 2003; NRC 2002d; Overpeck and Cole 2006). For the purposes of this assessment a useful definition is articulated by CCSP (2008): "A large-scale change in the climate system that takes place over a few decades or less, that persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems."

By contrast, irreversible climate changes are ones that represent fundamental regime shifts in major climatic variables that are likely to persist over very long times of hundreds to thousands of years. Irreversibilities are related to abrupt climate changes in that they embody the idea of thresholds or "tipping points" in physical or biogeochemical variables, which once crossed result in a large (implicitly rapid rate) and for all intents and purposes permanent change. In terms of climate responses, changes of this nature include such possibilities as the collapse of the Greenland or West Antarctic ice sheets, loss of coral reefs, or the shutdown of the North Atlantic thermohaline circulation. However, incremental climate changes can eventually cross some threshold related to physical processes, and thus also could lead to irreversible climate change.

One concern about such climate changes is the potential for them to trigger serious or catastrophic follow-on impacts such as the release of methane and CO_2 trapped in ocean sediments and permafrost, loss of biodiversity through extinction, disruption of species' ecological interactions, and major changes in ecosystem structure and disturbance regimes such as wildfire and insects. Another reflection of this concern is the tendency of these sorts of changes to be discussed in parallel with potential downstream consequences for human society, in particular the value of lost species, ecosystem services, arable land and attendant effects on food security, as well as adverse effects on human settlements, migration, and the potential human insecurity (i.e., refugees, violent conflict) arising therefrom.

An important feature of the preceding definitions is that they say little about the likelihood of occurrence of the events in question. While it is tempting to view climatic thresholds as a "bright line", there is little empirical basis for inferring just how much of a change in probability they occasion. On one hand, there is the probability of the threshold being reached, which depends on the trajectory of GHG emissions and consequent radiative forcing. Some indication of the relevant probabilities is given in Table 5-2. On the other hand, how the probability of occurrence of the impacts in question might change for increments in, say, temperatures in excess of the threshold is largely unknown. For example, IPCC (2007a) concludes that 20-30% of assessed species face about a 50% chance of increasingly high risk of extinction as global mean temperatures exceed 2 to 3°C above preindustrial levels, but does not characterize the dependence of the probability of extinction on temperatures beyond the threshold.[12] This kind of impact is distinct from events which are low probability but very high consequence, and for which

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[12]IPCC (2007) does characterize how the magnitude and geographic distribution of extinction impacts increase with temperature (Table 4.1).

is unclear that climatic thresholds apply—such as a massive decadal-scale release of methane to the atmosphere from rapid clathrate destabilization.

Solomon et al. (2009) focus attention on atmospheric warming, precipitation changes, and sea-level rise driven by thermal expansion as adverse irreversibilities for which three criteria are met: the relevant changes are already being observed and there is evidence for their anthropogenic precursors, the phenomena are based upon physical principles that are thought to be well understood, and projections are available and are broadly robust across earth-system models. These authors employ results from a suite of models to construct ranges of very long run equilibrium changes in the climate. Their estimate of the irreversible temperature increase ranges from 1 to 4°C, with a corresponding 0.2-0.6 meter sea-level rise per degree of global warming, for an irreversible global average sea-level rise of at least 0.4-1.0 meters (and as much as 1.9 meters for peak CO_2 concentrations in excess of 1,000 ppmv), and complete losses of glaciers and small ice caps adding a further 0.2-0.7 meters. The corresponding estimates of shifts in precipitation are subject to considerable uncertainty, but a robust change is an enhanced dry season in several regions, on the order of 20% in northern Africa, southern Europe, and western Australia, and 10% in southwestern North America, eastern South America, and southern Africa for 2°C of global mean warming. The equilibrium dependence of regional dry season precipitation impacts on CO_2 concentrations are illustrated in Figure 5-8.

At the other end of the spectrum, the implications of these climatic changes for biodiversity loss, highly nonlinear impacts such as ice sheet instability, thermohaline circulation collapse or methane clathrate releases, and climate-induced violent conflict, all represent unknowns that derive from fundamental gaps in scientific understanding of the mechanisms of the relevant impact pathways in Figure 5-1 (NRC 2002d; Tol, 2008). For the sake of completeness, brief notes are provided about the current state of the literature in each of these areas.

There are comparatively few quantitative studies of the direct impacts of climate change on ecosystems and biodiversity at broad geographic scales,[13] and projecting changes in biodiversity at the regional and global levels is complicated by the need to account for large-scale, potentially nonlinear interactions associated with factors such as shifting anthropogenic land use and invasive species (see, e.g., Sala et al., 2000). The theoretical basis for valuation of ecosystem changes at these scales is very weak. Nicholls et al. (2008) assess the impacts of a collapse of the West Antarctic Ice Sheet (WAIS), exploring a wide range of scenarios of resulting sea-level rise, from 0.5-5 meters per century. Their estimates of annual costs, which are not explicitly linked to temperature change, range between $0-28 billion in 2050 and $0.1-31 billion in 2100.

The full range of impacts arising from a slowdown or collapse of the Atlantic thermohaline circulation (THC) has yet to be systematically characterized. The only studies from which cost figures can be drawn are Keller et al (2004), who arbitrarily assume an uncertain cost in the range of 0-3% of gross world product, and Link and Tol (2004), who estimate that THC shutdown increases the marginal damage of greenhouse gas emissions by $0.1-2.2 per ton of carbon. The seemingly small magnitude of these figures may be appreciated when one considers that in the Link and Tol study THC collapse has a negligible influence on global average surface temperature, but has a substantial impact on temperatures in the USA, Canada and western Europe, inducing cooling of 0.5-1.5°C by 2150 and 1-3°C by the year 2300.

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[13]Scientific studies have mostly focused on aggregate indicators of change. For example, Scholze et al. (2006) use the results of a suite of climate model runs as inputs to a dynamic global vegetation model, and map the proportions of simulations which exhibit forest-nonforest shifts and exceedance of natural variability in wildfire frequency and freshwater supply. A landmark study by Thomas et al. (2004a) estimated that among the groups of organisms they assess in regions covering 20% the Earth's land surface, the committed warming by 2050 will cause extinction of 15-37% of species. However, the methods for combining climatic stressors with geographically localized data on individual species to characterize species extinctions are the subject of vigorous debate (Buckley and Roughgarden, 2004; Harte et al, 2004; Lewis, 2006; Thomas et al., 2004b; Thuiller et al, 2004).
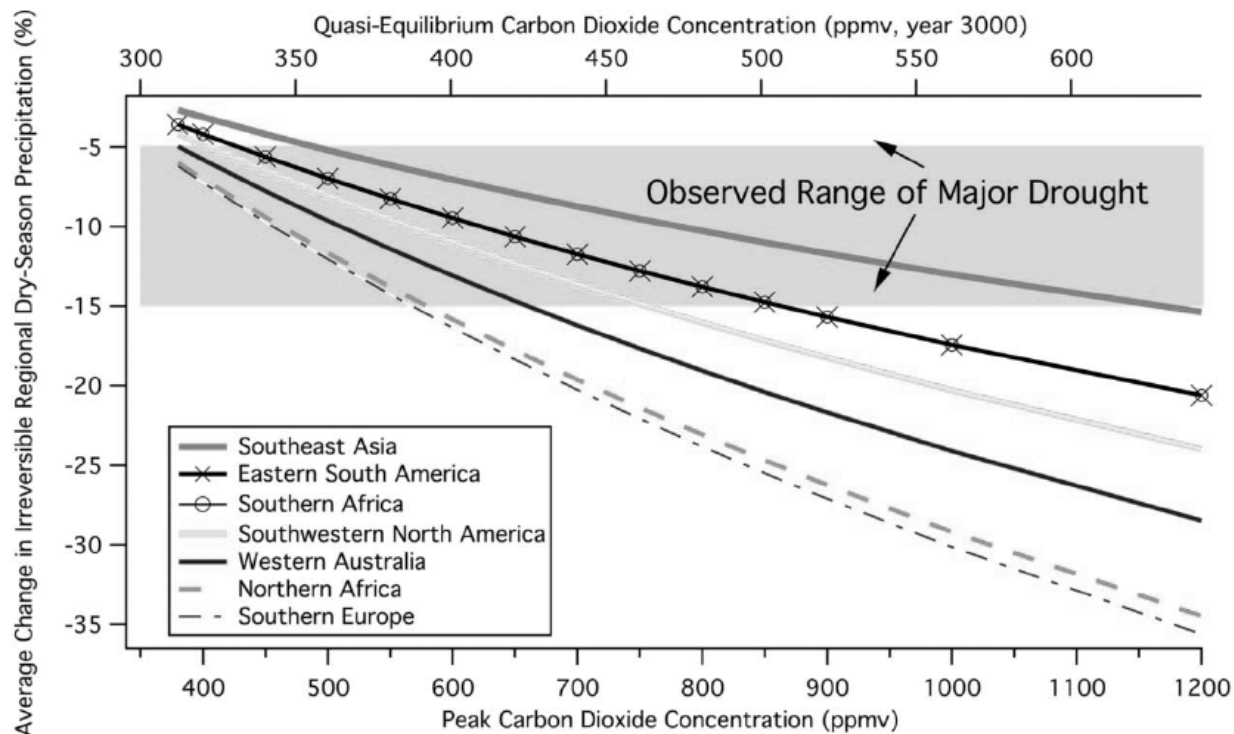
FIGURE 5-8 Irreversible Precipitation Changes by Region. Source: Solomon et al 2009, Figure 4.

Considerable scientific uncertainty still besets the characterization of methane releases from clathrates in ocean sediments and permafrost. The most widely cited study by Harvey and Huang (1995) estimates a cumulative methane release of 53-887 GtC after 2000 years (Table 9 of the cited document), resulting in an equilibrium atmospheric temperature rise of 1-9°C (their Fig. 9). These authors find an amplification of global warming of 10-25%, but this range depends strongly on assumptions about the climate sensitivity and the warming due to projected anthropogenic CO_2 emissions, and is substantially outweighed by the latter uncertainties. Recent results by Renssen et al (2004) highlight the importance of uncertainties regarding the "worst case" quantity of methane released. A massive emission (1,500 GtC) over the course of a millennium would entail large climatic changes,[14] with peak additional surface warming of 2.6°C on average and up to 10°C at the poles, accompanied by regime shifts in the global overturning ocean circulation.

The discussion above describes the possibility of extreme climate changes that could result in large, irreversible economic damages to the planet. As noted at the beginning of the chapter, the possibility of extreme events is not well handled by IAMs in calculating the marginal damages of CO_2. The RICE/DICE models attempt to handle extreme events by calculating what a risk-averse individual would pay to avoid a catastrophic event (of given probability) that would reduce GDP from 22% to 44% depending on the region of the world. The probability of such an event is calculated, for each T, based on expert judgment. For a 2.5°C change in mean global temperature willingness to pay to avoid catastrophic risk ranges from 1.9% of GDP in OECD Europe and India to 0.45% of GDP in the United States. The corresponding figures are 10.79% and 2.53% of GDP to avoid catastrophic risk associated with a 6°C change in mean global temperature.

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[14]The authors design this scenario to be consistent with the Paleocene-Eocene thermal maximum, a period about 55.8 million years ago which experienced drastic changes in climate possibly as the result of releases of methane from hydrates.

Weitzman (2009) has demonstrated that, if one were to ask a risk-averse individual what he would pay to avoid the gamble described above, the amount would be infinite if the distribution over the catastrophic GDP loss were "fat-tailed." (Formally, if the distribution has an infinite moment generating function.) Clearly, the nature of the probability distribution of catastrophic outcomes matters, and is handled only imperfectly by the WTP calculations described in the preceding paragraph or by the Monte Carlo simulations performed to capture uncertainty in the key parameters of IAMs. The key problem here is that low-probability extreme-impact events located in the fat tails, which are extremely difficult to quantify, might drive the results of cost-benefit analysis. This is disturbing because the answers to important questions about how much effort to put into climate-change mitigation can depend to an uncomfortable degree on subjective estimates about the likelihood of catastrophic outcomes.

AGGREGATE IMPACTS OF CLIMATE CHANGE

To quantify the marginal impact of an additional ton of GHG emissions requires a number of steps beyond quantifying the individual impacts associated with a particular magnitude of climate change. Within each region, for a particular climate change scenario (e.g., doubling of CO_2 concentrations in the atmosphere), individual components of impact must be aggregated across sectors, raising difficulties for inclusion of impacts that have not been expressed in monetary metrics, as well as interaction effects such as between water and agriculture. Next, because the impacts of GHG emissions emitted anywhere are felt globally, there is much interest in understanding the global impacts of climate change, not simply the effects of each country's emissions within its own borders. This requires aggregating impacts on people with widely differing incomes, raising questions about whether monetized impacts should be adjusted to account for differing marginal values of income across countries. Moreover, because the consequences of current GHG emissions are expected to persist for centuries, it is necessary to aggregate impacts on people living at different future times. Previous surveys of these issues include Pearce et al. (1996), Tol and Fankhauser (1998), Tol et al. (2000), Smith et al. (2001), Hitz and Smith (2004), Stern et al. (2006) , Yohe et al. (2007), and Tol (2008).

Tol (2008) identifies a total of 13 published studies that have estimated the monetized impacts of climate change at a global level, several of which also include total climate change damage estimates individually for the United States and other regions (Fankhauser 1995a; Tol 1995, 2002b; Nordhaus 1994a, 1994b, 2006; Nordhaus and Yang 1996; Nordhaus and Boyer 2000; Plambeck and Hope 1996; Mendlesohn et al. 2000a,b; Maddison 2003; Rehdanz and Maddison 2005; Hope 2006). In addition, Nordhaus (2008) contains an update based on Nordhaus and Boyer (2000), and at least another three published studies contain total damage estimates for the United States alone (Nordhaus 1991; Cline 1992; Titus 1992; Mendelsohn and Neumann 1999). Note that these estimates are not independent, because many of them represent revised estimates by the same researchers over time (e.g., Nordhaus, Tol, Hope, Maddison), and other estimates are based on models that draw from several other prior studies (e.g., impact valuation in Plambeck and Hope (1996) derives from Tol (1995) and Fankhauser (1995b); see discussion in Tol (2008). A review of impact estimates within integrated assessment models (Warren et al. 2006b)—including the DICE/RICE model (Nordhaus), FUND model (Tol), and PAGE model (Hope)—found that the impacts in these models are based on literature from 2000 and earlier.

Table 5-7 summarizes results from many of these studies, for consistency expressed in terms of percent loss in gross domestic product (GDP). Most, but not all of the scenarios are benchmarked to a 2.5-3°C temperature increase by 2100 associated with central estimates of the likely warming from a doubling of GHG concentrations in the atmosphere. Note that Mendlesohn et al (2000a,b) and Nordhaus (2006) include only market impacts while the other studies also include estimates of non-market impacts, at least to some degree.[15]

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[15]Maddison (2003) and Rehdanz and Maddison (2005) are not included in this table due to the incompleteness of these estimates relative to the others included. Maddison (2003) estimates the effect of temperature and precipitation

TABLE 5-7 Estimates of Total Damage Due to Climate Change from Benchmark Warming (Percent Change in Annual GDP)

Study	Temperature Change (°C)	Global[e]	United States	Range Across Regions
2.5-3.0°C warming benchmark				
Nordhaus (1991)	3.0	NA	-1.0	NA
Cline (1992)	2.5	NA	-1.1	NA
Nordhaus (1994a)	3.0	-1.3	NA	NA
Nordhaus (1994b)	3.0	-1.9[c]	NA	NA
Fankhauser (1995b)	2.5	-1.4	-1.3	-4.7 – -0.7
Tol (1995)	2.5	-1.9	-1.5	-8.7–0.3
Nordhaus and Yang (1996)	2.5	-1.7[a]	-1.1	-2.1–0.9
Plambeck and Hope (1996)	2.5	-2.5[a]	-1.6	-8.6–0.0
Nordhaus and Boyer (2000)	2.5	-1.5	-0.5	-4.9–0.7
Mendlesohn et al. (2000a,b)[b,d]	2.5	0.00.1	NA	-3.6–4.0[a] -0.5–1.7[a]
Hope (2006)[d]	2.5	-1.0	-0.3	-3.1–0.3
Nordhaus (2006)[b]	3.0	-1.0	NA	NA
Nordhaus (2008)	2.5	-1.8	-0.7	-20.0–16.4
Other warming benchmarks				
Titus (1992)	4.0	NA	-2.5	NA
Tol (2002b)	1.0	2.3	3.4	-4.1–3.7

Notes: Positive damage estimates indicate benefits from warming. NA indicates data are not available.
[a]As computed by Tol (2008).
[b]Estimate includes only market impacts; non-market impacts are not monetized.
[c]Median estimate from an expert opinion survey of 19 individuals.
[d]The study's mean estimates are given.
[e]Global GDP losses are simple (unweighted) sums of regional GDP losses.

Table 5-7 shows that these studies typically estimate the aggregate global market plus non-market impact of doubling GHG concentrations at 1-2% of lost world GDP. The aggregate impacts mask significant differences in regional impacts and in the underlying impacts for individual damage categories estimated within each study. Estimated percent damages tend to be lower in industrialized countries, but significantly higher in many developing countries with relatively higher current temperatures, heavier dependence on agriculture, and lower adaptive capacity. No individual impact category consistently dominates other categories across studies. Previous surveys have also been careful to note the low quality of the numbers and the many shortcomings of the underlying studies.

In addition to differences across aggregate climate impact studies in terms of methods, and estimated regional and individual impact categories, there are a number of other key assumptions and sensitivities. One issue is whether GDP impacts in individual regions are weighted during aggregation to a global total. The global estimates noted above simply add up the estimated regional impacts in dollar terms (i.e., they are output weighted), regardless of income levels in the different regions. However, it is widely accepted that individuals with low income tend to value a given dollar impact more heavily than a relatively high-income individual. This is known as the declining marginal utility of income, and approaches for incorporating it are often called "equity weighting" or "population weighting" (if global losses are based on regional percent losses weighted by population shares as opposed to output shares). Estimates that allow for equity weighting typically find significantly more negative aggregate global

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on household market good impacts based on historical country-level demand data, while Rehdanz and Maddison (2005) estimate the effect of temperature and precipitation on historical country-level measures of "happiness".

impacts because regions with more substantial projected impacts are also relatively poor (Yohe et al. 2007).

Estimates of total climate damage also depend critically on the degree of temperature change that is being assessed. With the exception of the Titus (1992) and Tol (2002b) assessments of a 4°C and 1°C temperature increase respectively, all the other studies in Table 5-8 focus on a benchmark warming scenario of 2.5-3.0°C, corresponding to best estimates of eventual temperature change from a doubling of GHG concentrations. Unsurprisingly, the pattern among available studies is that—beyond some amount of warming that is beneficial for certain regions and impact categories—greater degrees of temperature increase are associated with correspondingly higher damages.[16]

As an approximation, modeling assessments (e.g., using DICE/RICE, FUND, and PAGE) that explore a range of emission, concentration, and temperature scenarios tend to assume that damages are proportional to the size of the world economy and that the fraction of world GDP lost (total or per capita) is a power-function of temperature increase. The power function is calibrated to the damage estimate from benchmark warming (i.e., it is one point on the function) and an assumed temperature level corresponding to zero damages. A linear relationship (i.e., percent climate damages per degree temperature change is constant) corresponds to a power of 1, while a quadratic or cubic relationship corresponds to a damage exponent of 2 or 3. The DICE model (Nordhaus 2008), for example, assumes a quadratic damage function based on Nordhaus and Boyer (2000), yielding estimates of global climate damages increasing over four-fold from -1.8% to -8.2% of world GDP for a two-fold increase in temperature from 3°C to 6°C. The PAGE model (Hope 2006), on the other hand, allows for a damage exponent ranging from 1 to 3, with an associated range of global impact that varies by a factor of almost 6 for a 6°C temperature increase (see Figure 5-9, where the PAGE damage function for 6°C is about 2.4 times the level at 2.5°C for linear damages, while it is about 14 times as high assuming cubic damages).

Yet, in the absence of substantial mitigation action, projections of baseline GHG emissions tend to imply estimates of likely temperature increase that are significantly greater than that associated with a doubling of GHG concentrations. For example, the IPCC (2007, p. 66, Figure 5.1) references plausible projections of GHG concentrations that go near to and beyond 1000 ppm by 2100, with an associated best estimate global mean temperature increase above preindustrial levels of about 5-6°C and a likely range from just under 4°C to over 8°C. But little is known about the precise shape of the temperature-damage relationship at such high temperatures.[17] Figure 5-10 illustrates dependence of GHG damage, as a percent of global gross domestic product, on the amount of temperature change.

MARGINAL IMPACTS OF GREENHOUSE GAS EMISSIONS

Given an estimate of the monetized global impact of a particular climate change scenario at a particular future point in time, this total damage estimate can then be translated into a marginal damage per ton estimate (often called the "social cost of carbon") by evaluating the linkage between current GHG emissions and future climate change impacts (see Equation 5-2). It is usually estimated as the net present value of the impact over the next 100 years (or longer) of one additional ton of CO_2-eq emitted into the atmosphere. It is this marginal damage per ton of emissions that is normally used as a measure of the global climate externality. This requires assumptions about the emissions-temperature and temperature-damages linkages over time, as well as the rate at which future damages are discounted back to the present to account for differing valuation of monetary impacts felt at different points in time. Finally, uncertainties at each step of the analysis imply that different possible future conditions may yield widely differing impacts. The expected value of damages may be more sensitive to the possibility of low-probability catastrophic events than to the most likely or best-estimate values.

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[16]Several studies have found positive impacts of climate change on agriculture in Canada, Europe and parts of China (see Figure 5-7 from Cline). Heating requirements are also predicted to decline in Russia and parts of Europe.
[17]See discussion in Stern (2007, p. 659-662).

TABLE 5-8 Marginal Global Damages from GHG Emissions: Estimates from Widely Used Models

Model	Study	Marginal GHG Damage ($/ton CO_2)	Discount Rate (%)[a]	Climate Warming Scenario[d]	Total Global Climate Damage (% GDP)
DICE	Nordhaus (2008)	8[e] 8	~4.5	No control: 3.1°C in 2100; 5.3°C in 2200 Optimal: 2.6°C in 2100; 3.5°C in 2200	-1.8% @2.5°C -4.5% @4.0°C -7.1% @5.0°C -10.2% @6.0°C
FUND	Tol (2003)[d]	0 2 6	5 3 2	No control: 3.7°C in 2100; 6.7°C in 2200	~0% @2.5°C ~-1% @4.0°C ~-1% @5.0°C
PAGE[b]	Hope (2006)[c] Hope and Newbery (2008)	6 (1-17) 22 (4-60) 108 (21-284)	~4.5 ~3 ~1.5	No control: 4.1°C in 2100; 7.9°C in 2200	-1.0% @2.5°C -2.6% @3.9°C -11.3% @7.4°C
	Stern et al. (2006)	102 36	1.4	No control: 3.9°C in 2100; 7.4°C in 2200 Stabilize at 550 ppm CO_2-eq: eventual 3°C	-1.0% @2.5°C -2.6% @3.9°C -11.3% @7.4°C

[a]Discount rate changes over time in Nordhaus (2008) and Hope (2006); the approximate effective discount rate is given.
[b]For PAGE model, mean global GDP impacts are given in Dietz et al. (2007), including market, non-market, and risk of catastrophic impacts.
[c]Mean estimate for 2001 emissions with 5th-95th percent confidence interval from uncertainty analysis in parentheses.
[d]Estimate is for emissions in 2000 from FUND version 2.4.
[e]Estimate is for emissions in 2005.
Note: Negative numbers indicate a negative impact on GDP.
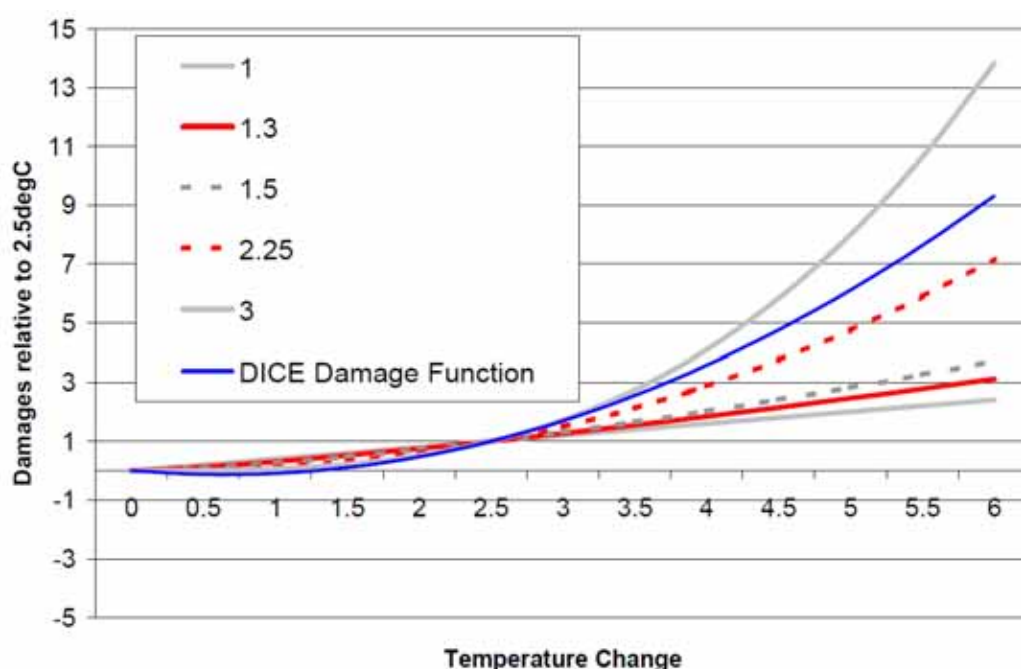
FIGURE 5-9 Dependence of GHG damage on the amount of temperature change. The lines show the PAGE2002 damages for damage exponents between 1 and 3. The damage function of the DICE model is also shown for comparison. In this figure, positive values indicate economic losses, while negative values indicate benefits from warming. Source: Stern 2006, Technical Appendix.
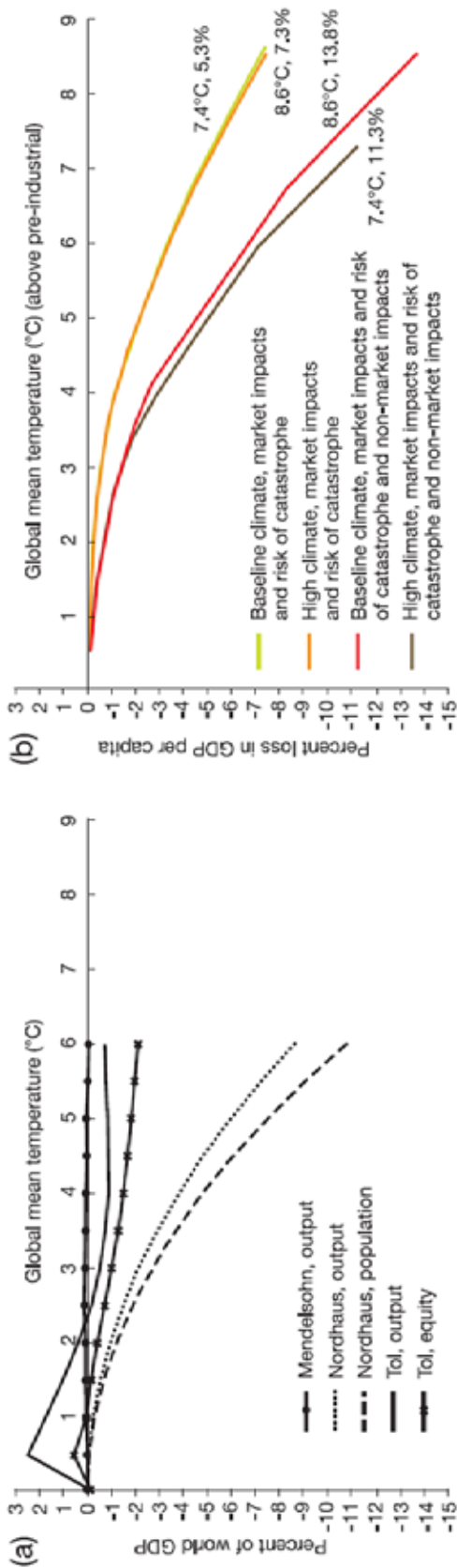
FIGURE 5-10 Dependence of GHG damage, as a percent of global gross domestic product, on the amount of temperature change. (a) Damage estimates, as a percent of global GDP, as a function of increases in global mean temperature. b) Damage estimates, as a percent of global GDP per capita, are correlated with increases in global mean temperature. In this figure, positive values indicate benefits from warming. Source: IPCC 2001, p. 1032 and Stern 2007 (as cited in Yohe et al. (2007, p. 822).

There have been many prior reviews of existing estimates of the marginal damages from GHGs, including Pearce et al. (1996), Tol (1999, 2005, 2008), Clarkson and Deyes (2002), and Yohe et al. (2007). Tol (2008) identifies a total of 211 marginal damage estimates from 50 studies, although this does not imply we know more about marginal than total damages (recall there are only twelve global total damage estimates in as shown in Table 5-7). The explanation for how so many marginal costs can be generated from so few total damage estimates lies in the variety of additional modeling assumptions that must be incorporated to translate total into marginal damages. As alluded to above, in addition to the benchmark estimate of total damages, important other assumptions include the change in damages with increased warming and with growth and changes in the composition of economic activity over time, the assumed emissions scenario, the climate sensitivity to GHG concentrations, the rate used to discount future impacts to the present, the timeframe over which impacts are considered, and the treatment of uncertainty and risk aversion. Box 5-2 discusses approaches used to determine a discount rate.

Pearce et al (1996, p. 215, Table 6.11) summarizes early estimates of marginal GHG damages, which ranged from $3 to $62 per ton of CO_2-eq for emissions occurring in the 2001-2010 decade.[18] As part of a United Kingdom effort to assess the social cost of carbon, Clarkson and Deyes (2002) suggested a pragmatic approach could be to employ a central estimate of $35 per ton of CO_2-eq, along with a sensitivity range of half and double this amount (i.e., $17 to $70 per ton of CO_2-eq). Tol (2005) identified 103 marginal climate damage estimates from 28 published studies, finding a median estimate of $4 per ton CO_2, a mean of $25 per ton CO_2, and a 95th percentile of $96 per ton CO_2-eq across the estimates. Tol (2005) also found that the subset of studies published in peer-reviewed journals reported lower estimates on average, with a mean of $12 per ton CO_2-eq. (Note that the Tol (2005, 2008) values are not adjusted for inflation.) Summarizing 211 estimates identified in Tol (2008), yields a median estimate of $8 per ton CO_2-eq, a mean of $29 per ton CO_2-eq, a 5th and 95th percentile of $0 and $105 per ton CO_2-eq respectively, and a peer-reviewed mean of $14 per ton CO_2-eq (University of Hamburg 2009). In cases where a single study generated multiple estimates, Tol (2008) includes a relative weight for each estimate that was provided by the author of each study. Using these weights one can construct a single weighted estimate for each of the 50 studies. Summarizing these 50 estimates from individual studies, yields a median estimate of $10 per ton CO_2eq, a mean of $30 per ton CO_2-eq, and a 5th and 95th percentile of $1 and $85 per ton CO_2-eq, respectively.

Note, however, that due to lack of necessary information, Tol does not adjust individual estimates for inflation nor does he account for the timing of emissions (i.e., year they occur) or the GHG concentration and temperature scenario onto which those emissions are added. Adjusting for inflation from the study year to current dollars would make these figures higher. The underlying estimates also differ in terms of their assumed discount rates and how they aggregate regional impacts (i.e., using output, equity, or population weighting), among other factors.

To provide a more consistent comparison of marginal damage estimates, it is helpful to focus on estimates using the most widely used impact assessment models, DICE, FUND, and PAGE, as shown in Table 5-9. The estimates represent the marginal damages from current emissions against an assumed reference case climate scenario without GHG mitigation. This subset of estimates spans approximately the same range as discussed above, from roughly 0 to $100 per ton of CO_2-eq. The table demonstrates that virtually all of this variation can be understood as a function of differences across the studies in what they assume about the discount rate and the magnitude of GDP losses expected from uncontrolled warming. Nordhaus (1996) made the same point, noting that "the two crucial parameters are the discount rate (which indicates the relative importance of the future compared to the present) and the damages from climate change (which measure the willingness to pay to prevent or slow climate change). *It is interesting to note that both major uncertainties involve human preferences rather than pure questions of 'fact' about the natural sciences*" (emphasis in original).

Perhaps the clearest illustration of the influence of the discount rate is a comparison of the "no-control" relatively high (4.5%) discount rate scenario of Hope (2006) and the low discount rate (1.4%) of

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[18]IAM results usually include CO_2 as the only GHG. Tol (2005) refers to a cost per tonne of carbon.

BOX 5-2 Discounting and Equity Weighting

Quantifying the damages from GHG emissions requires aggregation of damages that occur at different times extending centuries into the future and to different populations across the globe at each point in time. The method chosen for aggregation has implications for how effects on different people are weighed.

Two methods for aggregating effects on different people are common: using monetary and utility measures. The monetary measure assumes that $1 of benefit to one person is equally as good as $1 of benefit to another. The utility measure assumes that the gain in utility (or well-being) from receiving $1 is larger for a poor person than for a richer person because the poor person is likely to have more pressing needs.

Aggregating across people using the monetary measure is straightforward: one simply sums the monetary values of benefits and harms across the relevant population. To implement the utility-based approach, one needs to make some assumptions about how individual utility varies with income (or wealth). Often, it is assumed that utility is proportional to the logarithm of income, or to a power function of income where the power is less than one. These functions have the property that utility increases with income but at a diminishing rate. After choosing a function, one can weight the monetary value of benefits and harms to each person by the incremental utility of income and sum these values. This "equity weighting" gives more weight to the same monetary value of damages when they are suffered by a poorer than a richer person.

For aggregating effects across time, it is conventional to discount the monetary value of future effects by a factor $[1 / (1 + r)]^t$ that depends on the discount rate r and number of years in the future t at which the effect occurs. The present value of a stream of effects occurring at various times in the future is calculated by summing the discounted monetary values of the effects.

In determining the appropriate discount rate to use for aggregating effects on the current and some future generation, one can distinguish between descriptive and prescriptive approaches. The descriptive approach infers the rate at which society chooses between consumption at different times from market interest rates.

In contrast, the prescriptive approach derives the appropriate discount rate on monetary values (the consumption discount rate) as the sum of utility and growth discount rates. The utility discount rate is the rate at which the future generation's utility is discounted relative to the present generation's. Many scholars have suggested that it is inappropriate to value other people's well-being less simply because they come later in time, and so argue for a utility discount rate of zero. The growth discount rate accounts for differences in income between the current and future generation. If the future generation will have greater income than the current generation, it will lose less utility from $1 of damages than will the current generation. To aggregate the effects on utility, it is necessary to down-weight the monetary value of the damages to the future generation, just as one would down-weight the monetary value of effects on richer people at the same point in time in accordance with equity weighting. The extent of this growth discounting effect depends on the economic growth rate (that determines the difference in income between the two generations) and the utility function (that determines how much the incremental effect of income on utility falls). Note that if the future generation will be poorer than the present, this growth discounting effect would apply in the opposite direction and would give greater weight to the monetary value of damages suffered by the future generation.

Following the prescriptive approach, Stern et al. (2006) adopts a near-zero utility discount rate of 0.1% per year, a relatively small value of the rate at which the incremental effect of income on utility falls of 1 (corresponding to a logarithmic utility function), and a low rate of economic growth, 1.3% per year. Together, these yield a consumption discount rate of 1.4%. In contrast, Weitzman (2007a,b) suggests that more plausible values are roughly 2%, 2, and 2%, yielding a much larger consumption discount rate of 6%. Nordhaus (2008) uses the descriptive approach, i.e. he calibrates his model parameters so that the consumption discount rate is consistent with market interest rates, yielding a discount rate of 4.5%.

Stern et al. (2006), which yield marginal damage estimates of $6 and $102 per ton, respectively: a 17-fold difference. Both studies used the same version of the PAGE model, so that the only significant difference in assumptions is the discount rate. When Hope and Newbery (2008) applied approximately the same discount rate as Stern et al. (2006) to the PAGE model, they found a similar marginal damage estimate of $108 per ton CO_2. Similarly, the Nordhaus (2008) estimate of $8 per ton CO_2, which also used a relatively high discount rate of about 4.5%, is quite close to the Hope (2006) 4.5% discount rate estimate. Finally, when Nordhaus (2008) applied low discount rates similar to Stern's to the DICE model, he found a marginal damage estimate similar in magnitude to Stern's ($88 per ton CO_2-eq).

TABLE 5-9 Indicative Marginal Global Damages From Current GHG Emissions ($/Ton CO_2-eq)

Discount rate	Damages from benchmark warming	
	Relatively low	Higher
1.5%	10	100
3.0%	3	30
4.5%	1	10

Note: At this point only order-of-magnitude estimates appear warranted.

The rate at which the future damages from current emissions are converted to present values in Stern et al. (2006) is only slightly greater than the rate at which damages for an incremental increase in global temperature are projected to grow over time. In Stern et al. (2006), damages are a fraction of world GDP per capita that depends on climate change. The rate at which GDP per capita is assumed to grow (1.3% per year) is nearly as large as the discount rate (1.4% per year). With impacts rising almost as fast as they are being discounted, it is primarily the limited time horizon (2200 in the PAGE model) that constrains the marginal damage estimate from becoming virtually unbounded given that the effects of current emissions on climate will persist for centuries. In contrast, the discount rates assumed in Nordhaus (2008) and Hope (2006) are high enough that even after accounting for these additional growth effects the present value of damages in the distant future is low.

The growth in incremental damages over time underpins the rationale for a marginal (per ton) GHG damage that rises over time. For example, in the PAGE model marginal damages rise by about 2.4% per year (Hope and Newbery 2008) and in the DICE model marginal damages rise by about 2.0% per year (Nordhaus 2008). Over a 20-year period (e.g., from 2010 to 2030) marginal damages rising at a rate of 2-3% per year would increase in total by a factor of 50-80%. This is due to a combination of a larger economy being affected and increasing proportionate impacts of increasing temperatures (i.e., non-linearity of the damage function).

Note, however, that the marginal damages from current emissions do not decrease appreciably for alternative scenarios with significantly lower GHG emissions and temperature increases in Nordhaus (2008) or in Hope and Newbery (2008). According to Hope and Newbery (2008) this is due to convexity of the damage function being roughly offset by concavity in the concentrations-temperature relationship, which is logarithmic. Given that Stern also uses the PAGE model, it is therefore surprising that Stern et al. (2006) finds that marginal damages fall dramatically from $102 per ton under a no-control scenario to $36 per ton CO_2-eq under a 550 ppm stabilization scenario. While Stern et al. (2006) does not provide an explanation for the derivation of these results, it appears to be a result of the much lower discount rate assumed in Stern, which gives higher weight to future damages, and which are much lower in a stabilization than no-control scenario. Recall that in contrast, Nordhaus (2008) and Hope (2006) use significantly higher discount rates where these future damages (or lack thereof) matter less. One implication is that even low discount rate scenarios that give rise to high marginal damages with no climate mitigation may be consistent with substantially lower marginal damage estimates (and corresponding Pigouvian emission prices) if in fact controls are undertaken. Put differently, even if one accepts marginal damage estimates on the order of $100 per ton, the implication is not that emission prices at this level would be efficient.

At the other end of the range in Table 5-8 are the estimates from the FUND model. These estimates also demonstrate the importance of the discount rate for present value marginal GHG damages, implying that GHG emissions move from having negligible effects (and in some scenarios positive benefits) with relatively high discounting of 5%, to a larger impact of $6 per ton CO_2-eq with relatively low discounting of 2%. The generally lower estimates of FUND are clearly due to the assumed damage function, which specifies benefits to global GDP up until about a 2-2.5°C of warming. Even after this point, damages do not go much beyond about 1% of lost GDP even for large temperature increases, in contrast to the other models where damages increase non-linearly.

The marginal damages of GHG emissions may be highly sensitive to the possibility of catastrophic events. While a number of potentially catastrophic outcomes have been identified (e.g., release of methane from permafrost that could rapidly accelerate warming, collapse of the West Antarctic or Greenland ice sheets raising sea level by several meters, changes in North Atlantic currents that would dramatically alter European climate), the damages associated with these events and their probabilities are very poorly understood. Nordhaus and Boyer (2000) and Stern (2007) include some provision for catastrophic outcomes that could lead to the loss of perhaps one quarter of world GDP. Weitzman (2009) raises the even more sobering possibility that the probabilities of extreme outcomes are much larger than currently estimated. If taken into account, low-probability extreme outcomes, such as the possibility of a 10 or even 20 degree increase in global mean temperature that could virtually destroy civilization as we know it, could dominate the expected value of damages, making it much greater than the values described above.[19]

Given the uncertainties and the still preliminary nature of the climate damage literature, the committee finds that only rough order-of-magnitude estimates of marginal climate damages are possible at this time. Depending on the extent of future damages and the discount rate used for weighting future damages, the range of estimates of marginal global damages can vary by two orders of magnitude, from a negligible value of about $1 per ton to $100 per ton of CO_2-eq. Roughly an order of magnitude in difference can be attributed to discounting assumptions, and another to assumptions about future damages from current emissions. Table 5-9 summarizes these findings for discount rates of 1.5%, 3.0%, and 4.5%, respectively, and for relatively low and higher climate damage assumptions (corresponding roughly to FUND-level damages versus DICE- or PAGE-level damages). For a discount rate of about 3%—a typical rate for use in long-term environmental analysis in the United States and elsewhere—the comparable marginal damage estimates could be on the order of about $3 per ton to $30 per ton CO_2-eq for relatively low versus higher damage assumptions.[20] As discussed earlier, however, the damage estimates at the higher end of the range are associated only with emission paths without significant GHG controls. Therefore, care must be taken in translating these estimates for use in policies for decreasing GHG emissions. In Stern (2008), for example, the marginal damage estimate is $36 per ton CO_2-eq for a stabilization trajectory associated with stabilization at about 550 ppm CO_2-eq, not the $102 per ton Stern found associated with uncontrolled emissions.

As described above, marginal damage estimates for emissions in 2030 could be as much as 50-80% larger than these estimates. Estimates of the damages specifically to the United States would be a fraction of these levels, because the United States is only about one-quarter of the world's economy and the proportionate impacts on the United States are generally thought to be to be lower than for the world as a whole (see Table 5-7).

Table 5-10 presents three different estimates of external global damages from GHG emissions on a per-unit-basis. The damages were calculated by multiplying GHG emission rates from Chapters 2 (electricity), 3 (transportation), and 4 (heat) by each of the committee's assumed low, middle and high marginal damages $10, $30, and $100 of damages per ton CO_2-eq.

In conclusion, the committee finds that the relative weight placed on potential impacts occurring decades to centuries in the future is absolutely central to the determination of a present value measure of

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[19]For further discussion and alternative view, see Aldy et al. 2009.

[20]To gain a rough sense for how marginal damages change as a function of growth and discounting, it is useful to consider the relative magnitude of the present value of a growing stream of damages, discounted at different rates. As mentioned above, a typical climate economic model might imply marginal damages growing over time at about 2% per year, due to economic growth and a convex damage function. Accumulated over several hundred years, the present value of a stream of damages growing at 2% per year, increases by a factor of 2.5 using a discount rate of 3% rather than 4.5%. Using a discount rate of 1.5%, the cumulative value of a stream of damages growing at 2% per year is only bounded by the time horizon of the sum. As another point of reference, studies cited in reviews by Tol (2005, 2008) using discounts rates of 3% also show a mean marginal damage in the range of $30 per ton CO_2-eq.

TABLE 5-10 Illustration of Ranges of Climate-related Damages for Selected Categories of Energy Use in the United States, 2005

Sector	Fuel and Technology	Climate-Related Damages for $10-30-100/Ton CO_2-eq[a]
Electricity		
	Coal plants (biomass)[b]	1-3.0-10 ¢/kWh
	Natural gas plants	0.5-1.5-5 ¢/kWh
	Nuclear, wind, solar	Much lower than natural gas
Transportation		
	Cellulosic E85/ car	0.02-(0.15-0.25)-2 ¢/VMT
	CNG	0.04-0.4-4.0 ¢/VMT
	Gasoline hybrid	0.04-0.4-4.0 ¢/VMT
	Gasoline/car	0.06-0.6-6.0 ¢/VMT
	E10	0.06-0.6-6.0 ¢/VMT
	$H_2(g)$	0.03-0.3-3.0 ¢/VMT
	Diesel/car	0.05-0.5-5.0 ¢/VMT
	E85 corn/car	0.05-0.5-5.0 ¢/VMT
	Grid-dependent HEV or EV[c]	0.05-0.5-5.0 ¢/VMT
Building and Industrial for Heating		
	Natural gas combustion[d]	0.07-0.7-7.0 $/MCF

[a]Rounded to one digit, 2007 USD.
[b]Biomass can be co-fired with coal in quantities up to about 20%.
[c]Ranges based on use of the fuel in a representative group of vehicles. Grid-electric cars are usually smaller than fleet average cars, so their better performance per vehicle-mile traveled (VMT) is also dependent on use of smaller cars with lesser driving ranges.
[d]Future additions to supplies may include imported LNG which will include non-climate damages outside the United States at the source and will have increased climate damages in the range of 30% or more depending on the gas field and the liquefaction plant details.

the damages from current GHG emissions. Over these time horizons the discount rate carries with it implications for intergenerational distribution. As with any social analysis involving significant distributional impacts, it is therefore crucial for decision makers not only to look at singular summary statistics (such as present value marginal damages), but also to understand the magnitude of impacts as individuals will bear them, both across time and at different points in time across regions. This concern is not particular to climate change, but the very long timeframes associated with GHG residence in the atmosphere and thermal inertia of the oceans raise the issue of discounting to a level that is present in few other problems. Nonetheless, the committee also finds that a consistent framework for discounting impacts occurring over similar timeframes across all potential policy investments is essential for reasoned policy analysis.

RESEARCH RECOMMENDATIONS

The committee makes the following recommendations to improve the understanding of physical, biological, and human impacts as well as economic valuation aspects related to climate change.

- More research on climate damages is needed, as current valuation literature relies heavily on climate change impact data from the year 2000 and earlier (see Tol (2008) for a number of fruitful areas).

- Marginal damages of GHG emissions may be highly sensitive to the possibility of catastrophic events. More research is needed on their impacts, the magnitude of the damage in economic terms, and the probabilities associated with various types of catastrophic events and/or impacts.

- Estimates of the marginal damage of a ton of CO_2 include aggregate damages across countries according to GDP, which gives less weight to the damages borne by low-income countries. This aggregate estimate should be supplemented by distributional measures that describe how the burden of climate change varies among countries.

6

Infrastructure and Security

INTRODUCTION

Our energy system depends on a massive infrastructure to produce and distribute energy to households and businesses. Table 6-1 gives a rough sense of the amount of fixed assets related to energy production. The infrastructure related to energy production amounted to nearly $2.9 trillion in 2007, or twelve percent of the value of the net stock of non-residential fixed assets in that year.[1] The bulk of energy related assets are structures—electrical generation facilities and mining exploration, shafts and wells.

In this chapter we consider a variety of externalities that are associated with our energy infrastructure. In particular, we consider disruption externalities in the electricity transmission grid, the vulnerability of energy facilities to accidents and possible attack, the external costs of oil consumption, supply security considerations, and national security externalities. Where possible we quantify the externalities that we identify.

DISRUPTION EXTERNALITIES IN THE ELECTRICITY GRID

In the interconnected bulk electric power system, "reliability" is the degree to which the system delivers power to consumers within accepted standards and in the amount desired (Abel 2006). Typically, reliability is good – the nation's electric power grid delivers power when needed and within an acceptable quality range.

Occasionally, however, electrical outages occur when the demand for electricity exceeds the supply. There are various causes of outages – including equipment failure, extreme weather events such as ice storms and hurricanes, trees or animals physically damaging parts of the electric system, accidents that damage parts of the system, equipment failure and operator error. Outages solely from overloads alone are rare. However, other things being equal, a greater load increases the likelihood of transmission congestion and of decreased reliability. Consequently, there are externalities associated with the consumption of electricity in the sense that when an electricity consumer draws from the grid, this increases the probability that demand will exceed supply and that an outage will occur.

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[1]This estimate does not include energy capital in the U.S. military nor does it include the value of transportation assets or computers and other equipment used in the production and distribution of energy. Adding transportation related equipment and structures alone would add an additional $1.3 trillion to the value of energy-related fixed assets.

TABLE 6-1 Net Stock of Energy-related Fixed Assets in 2007 ($Billions)

Private Fixed Assets		
Equipment and Software		523.9
Engines and turbines	83.5	
Electrical transmission, distribution, and industrial apparatus	358.4	
Mining and oilfield machinery	49.5	
Electrical equipment, not elsewhere classified	32.5	
Structures		2,120.4
Power	1,230.6	
Mining exploration, shafts, and wells	889.8	
Government Fixed Assets		*241.5*
Power	241.5	
TOTAL		2,885.8

Source: Bureau of Economic Analysis, National Income Accounts, Fixed Asset Tables (www.bea.gov, accessed June 1, 2009).

In addition to outages or interruptions in electricity service, voltage sags, harmonic distortions and other power quality events occur. Although each event generally causes little damage, except for customers whose commercial activities depend on very high-quality power, these events occur more much frequently and result in significant annual damage.

The possible externality that an individual consumer imposes when he uses additional electricity is the expected damage to all other users of the grid from an outage or power quality event (the damages of an event weighted by the increased risk of an outage from the marginal consumer's use). The optimal price to internalize this externality would include this marginal damage (unless the costs of implementing such a pricing scheme exceed the benefits). This externality has long been recognized, and as we discuss later, various means of internalizing this externality are in place to varying degrees.

To the extent transmission externalities exist, they apply to all of the electricity-generation options—coal, natural gas, oil, wind, hydropower, etc. However, intermittency in generation has the potential to affect the frequency of outage events, as well as power quality.

The Magnitude of the Electricity Disruption Externality

To calculate the magnitude of this externality, one needs an estimate of the damages from outages and power quality events, and an estimate of the increased probability of these events occurring due to the consumption of additional electricity. The nature and severity of the impacts of an outage or power quality disturbance vary and depend on the affected sector (i.e., manufacturing, commercial, or residential) and also on the specific functions affected, as well as the availability of backup power, the duration of the outage, the time of the year, the time of day, the geographic region, and the extent to which customers are notified prior to the outage.

A number of empirical studies estimating the damages from outages and power quality disturbances have been undertaken, some of which are based on estimates of lost output and damage from actual outages, others of which value the prevention of an outage. Previous estimates are typically of the total annual cost, cost per kWh, value of lost load, or damage divided by total kWh (Primen 2001, LaCommare and Eto 2004, Lawton et al. 2003, Layton and Moeltner 2005, Mount et al. 2008, Overdomain 2003, Van der Welle and van der Zwann 2007). None of these estimates measure marginal damages *per se*. Table 6-2 below provides estimates of average damages for different sectors.

TABLE 6-2 Estimates of the Average Cost of Outages[a,b]

Source	Estimate of Cost of Outages per kWh	Method Used for Estimate
Lawton, L., Eto, J., Katz, A., and M. Sullivan (2003)	*Averages* over all U.S. regions (costs vary by region), for studies done in 2001-02. Large commercial and industrial – Outages All durations: $0.0038 1 hr. duration: $0.0029 Small-medium commercial/industrial – Outages All durations: $0.015 1 hr. duration: $0.0083	Meta-analysis -- Reviewed previous studies over the past 15 years ending in 2002. Studies were of outage costs conducted by seven electric utilities, in 20 studies. Authors also provide ranges, regional breakdown, and by length of duration.
Authors	(see sub-table below)	Calculated based on estimates of costs per event and on ranges of the System Average Interruption Frequency Index, System Average Interruption Duration Index and Momentary Average Interruption Frequency Index in LaCommare and Eto (2004), combined with Energy Information Administration data on annual sales to each sector (in MWh). Estimates do not account for anecdotal evidence that larger commercial and industrial establishments have back-up power and thus experience fewer outages than smaller establishments and residential consumers. Thus, the estimates of average cost per kWh are significantly over-estimated for the larger establishments.

Sector	Type of occurrence	Average damage per year per customer	Average damage in $ per kWh
Residential	Power quality	$7.90 – $40.00	$0.00072 – $0.0037
	Outages	$2.80 – $6.40	$0.00025 – $0.00072
Commercial	Power quality	$2,800 – $9,100	$0.038 – $0.13
	Outages	$1,200 – $2,300	$0.016 – $0.03
Industrial	Power quality	$9,400 – $25,000	$0.0069 – $0.018
	Outages	$4,800 – $8,500	$0.0036 – $0.0062

Note: Estimates for the residential sector are likely *under*-estimated and for the commercial and industrial sectors, they are likely *over*-estimated.

[a] $2007 USD/kWh.

[b] The top part this table provides a summary of a meta-analysis on outage costs based on studies written between 1987 and 2002. Outage costs are reported by utilities taking part in the studies. Costs are reported in dollars per kWh. The bottom part of the table reports estimates for power quality events and outages for different customer classes. The right-hand column explains how the numbers in the table are obtained (top-half) or constructed (bottom-half).

In viewing the estimates in Table 6-2, it is important to note that SAIFI and SAIDI estimates were unavailable for the different sectors so that the same, overall averages were used for the residential, commercial and industrial sectors.[2] Anecdotal evidence strongly indicates, however, that commercial and industrial establishments are likely to have back-up power and thus less frequent loss of power (i.e., lower SAIFI values). Thus, the estimates in Table 6-2 for the commercial and industrial sectors likely significantly *over*-estimate the average damage per kWh consumed in these sectors.

The most striking observation from Table 6-2 is that smaller, commercial businesses are most vulnerable to outages and power quality disturbances, especially the latter. Assuming for the purpose of discussion that the estimates of average damage per kWh consumed over-estimate these damages in the commercial and industrial sectors by, say, an order of magnitude, they are nevertheless sizeable compared to the average U.S. retail commercial electricity price of $0.094/kWh in January 2008 (EIA 2009k, Table 5.6a).

Although an outage, if it were to occur, causes greater damage to industrial firms, there are far fewer of them compared to commercial establishments and industrial firms use much more electric power than commercial establishments. The upshot of these differences is that average damage per kWh consumed in the industrial sector is almost an order of magnitude less than that in the commercial sector. Average damage per kWh consumed in the residential sector is, in turn, about an order of magnitude less than that in the industrial sector. As previously noted, these numbers measure *average* damages per kWh consumed rather than *marginal* damages. Note also that not all damages are congestion-related network disruption damages. It is not possible to disentangle the marginal effect of network congestion's contribution to outages, apart from other factors. Thus the numbers in Table 6-1 are upper bounds on (and likely significantly higher than) the marginal damages from outages and power quality events due to congestion.

Differences in the Effects of Alternative Electricity-Generation Technology-Fuel Options on Grid Reliability

Renewable energy sources—especially wind and solar—might have different effects on the reliability of the grid, compared to conventional sources. The timing and duration of wind and sunshine cannot be controlled. Since wind velocities and sun intensity determine power output, it is variable and not entirely predictable. Electricity generally cannot be stored and transmission is costly. While reserves and transmission must be provided with any type of electricity generation technology, the issues are more prominent with some of the renewable energy resources.

There are concerns that, if interconnected to the grid, wind and solar facilities might reduce grid reliability or power quality. More back-up sources and power-quality control devices might be needed, as well as additional wind or solar capacity to account for their lower capacity factors, and transmission lines to carry power from more remote areas, where some of these facilities would be located, to where power is needed. These measures are costly, but could be internalized in market transactions.[3]

Extent to Which Grid Externalities Are Internalized

The degree to which externalities are internalized is difficult to determine as there are several ways in which internalization could occur. First, we should distinguish between the local distribution

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[2]SAIFI is the System Average Interruption Frequency Index – the average number of interruptions a customer experiences in a year. SAIDI is the System Average Interruption Duration Index – the average cumulative duration of outages a customer experiences in a year.

[3]There has been an interesting debate about how great these costs would be (for example, Jacobson and Masters 2001 and DeCarolis and Keith 2001).

network and regional transmission grids. For the former, it is likely that some of the externalities are internalized through pricing by the local distribution companies. Electricity pricing can take many forms.[4] For example, it can be implemented through differing block prices for peak and off-peak periods. If these periods and tariffs are pre-established, then this is a form of time-of-use pricing and is common for commercial and industrial customers. Dynamic pricing, which itself has several forms, varies the price dynamically depending on the load at different times of the day each day. As of 2004, over seventy utilities have experimented with dynamic pricing systems.[5]

For the bulk-level transmission grid, the rulemaking, standards and regulations set forth by FERC and NERC help increase reliability and act to internalize some of the externalities. Utilities have long been required to have operating reserve margins. More recently, the Energy Policy Act of 2005 empowered FERC to enforce mandatory reliability standards, set by NERC, which apply to all participants in the bulk power system; in 2007, monetary penalties were established of up to $1 million per day for non-compliance with these standards. Performance-based incentives that allow increased rates of returns on transmission projects intended to reduce transmission congestion costs or increase reliability are another recent development. Regulators may also use performance-based rates that reward utilities for good reliability and penalize them for poor reliability.

However, electricity markets are still in their infancy in providing incentives for socially efficient investment in grid infrastructure, especially transmission (Hogan 2008). Transmission system operators responsible for providing transmission services have an incentive to reduce their private (as opposed to social) costs.[6] The transition toward more competitive power markets has resulted in declining reserve capacity because producers are striving to minimize their costs; this situation reflects the lack of adequate incentives to improve power reliability.[7]

Also, reserve capacity has public-good attributes. For technical and economic reasons, it is not possible to prevent customers from benefiting from it, even when they are not paying for the power delivered by that reserve capacity (van der Welle and van der Zwaan 2007).

Reserve requirements, the possibility of fines for non-compliance with NERC reliability standards, and performance-based incentives internalize some of the externalities. However, the extent to which these standards, associated fines and incentives ensure a certain level of reliability—as measured by frequency and duration of outages—is uncertain. Compliance with many of the standards relies on self-certification and penalties levied by FERC may be negotiated, possibly with economically inefficient agreements.

Many of the problems with the transmission grid are due to the age of the infrastructure.[8] Investing in a modern, "smart grid" will alleviate many of the problems that were noted above. New capital investment will also likely reduce risks associated with intermittent renewable electricity sources. This is an example where technological innovation can reduce or eliminate externalities.

FACILITY VULNERABILITY TO ACCIDENTS AND ATTACKS

The United States has over 1.5 million miles of oil and gas pipelines, 104 operating nuclear plants, 9 liquefied natural gas (LNG) import facilities, 100 LNG peaking facilities, and over 17,000 non-nuclear electricity generators in the United States. Our domestic infrastructure to deliver energy is

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[4] See Borenstein 2005 for a description of different forms of peak-load pricing.

[5] See Barbose et al. 2004.

[6] Social costs exceed private costs to the extent that disruption affects customers in other regions and out-of-region impacts are not taken into account by system operators.

[7] Reserve capacity is the amount of generating capacity in excess of capacity required for generating needs at any time. At periods of peak usage, reserve capacity is low. Lowering reserve capacity reduces costs for utilities but raises the risks of outages.

[8] See the discussion in *America's Energy Future,* Chapter 9.

complex and critical to the smooth functioning of our economy. We focus in this section on the following questions:

1. To what extent is our energy infrastructure vulnerable to accidents and terrorist attacks?
2. To what extent should infrastructure vulnerability be regarded as an externality?

The following subsections explore these questions in the context of four infrastructure areas. Liquefied natural gas is a growing source of natural gas in the U.S. LNG facilities are large and complex and have been the source of some community concern over safety. Oil transportation and storage are vulnerable to accidents and spills. The oil and gas pipeline network is extensive and critical to the flow of gas and oil around the United States. Finally nuclear power accidents continue to be of concern to the public. Analyzing these forms of energy infrastructure sheds light on the nature of externalities associated with our production and consumption of energy.

LNG Infrastructure and Hazards

The infrastructure associated with LNG distribution in the United States includes tankers used to transport the gas from foreign ports, import terminals which are dedicated to LNG, and inland storage facilities. There are nine operating terminals within the United States (Parfomak 2008). The most significant hazards associated with LNG infrastructure includes a pool fire, which occurs if there is a spill that is ignited, or flammable vapor clouds, which occur if there is a spill that is not immediately ignited. In this case, the evaporating natural gas can travel some distance and during that time is at risk of ignition. Other safety hazards include LNG spilled on water that may be able to re-gasify, cold LNG can injure people and/or damage physical structures. Since LNG dissipates with no residue, the only environmental damages that might occur would be linked to fire or cold damage. Finally, terrorism hazards, directed at ships carrying LNG and/or at land facilities, is also a risk.

These damages can be associated with damage to a tanker, terminal or inland storage facility. The most dangerous possibilities include a spill on water since such a spill could spread the farthest, and if ignited, seriously harm people and property at some distance. The safety record of tankers carrying LNG is quite good; since international shipping started in 1959, there have been no spills, though there have been a few groundings and collisions (Parfomak 2008). Tankers are double-hulled and engage GPS, radar, and other safety systems to reduce the risk of accidents and grounding.

In contrast to tanker safety, there have been a number of incidents at terminals and onshore storage facilities. Worldwide, there are over 40 terminals and 150 onshore storage facilities and there are 13 known accidents at those sites reported since 1944. These data are summarized in Table 6-3. There are no LNG tankers that fly under the U.S. flag so only a worldwide number is reported for number of tankers.

The number of serious accidents has been quite small, only 13 since 1959 with 29 fatalities and 74 injuries. With such a small number of incidents, it would be difficult to extrapolate from the historical data to estimate expected damages in the future. On average, over 260,000 million cubic feet (MMCF) of LNG has been imported or exported from the United States annually since 1985 (EIA 2009). In this context, the apparent risk of accidental injury, death, or property damage is small.

A number of studies have quantitatively evaluated the hazards and risk of accidents or terrorist attacks, largely on a facility by facility basis. Parfomak and Vann (2008) summarize recent and most cited studies in their Table 6-2. A report prepared for DOE by Sandia National Laboratories summarizes and assesses four of these studies to develop estimates of the damages of a large pool spill from a tanker over water. The report does not monetize damages but provides estimates of numerous endpoints of damage (asphyxiation, cryogenic burns, structural damage, etc.).

TABLE 6-3 LNG Infrastructure and Safety Record[a]

Infrastructure Type	Worldwide Numbers	U.S. Numbers	Expected Growth	Serious Incidents Since 1959	Fatalities	Injuries
Tanker Ships	200	Not relevant	200 additional worldwide by 2013	0	0	0
Terminals[d]	40	10	21[b]	13[c]	29	74
Storage Facilities	>150	103	Not available			

[a]The data in this table are taken from Parfomak and Vann (2008).
[b]Six terminals have been approved and are under construction in the United States and another 15 have been approved, but construction has not yet begun.
[c]Data on accidents, fatalities, and injuries are not separately reported for terminals and storage facilities. These numbers represent the worldwide sum since records are available.
[d]These numbers reflect import and export terminals.

Based on their review, the Sandia report provides estimates of the effects of various small and large scale accidents and intentional damage. For example, they provide estimates of the size of a pool fire from different sized holes of a tanker breach, the size of the pool, the distance of thermal hazards, and the burn time. This information could be combined with data on population density, and on monetary damages of death, injury and property loss to quantify this externality, at least for specific locations. However, the committee did not attempt such quantification. Further, the small risk of these incidents suggested by the historical record implies that the magnitude of this externality relative to other energy based externalities is likely to be small.

The LNG industry faces unlimited liability for damages from accidents. In fact significant fines have been in the case of a pipeline fire in Bellingham, Washington in 1999 and in training violations at the Everett, Massachusetts LNG terminal. These facts suggest that the risk of accidents and spills is internalized in the LNG industry. In addition private insurance held by facility owners contributes to internalization of the externality.

Finally, LNG tankers and facilities face considerable regulatory oversight. The Coast Guard has responsibility (and bears the cost) for shipping and terminal security, the Office of Pipeline Safety and the Transportation Security Administration have security authority for LNG storage plants and terminals and the Federal Energy Regulatory Commission approves facility siting in conjunction with the other three agencies.

As an aside, the Coast Guard has estimated that it incurs about $62,000 to accompany a tanker through Boston harbor to the Everett facility. This figure, combined with estimates of policy, fire, and security costs incurred by the cities of Boston and Chelsea and the state of Massachusetts suggests that these "shepherding" costs run to about $100,000 per tanker. While public costs of providing safe passage to tankers or to assess health and safety standards are not externalities (they represent the costs of mitigating the externalities), unless there are requirements that industry pay some of these costs, these costs will not be represented in the market price of energy. This provides another example of a situation where private costs do not reflect social costs in ways that are unrelated to externalities. Here the divergence arises from the government provision of services that are not priced in the fuel.

Oil Spills from Ships and Facilities

Oil is transported by tankers, barges, and other vessels where it can be accidentally spilled during its transfer between vessels or due to an accident to the vessel itself. Further, oil is stored in a variety of facilities where spills are possible. A number of highly publicized oil spills have occurred in the previous two decades that have increased the public's awareness of the ecological harm and other damages that

such spills can envisage. Seabirds, marine mammals, a variety of reptiles and amphibians, fish, and invertebrates are all at risk of death or injury when they come into contact with oil. In addition, many coastal and wetland habitats can be significantly altered by the presence of large quantities of spilled oil and oil spills deleteriously affect human use of the environment when recreational sites are damaged and when commercial activities are harmed (such as fishing or shrimping). Important cultural sites can also be damaged by these spills (Ramseur 2008).

Data on the prevalence and size of oil spills that occur on U.S. soil are collected and maintained by the U.S. Coast Guard. Table 6-4 reports the average number of spills in the United States between 1990 and 1998 as well as the average amount of oil spilled (in gallons).[9]

A number of studies of the ex post damages caused by oil spills have been completed (e.g., Garza-Gil et al. 2003, and Cohen 1995). Talley (1999) estimates the property damage costs from tanker accidents, but does not attempt to consider environmental damages. Overall, little research is available to estimate the expected damages from spills that could be appropriately attributed on a per gallon transported basis. One exception is the study by Cohen (1986) where he provides estimates of the per gallon benefits of avoiding oil spills. Based on the compensation payments from 11 spills and in-depth environmental damage studies from four large spills, Cohen estimated a $6.08/gallon benefit of avoided spillage for reduced environmental damages, $1.72/gallon benefit for avoided loss of oil, and $6.93/gallon for avoided cleanup costs (values converted to 2007 dollars). The first of these categories clearly represents an externality of interest to this Committee, the second is a private cost and therefore not relevant for our study. The third component is also not an externality—it represents the costs of cleaning up an externality once it has occurred. But if the optimal level of clean-up is chosen then the marginal damages averted through clean-up would just equal the marginal costs of clean-up and we can use this third component as a proxy for the damages averted through clean-up giving aggregate marginal damages per gallon spilled of $13.01.[10]

We need to convert from damages per gallon spilled to damages per gallon produced or consumed. According to data reported in Huijer (2005)[11] tanker spills worldwide averaged 115,810 barrels between 2000 and 2004 (Huijer 2005, Table 2). Average global oil-trade movements over that period were 16.7 billion barrels per year (BP 2008, p. 20). Not all of these trade movements were over water. Casual inspection of the inter-area trade in oil suggests that nearly 80 percent of oil trade is by ship. To be conservative let us assume that one-half of oil trade occurs by ship. Then the ratio of oil spilled to oil shipped is 115,810/(0.5 x 16.7 billion) = 0.0000139 or one barrel spilled for every 72,000 barrels shipped. Applying this percentage to the marginal damages per gallon spilled and converting gallons to barrels gives marginal damages of $0.0076 per barrel shipped.[12]

In 1990, the Oil Pollution Act was passed by Congress which imposed comprehensive liability for spills. The U.S. Coast Guard promulgated a number of regulations as part of the Act that included the requirement that all tanker ships have double hulls by 2015. There is also evidence that these requirements and negative publicity have resulted in the improved safety records of the industry. Etkin

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[9]More detailed information on the source and type of spills can be obtained in Table 2-2 from the recent NRC report "Oil in the Sea III: Inputs, Fates, and Effects," (NRC 2003c). That report also contains detailed estimates of spills worldwide.

[10]To be clear Cohen estimates average damages but assumes they proxy for marginal damages. With a convex damage function using average damages underestimates marginal damages.

[11]Paper cited at http://www.itopf.com/information-services/data-and-statistics/statistics/#quantities.

[12]Cohen notes the Coast Guard uses a "rule-of-thumb" cleanup cost for planning purposes of $20 per gallon for an oil spill between 500 and 1000 gallons (in 2007 dollars). Using this value rather than the $6.93 cost figure used in the text doubles the marginal damage per barrel of oil shipped raising the marginal damage to 1.5 cents per barrel. Even if marginal damages were four times average damages due to convexity in the damage function, this would only raise the marginal damages to 6¢ per barrel of oil.

TABLE 6-4 Average Number and Volume of Oil Spills on U.S. Soil, 1990-1998[a]

		Annual Number per year	Volume per Year (gallons)
Total		8831	2,645,247
Spills by Size	< 100,000 gals	8828	1,163,484
	> 100,000 gals	3	1,481,763
Spills by Source	Tanks and Barges	506	1,273,950
	other vessels	4214	344,621
	Facilities and unknown[b]	4055	776,263

[a]Data from the U.S. Census 2006.
[b]Data excludes spills from pipelines—information on pipeline spills is contained in the following section of the report.

(2001) and Homan and Steiner (2008) report data from the U.S. Coast Guard showing a general decline in ship and barge spills during the 1990s. Homan and Steiner's analysis of the data supports the interpretation that this decline is attributable to the requirements that came on line after the passage of the Act. However, a recent GAO report (2007, page 28) notes that limits to liability to the responsible parties exist and while, these limits have recently been increased, they may still not be high enough to cover all potential damages. A complete description of the various federal and international laws and liability rules see Ramseur 2008 report. Based on this set of information, it appears that there has been at least partial internalization of the externalities from oil spills.

Oil and Natural Gas Pipelines

The United States depends on a large network of pipelines to move natural gas and oil around the country. A recent National Academy of Sciences report (TRB 2004) notes that nearly all natural gas and roughly two-thirds of petroleum is moved through transmission pipelines in the United States. Transmission pipelines are but one part of the national pipeline network that includes gathering, transmission, and distribution pipelines.

Table 6-5 provides information on significant pipeline incidents in the United States on an annual basis for the period 2002 through 2006. A significant incident is an incident in which at least one of the following conditions occur: (1) fatality or injury requiring in-patient hospitalization, (2) $50,000 or more in total costs, (3) highly volatile liquid releases of 5 barrels or more or other liquid releases of 50 barrels or more, or (4) liquid releases resulting in an unintentional fire or explosion.

The table provides information on hazardous liquid pipelines. Hazardous liquids are defined by the Office of Pipeline Safety as petroleum, petroleum products, and anhydrous ammonia. Most hazardous liquids moving through the pipeline are petroleum or petroleum products. Nearly half of the incidents reported to OPS are associated with hazardous liquids and are triggered by releases of 50 barrels of oil or more.

Focusing on natural gas, distribution is responsible for the bulk of fatalities and injuries and over half the property damage arising from significant incidents. Partly this reflects the fact that nearly 80 percent of natural gas pipeline stock in 2006 was distribution pipelines with transmission making up most of the rest (BTS 2009, Table1-10).

Table 6-6 provides information on incidents per mile of transit averaged over the 2002 – 2006 period. Scaling by the amount of gas traveling through pipelines indicates that the incidence of fatalities, injuries and property damage are highest in the gathering pipelines.

TABLE 6-5 Annual Averages for Significant Pipeline Incidents, 2002-2006

Pipeline Type	Significant Incidents	Fatalities	Injuries	Property Damage ($1,000)
Hazardous liquid	124.4	1.6	5.0	$8,729
NG Transmission	75.2	1.0	4.6	$81,019
NG Gathering	9.8	0.0	1.0	$40,875
NG Distribution	93.2	13.8	41.6	$129,317
Total	302.6	16.4	52.2	$349,940

Note: Significant Incidents are those incidents reported by pipeline operators with any of the following conditions are met: 1) fatality or injury requiring in-patient hospitalization. 2) $50,000 or more in total costs. 3) highly volatile liquid releases of 5 barrels or more or other liquid releases of 50 barrels or more. 4) liquid releases resulting in an unintentional fire or explosion. Property damage estimates are in year 2007 dollars.
Source: Office of Pipeline Safety and Bureau of Transportation Statistics.

TABLE 6-6 Annual Averages for Pipelines Per Ton Miles, 2002-2006

Pipeline Type	Ton Miles of Freight Per Year (millions)	Number of Incidents (Per Billion Ton Miles)	Fatalities (Per Billion Ton Miles)	Injuries (Per Billion Ton Miles)	Property Damage (Per Million Ton Miles)	Net Barrels Lost (Per Billion Ton Miles)
Hazardous liquid	593,560	0.2	0.003	0.008	$166	100
Natural Gas	336,493	0.5	0.044	0.140	$747	NA
Gathering	3,365	22.3	0.297	1.367	$24,077	NA
Transmission	67,299	0.1	0.000	0.015	$607	NA
Distribution	265,829	0.4	0.052	0.156	$486	NA
Total	930,053	0.7	0.047	0.149	$913	100

Note: Estimates of ton miles for components of natural gas pipeline system are based on distribution of pipeline miles from BTS. Property damage estimates are in year 2007 dollars.
Source: Office of Pipeline Safety and Bureau of Transportation Statistics.

An alternative way to scale the damages is to report fatalities, injuries, and property damage per unit of oil or natural gas consumed in the United States. Using the average fatalities, injuries, and damages from Table 6-5 over 2002 through 2006 and average consumption of oil and gas over that same period, we measure 0.29 fatalities and 0.90 injuries per billion barrels of oil that is delivered to refineries in the United States and $18 of property damage per thousand barrels of oil. For natural gas the numbers are 0.72 fatalities and 2.30 injuries per trillion cubic feet (Tcf) of natural gas consumed and $12 of property damage per million cubic feet of natural gas consumed. The property damage and injuries are modest and likely internalized to a great extent. We do not consider these damages in subsequent analysis.

Nuclear Power Accidents

In addition to potential damages associated with generation of electricity through nuclear technologies (see chapter 2) there are several potential external costs associated with potential for a nuclear accident. Unlike the situation with other potential damages associated with nuclear technologies, these possibilities are distinctive in that two very well studied accidents have already occurred (Three Mile Island and Chernobyl), providing the basis for widespread public concern about the issue. Specifically, the following considerations have been raised:

1. To what extent does the existing technology alter the probability and damage functions associated with an accident for the existing facilities or those under design.

2. To the extent that the above can be quantified, to what extent have they been internalized by existing regulations, insurance requirements (including liability costs required by regulations) or other market mechanisms.

Unlike the speculation surrounding nuclear waste issues, the experience at Chernobyl highlighted both the extent of potential local damages and the spread of damages over a wide region, with health and other impacts demonstrated thousands of miles away (for example, Almond et al. [2007] find that Swedish children who were in utero during the Chernobyl accident had worse school outcomes than adjacent birth cohorts). Moreover, in the absence of technological change, it seems reasonable to assume that risks will increase in proportion to the expansion of nuclear power; i.e., each new facility engenders an additional, theoretically calculable risk. These risks vary, depending on geography and population distribution, but may affect large regions.

That recognized, there are abundant data to suggest that the risk going forward, at least in the United States, will be dramatically lower than in the past based on advances in the technology and regulations, including most recently the Energy Policy Act of 2005. There appear to be no comprehensive direct estimates on which to base a numerical cost estimate.

The magnitude of the externality depends in large part on the extent to which insurance accounts for these costs. If the industry were fully insured against all risks from accidents, then there would be no external damages not reflected in market prices. The Price-Anderson Act regulates and establishes insurance pools and limits liability for the nuclear industry. The Act, enacted in 1957 and most recently revised in the Energy Policy Act of 2005, requires all commercial nuclear power plants to carry liability insurance in the amount of $300 million.[13] In the event of an accident that creates losses in excess of $300 million, each commercially active reactor is to be assessed an amount up to $95.8 million (payable over several years; annual payments are capped at $15 million) for a total pool of approximately $10 billion. The industry is exempt from any liability in excess of this amount. Insurance covers "bodily injury, sickness, disease or resulting death, property damage and loss as well as reasonable living expenses for individuals evacuated." (USNRC 2008d). Over its history, a total of $150 million has been paid in claims under the Price-Anderson Act, with the accident at Three Mile Island in 1979 accounting for nearly half. As of 1997, over $70 million had been paid out in indemnity settlements and expenses from this accident (ANS 2005). Claims have been paid through the primary insurance held by each plant; the supplemental assessments have never been required.

The appropriate measure of any uninternalized externality arising from insufficient insurance depends critically on the distribution of damages from potential nuclear reactor accidents in excess of the supplemental assessment (approximately $10 billion). Estimation of these low probability-high consequence events is difficult, in part because the events are sufficiently rare that empirical data are (fortunately) lacking.[14] One recent study (Jones et al. 2001) suggests that uncertainty about key factors associated with population dose and human fatality risk in the event of a release of radioactivity are such that the true value could be ten times larger or smaller than the central estimate. Because estimates of the

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[13] These amounts are subject to inflation adjustments at five year intervals.

[14] Dubin and Rothwell (1990) constructed an estimate of the distribution of damages in the 1980s that was revised by Heyes and Heyes (1998). These estimates are based on insurance premiums and one estimate of a worst-case scenario (damages of $10 billion with annual probability 8/10 million). Note that the expected loss associated with this worst-case scenario is $8,000 per reactor-year, only 0.2 percent as large as the insurance premiums associated with the first $300 million of loss, suggesting that the contribution of losses in excess of $300 million to the total expected value of losses is negligible. Both papers contain logical errors (Dubin and Rothwell misinterpreted the insurance limit and Heyes and Heyes estimated parameters that are inconsistent with the assumed distribution) and so we do not rely on their estimates.

consequences of low-probability events are calculated by multiplying several of these factors together, the resulting estimates could be wrong by several orders of magnitude.

The component of the externality that is internalized includes the primary insurance required of each operating unit plus the risk of the supplemental assessment that may be required in the event of an accident causing damages in excess of $300 million. The probability that this supplemental assessment will be levied is again difficult to estimate; to date, it has never been required. The component associated with primary insurance, that covers the first $300 million of damages, may be estimated from the premium paid, approximately $400,000 per reactor-year (USNRC 2008d), roughly $0.50 per MWh of electricity production (the 104 operating units produced an average of 80 GWh in 2007). This quantity overestimates the expected value of the first $300 million of losses (because it includes insurers' administrative costs) but is likely to underestimate the total externality, as it excludes the expected value of damages exceeding $300 million per incident.

EXTERNAL COSTS OF OIL CONSUMPTION

The United States is a significant consumer of oil. In 2007 it consumed over 20 million barrels of oil a day, representing one-quarter of world oil supply (see Table 6-7). Imports as a share of domestic consumption have steadily risen over time to their current level of nearly sixty percent and are not projected to decline significantly over the next twenty years. Meanwhile OPEC continues to be a significant source of world oil supply with its share projected to rise to nearly fifty percent by 2030. While our consumption continues to grow, the importance of oil in the economy continues to decline. Oil intensity (measured as 1,000 BTUs of oil consumption per dollar of GDP) has fallen by over one-quarter since 1990 and is projected to fall an additional one-third by 2030. Rising oil prices, however, offset the declining physical intensity so that the value of oil consumption in GDP is projected to remain at about two percent (though down from its anomalous level of 3.6 percent in 2007 with the sharp run-up in prices that year).

The importance of oil in the U.S. economy has given rise to a large literature measuring the external costs of oil consumption.[15] Parry and Darmstadter (2003), for example, attempt to quantify the marginal external cost of petroleum consumption, defined as "the difference between the costs to the U.S. economy as a whole and that to individuals or firms from additional oil consumption. Marginal external costs, expressed in $/BBL, are referred to as the oil premium" (p. 11).

In this section we consider three questions:

- What is the Oil Premium?
- Is the oil premium an externality?
- How does the oil premium relate to the optimal tax on oil consumption or imports?

What is the Oil Premium?

As the quotation from Parry and Darmstadter (2003) above indicates, the oil premium is a measure of the difference between the private and social costs of petroleum consumption measured in dollars per barrel. The literature identifies two major quantifiable sources of the discrepancy between private and social costs: U.S. monopsony power and economic disruptions arising from unanticipated price shocks. We discuss these in turn.

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[15]See, for example, Bohi and Toman (1993, 1995); Greene and Leiby (2006); Leiby (2007); Greene (2009 in press).

TABLE 6-7 U.S. Oil Dependence

	1990	2000	2007	2030
Net oil imports as percent of total U.S. Supply	42.2	52.9	58.2	55.5
World Oil Price (2007 $/BBL)	38	35	72	60
World Crude Production (million BBD)	65.5	74.9	81.5	102.9
Opec Share (percent)	38.3	42.9	43.2	46.4
U.S. Petroleum Consumption (million BBD)	17	19.7	20.7	22.8
U.S. Share of World Production (percent)	26.0	26.3	25.4	22.2
Oil Intensity (1,000 BTUs/GDP) $2000	4.7	3.9	3.4	2.2
Oil Intensity (Value of oil as a percent of GDP)	2.6	2.0	3.6	1.9

Source: BP 2008; EIA 2008a,b,g.

The literature on monopsony power takes as its point of departure the observation that the United States is a large consumer of oil. As such, any policy to reduce domestic oil demand reduces the world oil price and benefits the United States through lower prices on the remaining oil it imports. The oil premium arising from monopsony power reflects the fact that individual consumers do not recognize the buying power that the nation has if it acts in a coordinated fashion.

Figure 6-1 illustrates the idea. Based on individual demands for oil, aggregate demand is given by the downward sloping curve marked D. With an upward sloping supply curve for oil, the market equilibrium occurs at point *e* where Q_0 barrels of oil are consumed at price per barrel P_0. If the U.S. government takes some action to reduce oil demand from D to D', the world oil price falls from P_0 to P_1. The gain to consumers from the fall in oil price is the rectangle P_0P_1fg. This is offset by losses to producers in oil revenue (equal to the same rectangle).[16] If all supply comes from domestic production, there is no gain to the United States. The gain to producers is exactly offset by the loss to U.S. producers. If all supply comes from non-U.S. producers then the gain to U.S. consumers is financed by a transfer from other oil-producing countries. This is the monopsony benefit identified in the literature. The marginal oil premium is the incremental income transfer to U.S. consumers from foreign producers from a small reduction in demand for oil arising from a U.S. policy.

One policy that would give rise to this income transfer is a tax on oil consumption. In Figure 6-1, an excise tax of *fh* per barrel would shift demand from D to D' and lower demand from Q_0 to Q_1. Since the tax (ignoring the efficiency costs of taxation for the moment) is simply a transfer within the United States, the result follows.

The literature on oil consumption correctly notes that private markets in the United States do not account for the potential market power that U.S. consumers could wield in world oil markets. The literature also generally recognizes that any policy to take advantage of consumer purchasing power affects a transfer from foreign oil producing nations to the United States. Such a "beggar thy neighbor" policy has been justified on the grounds that OPEC is artificially inflating world oil prices at the expense of consuming nations and that the exercise of monopsony power is a countervailing policy.

Disruption costs have also been identified as a cost that is not incorporated into the price of oil. Leiby (2007) identifies two components of a disruption premium. First, a cost increase increases transfers of U.S. wealth from domestic consumers to foreign producers. The magnitude of this transfer depends on the price increase and the amount of oil imported into the United States. Second, cost increases induce shocks to the economy with resulting losses in economic output, income, and jobs.

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[16]This ignores efficiency losses for the moment. We return to this issue in a moment.
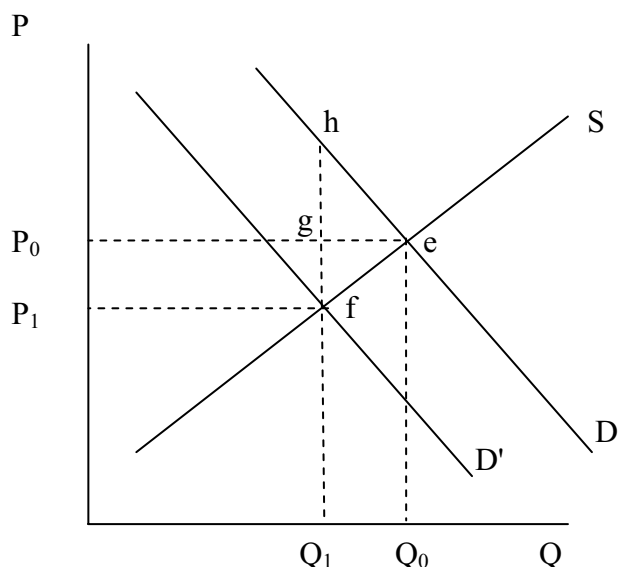
FIGURE 6-1 Illustration of monopsony. D = aggregate demand; e=market equilibrium Q_o consumption and P_o price; f=market equilibrium for Q_1 consumption and P_1 price; P= price per barrel of oil; Q = barrels of oil consumed.

Is the Oil Premium an Externality?

We consider the two components of the oil premium in turn. With respect to the issue of monopsony power, it is unquestionable that domestic policy can reduce aggregate demand and lead to a reduction in the world price of oil. Such a policy would generate a transfer in wealth from foreign oil producing nations to the United States.[17] But the ability to exercise monopsony power is not the same as an externality. Externalities create a market failure. Exercising monopsony power creates a market failure where one did not exist before. In Figure 6-1 the exercise of market power creates deadweight loss equal to the triangle *efh*.[18] In fact, this market failure is designed purely to transfer income from another country to the United States.

Bohi and Toman (1995) note that the exercise of monopsony power is an example of a pecuniary externality designed to shift wealth from one nation to another.[19] They note that the existence of market power on the part of energy producers complicates the analysis slightly. For one thing market power leads to the creation of rents that transfer wealth from energy consuming to producing countries. The exercise of monopsony power can then perhaps be justified as a countervailing policy to prevent the excessive transfer of wealth from consuming to producing countries. While this may provide a legitimate political reason to undertake such an action, we should stress that no externality in the sense considered in this report exists.[20] That the ability of the United States to exercise monopsony power is not an

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[17]This transfer occurs even if foreign oil producing countries curtail production to stem the price reduction. Reductions in oil supply and demand from the countervailing policies will lead to a reduction in expenditures on imported oil in the United States.

[18]If OPEC is exercising cartel output restricting power, then the exercise of monopsony power adds to a pre-existing distortion and the deadweight loss is slightly more complicated than suggested by the triangle in Figure 6-1.

[19]A pecuniary externality is not an externality in the sense defined in Chapter 1. Rather it is a transfer of income or wealth arising from some action or policy that is transmitted through the marketplace. Unlike standard externalities, pecuniary externalities do not involve any loss of efficiency.

[20]The use of monopsony power to extract rents from an energy cartel raises the question of the response by the cartel to the use of this power. An optimizing cartel will wish to raise price to offset the exercise of monopsony power. But it will be unable to recover all of the rents extracted by the use of monopsony power. A clumsy cartel

externality is recognized by Leiby (2007) and Greene (2009 in press) among others. Green notes that the "costs of oil dependence are not external costs and neither a tax on oil nor a tax on imported oil is an adequate solution to the problem" though he argues that either of these taxes can ameliorate the problem (see pp. 10-11 in Green 2009 in press).

Turning to disruption costs, we consider the following questions. First, is macroeconomic disruption an externality? Second, if it is an externality, is the cost substantive and quantifiable? On the first question, most economists that have studied this issue would agree that abrupt increases in oil prices adversely impact the economy. Where differences arise are over the magnitude of the impact and the extent to which other events and actions play a role in magnifying the impacts.[21] The most recent run up in oil prices in 2007 and 2008 was in large part a demand shock coupled with stagnation in supply according to Hamilton (2009). Hamilton argues that the onset of the current recession would have been likely delayed from the fourth quarter of 2007 to the third quarter of 2008 in the absence of the price run-up (Hamilton 2009).

That there are links between oil shocks and economic performance is uncontroversial. Leiby (2007) estimates the macroeconomic disruption and adjustment costs for 2006 market conditions. He reports a mean estimate of $5.14 per barrel (2007 dollars) and a range from $2.39 to $8.57 per barrel.[22] But does this imply an externality associated with oil consumption? The literature on the oil premium and the oil disruption component focuses on measuring the relationship between incremental oil consumption and its effect on disruptions to economic activity. We believe that oil disruption costs are not an externality. That said, it is certainly the case that policies that lead to a reduction in oil consumption in the United States will most assuredly reduce our vulnerability to future oil shocks.

In summary, quantifying this possible externality is a challenge. The cost depends importantly on the type of shock and policy response. Changes over time in economic institutions also pose a challenge to measuring the size of this externality. Given the conceptual difficulties in identifying the basis for and size of the externality, we do not feel it makes sense to include a disruption cost as a component in the list of externalities associated with the production or consumption of energy. We do recommend that further research be carried out to better understand this issue.

SECURITY OF ENERGY SUPPLY

Concerns about security of energy supply (as distinct from national security as discussed in the next sub-section) arise from the possibility that resources may become unavailable. Security concerns may pertain to energy sources (e.g., oil, natural gas, uranium) or materials that are critical for energy production, distribution, or consumption (e.g., lithium for lithium-ion batteries). Risk of disruption exists when supply is dominated by one or a few countries (or facilities) that are unreliable (e.g., unstable in ways that may disrupt operations, as from civil strife within the country) or that may choose to restrict supply for political or other objectives (e.g., the OPEC oil price shocks).

We argue that these sources of insecurity are not an externality. They are supply conditions that are presumably incorporated in market outcomes. For example, buyers of a resource that is subject to risk of supply interruption will seek ways to reduce the risk of disruption, or the harm if disruption occurs,

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(viz. Adelman (1980)) may be able to retaliate in a way that raises their profits. This simply reflects their previously non-optimizing behavior. The analysis in Figure 6-1 assumes a competitive market supplying the product. How a cartel responds affects the welfare transfer to the United States. Alhajji and Huettner (2000) statistically reject the hypothesis that OPEC acts as a cartel. They cannot reject the hypothesis that Saudi Arabia acts as a dominant firm. In this view, Saudi Arabia can influence world oil prices but not OPEC member production decisions.

[21]Bernanke et al. 1997, for example, argue that tightening of monetary policy exacerbated the output effects of the 1973 oil shock. Hamilton and Herrara (2004) present results suggesting that monetary policy did not play a role. Blanchard and Gali (2008) argue that real wage rigidities in the 1970s exacerbated oil shocks.

[22]Leiby reports values in 2004 dollars.

through reducing reliance on the resource, seeking alternative suppliers, maintaining a stockpile, financial insurance, and other measures. The expectation that demand for the resource would increase if its supply were more secure provides an incentive for suppliers to develop methods for enhancing security.

NATIONAL SECURITY EXTERNALITIES

Energy is inextricably linked with national security. The U.S. demand for oil contributes to high oil prices that provide support for hostile foreign regimes with large reserves of oil. Second, dependence on foreign energy sources creates dependencies that may constrain foreign policy. Third, some have argued that the oil price paid by U.S. consumers does not reflect the true cost of oil, in particular the cost of our military presence in the Middle East or of maintaining military readiness to protect oil supply lines. We discuss these issues in this section.

Energy and Foreign Policy Considerations

High oil prices provide a source of revenue for countries with foreign policies at odds with the United States (e.g., Iran and Venezuela). One could make the argument that U.S. consumers do not take into account the fact that their oil consumption contributes to actions by foreign countries that negatively impact the United States.

A simple analogy illustrates the problem with viewing this as an externality. Let us assume that my neighbor burns trash in his backyard causing pollution that adversely affects my household. This is a clear externality. Further assume that I purchase commodities in a store owned by my neighbor. My consumption thus provides income for my neighbor that leads him to purchase more commodities and produce more trash to be burned. My purchase of goods from my neighbor's store is not an externality. Rather the neighbor's burning of trash is the externality. Restricting (or taxing) my purchases indirectly reduces the externality but it does so in a highly inefficient manner. It would be more efficient to address the externality directly.

In a similar vein, U.S. oil consumption that enriches countries with whom we have differences is not an externality. Rather our consumption makes possible actions that are inimical. In the absence of any ability to address the foreign policy problem directly, it may be desirable to reduce oil consumption to lower world prices. But it should be noted that this is an imperfect proxy for better targeted instruments and will hurt oil producing friend and foe alike.[23]

In addition to funding activities that are inimical to our interests, rising oil prices may weaken the instruments of economic statecraft. One could argue, for example, that high oil prices through the latter half of 2008 rendered economic sanctions on Iran for their nuclear activities ineffective.[24]

Dependence on foreign energy sources may constrain our foreign policy. For example, the Bush Administration's goal of furthering the spread of democracy in the world was constrained by our ties to major oil producing states with autocratic regimes in control. The 2006 report by the Council on Foreign Relations on U.S. oil dependency also notes that oil dependence can cause "political realignments that constrain the ability of the United States to form partnerships to achieve common objectives. Perhaps the most pervasive effect arises as countries dependent on imports subtly modify their policies to be more congenial to suppliers. For example, China is aligning its relationships in the Middle East (e.g., Iran and Saudi Arabia) and Africa (e.g., Nigeria and Sudan) because of its desire to secure oil supplies" (pp. 26-27).

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[23]See Fullerton, Hong and Metcalf (2001) for a discussion of the efficiency of imperfectly targeted instruments.

[24]See Deutch and Schlesinger 2006 for further discussion of the role oil funds play in providing flexibility to countries to pursue policies at odds with those of the United States.

In addition, the CFR report notes that oil revenues can undermine efforts to support good governance. This is another example of the way in which oil revenues can undermine the tools of economic statecraft. Russia, for example, is less responsive to efforts to promote democracy when they have ample oil and gas revenues that reduce their reliance on Western economic assistance.

The constraints that oil dependence places on foreign policy goals is arguably an externality that is not recognized in the price of oil but note two points. First, it is not clear what the incremental reduction in these costs would be were we to reduce our oil consumption by some modest amount (say 10 percent). Second, it is not clear that one can monetize this cost even if the marginal cost were positive. Therefore we note the possibility of this as an externality and recommend further research on this topic to better understand these important issues.

Energy and Military Considerations

The argument has also been made that the true cost of oil does not reflect the cost of maintaining a military presence in the Middle East or of maintaining a military preparedness. Parry and Darmstadter (2003) note that analysts generally don't include this cost in any exercise to measure an oil premium for two reasons. First it is difficult to disentangle military spending for such political goals as reducing terrorism or providing support for Israel from spending to protect oil supply routes. And it is unlikely that whatever spending is specific to securing the supply routes would change appreciably for a moderate reduction in oil flowing from that region to the United States. In other words, the marginal cost is essentially zero. This view is held by a number of other researchers in the area including Bohi and Toman (1995). We adopt this position in this report. We note, however, that military expenditures could be affected by a large drop in oil consumption—for example a reduction in oil consumption to zero. Measuring the impacts on military spending (or for that matter on a whole host of economic and political responses) from a large change in oil consumption would require extrapolating existing statistical evidence well out of sample. To do so would give rise to—at best—speculative estimates. We would go further and argue that military spending—to the extent it occurs to safeguard oil production sites and transportation lanes—is a government subsidy to production. It replaces the need for private security expenditures that would otherwise have to be incurred to provide equivalent protection for oil production and transport.

Nuclear Waste and Security

In addition to the potential health and environmental damages associated with generation of electricity through nuclear technologies (see Chapter 2) are several potential external costs associated with nuclear security. Specifically, the following considerations have been raised:

1. To what extent does the transportation and deposition of fissionable material post-use represent an increased opportunity for terrorists or other parties interested in unlawful use of the material.
2. To what extent does the long-term deposition of fissionable material create risk of catastrophic accident, above and beyond the theoretical risk for nuclear accident at the sites themselves.
3. To the extent that either of the above costs can be quantified, to what extent have they been internalized by existing regulations, insurance requirements (including liability costs required by regulations) or other market mechanisms.

Concerns about the environmental hazard of nuclear waste, which may continue to emit radioactive particles for thousands to millions of years, has been the subject of national debate as an environmental question for decades, and came to a head after the incident at Three Mile Island. At that juncture Congressional legislation created an affirmative obligation of the federal government to provide

long-term storage in the future, although this was not accomplished by 1998, and the U.S. government has been paying liability payments of approximately 0.5 billion dollars per year to the operators of the existing 104 nuclear power facilities for this failure; the facilities remain under private control, but are regulated tightly by the U.S. Nuclear Regulatory Commission (U.S NRC).

During the cold war, the U.S. NRC developed plans to protect sites from "enemies of the United States" based on "Design Based Threat" scenarios contained in a series of classified documents, but not until after 9/11, however, did the reference point change to consider nuclear waste as potential materials for harm, likely one of the reasons for legislative progress since that time, most notably the Energy Policy Act of 2005 (EPACT), which has led to substantial upgrades in security procedures and oversight by the U.S. NRC by all accounts (NAS report 2005, GAO report 2006). However, the NAS report in 2005 concluded that despite progress there remained at least some finite risk of security breaches at existing or planned sites, and made a series of recommendations to further enhance security. However, neither the probability of such a breach, nor the damages that might ensue, either locally or in the aggregate, have been estimated in quantitative terms.

Specific to the waste storage issue, DOE finally submitted to the U.S. NRC in 2008 the formal license application to operate a national waste-material repository at Yucca Mountain Nevada, and provided extensive estimates of the cost, in the range of $100 billion through 2030. Almost as quickly the new administration has announced its intent to abandon this project, but the future strategy for waste disposal remains open. The case for a deep central repository such as the one proposed, in addition to the potential economic efficiency and compliance with earlier legislation, is that security would be more readily achieved at a single site than at many, an argument that has not won favor among some near the site. As with the broader security issues at the nuclear facilities, probabilities of an adverse event involving waste storage, under the current (disseminated) or envisioned (single-site) schemes have not been quantified, nor have the potential damages under any scenario.

A further level of complexity relates to emerging technologies to modify the life-cycle of nuclear fuels at the back end to reduce the long-term storage need. Simplifying the principle, reprocessing of spent-fuel could, based on current knowledge, result in reuse of the material to extract almost all, if not in theory all of its radioactivity; this is the same approach being taken to achieve sustainability in all materials cycles. While this may, in the future, displace in part or whole the security risks associated with storage, the technology itself, including the new facilities created and the likelihood the reprocessed materials would need at various phases to be transported creates new risks, for which neither the costs of appropriate controls nor any estimate of risk of breach has been calculated.[25]

Finally, it must be mentioned that there is also some potential in the security arena for external *benefit* from expanding the American nuclear energy capability, namely the likelihood the United States and its government could be proportionately more influential in global nuclear negotiations. Based on current developments, it is a certainty that many countries will turn to nuclear energy as the best solution to their energy needs, including many that are politically unstable or hostile to the United States; the potential the United States could be a leader, both technologically but also politically, hinges, in the views of some (NEAC 2008) on the degree to which the United States also follows this energy pathway.

Taking the available information, the Committee concludes as follows:

1. The direct cost of nuclear storage under present and envisioned scenarios is high, but the potential for damages from security breaches not incorporated in these costs cannot be quantified. Even if the probability of such an event or its damages could be quantified, it would still be impossible to calculate the marginal cost—i.e., the risk of an additional facility to a world still populated with nuclear warheads and with many foreign countries already committing to a nuclear energy future.

2. Like other damage possibilities associated with generation of electricity, the distribution of potential damages is certain to be unevenly shared; the move to Yucca Mountain or another centralized

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[25]Note however that the MIT 2003 concluded that once through technology with permanent storage of waste material was preferable to a closed fuel cycle technologies.

storage site, if approved, would likely reduce aggregate risk but obviously increase local and regional risk; conversely, a centralized site would reduce local and regional risks at the 100+ sites where waste is presently disposed at U.S. government cost, and all future locations.

  3. The extent to which the potential damage from security risk has already been internalized is also very difficult to assess. Certainly the net upgrade of security requirements brought about by EPACT and other post 9/11 U.S. NRC changes has internalized some of the costs. However, since taxpayers presumably bear some of the costs in the event of a high cost security incident (through an implicit commitment to compensate victims of the event through government relief), the degree to which the market has internalized these risks is difficult if not impossible to measure.

CONCLUSION

  In conclusion, we find the following:

  1. The nation's electricity transmission grid is vulnerable to failure at times due to transmission congestion and the lack of adequate reserve capacity. Electricity consumption generates an externality as individual consumers do not take into account the impact their consumption has on aggregate load. Damages from this could be significant and it underscores the importance of investing in a modernized grid that takes advantage of new smart technology and that is better able to handle intermittent renewable power sources.

  2. Externalities from accidents at facilities are largely internalizied and—in the case of our oil and gas transmission network—of negligible magnitude per barrel of oil or thousand cubic feet of gas transshipped. We find that the monopsony component of the oil consumption premium is not an externality.

  3. While government policy may be desirable to serve as a countervailing force to monopoly or cartel producer power, this is a separate issue from the focus of this report.

  4. We find that macroeconomic disruptions from oil supply shocks are not an externality. We also find that sharp and unexpected increases in oil prices adversely affect the U.S. economy. Estimates in the literature of the macroeconomic costs of disruption and adjustment range from $2 to $8 per barrel in 2007 dollars.

  5. Dependence on imported oil has implications for foreign policy and we find that some of these can be viewed as an externality. We find, however, that it is impossible to quantify these externalities. The role of the military in safeguarding foreign supplies of oil is often identified as a potential externality. We find it difficult if not impossible to disentangle non-energy related reasons for a military presence in certain regions of the world from energy-related reasons. Moreover much of the military cost is likely to be fixed in nature. A twenty percent reduction in oil consumption, for example, would likely have little impact on the strategic positioning of military forces in the world.

  6. Nuclear waste and proliferation raises important issues and poses difficult policy challenges. The extent to which uninternalized externalities exist is difficult to measure. Moreover it is very difficult to quantify them. Thus we do not report numerical values in this report but recognize the importance of studying this issue further.

7

Overall Conclusions and Recommendations

In response to a charge from Congress, the committee defined and evaluated key external costs and benefits associated with the production, distribution, and consumption of energy from various selected sources. We were asked to focus on health, environmental, security, and infrastructure effects that are not—or may not be—fully incorporated into the market price of energy, or into government policies related to energy production, distribution, or consumption. The external effects of energy are mostly negative, but the overall benefits of our energy systems to society are enormous. However, the estimation of those benefits, which are mostly reflected in energy prices and markets, was not in the committee's charge.

The results of this study are intended to inform public policy choices, such as selecting from among fuel types, or to help identify situations where additional regulation may be warranted for reducing external costs produced by an energy-related activity. In addition, identifying sources with large aggregate damages can help identify situations where further analysis of the costs and benefits of reducing some sort of burden resulting from that source is warranted.

This chapter presents an overview of the results of the committee's analyses, factors to keep in mind when interpreting the results of the evaluations, overall conclusions, and recommended research to inform future consideration of various issues.

THE COMMITTEE'S ANALYSES

Our study examined external effects over the life cycle for electricity generation, transportation, and production of heat for the residential, commercial and industrial sectors. We estimated damages that remained in 2005 after regulatory actions as well as the damages expected to remain in 2030 in light of possible future regulations. Our boundaries for analysis are not identical in all sectors, but seek to use existing data and methods for well recognized externalities. We did not attempt to wholly develop new methods for estimating impacts and damages, but we did identify areas where additional research would be particularly valuable.

For electricity generation and production of heat, we focused on monetizing downstream effects related to air pollution from coal-fired and gas-fired processes. Upstream effects and other downstream effects have been quantified but not monetized or have been discussed in qualitative terms. We did not assess effects associated with power plant construction and we did not assess effects from methane emissions from transporting natural gas by pipeline for heat. For transportation, we monetized effects related to air pollution for essentially the full life cycle including vehicle manufacture. We considered climate change effects associated with energy production and use and we reviewed various attempts that have been made in the literature to quantify and monetize the damages associated with the effects of climate change. We also considered the literature on a variety of damages that are associated with our nation's energy infrastructure: disruption in the electricity transmission grid, vulnerability of energy

facilities to accidents and possible attack, external costs of oil consumption, supply security considerations, and national security externalities.

The committee focused its attention on externalities as generally defined by economists. As discussed in Chapter 1, there are many other distortions that occur in markets related to energy production and consumption that may create opportunities for improvement of social welfare, but that are not externalities. There are also equity or "fairness" consequences of market activities. While other distortions and equity concerns may be appropriate for policy formulation, they are beyond the scope of this study and were not considered.

LIMITATIONS IN THE ANALYSES

Estimating most of the impacts and damages involves a several-step process based on many assumptions; this is true for even relatively well-understood impacts. In summarizing our results, we attempt to convey the uncertainty surrounding our estimates. The results of the committee's study should be considered in light of important caveats. Although our analysis was able to consider and quantify a wide range of burdens and damages (e.g., premature mortality resulting from exposure to air pollution), there are many potential damages that we did not quantify. Therefore our results should not be interpreted as a full accounting. As discussed in Chapter 1, studying selected sources was necessary because it would have been infeasible to evaluate the entire energy system with the time and resources available to the committee. Also, within the sources selected by the committee, we were unable to monetize all externalities over a life cycle.

Our analysis required use of a wide set of assumptions and decisions about analytic techniques that can introduce uncertainty in the results. Although we did not attempt to conduct a formal uncertainty analysis, we have been cautious throughout our discussion of results—and urge the reader to be cautious—that is, not to over-interpret small differences in results among the wide range of energy sources and technologies we assessed.

There is uncertainty concerning the analyses with respect to the quality of the data available, the completeness of the analyses (factors that may have been left out or have been unintentionally given inappropriate weight), and the degree to which computation models correctly include the most important variables. Uncertainty also involves unknowns. For example, some climate effects of greenhouse gas (GHG) emissions are poorly understood, and might continue to be for some time. In some cases where effects are unknown, the committee has been able to conclude that they are probably small compared with other, known effects. But in other cases, the committee has not been able to provide even qualitative estimates of unknown effects; in such cases, we must accept that we just do not know. The summaries that follow point out some uncertainties and their sources, but for more detail, it is necessary to consult the individual treatments in previous chapters.

ELECTRICITY GENERATION

Chapter 2 examined burdens, effects, and damages associated with electricity generation from coal, natural gas, nuclear power, wind, solar energy, and biomass. In the cases of fossil fuels (coal and natural gas) and nuclear power, the analysis included externalities associated with upstream activities, exploration, fuel extraction and processing, and the transportation of fuel to generating facilities, as well as damages associated with downstream activities of electricity generation and distribution. Some effects have been discussed in qualitative terms while others have been quantified and, where possible, monetized. Although this section presents estimates of GHG emissions due to electricity generation, it does not present damages associated with effects related to climate change. Those damages are discussed in separate sections within this chapter.

Electricity from Coal

For electricity generation from coal, we monetized effects on human health, visibility of outdoor vistas, agriculture, forestry, and damages to building materials associated with emissions of airborne particulate matter (PM), sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) from 406 coal-fired power plants in the United States, excluding Alaska and Hawaii. More than 90% of monetized damages are associated with premature human mortality and approximately 85% of damages come from SO_2 emissions, which are transformed into airborne PM. Aggregate damages (unrelated to climate change) in 2005 were approximately $62 billion (2007 USD), or 3.2 cents per kWh (weighting each plant by the electricity it produces); however, damages per plant varied widely. The distribution of damages across plants is highly skewed (see Figure 7-1). The 50% of plants with lowest damages per plant accounted for 25% of net electricity generation and produced 12% of damages. The 10% of plants with the highest damages per plant also accounted for 25% of net generation, but produced 43% of the damages. Although damages are larger for plants that produce more electricity, less than half of the variation in damages across plants is explained by differences in net generation. The map in Figure 7-2 shows the size of damages created by each of the 406 plants, by plant location. Plants with large damages are concentrated to the east of the Mississippi River, along the Ohio River Valley, in the Middle Atlantic and the South.

Damages per kWh also varied widely across plants (Figure 7-3): from over 12 cents per kWh (95th percentile) to less than a cent (5th percentile) (2007 USD).[1] Most of the variation in damages per kWh can be explained by variation in emissions intensity (emissions per kWh) across plants. In the case of SO_2 emissions, over 80% of the variation in SO_2 damages per kWh is explained by variation in pounds of SO_2 emitted per kWh. Damages per ton of SO_2, which vary with plant location, are less important in explaining variation in SO_2 damages per kWh. (They are, by themselves, capable of explaining only 24% of the variation in damages per kWh.)

For 2030, despite increases in damages per ton of pollutant due to population growth and income growth, average damages per kWh (weighted by electricity generation) at coal plants are estimated to be 1.7 cents per kWh, compared to 3.2 cents per kWh in 2005 (2007 USD). The fall in damages per kWh is explained by the assumption that pounds of SO_2 per MWh will fall by 64% and that NO_x and PM emissions per MWh will fall by approximately 50% (see Chapter 2).

Greenhouse Gas Emissions

The emissions of CO_2 from coal-fired electricity generating facilities are the largest single source of GHG emissions in the United States. Because the heat rate (energy from coal needed to generate 1 kWh of electricity) varies widely among coal-fired plants, the CO_2 emissions vary as well. The 5th-95th percentile range is 0.95-1.5 tons (with an average of about 1 ton of CO_2 per MWh of power generated). The main factors behind the differences in the CO_2 emitted are the technology used to generate the power and the age of the plant.

Electricity from Natural Gas

For estimating non-climate-change-related damages for 498 facilities that generate electricity from natural gas in the United States, we used a similar approach as in the coal analysis. The gas facilities, which include electric utilities, independent power producers, and combined heat and power facilities, each generated at least 80% of their electricity from gas and had installed capacity of at least 5 MW. The aggregate damages associated with emissions of the SO_2, NO_x, and PM from these facilities, which generated 71% of electricity from natural gas, were approximately $0.74 billion (2007 USD), or 0.16 cents per kWh. Thus, on average, non-climate change damages associated with electricity

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[1]These estimates are not weighted by electricity generation.

generation from natural gas are an order of magnitude lower than damages from coal-fired electricity generation. The distribution of damages across plants is, however, highly skewed (see Figure 7-4). The 10% of plants with highest damages per plant accounted for 65% of the air pollution damages produced by all 498 plants. The 50% of plants with lowest damages per plant accounted for only 4% of the aggregate damages. (Each group of plants, respectively, accounted for approximately one-quarter of the electricity generation.) Although damages were larger for plants that produced more electricity, less than 40% of the variation in damages across plants is explained by differences in net generation. The largest damages are produced by gas plants located in the Northeast (along the Eastern seaboard), and in Texas, California and Florida (see Figure 7-5).

Damages per kWh also vary widely across plants: from more than 1.5 cents per kWh (95th percentile) to less than 0.05 cents (5th percentile) (2007 USD).[2] Most of the variation in NO_x damages per kWh can be explained by variation in emissions intensity across plants; however, for $PM_{2.5}$, which accounted for more than half of the monetized air pollution damages, variation in damages per ton of $PM_{2.5}$ (that is, variation related to the location of the plant relative to population distribution and prevailing winds) are as important in explaining variation in $PM_{2.5}$ damages per kWh as differences in $PM_{2.5}$ emissions intensity.

Damages per kWh at the 498 facilities are predicted to be 30% lower in 2030 relative to 2005; i.e., they are predicted to fall from 0.16 cents to 0.11 cents per kWh on average (2007 USD) (weighting each plant by electricity generation). This is due to a predicted 19% fall in NO_x emissions per kWh hour and 32% fall in $PM_{2.5}$ emissions per kWh (see Chapter 2).
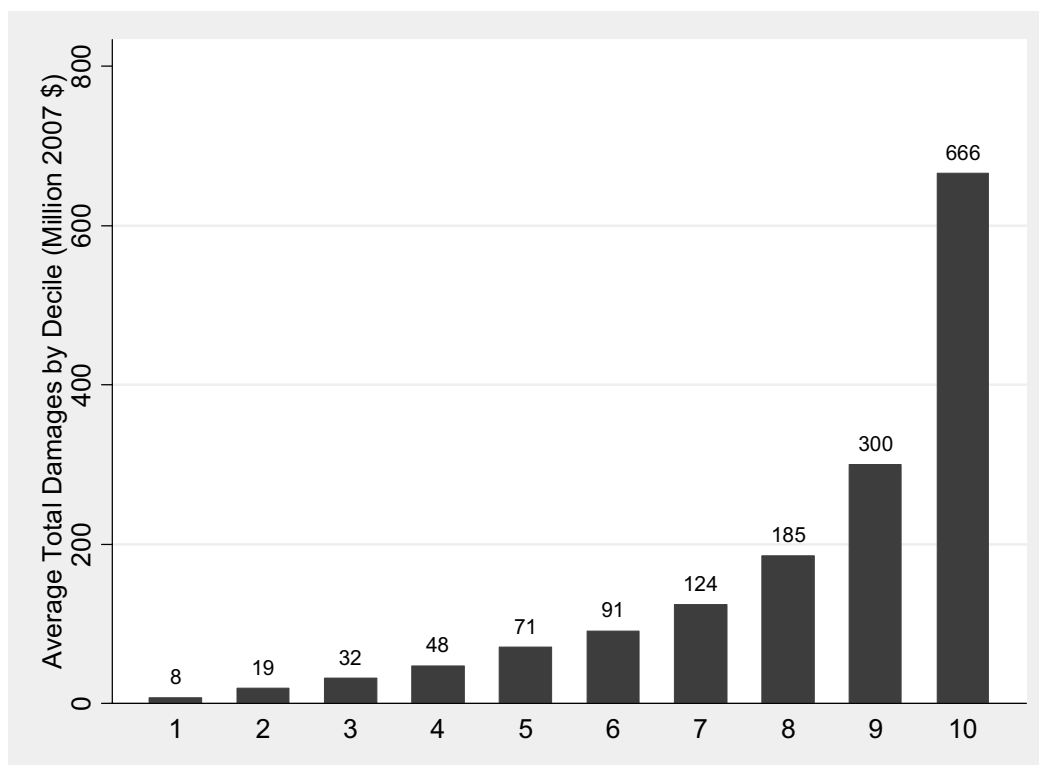
FIGURE 7-1 Distribution of aggregate damages by decile: Coal plants (2007 USD). In computing this chart, plants were sorted from smallest to largest based on aggregate damages. The lowest decile represents the 40 plants with the smallest aggregate damages per plant. The figure on the top of each bar is the average across all plants of damages associated with SO_2, NO_x, $PM_{2.5}$ and PM_{10}. Damages related to climate-change effects are not included.

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[2]These estimates are not weighted by electricity generation.
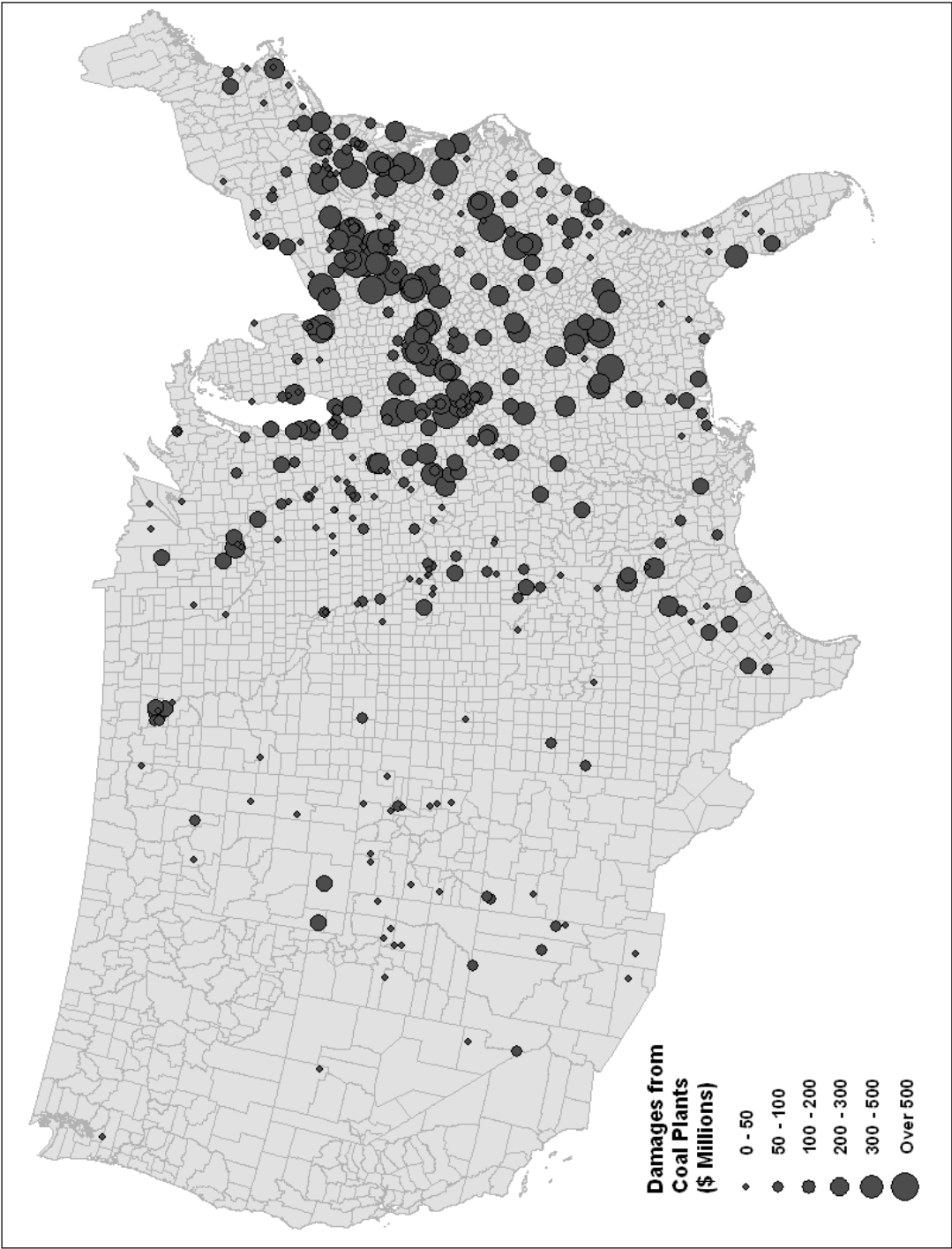
FIGURE 7-2 Air Pollution damages from coal generation for 406 plants, 2005. Damage estimates are reported in 2007 USD. Damages related to climate-change effects are not included.
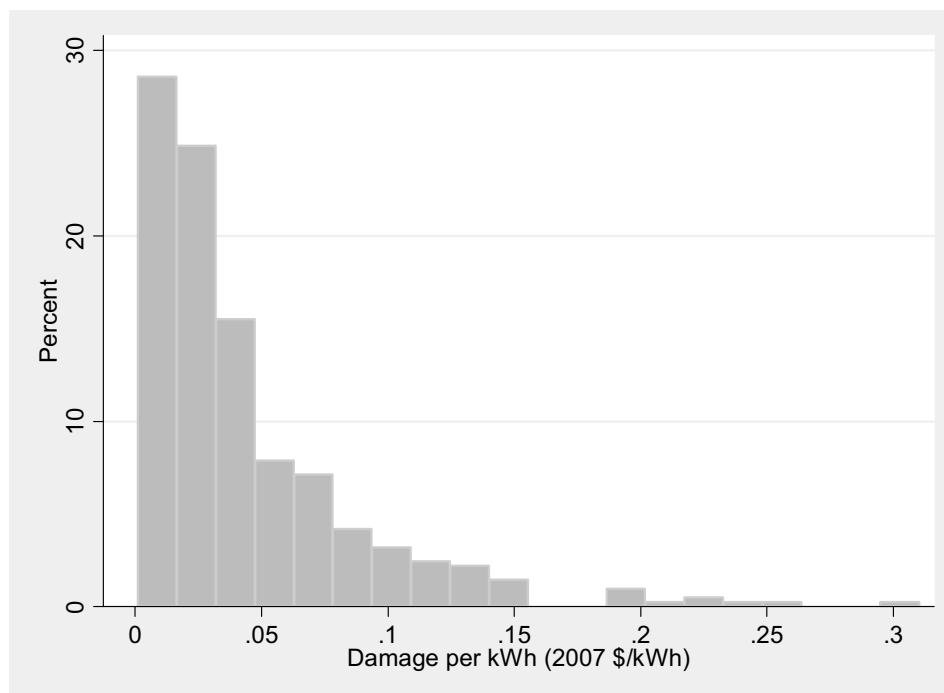
FIGURE 7-3 Distribution of air pollution damages per kWh for 406 coal plants, 2005 (2007 USD). All plants are weighted equally. Damages related to climate-change effects are not included.
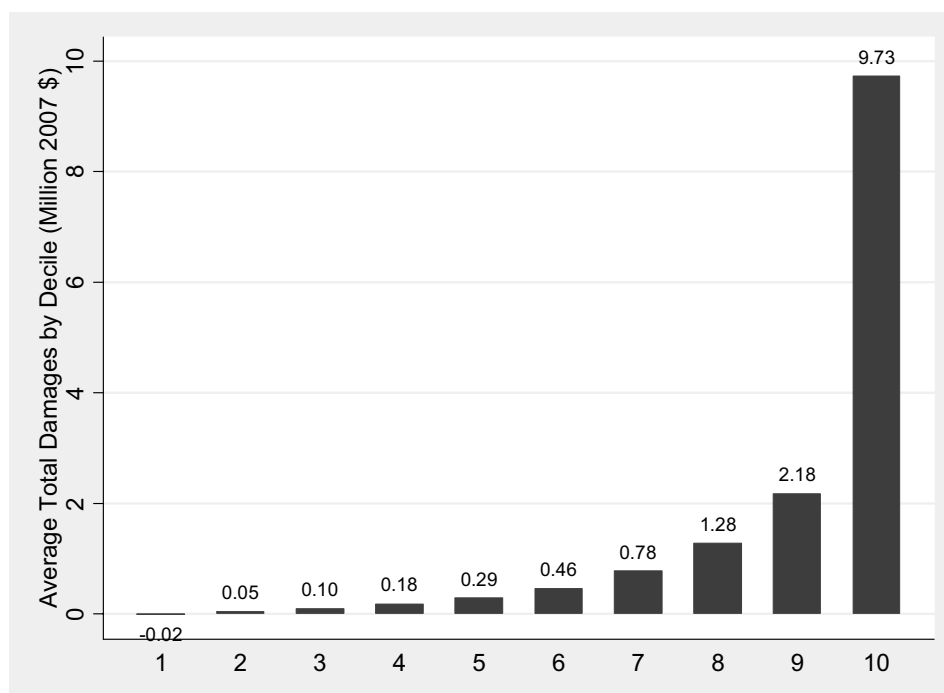
FIGURE 7-4 Distribution of aggregate damages by decile: gas plants (2007 USD). Plants were sorted from smallest to largest based on aggregate damages to compute this chart. The lowest decile represents the 50 plants with the smallest aggregate damages per plant. The number on the top of each bar is the average across all plants of damages associated with SO_2, NO_x, $PM_{2.5}$ and PM_{10}. Damages related to climate-change effects are not included.
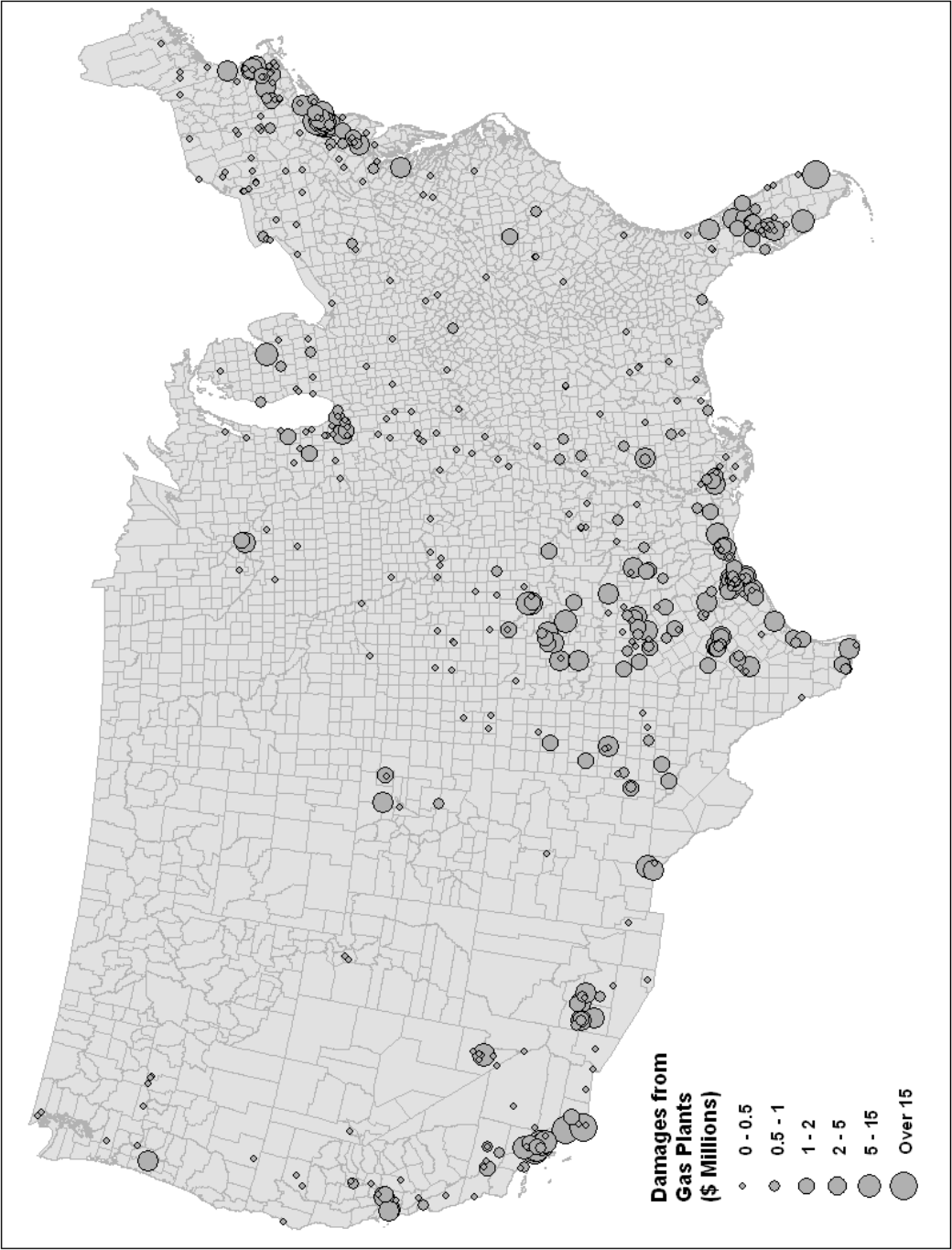
FIGURE 7-5 Air Pollution damages from gas generation for 498 plants, 2005. Damages are expressed in 2007 USD. Damages related to climate-change effects are not included.

Greenhouse Gas Emissions

Natural gas plants on average emitted approximately half as much CO_2 at the generation stage as did coal-fired power plants in 2005—about half a ton of CO_2 per MWh. As the heat rate (energy from gas needed to generate 1 kWh of electricity) varied among gas-fired plants, so did CO_2 emissions, the 5th-95th percentile ranged from 0.3 to 1.1 tons per MWh. As discussed later in this chapter, non-climate change damages from natural gas-fired electricity generation are likely to be much smaller than are its damages related to climate change.

Electricity from Nuclear Power

The committee did not quantify damages associated with nuclear power; however, we reviewed studies conducted by others and believe that their conclusions are relevant.[3] Overall, other studies have found that damages associated with the normal operation of nuclear power plants (excluding the possibility of damages in the remote future from the disposal of spent fuel) are quite low compared with those from fossil-fuel-based power plants.

For surface mine workers, exposure to radon is generally less important than direct irradiation or dust inhalation, but radon exposure can be important for underground miners. However, if radiologic exposure is taken into account in the miners' wages, it would not be considered an externality. For members of the public, the most significant pathways from an operating uranium mine are radon transport and radionuclide ingestion following surface water transport; from a rehabilitated mine, the more significant pathways over the long term are likely to be groundwater as well as surface water transport and bioaccumulation in animals and plants located at the mine site or on associated water bodies. Little uranium is currently mined in the United States; most of the uranium supplied to U.S. nuclear power plants comes from Canada and Russia.

Downstream impacts are largely confined to the release of heated water used for cooling and the production of low-level radioactive wastes (LLRW) and high-level radioactive wastes (HLRW) from spent fuel. Release of highly radioactive materials has not occurred on a large scale in the United States (but obviously has occurred elsewhere). LLRW is stored for decay to background levels and then disposed of as non-radioactive waste (a practice possible with slightly contaminated materials), or it is disposed of in near-surface landfills designed for radioactive wastes. For spent nuclear fuel that is not reprocessed and recycled, HLRW is usually stored at the plant site. No agreement has been reached on a geologic repository for HLRW in the United States, and therefore little HLRW is transported for long distances. The issue of having a permanent repository is perhaps the most contentious nuclear-energy issue, and considerably more study on the externalities of such a repository is warranted.

Electricity from Wind Energy

The committee relied on information in the scientific literature for its assessment of wind power for producing electricity; it focused on land-based wind turbines, because no off-shore turbines have been permitted yet in the United States. Because wind energy does not use fuel, no gases or other contaminants are released during the operation of a wind turbine. Emissions of SO_2, NO_x, and PM and GHGs over the life cycle are much smaller per kWh than for coal or natural gas. Upstream effects are related to the mining, processing, fabrication, and transportation of raw materials and parts; those parts are normally transported to the wind-energy plant's site for final assembly. Effects related to downstream activities

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[3]The Committee did not quantify damages associated with nuclear power because the analysis would have involved power plant risk modeling and spent-fuel transportation modeling that would have taken far greater resources and time than were available for this study.

include visual and noise impacts, impacts on bird and bat species, and land-use effects that accompany the construction of any electricity generating plant and transmission of electricity.

Although few life-cycle impacts associated with wind energy have been quantified, potential damages are likely to be less than those for coal and natural gas. For example, aggregate land-use damages over the entire life cycle are also likely smaller for electricity generation from wind than for coal and natural gas. However, better information is needed, especially in light of the probable increase in the number and density of wind turbines. Even if the expansion of wind energy is taken into account, the estimated number of birds killed by wind turbines is dwarfed by the number killed by transmission lines. On the other hand, bat deaths appear to be largely, if not uniquely, associated with wind-generation, but good estimates of the numbers of bats killed are not available. In addition, the lack of understanding of the demography and ecology of bats makes it difficult to assess the importance of bat deaths. Societal damages associated with the killing of bats by wind turbines are currently small by comparison with the aggregate damages associated with electricity generation by coal, natural gas, and the sum of all other sources.

Electricity from Solar Energy

Much of the United States receives enough solar energy to produce about 1 kWh per square meter of panel area per day, with considerable local variability from north to south and regionally as a result of sun angles and weather patterns. At present, most solar panels are installed on building roofs or immediately adjacent to buildings to provide electricity on site. When a site's electricity use exceeds solar energy availability, electricity is supplied from the grid (or from batteries, if electricity demand is low). In this case, solar panels reduce grid-based electricity demand at the end-use, thus becoming similar to an energy efficiency improvement. Some solar panel installations also can feed excess electricity back into the grid during periods of peak solar or low local on-site demand periods.

Concentrating solar power (CSP)[4] and photovoltaic (PV) electricity generation by the electricity sector combined to supply 500 GWh in 2006 and 600 GWh in 2007, which constitute about 0.01 percent of the total US electricity generation. EIA data indicate that the compounded annual growth rate in net US generation from solar was 1.5% from 1997 to 2007 (NRC Renewables 2009). However, this estimate does not account for the growth in residential and other small PV installations, which are applications that have displayed the largest growth rate for solar electricity. While solar PV and CSP are still developing technologies, they will be an increasing, but still small, part of electricity generation through 2020.

Like wind power, solar power emits no gaseous pollutants during operations to produce electricity. Upstream life-cycle activities include mining of materials for solar panels and the balance-of-system components used to convert the electricity to alternating current. Downstream life-cycle activities include electricity generation, storage, and disposal or recycling of worn-out panels. Worn-out panels have the potential to produce a large amount of waste, and improper disposal may lead to the possibility of leaching of toxic chemicals. If solar energy for electricity were to become a significant part of the U.S. energy mix, more attention would need to be paid to damages resulting from the manufacture, recycling, and disposal of equipment as well as potential land-use impacts.

Electricity from Biomass

No attempt has been made to estimate the damages associated with generating electricity using biomass feedstock that are derived from forestry practices, agricultural activities, or from municipal solid

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[4]Concentrating solar power (CSP) installations use arrays of mirrors to focus direct beam incident sunlight to heat a working fluid and generate electricity through a thermal power cycle. Desert locations with low humidity and high insolation could allow large scale CSP) electricity generation at lower costs than PV installations. Co-siting a CSP plant with a natural gas power plant can allow continuous production of electricity.

waste. This is because the amount of electricity generated from biomass feedstock is relatively small (total installed capacity is less than 1600 MW) and is likely to remain so.[5] Many of the issues facing biomass combustors are similar to issues faced by large scale fossil fuel generation. Emissions from the combustion of biomass can include polychlorinated biphenyl compounds, although the focus of recent analysis has been primarily on enclosed systems. Non-climate change related damages from biomass-generated electricity on a per-kWh basis might equal or even exceed those from coal in some cases. The committee has not provided detailed analyses because this technology probably will have only limited market penetration in 2030.

Transmission and Distribution of Electricity

Transmission lines have raised concerns about health risks (e.g. risks associated with exposure to extremely low frequency (ELF) electromagnetic radiation), visual disamenities, and loss of property values. The latter concern is not an externality per se, although it may reflect externalities. Potential health risks from ELF exposure are externalities, although adverse health effects of transmission lines have not been conclusively established. Visual disamenities are also externalities, and may become an increasing concern in association with renewable energy sources. Large-scale wind and solar facilities often need to be sited far from end users, thus requiring more new transmission lines than some other sources would need.

TRANSPORTATION

We considered a wide range of potential emissions and damages related to air pollution from the use of energy in transportation. Our discussion and analysis focused on the components of transportation energy use—for light-duty and heavy-duty on-road vehicles—that account for more than 75%, i.e. the great majority, of annual U.S. transportation energy use. Other transportation energy uses (e.g., for nonroad vehicles, aircraft, locomotives, and ships) are not inconsequential, but they account for a smaller portion of transportation energy use and so were not considered. For each fuel and vehicle combination, the committee analyzed the life-cycle energy use and emissions, and then used those emissions data in a nationwide analysis of exposures and health effects as well as other non-climate effects, and then developed estimates of monetized damages (described in Chapter 3). This section also presents estimates of GHG emissions due to transportation, but it does not present estimates of climate change related damages associated with those emissions. Those damages are discussed in a separate section of this chapter.

Health Effects and Other Damages Not Related to Climate Change

Despite limitations, our analysis provides some useful insight into the relative levels of damages from different fuel and technology mixes. Overall, we estimate that the aggregate national damages in 2005 to health and other non-climate-change-related effects were approximately $36 billion per year (2007 USD) for the light duty vehicle fleet; the addition of medium-duty and heavy-duty trucks and buses raises the aggregate estimate to approximately $56 billion (2007 USD). These estimates are likely conservative, as they include but do not fully account for the contribution of light-duty trucks to the aggregate damages, and should be viewed with caution, given the significant uncertainties in any such analysis.

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[5] Source: National Electric Energy System (NEEDS) database for Integrated Planning Model, 2004.

Health and Other Non-Climate-Change-Related Damages on a per VMT Basis

Although the uncertainties in the analysis preclude precise ranking of different technologies, Table 7-1 below illustrates that on a cents per vehicle mile traveled (VMT) basis there are some important differences in the levels of damages attributable to different fuel and technology combinations in 2005 and 2030.

Among the fuel and technology choices, there are some differences in damages although overall, especially in 2030, the different fuel and technology combinations have remarkably similar damage estimates.

- Some fuels—E85 from herbaceous and corn stover feedstock, and CNG—have relatively lower damages than all other options in both 2005 and 2030.
- Diesel, which has relatively high damages in 2005, has one of the lowest levels of damage in 2030. This is due to the substantial reductions in both PM and NO_x emissions that a diesel vehicle is required to attain following the 2006 introduction of low-sulfur fuel.
- Corn-based ethanol, especially E85, has relatively higher damages than most other fuels; this is in large measure due to the higher level of emissions from the energy required to produce the feedstock and the fuel.
- Grid-dependent HEVs and electric vehicles have somewhat higher damages in both 2005 and 2030. As noted in Chapter 3, these vehicles actually have significant advantages over all other fuel and technology combinations when considering only damages from operations. However, the damages associated with the present and projected mixes of electricity generation (with the latter still being dominated by coal and natural gas in 2030, albeit at significantly lower rates of emissions) add substantially to the life-cycle damages. In addition, the increased energy associated with battery manufacture adds approximately 20% to the damages from vehicle manufacture. However, further legislative and economic initiatives to reduce emissions from the electricity grid could be expected to improve the relative damages from electric vehicles substantially.

Although the underlying level of aggregate damages in the United States could be expected to rise between 2005 and 2030, due to projected increases in population and to increases in the value of a

TABLE 7-1 Relative Categories of Health and Other Non-Climate Change Damages 2005 and 2030 for Major Categories of Light-Duty Vehicle Fuels and Technologies (Damage Estimates Based on 2007 USD)

Category of Aggregate Damage Estimates (Cents/VMT)	2005	2030
1.10 – 1.19		CNG Diesel with low sulfur and biodiesel
1.20 – 1.29	E85 Herbaceous E85 Corn Stover CNG Grid-independent HEV	E85 Corn Stover E85 Herbaceous
1.30 – 1.39	Conventional Gasoline and RFG E10 Hydrogen gaseous	Conventional Gasoline and RFG E10 E85 Corn
1.40 – 1.49	Diesel with low sulfur and biodiesel Grid-dependent HEV	Electric Vehicle
1.50 – 1.59	E85 Corn	Grid-independent HEV Grid-dependent HEV
>1.60	Electric Vehicle	Hydrogen gaseous

statistical life, the results in our analysis for most fuel and technology examples are very similar in 2030 to those in 2005, in large measure because of the expected improvement in many technology/fuel combinations (including conventional gasoline) as a result of enhanced fuel efficiency (i.e., 35.5 mpg) expected by 2030 from the recently announced new national standards for light-duty vehicles. (It is possible however that these improvements are somewhat overstated, as there is evidence that improved fuel efficiency, by reducing the cost of driving, could also lead to increased travel, and consequently result in higher aggregate damages than would otherwise be seen.)

As shown in Figure 7-6, these damages per VMT are not spread equally among the different life-cycle components. For example, in most cases the actual operation of the vehicle is one-quarter to one-third of the damages per VMT, while the emissions incurred in creating the feedstock, refining the fuel, and making the vehicle, are responsible for the larger part of damages.

Health and Other Non-Climate Damages on a per Gallon Basis

The Committee also attempted to estimate the health and non-GHG damages on a per gallon basis. This is made somewhat more complicated by the fact that simply multiplying expected miles per gallon for each fuel/vehicle type by the damages per mile will tend to make the most fuel efficient vehicles, which travel the most miles on a gallon, appear to have higher damages per gallon than a less fuel efficient vehicle. With that caveat in mind, the Committee analysis estimated that in 2005, the mean damages per gallon for most fuels ranged from 23 cents/gallon to 38 cents/gallon, with the damages for conventional gasoline engines being in approximately the middle of that range at approximately 29 cents per gallon.

Limitations in the Health and Other Non-Climate Damages Analysis

When interpreting these results, it is important to consider two major limitations in the analysis: the emissions and damages that were not quantifiable and the uncertainty in the analytical results that were obtained.

Although our analysis was able to consider and quantify a wide range of emissions and damages throughout the life cycle, and included what arguably could be considered the most significant contributors to estimates of such damages (e.g., premature mortality resulting from exposure to air pollution), there are many potential damages which could not be quantified at this time. These include, among others:

- *Overall:* Estimates of impacts of hazardous air pollutants, and estimates of damages to ecosystems (e.g. from deposition), the full range of agricultural crops, in that some crops were included, and others were not.
- *For biofuels:* Impacts on water use and water contamination, as well as any formal consideration of potential indirect land use effects (see however our discussion of the latter in Chapter 3).
- *For battery electric vehicles:* Potential exposures to toxic contaminants as a result of battery manufacture, battery disposal, and accidents.

Any such analysis includes a wide set of assumptions and decisions about analytic techniques that can introduce uncertainty in the results. Although we did not attempt to conduct a formal uncertainty analysis, we engaged in limited sensitivity analyses to check the impacts of key assumptions. We urge the reader to be cautious when interpreting small differences in results among the wide range of fuels and technologies we assessed.

a)

Health and Other Damages by Life-Cycle Component
2005 Light-Duty Automobiles

Damages (cents/VMT)

: Operation ■ Feedstock ▨ Fuel ⬚ Vehicle

b)

**Health and Other Damages by Life-Cycle Component
2030 Light-Duty Automobiles**

Damages (cents/VMT)

: Operation ▪ Feedstock ▨ Fuel ⧄ Vehicle

RFG SI Autos (Convent. Oil)
CG SI Autos (Tar Sands)
CG SI Autos (Convent. Oil)
RFG SIDI Autos (Tar Sands)
RFG SIDI Autos (Convent. Oil)
CNG
E85 - Dry Corn
E85 - Wet Corn
E85 - Herbaceous
E85 - Corn Stover
E10 - Dry Corn
E10 - Wet Corn
E10 - Herbaceous
E10 - Corn Stover
Electric
Hydrogen (Gaseous)
Grid Independent SI HEV
Grid Dependent SI HEV
Diesel (Low Sulfur)
Diesel (Fischer Tropsch)
Diesel (Soy BD20)

FIGURE 7-6a-b Aggregate life-cycle damages of light-duty vehicles from air pollutants, excluding GHGs emissions (cents/VMT) for 2005 and 2030. Costs are in 2007 USD.

Greenhouse Gas Emissions

Similar to the damages estimates presented above, the GHG emission estimates from each fuel and technology combination can provide relative estimates of GHG performance in 2005 and 2030. Although caution should be exercised in interpreting these results and comparing among fuel and technology combinations, some instructive observations from Table 7-2 are possible.Overall, the substantial improvements in fuel efficiency in 2030 (to a minimum of 35.5 mpg for light-duty vehicles) result in most technologies becoming much closer to each other on a per-VMT basis for life-cycle greenhouse gas emissions. There are however some differences:

- As with damages above, the herbaceous and corn stover E85 have relatively low GHG emissions over the life cycle; in terms of aggregate g/VMT of CO_2-eq[6] emissions, E85 from corn also has relatively low GHG emissions
- The tar sands based fuels have the highest GHG emissions of any of the fuels that we considered.

As shown in Figure 7-7, and in contrast to the damages analysis above, the operation of the vehicle is in most cases a substantial relative contributor to total life-cycle GHG emissions. This is not the case, however, with either the grid-dependent technologies (e.g., electric or grid-dependent hybrid) or the hydrogen fuel cell vehicles. In these latter vehicle technologies, the dominant contributor to life-cycle GHG emissions is electricity generation and the production of hydrogen, rather than in the operation of the vehicle.

TABLE 7-2 Relative Categories of GHG Emissions 2005 and 2030 for Major Categories of Light-Duty Vehicle Fuels and Technologies (Emission Estimates in Units of g/VMT)

Category of Aggregate CO_2-eq Emission Estimates (g/VMT)	2005	2030
150 – 250	E85 Herbaceous E85 Corn Stover	E85 Herbaceous E85 Corn Stover
250 – 350	Hydrogen Gaseous	E85 Corn Diesel with biodiesel Hydrogen Gaseous CNG
350 – 500	E85 Corn Diesel with biodiesel Grid-independent HEV Grid-dependent HEV Electric Vehicle CNG	Grid-independent HEV SI Conventional Gasoline, RFG Grid-dependent HEV Electric Vehicle Diesel with low sulfur E10 Herbaceous, Corn Stover SIDI Conventional Gasoline E10 Corn SI Tar Sands
500 – 599	Conventional Gasoline and RFG E10 Low sulfur diesel	
>600	Tar Sands	

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[6] CO_2-equivalent (CO_2-eq) expresses the global warming potential of a greenhouse gas, such as methane, in terms of CO_2 quantities.

**Greenhouse Gas Emissions by Life-Cycle Component
2005 Light-Duty Automobiles**

a)

b)
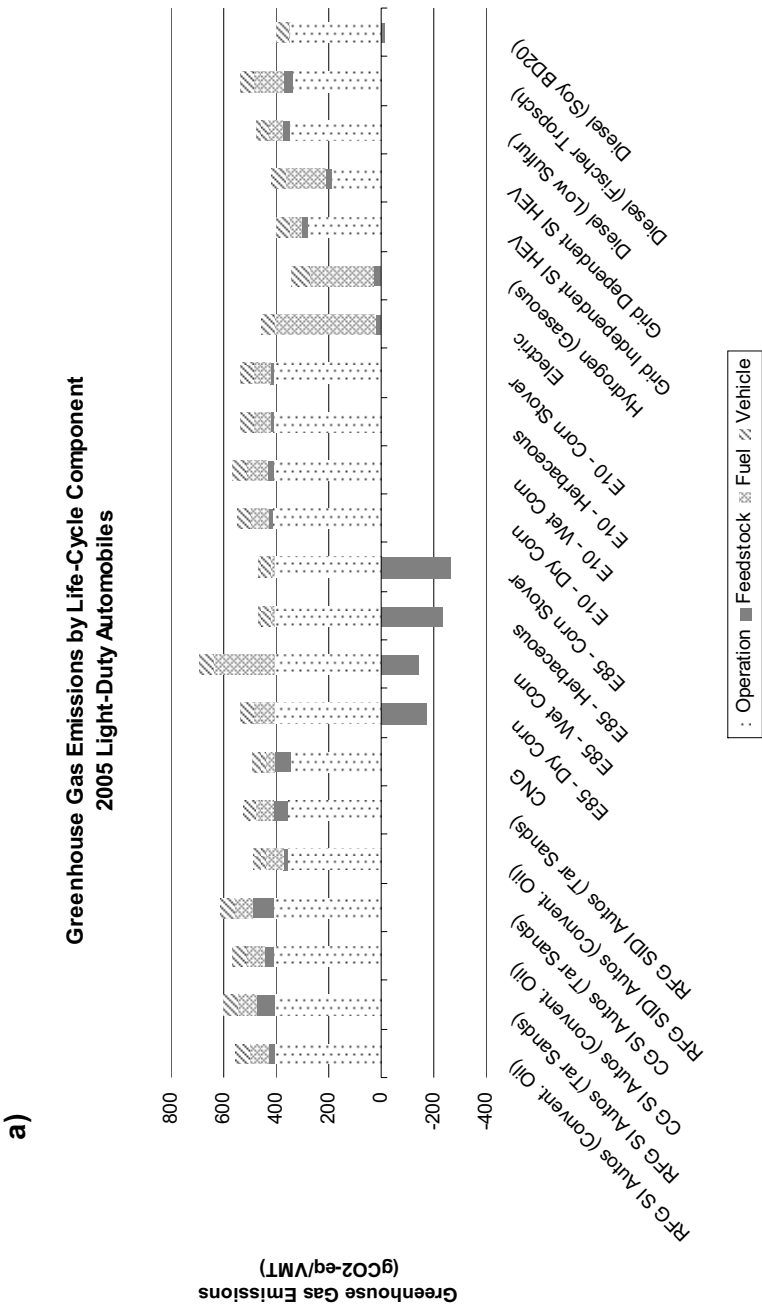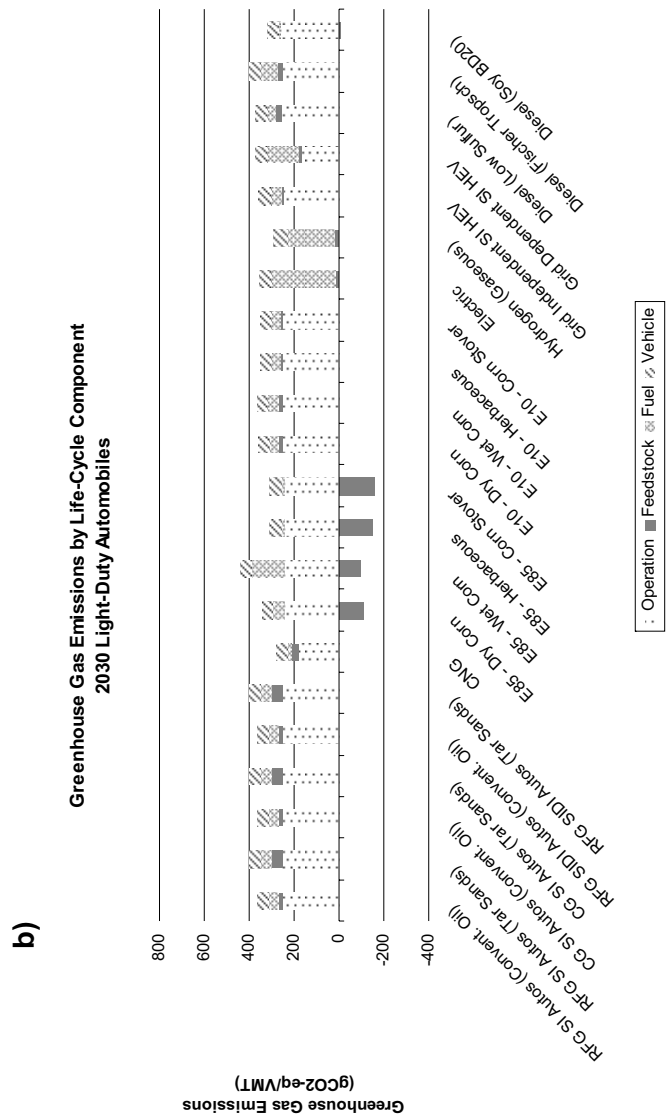
FIGURES 7-7a-b GHG emissions (grams CO_2-eq)/VMT by life-cycle component for light-duty automobiles in 2005 and 2030. Blue refers to vehicle operation, red to feedstock for fuels, green to fuel refining, and purple to vehicle manufacture (going from bottom to top of each bar). One exception is ethanol fuels for which feedstock production exhibits negative values due to CO_2 uptake. The amount of CO_2 consumed should be subtracted from the positive value to arrive at a net value.

Heavy-Duty Vehicles

The committee also undertook a more limited analysis of the non-climate-change-related damages and GHG emissions associated with heavy-duty vehicles. Although this analysis included operation, feedstock, and fuel components of the life cycle, it could not—due to the wide range of vehicle types and configurations—include a vehicle manufacturing component. In sum, there are several conclusions that can be drawn:

- The non-climate-change-related damages per VMT in 2005 are significantly higher than those shown for light-duty vehicles above, although they of course pertain to a much higher weight of cargo and/or number of passengers being carried per vehicle mile as well.
- Damages not related to climate-change effects drop significantly in 2030, due to the full implementation of the 2007-2010 Highway Diesel Rule which requires substantial reductions in PM and NO_x emissions.
- Amounts of GHG emissions are driven primarily in these analyses by the operations component of the life cycle, and do not change substantially between 2005 and 2030 (except for a modest improvement in fuel economy). EPA and others are currently actively investigating possible future enhanced requirements for fuel economy among heavy-duty vehicles.

HEAT GENERATION

The committee conducted an assessment focused on air pollution impacts associated with the present and future (2030) use of natural gas for heat in residential and commercial building sectors. The industrial sector was considered more qualitatively, as published statistics do not differentiate clearly between fuel used for heating and for process feedstocks. We focused our assessment on natural gas because it is the major energy source for heat in buildings, although buildings also consumed about 5% of the 39.7 quads of petroleum used in 2008. Only about 12% of U.S. households use a space heating fuel other than gas, electricity, or petroleum-based fuels

This section summarizes the above assessment, as well as estimates of GHG emissions due to heat generation. Climate change related damages are discussed later in this chapter.

Heat for Residential and Commercial Buildings

We estimated damages attributable to SO_2, NO_x, $PM_{2.5}$, VOC, and NH_3 emissions from on-site combustion across 3100 U.S. counties. Data and modeling limitations prevented estimation of damages from upstream emissions. The median estimated damages (in 2007 USD) attributable to natural gas combustion for heat in residential buildings are approximately $0.11 per thousand cubic feet (MCF), or 1% of the 2007 residential price of natural gas. Aggregate damages (unrelated to climate change) were approximately $500 million (2007 USD). The median *regional* estimated damages from natural gas combustion for heat in residential buildings ranged from $0.06 to 0.14/MCF, the upper tail of the distribution was as much as 5% of the current residential price of natural gas when evaluating the 90th percentile value in the South region of the United States. We estimate that damages from combusting natural gas for direct heat are much lower than the damages related to heat produced from electricity, based on average values of the U.S. electricity grid.

Estimated damages from natural gas for heat in commercial buildings are very similar to the estimates for residential buildings. The median estimated externality of natural gas combustion for heat in the commercial building sector is approximately $0.11/MCF and aggregate damages are about $300 million (excluding damages related to climate change) (2007 USD). The variation across U.S. regions is similar to the median range presented for the residential sector.

In 2007, the combined residential and commercial building sectors emitted an estimated 618 million tons of carbon dioxide.

Damages associated with energy for heat in 2030 are likely to be approximately the same as those that exist today, contingent upon the development of additional sources to meet demand. Reduction would likely result from changes in the electricity sector, as emission from natural gas are relatively small and already well-controlled. Increases are possible if new domestic development has higher emissions, or if additional imports of liquefied natural gas are needed.

Heat for Industry

Natural gas use for heating in the industrial sector (6 quads), excluding use for feedstock, is less than natural gas use in the residential and commercial building sectors (8 quads) for 2007, thus health and environmental damages associated with industrial natural gas usage are likely the same order of magnitude or less than the damages associated with natural gas use for heat in residential and commercial buildings. A very rough order of magnitude estimate of average externalities associated with the industrial sector usage of natural gas is therefore $0.10/MCF, excluding GHG damages

For 2007, about 1,084 million tons of CO_2 were emitted from the industrial sector due to natural gas combustion for heat. That amount is greater than the combined amount of 617 million tons of CO_2 from the residential and commercial sectors. As discussed below, non-climate change damages from natural gas combustion for direct heat are likely to be much smaller than its damages that are related to climate change.

In Sum

Aggregate damages from combustion of natural gas for direct heat are estimated to be about $1.4 billion per year (2007 USD), assuming the magnitude of effects resulting from heat production in industrial activities is comparable to those of residential and commercial sectors. Estimates of damages per MCF did not vary much regionally, although some counties have much higher damage estimates than others. The largest potential for reducing damages associated with the use of energy for heat lies in greater attention to improving the efficiency of energy use.

Damages associated with energy for heat in 2030 are likely to be about the same as those that exist today, assuming that the effects of additional sources to meet demand are offset by lower-emitting sources. *Reduction* in damages would only result from more significant changes—largely in the electricity-generating sector, as emissions from natural gas are relatively small and well controlled. But the greatest potential for reducing damages associated with the use of energy for heat lies in greater attention to improving efficiency. *Increased* damages would also be possible, however, if new domestic energy development resulted in higher emissions or if additional imports of liquefied natural gas, which would increase emissions from the production and international transport of the fuel, were needed.

Combustion of natural gas results in relatively lower GHG and criteria pollutant forming emissions compared to similar emissions from coal (the main energy source for electricity generation) and petroleum combustion.

CLIMATE CHANGE

Energy production and use is a major source of GHG emissions, principally CO_2 and methane. Externalities are created as increased atmospheric GHG concentrations affect climate, and subsequently weather, water quality and availability, sea-level rise, and biodiversity. Changes in these physical and biological systems in turn impact a variety of aspects of human life, including water resources, ecosystem

services, food production, and health among other impacts. Quantifying and valuing climate change impacts in order to calculate the marginal damage of a ton of carbon, often referred to as the "the social cost of carbon", is an intricate process that involves detailed modeling and analysis. Integrated Assessment Models (IAMs), which produce such estimates, must make assumptions about the relationship between emissions and temperature change and temperature and economic impacts in multiple sectors. The magnitude of these impacts depends, to a large extent, on changes in climate and on human adaptation to climate change in the distant future. The discount rate used to determine present-day value of future impacts is thus of key importance, as well as the extent to which various climatic changes are expected to be extreme and irreversible.

Due to the complexity in evaluating the externalities of energy-induced climate change, the committee focused its efforts on a review of existing IAMs (specifically, the DICE, FUND and PAGE models) and the associated climate change literature. The committee came to the following conclusions, as discussed in Chapter 5:

- The two features of IAMs that drive estimates of the marginal damage associated with emitting an additional ton of carbon are the choice of discount rate and the relationship between mean temperature change and the percentage change in world GDP (i.e., the aggregate damage function).
- Holding the discount rate constant, the choice of damage function can alter estimates of marginal damages by an order of magnitude: for example, at a 3% discount rate, the marginal social cost of carbon is approximately $2 per ton of CO_2-eq using the FUND model and $22 per ton of CO_2-eq using the PAGE model. The differences between these two well-reviewed and respected IAMs illustrate the scientific uncertainties inherent in predicting the magnitude of climate change damage functions.
- Holding the damage function constant, changing the discount rate from 4.5% to 1.5% will cause the marginal social cost of carbon to rise by an order of magnitude: in the PAGE model, for example the marginal social cost of carbon is approximately $100 per ton of CO_2 at a 1.5% discount rate and $10 at 4.5% discount rate.
- In all IAMs, marginal damage estimates for 2030 GHG emissions are 50 to 80 percent larger than estimates of damages from emissions occurring within the past few years.
- The impacts of climate change are likely to vary greatly across countries. The estimates of the marginal damage of a ton of CO_2-eq, cited in this report, sum damages across countries using relative GDP as weight, which gives less weight to the damages borne by low-income countries.
- There is great uncertainty about the impact of GHG emissions on future climate and about the impacts of changes in climate on the world economy. This uncertainty is usually handled in IAMs using Monte Carlo simulation: the model is run many times, drawing key parameters from their probability distributions that reflect the uncertainty about these values. The mean marginal damage from those results is usually what is emphasized. This approach does not adequately capture the small probability of catastrophic climate changes and/or impacts. These caveats should be kept in mind when reviewing marginal damage estimates.

COMPARING CLIMATE AND NON-CLIMATE DAMAGE ESTIMATES

Table 7-3 summarizes the results of the committee's quantitative analyses of damages related to the production and use of energy. The table presents the monetized health damages and other monetized damages not related to climate change that were presented in this report. In addition, for illustrative purposes, the table presents three different estimates of external global damages on a per unit basis from effects related to climate change. The different estimates were obtained by selecting three alternative marginal GHG damage values ($10, $30, and $100 per ton CO_2-eq) multiplying each by GHG emission rates for electricity generation (coal-fired and natural gas fired), a range of transportation fuels, and

production of heat by combusting natural gas. It is important to note, that the damage estimates at the higher end of the range area associated only with emission paths without significant GHG controls.

The estimated damages related to climate change on a per-unit of fuel basis differ across various primary fuels and energy end-uses. These estimates are summarized in Table 7-3. How the monetized value of damages related to climate change compares to the value of damages from SO_2, NO_x, and PM emissions depends on the value chosen for the social cost of carbon. If the social cost of carbon were $30 per ton of CO_2-eq, climate change related damages would be approximately 3 cents per kWh at coal fired power plants and 1.5 cents per kWh at natural gas plants, equaling or exceeding in value the damages from SO_2, NO_x, and PM. For transportation, damages related to climate change begin to approach the value of non-climate damages at $30/ton of CO_2-eq. For direct heat, each estimate of climate-related damages substantially exceeds the damage estimate from non-climate damages. Thus, damages related to climate change are dominant for electricity generated from natural gas and for heat production at all levels of the social cost of carbon in Table 7-3. Climate damages for electricity generation from coal and for transportation can be larger than non-climate damages if a high value is chosen for the social cost of carbon.

Estimates of damages presented in this report do not by themselves provide a guide to policy. Economic theory suggests that the damages associated with pollution emissions should be compared to the costs of reducing emissions: If distributional equity issues are put aside, the theory suggests that damages should not be reduced to zero, but only to the point where the marginal cost of reducing another ton of emissions or other type of burden equals the marginal damages avoided. Whether emissions should be reduced from the viewpoint of economic efficiency depends on the current level of emissions and the cost of reducing them; it cannot be determined from the size of damages alone. We emphasize, however, that economic efficiency is only one of several potentially valid policy goals that need to be considered in managing pollutant emissions and other damages.

OVERALL CONCLUSIONS AND IMPLICATIONS

Electricity Generation

Our analysis of the damages associated with energy for electricity focused on air pollution damages—both local and global—associated with electricity generation. These estimates can be used to inform the choice of type of fuel used to generate electricity and to guide policies regarding the regulation of air emissions from electricity generation.

TABLE 7-3 Monetized Damages Per Unit of Energy-Related Activity[a]

Energy-Related Activity (Fuel Type)	Non-climate Damage	CO_2-eq Intensity	Climate Damages (per ton CO_2-eq)[c]		
			@ $10	@ $30	@ $100
Electricity Generation (coal)	3.2 cents/kWh	2 lbs/kWh	1 cent/kWh	3 cents/kWh	10 cents/kWh
Electricity Generation (natural gas)	0.16 cents/kWh	1 lb/kWh	0.5 cent/kWh	1.5 cents/kWh	5 cents/kWh
Transportation[b]	1.2 to > 1.7 cents/VMT	0.3 to > 1.3 lb/VMT	0.15 to > .65 cent/VMT	0.45 to > 2 cents/VMT	1.5 to > 6 cents/VMT
Heat production (natural gas)	11 cents/MCF	140 lbs/MCF	70 cents/MCF	210 cents/MCF	700 cents/MCF

[a]Based on emission estimates for 2005. Damages are expressed in 2007 USD. Damages that have not been quantified and monetized are not included.
[b]Transportation fuels include: E85 Herbaceous, E85 Corn Stover, Hydrogen Gaseous, E85 Corn, Diesel with biodiesel, Grid-independent HEV, Grid-dependent HEV, Electric Vehicle, CNG, Conventional Gasoline and RFG, E10, Low sulfur diesel, Tar Sands (see Table 7-1 for relative categories of non-climate damages and Table 7-2 for relative categories of GHG emissions).
[c]Often called the "social cost of carbon."

Regarding Comparisons Among Fuels for Electricity Generation

- In 2005 damages per kWh from SO_2, NO_x, and PM emissions were an order of magnitude higher for coal than for natural gas plants: on average, approximately 3.2 cents per kWh for coal and 0.16 cents per kWh for natural gas (2007 USD). SO_2, NO_x, and PM emissions per kWh were virtually nil for electricity generation from nuclear, wind, and solar plants and not calculated for plants using biomass for fuel.

- Average figures mask large variations in air pollutant damages per kWh across plants, which primarily reflect differences in pollution control equipment. For coal plants, the 5th percentile of the distribution of damages was only 0.5 cents per kWh (2007 USD). Newer plants emit significantly less SO_2 and NO_x per kWh than older plants.

Regarding the Regulation of Air Emissions from Electricity Generation

- Estimates of aggregate air pollutant damages (damages per kWh times kWh generated) can help to identify situations where additional pollution controls might pass the benefit-cost test. We note that the damages from SO_2, NO_x, and PM at all coal plants, conservatively calculated, were approximately $62 billion in 2005 (2007 USD). (This represents the damages from emissions in 2005 relative to zero emissions.) When considering regulations, these damages provide important information to be compared with the costs of controlling emissions related to criteria air pollutants – in particular, comparing the marginal damages per kWh or ton of pollutant to the marginal costs of reducing the emissions.

- The distribution of damages associated with emissions of SO_2, NO_x, and PM is highly skewed for both coal-fired power plants and natural gas-fires plants. The 10% of coal plants with the lowest damages produce 43% of air pollution damages from all coal plants, while the 50% of the plants with the lowest damages produce less than 12% of aggregate damages. (Each group of plants produces the same amount of electricity—about 25% of net generation from coal.) The 10% of natural gas plants with the highest damages per plant in our study produce 24% of the electricity but 65% of the damages.

- For policy purposes it is useful to know the damages associated with emitting an additional ton of a pollutant, because the most economically efficient pollution control policies are those that target emissions directly. These damages vary significantly depending on the pollutant (NO_x v. PM) and on where it is emitted. The damage associated with a ton of SO_2 varies from $1,800 to $10,700 (5th and 95th percentile) at coal plants and from $1,800 to $44,000 at natural gas plants (2007 USD). This reflects the fact that most coal-fired power plants are located farther away from population centers than are natural gas plants. The highest damages per ton are associated with directly emitted PM. These vary from $2,600 to $160,000 (5th and 95th percentile) at natural gas plants and from $2,600 to $26,000 at coal-fired power plants (2007 USD).

Transportation

Perhaps the most important conclusion to be taken from the transportation analyses is that, when viewed from a full life-cycle perspective, the results are remarkably similar across fuel-technology combinations. One key factor contributing to this is the relatively high contribution to health and other non-GHG damages from emissions in life-cycle phases *other* than the operation of the vehicle (i.e., the development of the feedstock, processing of the fuel, and manufacturing of the vehicle). There are some differences though, and from these some conclusions can be drawn:

- The gasoline-driven technologies have somewhat higher damages related to air pollution (excluding climate change) and GHG emissions in 2005 than a number of other fuel-technology combinations. The grid-dependent electric options have somewhat higher damages than many other

technologies, even in our 2030 analysis, in large measure due to continued conventional emissions and GHG emissions from the existing and likely future grid.

- The choice of feedstock for biofuels can significantly affect the relative level of life-cycle damages, with herbaceous and corn stover feedstock having some advantage in this analysis.
- Additional regulatory actions can significantly affect levels of damages and GHG emissions:
  o This is illustrated in the health and non-climate damages analysis by the substantial reduction in diesel damages from 2005 to 2030. Major regulatory initiatives to reduce electricity generation emissions or legislation to regulate carbon emissions would be expected to significantly reduce the relative damages and emissions from the grid-dependent electric vehicle options. Similarly, a significant shift to lower-emitting grid technologies, such as natural gas, renewable sources, nuclear, would also reduce these damages.
  o Also, in 2030, with the implementation of enhanced 35.5 mpg requirements now being put in place for light-duty vehicles under CAFE and EPA Greenhouse Gas Emission Rules, the differences among technologies tend to converge somewhat, although the fact that operation of the vehicle is generally less than a third of overall life-cycle emissions and damages tend to dampen the magnitude of that improvement. Further enhancements in fuel efficiency, for example, the likely push for an extension beyond 2016 to further improvements, would further improve the GHG emissions estimates for all liquid-fuel driven technologies.

Overall, there are somewhat modest differences among different types of vehicle technologies and fuels, even under the likely 2030 scenarios although some technologies (for example, grid-dependent electric) had higher life-cycle emissions. It appears therefore that some breakthrough technologies (such as, cost-efficient conversion of advanced biofuels, cost-efficient carbon capture and storage, and/or a shift to a mix of lower-emitting sources of electricity (such as natural gas, renewable sources, nuclear) will be needed to dramatically reduce transportation-related externalities.

Heat Generation

- The damages associated with criteria pollutant related emissions from the use of energy (primarily natural gas) for heating in the residential and commercial buildings sectors and industrial sectors are low relative to damages from energy use in the electricity generation and the transportation sectors. This is largely because natural gas has low rates of those emissions compared to emissions typically resulting from the electricity generation sector and the transportation sector.
- The climate change related damages from the use of energy (primarily natural gas) for heating in the buildings and industrial sectors are low relative to climate change related damages associated with transportation and electricity production because natural gas carbon intensity is lower than that of coal and of gasoline. Regarding energy use for heating, the climate-related damages are in general significantly higher than the non-climate damages.
- The largest potential for reducing damages associated with the use of energy for heat lies in greater attention to improving the efficiency of energy use. A report from the National Academies study *America's Energy Future* suggests a potential for improving efficiency in the buildings and industrial sectors by 25% or more—with likelihood that emissions damages in these sectors could be held constant in spite of sectoral growth between now and 2030 (NAS/NAE/NRC 2009a).

Climate Change

Due to the complexity in evaluating the externalities of energy-induced climate change, the committee focused its efforts on a review of existing Integrated Assessment Models (IAMs) and the

associated climate change literature. The committee came to the following conclusions, as discussed in Chapter 5:

- The two features of IAMs that drive estimates of the marginal damage associated with emitting an additional ton of carbon (the marginal social cost of carbon) are the choice of discount rate and the relationship between mean temperature change and the percentage change in world GDP (i.e., the aggregate damage function).
- Holding the discount rate constant, the damage function used in current IAMs can alter estimates of marginal damages by an order of magnitude.
- Holding the damage function constant, changing the discount rate from 4.5% to 1.5% in an IAM will cause the marginal social cost of carbon to change by an order of magnitude.
- In all IAMs, marginal damage estimates for 2030 GHG emissions are 50 to 80 percent larger than estimates of damages from emissions occurring within the past few years.
- There is great uncertainty about the impact of GHG emissions on future climate and about the impacts of changes in climate on the world economy. Mean values of marginal damage estimates are usually reported from integrated planning model simulations. This approach does not adequately capture the small probability of catastrophic climate changes.

Infrastructure and Security

In Chapter 6, we considered damages related to disruptions in the electricity transmission grid, the vulnerability of energy facilities to accidents and possible attack, the external costs of oil consumption, supply security considerations, and national security externalities. The committee strove to clarify approaches for considering security externalities and disentangle externalities from other motivations for energy policy. The committee concludes as follows:

- The nation's electricity transmission grid is vulnerable to outages and to power quality degradation events because of transmission congestion and the lack of adequate reserve capacity. Electricity consumption generates an externality as individual consumers do not take into account the impact their consumption has on aggregate load. Damages from this could be significant and it underscores the importance of careful analysis concerning the costs and benefits of investing in a modernized grid that takes advantage of new smart technology and that is better able to handle intermittent renewable power sources.
- Externalities from accidents at facilities are largely internalized and—in the case of our oil and gas transmission network—of negligible magnitude per barrel of oil or thousand cubic feet of gas transshipped.
- The monopsony component of the oil consumption premium is not an externality. While government policy may be desirable as a countervailing force to monopoly or cartel producer power, this is a separate issue from the focus of this report.
- . We find that macroeconomic disruptions from oil supply shocks are not an externality. We also find that sharp and unexpected increases in oil prices adversely affect the U.S. economy. Estimates in the literature of the macroeconomic costs of disruption and adjustment range from $2 to $8 per barrel in 2007 dollars
- Dependence on imported oil has implications for foreign policy and we find that some of these should be viewed as externalities. We find, however, that it is impossible to quantify these externalities. The role of the military in safeguarding foreign supplies of oil is often identified as a potential externality. We find it difficult if not impossible to disentangle non-energy related reasons for a military presence in certain regions of the world from energy-related reasons. Moreover much of the military cost is likely to be fixed in nature. A twenty percent reduction in oil consumption, for example, would likely have little impact on the strategic positioning of military forces in the world.

- Nuclear waste and security raises important issues and poses difficult policy challenges. The extent to which externalities exist is difficult to measure. Moreover it is very difficult to quantify them. Thus we do not report values in this report but recognize the importance of studying this issue further.

RESEARCH RECOMMENDATIONS

The committee's results include two major caveats: a significant number of potential damages that cannot be quantified at this time; and substantial uncertainties are associated with the damages that have been quantified. Developers of the committee's statement of task anticipated such circumstances, stating that when it is not feasible to assess specific externalities comprehensively, the committee should recommend assessment approaches and identify key information needs to inform future assessments. In response, the committee has developed a number of research recommendations specific to key topics in this report—electricity, transportation, heat generation and climate change, as well as one overarching recommendation. The topic-specific recommendations are provided in the paragraphs below. An overarching recommendation is as follows:

- Federal agencies should provide sufficient resources to support new research on the external costs and benefits of energy. In assembling its repository of literature, models, and data needed to carry out an assessment of externalities, the committee became aware that there is limited research funding available to address the topic of externality assessment. In particular, extramural funding from federal agencies provides little support or incentive to pursue this line of research. For example, the APEEP model used in our analysis was funded by a foundation. The GREET model, which we used to estimate transportation-related emissions, is federally supported, but does not explicitly address damages so it must be coupled with a damage assessment model. The EPA has had strong interest and ongoing programs in damage/benefit assessment for air pollution, but offers limited resources for research to improve and evaluate its approaches or develop and assess approaches for other environmental concerns. Because of the growing importance of impact assessment and impact valuation for policy decision making at all levels of government and to avoid a situation where key uncertainties are addressed only as an adjunct to other research programs, the committee encourages federal agencies such as DOE, DOT, EPA, NIH, or NSF to support new research specific to externalities with financial resources that are sufficient to address the recommendations below in a timely manner.

Electricity

Although many of the significant externalities associated with electricity generation can be estimated quantitatively, there are nevertheless several important areas where additional research is needed:

- Although it appears that life-cycle activities pre- and post- generation are generally responsible for a smaller portion of the life-cycle externalities than electricity generation itself, it is desirable to have a systematic estimation and compilation of the externalities from these other activities that are comparable in completeness to the externality estimates for the generation part of the life cycle. In this compilation, it will be particularly important to take into account activities (e.g., the storage and disposal of coal combustion byproducts, in-situ leaching techniques for uranium mining) that may have locally or regionally significant impacts.
- The "reduced form" modeling of pollutant dispersion and transformation is a key aspect in estimating externalities from airborne emissions on a source by source basis; these models should continue to be improved and evaluated.

- The health effects associated with toxic air pollutants, including specific components of particulate matter, from electricity generation should be quantified and monetized. Due to the importance of VSL in determining the size of air pollution damages, further exploration is needed of how willingness to pay varies with mortality-risk changes and with population characteristics such as age and health status.

- Because current data on electricity-generation facilities are available mainly as national averages, improved data and methods are needed to characterize the mix of electricity-generation technologies (and their associated range of emissions per kWh) at city, state, and regional levels. The current disaggregation of national-level information to regional or state levels that are available from DOE or EPA are often not sufficiently detailed for impact or damage assessments within specific areas of the United States.

- Continued improvement is necessary of methods to quantify and monetize ecological impacts of all stages of the life cycle of electricity generation, especially of fuel extraction, emission of pollutants, and land-use changes. Similar needs exist for other types of energy production and use.

- For fossil fuel options, more research is needed to quantify and monetize the ecological and socio-economic impacts of fuel extraction, e.g., of mountaintop mining/valley fill.

- For nuclear power, significant challenges in estimating potential damages include appropriately estimating and valuing risks when the probabilities of accidents and of radionuclide migration (e.g., at a high-level waste repository) are very low but the consequences potentially extreme. It is important to assess how such risks would change based on advances in the technology and regulations, and whether the cost to utilities of meeting their regulatory requirements fully reflects these potential damages.

- The analysis of risks associated with nuclear power in ORNL/RFF (1992-98) should be updated to reflect advances in technology and science.

- For wind technologies, the major issues lie in quantifying bird and bat deaths; in quantifying or otherwise systematically assessing disturbances to local landscapes, ecosystems, and human populations; and valuing them in terms comparable to economic damages.

- For solar technologies, one of the greatest needs is an analysis of the upstream activities that quantifies the possible releases of toxic materials and their damages; other needs are a better understanding of the externalities that would accompany disposal or re-cycling of worn-out panels and dedicating tracts of land to solar power equipment.

- For transmission lines needed in a transition to a national grid system, better estimates are needed of both the magnitude and the spatial distribution of negative and positive externalities that would accompany this transition.

Transportation

- It is imperative to better understand potential negative externalities at the earliest possible stage in the research and development process for new fuels and technologies so as to avoid these externalities as the fuels and technologies are being developed.

- Improved understanding is needed of the currently unquantifiable effects and potential damages related to transportation, especially as they relate to biofuels (e.g. effects on water resources and ecosystems) and battery technology (e.g. effects throughout the battery life cycle of extraction through disposal).

- More accurate emissions factors as needed for each stage of the fuel/vehicle life cycle. In particular there is a need to make measurements to confirm or refute the assumption that all vehicles will only meet but not exceed emissions standards. In actual practice, there can be significant differences between on-road performance relative to emissions requirements and some alternative-fuel vehicles may do better or worse than expected.

- Because a significant fraction of life-cycle health impacts comes from both vehicle manufacture and fuel production, it is important to improve and expand the information and databases used to construct emissions factors for these life stages. In particular, there is a need to understand whether and how energy-efficiency improvements in these industrial components might change the overall estimates of life-cycle health damages.
- The issue of indirect land use change is central to current debates about the merit of biofuels. Regardless of whether this impact is regarded as an externality associated with U.S. or foreign biofuels production, it is important to obtain more empirical evidence about its magnitude and causes, as well as to improve the current suite of land use change models.
- As better data become available, future studies should take a range of transportation modes into account—not only those that are alternatives to automobiles and light trucks (i.e., public transit), but also air, rail and marine, which are alternatives for longer-distance travel and for freight.

Heat Generation

- Assessment of energy use and its impacts in the industrial sector, in particular (but in all sectors to some extent), could be improved by more extensive databases that contain details about specific forms of energy use and associated waste streams. Such databases should be designed so that life-cycle analysis of alternatives can be made without inadvertent double counting.
- A more quantitative assessment of industrial sector externalities, done collaboratively between the government and industry, would be valuable in informing priorities for future initiatives to reduce the externalities associated with industrial operations. Such an assessment was not possible in this study, largely because of data limitations.

Climate Change

- More research on climate damages is needed to estimate impacts of climate change, especially impacts that can be expressed in economic terms, as current valuation literature relies heavily on climate change impact data from the year 2000 and earlier.
- Marginal damages of GHG emissions may be highly sensitive to the possibility of catastrophic events. More research is needed on their impacts, the magnitude of the damage in economic terms, and the probabilities associated with various types of catastrophic events and/or impacts.
- Estimates of the marginal damage of a ton of CO_2-eq include aggregate damages across countries according to GDP, which gives less weight to the damages borne by low-income countries. This aggregate estimate should be supplemented by distributional measures that describe how the burden of climate change varies among countries.

In Conclusion

In aggregate, the damage estimates presented in this report for various external effects are substantial. Just the damages from external effects the committee was able to quantify add up to more than $120 billion for the year 2005.[7] Although large uncertainties are associated with the committee's estimates, there is little doubt that this aggregate total substantially underestimates the damages, because it does not include many other kinds of damages that could not be quantified for reasons explained in the

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[7]These are damages related principally to emissions of NO_x, SO_2, and PM relative to a baseline of zero emissions from energy-related sources for the effects considered in this study.

report, such as damages related to some pollutants, climate change, ecosystems, infrastructure and security. In many cases we have identified those omissions, within the chapters of this report, with the hope that they will be evaluated in future studies.

But even if complete, our various damage estimates would not automatically offer a guide to policy. From the perspective of economic efficiency, theory suggests that damages should not be reduced to zero but only to the point where the cost of reducing another ton of emissions (or other type of burden) equals the marginal damages avoided. That is, the degree to which a burden should be reduced depends on its current level and the cost of lowering it; the solution cannot be determined from the amount of damage alone. Economic efficiency, however, is only one of several potentially valid policy goals that need to be considered in managing pollutant emissions and other burdens. For example, even within the same location, there is compelling evidence that some members of the population are more vulnerable than others to a particular external effect.

While not a comprehensive guide to policy, our analysis does indicate that regulatory actions can significantly affect energy-related damages. For example, the full implementation of the federal diesel-emissions rules would result in a sizeable decrease in non-climate damages from diesel vehicles between 2005 and 2030. Similarly, major initiatives to further reduce other emissions, improve energy efficiency, or shift to a cleaner electricity-generating mix (e.g., renewable sources, natural gas, and nuclear) could substantially reduce external effects' damages, including those from grid-dependent hybrid and electric vehicles.

It is thus our hope that this information will be useful to government policy makers, even in the earliest stages of research and development on energy technologies, as an understanding of their external effects and damages could help to minimize the technologies' adverse consequences.

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Abbreviations

AEF	America's Energy Future
Ag	silver
APEEP	Air Pollution Emission Experiments and Policy
As	arsenic
AWEA	American Wind Energy Association
BD2-	biodiesel 20% blend
BOS	balance of system
Btu	British thermal unit
CAFÉ	corporate average fuel economy
CAIR	Clean Air Interstate Rule
CAMR	Clear Air Mercury Rule
CARB	California Air Resources Board
CCB	coal combustion byproduct
CCR	coal combustion residue
CCS	carbon capture and sequestration
Cd	cadmium
CdTe	cadmium-telluride
CFR	Council on Foreign Relations
CG	compressed gasoline
CH4	methane
CHP	combined heat and power
CMAQ	Community Multiscale Air Quality model
CNG	compressed natural gas
CO	carbon monoxide
Co	cobalt
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
Cr	chromium
CRP	Conservation Reserve Program
CRS	Congressional Research Service
Cu	copper
DICE	Dynamic Integrated Model of Climate and the Economy
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
E10	ethanol 10% blend
E85	ethanol 85% blend
EGR	enhanced gas recovery
EGU	electricity generating unit
EIA	Energy Information Agency

EISA	Energy Independence and Security Act
EOR	enhance oil recovery
EPA	U.S. Environmental Protection Agency
ERR	estimated recoverable reserves
EtOH	ethanol
FBC	fluidized bed combustion
FGD	flue gas desulfurization
FPEIS	Final Programmatic Environmental Impact Statement
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution
GCM	global climate model
GDP	gross domestic product
gge	gasoline gallon equivalent
GHG	greenhouse gas
GWP	global warming potential
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTCC	greater than Class C
GW	gigawatt
GWh	gigawatt hours
HAP	hazardous air pollutant
HDDV	heavy-duty diesel vehicle
HDGV	heavy-duty gasoline vehicle
HDV	heavy-duty vehicle
HDDV	heavy-duty diesel vehicle
HDGV	heavy-duty gasoline vehicle
HEV	hybrid electricity vehicle
HFCV	hydogren fuel cell vehicle
Hg	mercury
HLRW	high-level radioactive wastes
IAM	integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
IRIS	Integrated Risk Information System
kW	kilowatt
kWh	kilowatt hours
LCA	life-cycle assessment
LCIA	life-cycle impact assessment
LDV	light-duty vehicle
LEED	Leadership in Energy and Environmental Design
LLRW	low-level radioactive wastes
LNG	liquified natural gas
LWR	light water reactors
MCF	thousand cubic feet
Mn	manganese
Mo	molybdenum
MOVES	Motor Vehicle Emission Simulater
MSRP	manufacturer's suggested retail price
MTM/VF	mountain top mining/valley fill
MW	megawatt
MWh	megawatt hours
N_2O	nitrous oxide
NEI	National Emissions Inventory
NEMS	National Energy Modeling System
NEPA	National Environmental Policy Act
NERC	North American Electric Reliability Corporation

NG	natural gas
NGV	natural gas vehicle
NH3	ammonia
NHI	Nuclear Hydrogen Initiative
Ni	nickle
NO_2	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
NRC	National Research Council
NWPA	Nuclear Waste Policy Act
OMB	Office of Management and Budget
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oakridge National Laboratory
PADD	petroleum administration for defense district
PAGE	Policy Analysis of the Greenhouse Effect
Pb	lead
PC	pulverized coal
PM_{10}	particulate matter less than or equal to10 micron in aerodynamic diameter (coarse particulate matter)
$PM_{2.5}$	particulate matter equal to or small than 2.5 micron aerodynamic diameter (fine particulate matter)
PRB	Powder River Basin
PV	photovoltaic
QALY	quality adjusted life year
Quads	quadrillion British thermal units
R&D	research and development
RCRA	Resource Conservation and Recovery Act
RFF	Resources for the Future
RFG	reformulated gasoline
RICE	Regional Integrated model of Climate and the Economy
SAB	Science Advisory Board
Se	selenium
SF_6	sulfur hexafluoride
SI	spark-ignition
SIDI	spark-ignition, direct-injection
SO_2	sulfur dioxide
SO_x	sulfur oxides
SPR	strategic petroleum reserve
SRR	source-receptor relationships
SUV	sports utility vehicle
THC	thermohaline circulation
Tl	thallium
TWh	terawatt hours
U.S. NRC	U.S. Nuclear Regulatory Commission
USD	U.S. dollar
USDA	U.S. Department of Agriculture
USGS	U.S. Geologic Service
VHTR	very-high-temperature reactor
VMT	vehicle miles traveled
VOC	volatile organic compound
VSL	value of a statistical life
WDL	workdays lost
Zn	zinc

Common Units and Conversions

Energy use in the United States involves many diverse industries and sectors, each of which uses its own conventions and units to describe energy production and use. Although these units are in common usage throughout the energy industry, they are not always consistent and are not well understood by non-experts. Similarly, different types of units are employed to describe emissions resulting from energy-related use activities. This appendix describes the units used for principal energy supply and consumption activities and provides some useful conversion factors. The U.S. Department of Energy's Energy Information Administration website provides additional information about energy (see www.eia.doe.gov/basics/conversion_basics.html) units and conversion factors, including easy-to-use energy conversion calculators. Total U.S. energy use in 2007 was 101.5 quadrillion (10^{15}) Btu or 96 Exa (10^{18}) Joules.

Electricity

- **Electrical generating capacity** is *power* and expressed in units of *kilowatts* (kW), *megawatts* (MW = 10^3 kW), and *gigawatts* (GW = 10^6 kW). It is defined as the maximum electrical output that can be supplied by a generating facility operating at ambient conditions. Coal power plants typically have generation capacities of about 500 MW; nuclear plants about 1,000 MW (1 GW); intermittent sources (e.g., natural gas peaking plants and individual wind turbines) about one to a few megawatts; and residential roof-top installations of solar photovoltaics about a few kilowatts.
- **Electricity supply and consumption** is expressed in units of *kilowatt hours* (kWh), *megawatt hours* (MWh), *gigawatt hours* (GWh), or *terawatt hours* (TWh) (10^9 kWh). One kWh is equal to a power of 1,000 watts (the typical electricity that is consumed by a hand-held hair dryer) supplied or consumed over the period of an hour. Annual total delivered electricity in the United States is about 4,000 TWh and the average annual electricity consumption per U.S. household is about 11,000 kWh.
  - 1 kWh of electricity is equivalent to 3,410 Btu of thermal energy if the conversion has no inefficiencies.
  - In a 33% efficient power plant, 10,230 Btu of input primary energy are required to produce 1 kWh of electricity.

Fossil Fuels and Other Liquid Fuels

- **Coal** supply and consumption in the United States is usually expressed in units of metric tons (sometimes written as tonnes and equal to1,000 kg or 2,200 pounds) or short tons (2,000 pounds); most of the rest of the world uses metric tons. This report uses short tons when discussing coal use in the United States.

- o A ton of typical coal contains about 22 MJ of energy.
- o A tonne of typical coal contains about 24 MJ of energy.
- **Petroleum and gasoline** supply and consumption quantities are expressed in the United States in gallons or barrels (1 barrel = 42 gallons) and internationally in liters (3.88 liters = 1 gallon). In the United States, the energy content of liquid fuel is expressed in British thermal units (Btu), million Btu (MMBtu or 10^6 Btu), and quadrillion Btu (Quad = 10^{15} Btu). The rest of world uses joules (J) to express the energy content of liquid fuels (1 Btu = 1,055 J). A Btu is defined as the amount of energy (in the form of heat) needed to raise the temperature of 1 pound of water by 1 degree Fahrenheit.[1] The energy content of different fuels can be converted to Btu using the following approximate factors:
  - o 1 barrel crude oil = 5,800,000 Btu = 5.8 MMBtu
  - o 1 barrel gasoline = 5.2 MMBtu
  - o 1 barrel fuel ethanol = 3.5 MMBtu
- When different liquid fuels and blends are compared, this is often done on the basis of what volume would give the same energy as a gallon of gasoline. Therefore, about 1.5 gallons of ethanol would provide the energy equivalent of 1 gallon of gasoline.
- **Natural gas** supply and consumption usage is expressed in units of a thousand cubic feet (MCF or mcf). This is the equivalent volume of gas at atmospheric pressure and temperature. Here the prefix M stands for a thousand, and MM is used to denote a million cubic feet. One MCF of natural gas contains about a million Btu of thermal energy.

Basis for Quantifying Impacts

- **Activity-specific** impacts result from particular energy use. For example, impacts from the emissions from an electric power plant or impacts from tailpipe emissions from a passenger car.
- **Activity-aggregate** impacts are used to describe the impacts from energy use in a set of activities that include all impacts starting with the processing of primary energy, its conversions and its transportation to its end use point, its use to provide a set of energy services, and impacts associated with disposal of end use equipment. The aggregations are based on life cycle assessment (LCA) methods and use a variety of data and models to estimate the impact. For example, electricity use to provide light in a building would include all the "upstream inputs" to produce feed energy for the power plant (mining, dams, etc.), the electricity production inputs to generate and distribute power to the site of the light bulb, and impacts associated with operation of the light bulb. Waste heat from the bulb and its disposal would be "downstream impacts." Larger downstream impacts would be associated with the health and other consequences from emissions at the power plant.

In this report, life-cycle impact assessment (LCIA) is a goal that can only be achieved incompletely due to limitations in data availability and complexity of the detailed systems, but where important impacts are present their magnitudes are estimated to the extent possible.

Waste Streams and Hazardous Air Emissions

- **Solid and liquid wastes** are usually described using familiar units of volume or weight per unit time or quantity of energy produced. (cubic feet per minute [cfm]; tons per MWh; gallons per day; etc.). Where these waste streams contain contaminants, the concentration of the contaminant of concern is

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[1] A Joule is the amount of energy needed to heat a kilogram of water by one degree Centigrade. 1055 Joules = 1 Btu.

also important. (parts per million by weight [ppm] is the weight of contaminant in a million units of carrier weight; or lb contaminant per ton of carrier, or lb contaminant per gallon of liquid, etc.)

- **Air emissions** are usually described by emissions per unit of energy produced or used—such as lbs per MWh of electricity, lbs per mcf of natural gas, or grams per vehicle-mile-travelled (VMT) and sometimes in terms of concentration of pollutants in emissions stream—such as parts per million (by volume) or pounds per cubic foot. The choice of a VMT basis is a compromise, since the more meaningful metric of passenger-mile-travelled would require information about the number of passengers per vehicle—and would only change the final result if more passengers on average travelled on vehicles powered by a particular fuel. Presentation of results per gallon of fuel makes for difficult comparisons since different fuels have different energy contents per gallon.

In this report, impacts are assessed nationally using detailed models for the overall activities. Using a VMT basis for the transportation emissions estimates includes not only the differences in the impacts for different fuels, but also includes differences in the size and weights of vehicles that constitute the national vehicle fleet.

Greenhouse Gases

- **Carbon dioxide (CO_2)** emissions from energy production and use are expressed in metric tons (tonnes) of CO_2-equivalent (CO_2-eq). Although CO_2 is the principal greenhouse gas associated with energy use, other gases such as methane, nitrous oxide, black carbon, and SF_6, also make some contributions to warming potential. These other contributions are converted to an equivalent amount of CO_2 with a similar effect and the total is therefore expressed as tonnes of CO_2-equivalent. The United States emits about 7 billion tonnes of CO_2-equivalent per year, about 6 billion of which is CO_2 arising primarily from energy production and use. Average annual CO_2 emissions in the United States are about 20 tonnes per person. [Note: Sometimes greenhouse gas emissions are reported in terms of tonnes of "carbon." One tonne of carbon emissions equals 3.7 tonnes of CO_2 emissions, since the weight of CO_2 also includes the weight of the oxygen in the molecule.]

Appendixes

A

Biographic Information on the Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption

Jared L. Cohon (*Chair*) is president of Carnegie Mellon University in Pittsburgh, Pennsylvania. His research interests focus on environmental system analysis, especially the development and application of techniques for planning and decision-making in situations with multiple conflicting objectives. Dr. Cohon has authored, co-authored, and edited more than 80 professional publications on this interdisciplinary field which combines engineering, economics, and applied mathematics. He came to Carnegie Mellon in 1997 after serving as dean of the School of Forestry and Environmental Studies and professor of environmental systems analysis at Yale University from 1992 to 1997. Dr. Cohon began his teaching career in 1973 at Johns Hopkins University, where he served as assistant, associate, and full professor in the Department of Geography and Environmental Engineering and as Assistant and Associate Dean of Engineering and Vice Provost for Research. Dr. Cohon is a member of the board of directors of Ingersoll-Rand Company (a producer of refrigeration and industrial equipment). The *Pittsburgh Post-Gazette* has named him one of Pittsburgh's "Top 50" business leaders. In 1996, the National Audubon Society and the American Association of Engineering Societies jointly awarded him the Joan Hodges Queneau Medal for outstanding achievement in environmental conservation. He served on the U.S. Nuclear Waste Technical Review Board, appointed by President Clinton in 1995, and he served as the board's chairman from 1997 to 2002. Dr. Cohon also was appointed by President George W. Bush in 2002 to his Homeland Security Advisory Council. He served as chairman of the Council's Senior Advisory Committee on Academe, Policy and Research and he served as co-chair of the Council's Secure Borders/Open Doors Advisory Committee. Dr. Cohon received his Ph.D. in civil engineering from the Massachusetts Institute of Technology.

Maureen L. Cropper (*Vice Chair*) is professor of economics at the University of Maryland, senior fellow at Resources for the Future, former lead economist at The World Bank, and research associate at the National Bureau of Economic Research. Dr. Cropper's research has focused on valuing environmental amenities (especially environmental health effects), on the discounting of future health benefits, and on the tradeoffs implicit in environmental regulations. Her recent research analyzes the externalities associated with motorization and the interaction between residential location, land use and travel demand. Dr. Cropper is a member of the National Academy of Sciences. She also is past president of the Association of Environmental and Resource Economists and a former chair of the Advisory Council for Clean Air Act Compliance Analysis, a subcommittee of EPA's Science Advisory Board. Dr. Cropper has served on the advisory boards of Resources for the Future, the Harvard Center for Risk Analysis, the Donald Bren School of the Environment and the AEI-Brookings Center on Regulation. She received her Ph.D. in economics from Cornell University.

Mark Cullen is professor of medicine and chief of the division of general internal medicine at Stanford University. His research interests are in occupational and environmental medicine, including isocyanate exposure in automobile-shop workers, lung cancer in people exposed to asbestos, and lead toxicity in workers. He has published several textbooks, including Clinical Occupational Medicine and Textbook of Clinical Occupational and Environmental Medicine. He is a member of the DuPont Epidemiology Review Board, a member of the MacArthur Foundation Network on Socioeconomic Status and Health, and a corporate medical director for the Aluminum Company of America. Dr. Cullen is a member of the Institute of Medicine and served as a member of its Board on Health Sciences. He also served as a member of the National Research Council (NRC)'s Committee on Human Biomonitoring for Environmental Toxicants. Dr. Cullen received his M.D. from Yale University and did his residency in internal medicine.

Elisabeth M. Drake is emeritus staff affiliated with the MIT Energy Initiative. Prior to her retirement in 2001, she served as associate director for new energy technologies at the MIT Energy Laboratory. With other MIT colleagues, she developed an interdisciplinary graduate course on sustainable energy and co-authored a textbook, *Sustainable Energy: Choosing Among Options*, published in 2005 by the MIT Press. Her research interests focus on new and emerging energy supply-side and demand-side technologies that may facilitate a transition to a more sustainable future, with lower greenhouse gas emissions at reasonable costs in both industrialized and developing countries. Early in her career she worked at Arthur D. Little, Inc. (ADL), initially as a cryogenic engineer working on liquid hydrogen refrigerators and the fueling system for the Saturn rocket. Later, she consulted on early liquefied natural gas (LNG) projects worldwide and on LNG safety research. She became a vice president for Technological Risk Management at ADL and later was vice president for their international Health, Safety, and Environmental Practice. She is a member of the National Academy of Engineering (NAE) and has served on a number of National Research Council (NRC) committees, including topics as diverse as oversight of the US Army's chemical weapons disposal operations and "Personal Cars and China" (a 2003 joint NRC report of the NAE and the Chinese Academy of Engineering). She presently serves as a member of the National Academies' Report Review Committee. She received a Sc.D. in chemical engineering from the Massachusetts Institute of Technology.

Mary R. English is a research leader at the Institute for a Secure and Sustainable Environment and an associate of the Center for Applied and Professional Ethics at the University of Tennessee at Knoxville. Her current research interests include the socioeconomic impacts of biofuels production; the ethics of energy production, distribution, and consumption; state and local transportation and land use planning; and participatory processes for environmental decision making. Over the past 20 years, her work has focused on the social and political aspects of various environmental management issues, such as siting controversial projects, cleaning up Superfund sites, the restoration and reuse of brownfield sites, and alternative mechanisms for involving stakeholders in environmental decisions. Dr. English is a member of the Tennessee Air Pollution Control Board. She previously served on the National Research Council (NRC)'s Board on Radioactive Waste Management and several NRC study committees, such as the Committee on the Environmental Impacts of Wind-Energy Projects. She also has served on the U.S. Environmental Protection Agency's National Environmental Justice Advisory Council and the National League of Women Voters' Advisory Committee to the Nuclear Waste Education Project. Dr. English received her Ph.D. in sociology from the University of Tennessee at Knoxville.

Christopher B. Field is the founding director of the Department of Global Ecology of the Carnegie Institution of Washington and professor of biology and of environmental earth system science at Stanford University. He is an ecosystem ecologist with research programs exploring the global carbon cycle and ecosystem responses to global change. Dr. Field is an author of more than 100 scientific papers, and he has served on the editorial boards of *Ecology*, *Ecological Applications*, *Ecosystems*, *Global Change Biology*, and *Proceedings of the National Academy of Sciences*. His recent National Research Council

(NRC) experience includes membership on the Board on International Scientific Organizations, Board on Environment Studies and Toxicology, Committee on Research at the Intersection of the Physical and Life Sciences, Committee on Earth-Atmosphere Interactions: Understanding and Responding to Multiple Environmental Stresses, Committee on Grand Challenges in the Environmental Sciences, Panel on Ecological Impacts of Climate Change, and chair of the U.S. National Committee for SCOPE. He is a member of the National Academy of Sciences. Dr. Field received his Ph.D. in biology from Stanford University.

Daniel S. Greenbaum is the president and chief executive officer of the Health Effects Institute (HEI), an independent not-for-profit research institute funded jointly by government and industry to provide trusted research on the health effects of air pollution. At HEI, Mr. Greenbaum has overseen the development and implementation of a strategic research plan that focuses the institute's efforts on providing critical research on and reanalysis of particulate matter, air toxics, and alternative fuels, increasingly on an international scale. He has served as chair of the Environmental Protection Agency (EPA) Blue Ribbon Panel on Oxygenates in Gasoline, as chair of EPA's Clean Diesel Independent Review Panel, and as a member of the national Clean Air Act Advisory Committee. Before joining the Health Effects Institute, he served as commissioner of the Massachusetts Department of Environmental Protection. In the National Research Council, he has served on the Board on Environmental Studies and Toxicology, as vice chair of the Committee on Air Quality Management in the United States, and most recently as a member of the Committee on Estimating Mortality Risk Reduction and Economic Benefits from Controlling Ozone Air Pollution. Mr. Greenbaum earned a master's degree in city planning from the Massachusetts Institute of Technology.

James K. Hammitt is professor of economics and decision sciences and director of the Harvard Center for Risk Analysis at the Harvard School of Public Health. His research and teaching concern the development of decision analysis, benefit-cost analysis, game theory, and other quantitative methods and their application to health and environmental policy in the United States and internationally. Dr. Hammitt is particularly interested in the management of long-term environmental issues, such as global climate change and stratospheric-ozone depletion, in comprehensive evaluation of risk-control measures (including ancillary benefits and countervailing risks) and in alternative methods for measuring the value of reducing health risks, including monetary and health-adjusted-life-year metrics. He serves as a member of the EPA Science Advisory Board and its Environmental Economics Advisory Committee and chairs the EPA Advisory Council on Clear Air Compliance Analysis. Dr. Hammitt previously served as a member of the American Statistical Association Committee on Energy Statistics (Advisory Committee to the U.S. Energy Information Administration) and the National Research Council (NRC) panel studying the implications of dioxin in the food supply. He held the Pierre-de-Fermat Chaire d'Éxcellence at the Toulouse School of Economics and served as senior mathematician at the RAND Corporation and a faculty member at the RAND Graduate School of Policy Studies. Dr. Hammitt received his Ph.D. in public policy from Harvard University.

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Russell Lee is a distinguished R&D staff member in science and technology policy at Oak Ridge National Laboratory (ORNL). Previously, he was director of the Center for Energy and Environmental Analysis, and leader of the Resource Modeling Group at ORNL. Dr. Lee's research focus is on science and technology policy, energy supply and demand, environmental externalities associated with energy production and use, and transportation analysis. He was the U.S. lead person in the joint U.S.-European Commission study that resulted in the eight-volume report on Fuel Cycle Externalities; and senior author of the book on Health and Environmental Impacts of Electricity Generation Systems: Procedures for Comparative Assessment. He is author of numerous other papers, book chapters and reports on the subject of energy externalities. Dr. Lee has been invited to present workshops, serve on expert panels, and consult on the subject of the impacts of electricity generation technologies, global climate change, environmental externalities, technology R&D policy, waste management, and related issues by the National Academies, the U.S. Department of Energy, the Organisation for Economic Cooperation and Development, the Commission of the European Communities, the International Energy Agency, the National Association of Regulatory Utility Commissioners, the International Atomic Energy Agency, the United Nations Framework Convention on Climate Change, foreign governments, universities, and industry. Prior to joining ORNL, he was an assistant professor at the University of Iowa and at Boston University. Dr. Lee is a member of the Committee on Social and Economic Factors of Transportation and of the Project Panel on Development of Research Performance Measurement Tool Box, both of the Transportation Research Board. Dr. Lee received his Ph.D. in geography from McMaster University in Canada.

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Richard G. Newell[1] was appointed by President Obama as administrator of the Energy Information Administration and sworn into office on August 3, 2009. Previously, he was the Gendell Associate Professor of Energy and Environmental Economics at the Nicholas School of the Environment, Duke University. He is a Research Associate of the National Bureau of Economic Research and a University Fellow of Resources for the Future. He has served as the Senior Economist for energy and environment on the President's Council of Economic Advisers, where he advised on policy issues ranging from automobile fuel economy and renewable fuels to management of the Strategic Petroleum Reserve. He has been a member of expert committees including the National Research Council Committee on Energy R&D, Committee on Innovation Inducement Prizes, and Committee on Energy Efficiency Measurement Approaches. Dr. Newell also served on the 2007 National Petroleum Council Global Oil and Gas Study. He currently serves on the boards of the *Journal of Environmental Economics and Management*, *Journal Energy Economics*, Association of Environmental and Resource Economists, and the Automotive X-Prize. He has served as an independent expert reviewer and advisor for many governmental, non-governmental, international, and private institutions including the OECD, Intergovernmental Panel on Climate Change, World Bank, National Commission on Energy Policy, U.S. Environmental Protection Agency, U.S. Department of Energy, U.S. Energy Information Administration, U.S. National Science Foundation, and others. Dr. Newell received his Ph.D. from Harvard University.

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[1]Dr. Newell resigned from the committee on August 2, 2009.

Richard L. Revesz is dean at New York University Law School, where he also serves as the Lawrence King Professor of Law. His work focuses on five distinct areas: federalism and environmental regulation, design of liability regimes for environmental protection, positive political economy analysis of environmental regulation, analytical foundations of environmental law, and the use of cost-benefit analysis in administrative regulation. Dean Revesz has also served as chair of the Committee on Judicial Review of the American Bar Association's Section on Administrative Law and Regulatory Policy and as a member of the Environmental Economics Advisory Committee of the U.S. Environmental Protection Agency's Science Advisory Board. In addition, he has also been a visiting professor at the Woodrow Wilson School of Public and International Affairs at Princeton University, Yale Law School, Harvard University Law School, and University of Geneva School of Law. He holds a J.D. from Yale University and a M.S. in engineering from the Massachusetts Institute of Technology.

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Terrance G. Surles is technology integration and policy analysis program manager for the Hawaii Natural Energy Institute. His research focuses on reducing dependence on petroleum from both a climate change and energy security perspective. Dr. Surles also serves as a senior advisor to the University of California's California Institute for Energy and Environment. In addition, he is director of the Pacific International Center for High Technology Research for which he works to develop and enhance collaborative programs between Japanese and American government and private sector clients. Previously, he was a vice president for the Electric Power Research Institute. He was a program director and assistant director for science and technology with the California Energy Commission. He was associate laboratory director for energy programs at Lawrence Livermore National Laboratory. Dr. Surles was deputy secretary for science and technology at the California Environmental Protection Agency. He was general manager of environmental programs at Argonne National Laboratory. He served as a member of the National Research Council (NRC)'s Committee for Development of Methodology for Evaluating Prospective Benefits of United States Department of Energy Programs, Phases I and II. He holds a Ph.D. in analytical chemistry from Michigan State University.

B

A Simple Diagrammatic Example of an Externality

A simple stylized example helps illustrate the concept of an externality. Consider a firm generating electricity that releases air pollutants as a by-product. It can carry out various activities to abate pollution. Initial pollution reductions are relatively inexpensive to carry out but costs rise as the firm reduces its pollution further. To illustrate that relationship, Figure B-1 diagrams pollution abatement along the horizontal axis and measures of cost per ton of abatement along the vertical axis. The figure provides an alternative approach to that shown in Figure 1-1 of Chapter 1 but leads to the same conclusion. Whereas Figure 1-1 focuses on optimal pollution levels, the discussion in this appendix focuses on optimal abatement activities. Both approaches are used in the literature.

The upward sloping line labeled "Marginal Abatement Cost" measures the cost to the firm for each additional ton of pollution reduction. In the absence of any policy intervention, the hypothetical firm will engage in no pollution abatement and incur no private abatement costs.

The horizontal line labeled "Marginal Benefit" is a measure of the reduction in aggregate damages across all people affected by pollution from this plant. The reduction could be a combination of reduced mortality risk and reduced morbidity summed over different populations. The marginal benefit of pollution abatement is simply a restatement of the marginal damages from pollution. Each ton of pollution avoided reduces incremental damages to society.

For purposes of this example, we assume that the marginal benefit of pollution abatement is constant and equal to $25 per ton of abated pollution. Equivalently, the dollar value of the marginal damages of pollution for this plant is $25 per ton. In practice, the shape of this curve will be pollutant-specific (and might well be location- and time-specific).

Society is made better off if the firm increases its abatement from 0 to 100 tons. The benefit to society is the avoided damages of $25 per ton times the 100 tons abated, or $2500. The cost to the firm of reducing its pollution is the sum of the incremental abatement costs. This is the area under the marginal abatement curve and it equals $1250. The net gain to society following the firm's abatement action is $1250.

Is 100 tons of pollution abatement the economically optimal amount? All other things being equal, the answer is yes. More generally the economically optimal level of pollution abatement occurs at the point where marginal benefits equal marginal costs. To see why, consider an additional ton of abatement from 100 to 101 tons. The benefit to society is $25. The marginal cost, however, is some amount greater than $25 since the marginal abatement curve rises above $25 for abatement levels greater than 100. For abatement levels greater than 100 tons, the incremental abatement costs to the firm outweigh the incremental benefits to nearby residents. Similarly, any level of abatement below 100 tons are not economically optimal. At any level less than 100 tons, the cost to the firm of reducing pollution by one more ton is less than the benefit to nearby residents of that incremental pollution reduction.

Note, however, that the illustrative example does not include consideration of important distributional issues by simply summing the costs and benefits of pollution reduction. Distributional considerations can be taken into account. They will affect the economically optimal level of pollution abatement in the example but not the fundamental concepts that the example illustrates.
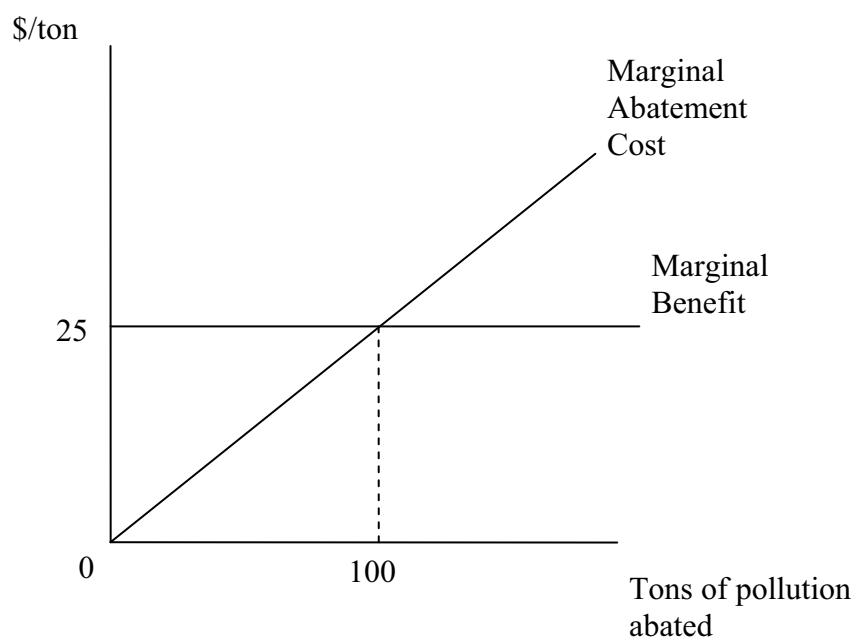
FIGURE B-1 Pollution abatement (horizontal axis) and cost per ton of abatement (vertical axis).

C

Description of APEEP Model and Its Application

The Air Pollution Emission Experiments and Policy (APEEP) analysis model (Muller and Mendelsohn, 2007; Muller and Mendelsohn, 2009), is a traditional integrated assessment model (Mendelsohn, 1980; Nordhaus, 1992; Burtraw et al., 1998; EPA 1999). Like other integrated assessment models, APEEP connects emissions of air pollution through air quality modeling to exposures, physical effects, and monetary damages. Making these linkages requires the use of findings reported in the peer-reviewed literature across several scientific disciplines.

APEEP is designed to calculate the marginal damage of emissions for nearly 10,000 distinct (individual and aggregated) sources of air pollution in the contiguous United States. Additionally, APEEP computes marginal damages of six pollutants: sulfur dioxide (SO_2), volatile organic compounds (VOCs), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10})[1] and ammonia (NH_3).

The individual and aggregate sources are defined by the U.S. Environmental Protection Agency (EPA 2006). Sources of emissions include both county-aggregated ground level sources as well as point sources. Ground-level sources include vehicles, residences, and small industrial or commercial facilities without a smokestack. Emissions from individual ground level sources are aggregated at the county level by the EPA. Point sources are differentiated by effective stack height and by location because the height of emissions affects the dispersion patterns from these sources. Emissions from point sources with an effective height of less than 250 meters are aggregated to the county level, as are emissions from point sources with an effective height of between 250 meters and 500 meters. In contrast, point sources with an effective height of greater than 500 meters, such as certain power plants and other large industrial facilities, are modeled individually. That is, APEEP does not aggregate emissions from these sources, they are modeled separately for each facility.

The air quality models in APEEP use these emission data provided by EPA to estimate corresponding ambient concentrations in each county in the coterminous states. The accuracy of the estimated pollution levels produced by the APEEP model has been statistically tested against the Community Multiscale Air Quality Model (CMAQ) (Byun and Schere 2006), which is considered the state-of-the-art air quality model. The results of these statistical comparisons are shown in the accompanying materials to Muller and Mendelsohn (2007).

APEEP can be used to compute the marginal damage of emissions, on a source-specific basis. This approach isolates the source-specific damage per ton for each of the six pollutants covered by the model. To calculate marginal damages, APEEP employs the following algorithm. In the first step, APEEP estimates total damages due to all sources in the model producing their baseline (observed) emissions (EPA 2006). Next, APEEP adds one ton of one pollutant from one source and recomputes total damages.

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[1]The definition of PM_{10}-for the purpose of this modeling analysis is total particles less than 10 microns in size minus $PM_{2.5}$. This approach ensures that the consequences of $PM_{2.5}$ are not double counted. Otherwise, the usual definition of PM_{10} is: particles with an aerodynamic diameter less than or equal to 10 microns.

The marginal damage is the damages that occur after adding one ton less the damages due to baseline emissions. The algorithm isolates the contribution of a single ton of emissions from each source to total, national damages. This approach captures the formation of secondary pollutants, such as sulfates and nitrates (constituents in $PM_{2.5}$) as well as tropospheric ozone (O_3), that are formed due to emissions of other substances. APEEP attributes the damage due to such secondary pollutants back to the source of emissions. As shown in (1) the marginal damage is computed by adding-up the change in damages across the complete set (R) of receptor counties. (Receptor counties are those counties that receive emissions from a source.)

$$MD_{i,p} = \Sigma r\ Dr,ep - \Sigma r\ Dr,bp \qquad\qquad (1)$$

where: $MD_{i,p}$ = damage per ton of an emission of pollutant (p) from source (i).
D_r = total dollar damage that occurs at receptor county r.
bp = 2002 baseline emissions of pollutant (p).
ep = 2002 baseline emissions plus 1 ton of (p) from source i.

After computing the marginal damage of emissions for a specific pollutant from source (i), this experiment can be repeated for each of the six pollutants covered in APEEP and the approximately 10,000 distinct (individual and grouped) sources in the United States. The total 10,000 sources encompass all anthropogenic emissions of these six pollutants in the lower 48 states. It is important to note that the APEEP model, in its current form, does not test for interactions among emissions of multiple pollutants in terms of the damages that such emissions cause. The model is designed to simulate the emissions of one ton of one specific pollutant from a particular source and to estimate its impact, rather than emitting multiple pollutants from a source and measuring their cumulative impact.

The following section briefly highlights the basic structure of the model and some of its most important assumptions. The model employs data on emissions (excluding carbon monoxide and lead, and including ammonia) that contribute to the formation of criteria air pollutants. The data were provided by the EPA's 2002 National Emission Inventory (EPA 2006). Concentrations due to the baseline levels of emissions are estimated by the air quality models in APEEP. The air quality modeling module makes use of a source-receptor matrix framework. That is, the marginal contribution of emissions in a source county (s) to the ambient concentration in a receptor county (r) is represented as the (s,r) element in a matrix. Using a linear algebraic approach, APEEP multiplies the matrix times an emission vector to generate a vector of predicted ambient concentrations. When the emission vectors represent changes to existing emissions, the corresponding estimated concentrations reflect changes to baseline, or existing concentrations. When the emission vector represents emission rates, then predicted concentrations reflect those rates, not changes to concentrations.

The model contains source-receptor matrices for the following pollutants in both summer and winter: $NO_x \rightarrow NO_x$, $SO_2 \rightarrow SO_2$. The matrix governing the relationship between NO_x emissions, VOC emissions and O_3 concentrations is calibrated to the summer season. The matrices representing formation and transport of particles ($PM_{2.5} \rightarrow PM_{2.5}$, $PM_{10} \rightarrow PM_{10}$, $NO_x \rightarrow PM$, $SO_2 \rightarrow PM$, $NH_3 \rightarrow NH_4$, $VOC \rightarrow PM$) produce annual means[2]. There is a unique matrix in APEEP for each of the emission-concentration relationships shown above.

The particulate matter source-receptor matrices compute the ammonium-sulfate-nitrate equilibrium which determines the amount of ambient ammonium sulfate $(NH_4)_2 SO_4$ and ammonium nitrate (NH_4NO_3) at each receptor county. The equilibrium computations reflect several fundamental aspects of this system. First, ambient ammonium (NH_4) reacts preferentially with sulfate (H_2SO_4). Second, ammonium nitrate is only able to form if there is excess NH_4 after reacting with sulfate. Finally,

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[2]PM indicates that the contribution of NO_x, VOCs, and SO_2 is counted to both $PM_{2.5}$ and $PM_{10.}$ Parameterization of the relationship between VOC emissions and the formation of PM is based on the work of Grosjean and Seinfeld (1989).

particulate nitrate formation is a decreasing function of temperature - so the ambient temperature at each receptor location is incorporated into the equilibrium calculations. In order to translate VOCs emissions into secondary organic particulates, APEEP employs the fractional aerosol yield coefficients estimated by Grosjean and Seinfeld (1989). These coefficients represent the yield of secondary organic aerosols corresponding to emissions of gaseous VOCs.

APEEP simulates O_3 concentrations using an empirical model that translates ambient concentrations of VOC, CO, and NO_x into ambient O_3 concentrations. The model captures many of the factors contributing to ambient concentrations of O_3 in addition to ambient concentrations of VOC, CO, and NO_x. These include forests and agricultural land uses which produce biogenic hydrocarbons, as well as the ambient air temperature and several geographic variables. For a complete depiction of the O_3 modeling in APEEP please see: Muller and Mendelsohn (2007). It is important to note that the inclusion of both linear and quadratic forms for NO_x, CO, and VOC concentrations in the O_3 models allow for the nonlinearity known to exist in O_3 production chemistry, (Seinfeld, Pandis, 1998). Specifically, the quadratic forms capture titration. This is critical to accurately predict O_3 levels in certain urban areas, where research has shown that additional emissions of NO_x can result in reduced O_3 concentrations (Tong et al. 2006).

The source-receptor matrices in APEEP are derived from the Climatological Regional Dispersion Model (CRDM), Latimer (1996). The original CRDM matrices have been calibrated to produce estimates of pollution levels that are in good agreement with the predictions produced by CMAQ. The correlations between APEEP's predicted surfaces and CMAQ's are especially strong for annual mean $PM_{2.5}$ levels and summer mean O_3 levels; the correlation coefficients are 0.82 and 0.77, respectively[3]. Additionally, the matrices have been expanded in scope to encompass nearly 10,000 sources and source areas.

Following the estimation of ambient concentrations, exposures are computed by multiplying county-level populations times county-level pollution concentrations. In APEEP, populations include number of people (differentiated by age)[4], crops produced, timber harvested, an inventory of man-made materials, visibility resources, and recreation usage (for each county in the contiguous U.S.). Each type of exposure is computed separately for each pollutant. The sources for each of these inventories are documented in Muller and Mendelsohn (2007).

In the next stage of the APEEP model, peer-reviewed concentration-response functions are used to translate exposures into the number of physical effects: these include premature mortalities, cases of illness, reduced timber and crops yields, enhanced depreciation of man-made materials, reduced visibility, and recreation usage. The studies that provide the concentration-response functions related to human health impacts are listed in Table C-1.

The final stage of the APEEP model attributes a dollar value to each of these physical effects. For effects on goods and services traded in markets (decreased crop yields, for example) APEEP multiplies the change in output due to exposures to air pollution times the market price. For non-market goods and services, APEEP employs valuation estimates from the non-market valuation literature in economics. APEEP values premature mortality risks using the value of a statistical life (VSL) approach (Viscusi, Aldy, 2003). APEEP employs EPA's preferred VSL which is equivalent to approximately $6 million (year 2000 real USD). APEEP provides the option of employing a VSL estimate of approximately $2 million from Mrozek and Taylor (2002) as an alternative to the EPA's VSL. The values attributed to chronic illnesses such as bronchitis and asthma are also derived from the non-market valuation literature. Acute illnesses are valued using cost of illness estimates. Each of the values applied to human health effects in APEEP are shown in Table C-3.

The studies that provide the concentration-response functions for the remaining welfare effects are listed in Table C-2.

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[3]The correlations for $PM_{2.5}$ are expressed over n = 3,110, reflecting the 3,110 counties in the contiguous 48 states. The correlations for tropospheric O_3 are expressed over n = 24,880, reflecting 8 hourly observations for the 3,110 counties in the coterminous U.S.

[4]Population data is provided by CDC Wonder.

TABLE C-1 Epidemiology Studies Employed in APEEP

Health Event	Pollutant	Study Author
All-cause Adult Chronic Exposure Mortality[a]	$PM_{2.5}$	Pope, et al. (2002)
Infant Chronic Exposure Mortality	$PM_{2.5}$	Woodruff et al. (2006)
Chronic Bronchitis	PM_{10}	Abbey, et al. (1993)
Chronic Asthma	O_3	McDonnell et al. (1999)
Acute Exposure Mortality	O_3	Bell, et al (2004)
Respiratory Admissions	O_3	Schwartz (1995)
ER-Visits Asthma	O_3	Steib, et al. (1996)
COPD Admissions	NO_2	Moolgavkar (2000)
IHD Admissions	NO_2	Burnett, et al. (1999)
Asthma Admissions	SO_2	Sheppard (1999)
Cardiac Admissions	SO_2	Burnett (1997)

[a]Acute exposure mortality for $PM_{2.5}$ was not included in this analysis as a separate effect. See Muller and Mendelsohn (2007) for further discussion. Source: Muller and Mendelsohn 2007. Reprinted with permission; copyright 2007, *Journal of Environmental Economics and Management.*

TABLE C-2 Concentration-Response Studies Employed in APEEP

Welfare Effect	Pollutant	Study Author
Crop Loss	O_3	Lesser et al.,1990
Timber Loss	O_3	Reich, 1987; Pye, 1988
Materials Depreciation	SO_2	Atteras, Haagenruud, 1982; ICP 2000
Visibility	PM_{10}	Muller, Mendelsohn, 2007
Forest Recreation	SO_2, NO_x, O_3	Muller, Mendelsohn, 2007

Source: Muller and Mendelsohn 2007. Reprinted with permission; copyright 2007, *Journal of Environmental Economics and Management.*

TABLE C-3 Value of Human Health Effects in APEEP[a]

Health Event	Unit	$
Chronic Exposure Mortality	Case	5,910,000
Chronic Bronchitis	Case	320,000
Chronic Asthma	Case	30,800
General Respiratory	Hospital Admission	8,300
General Cardiac	Hospital Admission	17,526
Asthma	Hospital Admission	6,700
COPD	Hospital Admission	11,276
Ischemic Heart Disease	Hospital Admission	18,210
Asthma	ER Visit	240

[a]Values are in (2000 USD), see Muller and Mendelsohn (2007). Source: Muller and Mendelsohn 2007. Reprinted with permission; copyright 2007, *Journal of Environmental Economics and Management*.

Because $PM_{2.5}$ is a subset of PM_{10}, APEEP avoids double-counting of damages due to $PM_{2.5}$ and PM_{10}. Specifically, APEEP estimates mortality impacts associated with emissions of $PM_{2.5}$, and the model measures chronic morbidity impacts of PM_{10}. In reporting the morbidity damages due to emissions of PM_{10}, APEEP nets out the mortality damages due to $PM_{2.5}$. In effect, the damages for PM_{10} are expressed as PM_{10}–$PM_{2.5}$.

Each of the other non-market impacts of air pollution modeled by APEEP (impaired visibility and reduced recreation services) are also expressed in dollar terms. The values employed in the APEEP model corresponding to these welfare effects are displayed in Table C-4.

TABLE C-4 Value of Non-Market Impacts of Air Pollution

Welfare Effect	$	Location	Source
Recreation Visibility (In-region)	170	Southwest	Chestnut and Rowe (1990)
Recreation Visibility (Out-region)	135	Southwest	Chestnut and Rowe (1990)
Recreation Visibility (In-region)	80	Southeast	Chestnut and Rowe (1990)
Recreation Visibility (Out-region)	50	Southeast	Chestnut and Rowe (1990)
Residential Visibility (In-region)	174	Eastern	McClelland et al. (1993)
Forest Recreation Visit	63	All	Kengen (1997)

Source: Muller and Mendelsohn 2007. Reprinted with permission; copyright 2007, *Journal of Environmental Economics and Management*.

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D

Description of GREET and Mobile6
Models and Their Applications

BACKGROUND

The Need for Emissions Data in the NRC Study

To evaluate the per VMT total damages from transportation, the APEEP county emissions unit damage costs must be evaluated against vehicle emissions. While the passenger and freight fleets are diverse, particular vehicle and fuel combinations dominated in 2005 and certain vehicles and fuels are of particular interest for 2030. Additionally, it is important to acknowledge life cycle considerations related to both the vehicles and the fuels. In particular, feedstock production, fuel production, and vehicle manufacturing could have significant emissions contributions in the life cycle inventory. The vehicle-fuel inventory should include these life cycle components in addition to vehicle operation.

Available Options for Constructing Emissions Estimates

While tools and data are available to evaluate the many vehicle-fuel operational emissions, GREET stands as one of the few resources to evaluate life cycle component emissions.[1] The GREET life cycle factors cover a range of light-duty vehicles and the fuels they consume. GREET evaluates the many processes involved from feedstock production through vehicle operation. Without using GREET, individual process assessments throughout the supply chain would need to be performed and combined for each vehicle and fuel of interest.

EMISSIONS DATA AND MODELING

The GREET Model

The Argonne GREET model is used to determine emissions from light-duty autos and trucks. The GREET model is a vehicle operation and fuel production life cycle assessment tool which captures fuel feedstock production, fuel refining, vehicle operation, and vehicle manufacturing. Feedstock production, fuel refining, and vehicle operation are estimated with the GREET 1.8b model while vehicle manufacturing is determined from GREET 2.7a. The version designations (1.8b and 2.7a) do not imply different generations of GREET, but instead distinguish between a version developed for the fuel cycle

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[1]Argonne National Laboratory, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, http://www.transportation.anl.gov/modeling_simulation/GREET/.

(1.8b) versus a version developed for the vehicle cycle (2.7). The strength of the GREET model lies in its ability to estimate a variety of fuel inputs and vehicle combinations and their associated well-to-wheel life cycle components. GREET allows for specification of critical inputs to these components (e.g., emission factors, combustion technologies, energy efficiencies, and fuel types).

GREET evaluates several life cycle components for the feedstock production, fuel production, and vehicle manufacturing emissions inventory. For the feedstock-fuel production cycle, GREET captures extraction/creation of raw feedstock, transport to refineries, refinery processes, and transport to fueling stations. This constitutes the well-to-pump components. On the vehicle-cycle side, GREET performs a materials-based life cycle assessment capturing raw material extraction, processing, transport, and ultimately assembly into an automobile or light-duty truck. GREET does not estimate heavy-duty vehicle life cycle factors so additional data sources were needed to evaluate these vehicle classes.

GREET allows for the adjustment of many feedstock, fuel, and vehicle operation input parameters, however, particular inputs were targeted for the vehicle-fuel combinations evaluated. The evaluation year was toggled for the 2005 and 2030 scenarios to capture changes in both vehicle operational performance as well as efficiency changes in other devices such as engines and turbines. The fraction of crude oil that comes from tar sands and the amount of reformulated gasoline was adjusted depending on the vehicle-fuel combination. For ethanol, GREET inputs for feedstocks (corn, herbaceous, and corn stover) and milling processes (dry or wet) were changed. Another critical input parameter for the assessment is the fraction of low sulfur diesel. Lastly, the electricity mix for 2005 and 2030 were adjusted based on U.S. Energy Information Administration's Annual Energy Outlook which reports historical mixes as well as future forecasts.[2]

Mobile 6.2

To evaluate heavy-duty vehicle emissions, EPA's Mobile 6.2 on-road emissions modeling tool was used[3]. Unlike GREET, Mobile 6.2 is designed to evaluate the many different conditions under which vehicles may operate and not feedstock production, fuel production, or vehicle manufacturing life cycle emissions. Mobile 6.2 heavy-duty vehicle operational emission factors were used in combination with GREET feedstock and fuel production factors to create life cycle inventories for several different vehicle classes.

GREET does not evaluate ammonia emissions so Mobile 6.2 is used to capture this pollutant for both light and heavy-duty vehicles. Ammonia, which leads to secondary particle formation, was determined by Mobile 6.2 for a set of vehicles that overlap with the vehicle-fuel combinations evaluated in GREET.

THE EMISSIONS MODELING PROCESS

Model Framework

The emissions model utilized GREET to generate feedstock, fuel production, operation, and vehicle manufacturing factors for light-duty vehicles and Mobile 6.2 to generate operational factors for heavy-duty vehicles. GREET feedstock and fuel production factors were applied to the heavy-duty vehicle Mobile 6.2 operational factors as described later in this appendix. For all vehicles, energy inputs, CO_2, CH_4, N_2O, VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x emissions are determined for the life cycle components. APEEP county unit damages are based on emissions of VOCs, NO_x, $PM_{2.5}$, and SO_x.

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[2]U.S. Energy Information Administration, Annual Energy Outlook 2007 and 2009.

[3]U.S. Environmental Protection Agency, Mobile 6.2 Onroad Emission Modeling Tool, http://www.epa.gov/OMS/m6.htm.

GREET Temporal Boundaries

GREET can evaluate vehicles and life cycle processes between 1990 and 2020. The tool has many time series for engines, turbines, and critical parameters that capture changes in efficiencies, emissions, and other parameters (e.g., ethanol yields from corn and fuel sulfur levels) historically and up to 2020. GREET also makes the assumption that fleet age is five years. When evaluating life cycle emissions in a year, GREET assumes that vehicles are five years older and assigns them the corresponding emissions. When using GREET to evaluate vehicles in 2005, emissions from vehicles correspond to year 2000. However, all other values in GREET's assessment (such as fuel sulfur levels or electricity mixes) correspond to 2005.

The 2030 assessment is outside of the GREET temporal upper range so 2020 is used as a baseline (although adjustments are made and described later in this section).

GREET Vehicle Manufacturing Emissions

The GREET 2.7a model was used to determine vehicle manufacturing emissions. The model performs a life cycle assessment from vehicle material inputs to determine emissions from manufacturing for cars and SUVs. Additionally, the model distinguishes between internal combustion engine vehicles, hybrid electric vehicles, and fuel cell electric vehicles from both conventional and light weight materials. The material inputs are evaluated for the body, powertrain system, transmission system, chassis, battery, fluids, paint, traction motor, generator, electronic controller, and fuel cell auxiliary system. These components are assessed from material extraction through assembly and emissions are determined at each stage. Additionally, disposal is included.

There is no time dependency with GREET's vehicle manufacturing assessment so process changes between 2005 and 2030 are not captured. Energy and emission factors are determined for the vehicle size, power delivery systems, and material composition combinations as shown in Table D-1 and Table D-2.

The car conventional material factors are used for all light-duty autos, and the SUV conventional material factors are used for light-duty trucks class 1 and 2.

GREET Light-Duty Auto and Truck Energy and Emissions Factors

Light-duty automobile and truck life-cycle energy inputs and emissions are determined from GREET. GREET distinguishes between light-duty trucks class 1 and 2 to capture the increased energy requirements and resulting emissions of the larger vehicles. Class 1 trucks are between zero and 6,000 lb gross vehicle weight rating (GVWR) and less than 3,750 lb loaded vehicle weight (LVW), and class 2 trucks have the same GVWR and greater than 3,750 LVW. For each vehicle-fuel combination, GREET is used to determine feedstock, fuel, and operational factors for light-duty autos (LDA), trucks in class 1 (LDT1), and trucks in class 2 (LDT2).

TABLE D-1 GREET 2.7a Vehicle Manufacturing Results for Cars

	ICEV: Conventional Material	ICEV: Light-weight Material	HEV: Conventional Material	HEV: Light-weight Material	FCV: Conventional Material	FCV: Light-weight Material
Lifetime VMT	160,000	160,000	160,000	160,000	160,000	160,000
Total energy	633	619	645	669	792	797
Fossil fuels	592	573	600	618	732	735
Coal	223	164	235	190	264	218
Natural gas	243	226	243	241	308	298
Petroleum	126	183	122	187	160	219
CO_2	47	46	50	50	62	60
CH_4	0.082	0.077	0.083	0.083	0.102	0.099
N_2O	0.001	0.001	0.001	0.001	0.001	0.001
GHGs	50	48	52	52	65	63
VOC	0.206	0.205	0.206	0.205	0.205	0.205
CO	0.250	0.093	0.226	0.098	0.217	0.089
NO_x	0.075	0.080	0.077	0.085	0.094	0.099
PM_{10}	0.082	0.066	0.080	0.071	0.092	0.081
PM2.5	0.033	0.028	0.031	0.029	0.036	0.033
SO_x	0.137	0.147	0.228	0.213	0.286	0.259

TABLE D-2 GREET 2.7a Vehicle Manufacturing Results for SUVs

	ICEV: Conventional Material	ICEV: Light-weight Material	HEV: Conventional Material	HEV: Light-weight Material	FCV: Conventional Material	FCV: Light-weight Material
Lifetime VMT	180,000	180,000	180,000	180,000	180,000	180,000
Total energy	730	728	840	833	1030	970
Fossil fuels	683	672	780	766	951	890
Coal	263	194	316	244	350	271
Natural gas	280	266	318	299	399	361
Petroleum	140	212	146	223	203	259
CO_2	54	54	65	62	80	73
CH_4	0.095	0.090	0.108	0.103	0.132	0.120
N_2O	0.001	0.001	0.001	0.001	0.001	0.001
GHGs	57	56	68	65	84	76
VOC	0.308	0.307	0.308	0.307	0.308	0.307
CO	0.298	0.105	0.316	0.116	0.297	0.103
NO_x	0.085	0.092	0.096	0.102	0.118	0.117
PM_{10}	0.095	0.078	0.107	0.089	0.121	0.100
PM2.5	0.038	0.033	0.041	0.036	0.047	0.041
SO_x	0.151	0.166	0.297	0.267	0.373	0.317

TABLE D-3 GREET Energy and Emission Factors for Light-Duty Autos in 2005

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO_2 g/VMT	CO_{2e} g/VMT	VOC g/VMT	NO_x g/VMT	$PM_{2.5}$ g/VMT	SO_x g/VMT
RFG SI Autos (Conventional Oil)	Feedstock	232	64	6	18	0.02	0.15	0.01	0.05
	Fuel	1241	457	72	77	0.13	0.17	0.02	0.11
	Operation	5259	5038	404	408	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
RFG SI Autos (Tar Sands)	Feedstock	853	62	50	64	0.02	0.14	0.01	0.06
	Fuel	1295	457	72	78	0.13	0.17	0.02	0.11
	Operation	5259	5038	404	408	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
CG SI Autos (Conventional Oil)	Feedstock	236	65	17	29	0.02	0.15	0.01	0.05
	Fuel	1007	447	68	71	0.13	0.14	0.02	0.10
	Operation	5334	5257	410	414	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
CG SI Autos (Tar Sands)	Feedstock	865	63	62	76	0.02	0.14	0.01	0.06
	Fuel	1059	447	68	72	0.13	0.14	0.02	0.10
	Operation	5334	5257	410	414	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
RFG SIDI Autos (Conventional Oil)	Feedstock	202	55	5	16	0.02	0.13	0.00	0.05
	Fuel	1080	397	62	67	0.12	0.15	0.02	0.10
	Operation	4573	4381	351	355	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
RFG SIDI Autos (Tar Sands)	Feedstock	742	54	44	56	0.02	0.12	0.01	0.05
	Fuel	1126	397	63	68	0.12	0.15	0.02	0.10
	Operation	4573	4381	351	355	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Diesel (Low Sulfur)	Feedstock	193	53	19	29	0.02	0.12	0.00	0.04
	Fuel	613	309	46	48	0.02	0.09	0.01	0.07
	Operation	4383	4383	347	350	0.09	0.30	0.07	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Diesel (Fischer Tropsch)	Feedstock	280	18	22	35	0.02	0.11	0.00	0.05
	Fuel	2882	68	106	114	0.03	0.25	0.06	0.09
	Operation	4383	0	334	338	0.09	0.30	0.07	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Diesel	Feedstock	427	213	-30	-13	0.03	0.23	0.01	0.13

(Soy BD20)	Fuel	9433	14	12	5	0.28	-0.03	0.00	-0.06
	Operation	4383	3555	344	348	0.09	0.30	0.07	0.04
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
CNG	Feedstock	436	24	31	64	0.03	0.16	0.00	0.07
	Fuel	415	20	35	36	0.00	0.05	0.01	0.12
	Operation	5615	0	333	342	0.15	0.30	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Dry Corn)	Feedstock	822	229	-225	-173	0.06	0.42	0.02	0.19
	Fuel	6277	345	72	82	0.26	0.50	0.05	0.18
	Operation	5334	1412	402	406	0.22	0.30	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Wet Corn)	Feedstock	898	498	-212	-144	-0.14	0.58	0.03	0.29
	Fuel	6386	201	221	233	0.25	0.41	0.12	0.40
	Operation	5334	1412	402	406	0.22	0.30	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Herbaceous)	Feedstock	570	216	-282	-237	0.06	0.29	0.02	0.06
	Fuel	4618	179	3	15	0.19	0.45	0.03	-0.02
	Operation	5334	1412	402	406	0.22	0.30	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Corn Stover)	Feedstock	407	229	-263	-261	0.03	0.24	0.02	0.11
	Fuel	4206	179	3	14	0.19	0.43	0.03	-0.02
	Operation	5334	1412	402	406	0.22	0.30	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Dry Corn)	Feedstock	287	79	1	17	0.02	0.17	0.01	0.06
	Fuel	1343	430	66	69	0.13	0.16	0.02	0.11
	Operation	5334	4990	409	413	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Wet Corn)	Feedstock	294	103	2	19	0.01	0.19	0.01	0.07
	Fuel	1352	417	79	82	0.13	0.15	0.03	0.12
	Operation	5334	4990	409	413	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Herbaceous)	Feedstock	265	78	-4	11	0.02	0.16	0.01	0.05
	Fuel	1197	416	60	63	0.13	0.15	0.02	0.09
	Operation	5334	4990	409	413	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14

(Continued)

TABLE D-3 Continued

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
E10 (Corn Stover)	Feedstock	251	79	-2	9	0.02	0.16	0.01	0.06
	Fuel	1161	416	60	63	0.13	0.15	0.02	0.09
	Operation	5334	4990	409	413	0.23	0.30	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Electric	Feedstock	159	56	12	25	0.03	0.08	0.13	0.04
	Fuel	2734	81	380	381	0.01	0.53	0.02	1.31
	Operation	1778	84	0	0	0.00	0.00	0.01	0.00
	Vehicle	645	122	50	52	0.21	0.08	0.03	0.23
Hydrogen (Gaseous)	Feedstock	180	10	13	27	0.01	0.07	0.00	0.03
	Fuel	1539	29	243	250	0.01	0.14	0.04	0.16
	Operation	2319	0	0	0	0.00	0.00	0.01	0.00
	Vehicle	792	160	62	65	0.21	0.09	0.04	0.29
Grid Independent SI HEV	Feedstock	159	44	11	20	0.01	0.10	0.00	0.04
	Fuel	680	302	46	48	0.09	0.10	0.01	0.07
	Operation	3604	3552	277	281	0.16	0.25	0.02	0.00
	Vehicle	645	122	50	52	0.21	0.08	0.03	0.23
Grid Dependent SI HEV	Feedstock	159	48	12	21	0.02	0.09	0.04	0.04
	Fuel	1358	229	156	158	0.06	0.24	0.01	0.48
	Operation	3002	2408	185	188	0.10	0.17	0.01	0.00
	Vehicle	645	122	50	52	0.21	0.08	0.03	0.23

TABLE D-4 GREET Energy and Emission Factors for Light-Duty Trucks 1 in 2005

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
RFG SI Autos (Conventional Oil)	Feedstock	297	82	7	23	0.02	0.19	0.01	0.07
	Fuel	1587	584	92	98	0.17	0.22	0.03	0.15
	Operation	6722	6439	516	520	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SI Autos (Tar Sands)	Feedstock	1090	79	65	82	0.03	0.18	0.01	0.08
	Fuel	1655	584	93	99	0.17	0.22	0.03	0.15
	Operation	6722	6439	516	520	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Conventional Oil)	Feedstock	301	83	22	37	0.02	0.19	0.01	0.07
	Fuel	1287	572	87	91	0.16	0.18	0.02	0.13
	Operation	6818	6719	524	528	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Tar Sands)	Feedstock	1106	80	80	97	0.03	0.18	0.01	0.08
	Fuel	1353	572	87	92	0.16	0.18	0.02	0.13
	Operation	6818	6719	524	528	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Conventional Oil)	Feedstock	258	71	6	20	0.02	0.16	0.01	0.06
	Fuel	1380	508	80	86	0.15	0.19	0.02	0.13
	Operation	5845	5599	449	453	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Tar Sands)	Feedstock	948	69	56	71	0.02	0.16	0.01	0.07
	Fuel	1439	508	80	86	0.15	0.19	0.02	0.13
	Operation	5845	5599	449	453	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Low Sulfur)	Feedstock	247	68	24	37	0.02	0.15	0.01	0.06
	Fuel	783	394	59	61	0.02	0.12	0.02	0.09
	Operation	5602	5602	443	447	0.19	0.67	0.08	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15

(Continued)

TABLE D-4 Continued

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
Diesel (Fischer Tropsch)	Feedstock	358	23	28	45	0.03	0.14	0.00	0.07
	Fuel	3684	87	136	146	0.04	0.32	0.08	0.11
	Operation	5602	0	427	431	0.19	0.67	0.07	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Soy BD20)	Feedstock	546	273	-39	-17	0.04	0.30	0.02	0.16
	Fuel	12057	17	16	7	0.35	-0.04	0.00	-0.07
	Operation	5602	4544	440	444	0.19	0.67	0.08	0.04
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CNG	Feedstock	557	31	39	82	0.04	0.21	0.00	0.09
	Fuel	530	25	44	46	0.00	0.07	0.02	0.15
	Operation	7177	0	426	436	0.21	0.52	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Dry Corn)	Feedstock	1051	292	-288	-222	0.08	0.53	0.03	0.24
	Fuel	8022	440	92	105	0.33	0.64	0.06	0.24
	Operation	6818	1804	514	518	0.30	0.52	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Wet Corn)	Feedstock	1148	636	-271	-184	-0.18	0.74	0.04	0.38
	Fuel	8162	256	282	298	0.32	0.53	0.15	0.51
	Operation	6818	1804	514	518	0.30	0.52	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Herbaceous)	Feedstock	728	276	-360	-302	0.07	0.37	0.02	0.07
	Fuel	5903	228	4	19	0.24	0.57	0.04	-0.03
	Operation	6818	1804	514	518	0.30	0.52	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Corn Stover)	Feedstock	520	293	-337	-333	0.04	0.31	0.02	0.14
	Fuel	5376	228	4	18	0.24	0.55	0.03	-0.03
	Operation	6818	1804	514	518	0.30	0.52	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Dry Corn)	Feedstock	367	101	1	21	0.03	0.22	0.01	0.08
	Fuel	1716	550	84	88	0.17	0.20	0.02	0.13
	Operation	6818	6378	523	527	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10	Feedstock	375	131	3	25	0.01	0.24	0.01	0.09

(Wet Corn)	Fuel	1728	534	101	105	0.17	0.19	0.03	0.16
	Operation	6818	6378	523	527	0.32	0.52	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Herbaceous)	Feedstock	339	100	-5	14	0.03	0.20	0.01	0.07
	Fuel	1530	531	77	80	0.16	0.20	0.02	0.11
	Operation	6818	6378	523	527	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Corn Stover)	Feedstock	320	101	-3	12	0.03	0.20	0.01	0.07
	Fuel	1484	531	77	80	0.16	0.19	0.02	0.11
	Operation	6818	6378	523	527	0.32	0.52	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Electric	Feedstock	203	72	16	32	0.04	0.11	0.16	0.05
	Fuel	3494	103	485	487	0.01	0.68	0.02	1.68
	Operation	2273	108	0	0	0.00	0.00	0.01	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Hydrogen (Gaseous)	Feedstock	230	13	16	34	0.02	0.09	0.00	0.04
	Fuel	1967	37	310	320	0.02	0.18	0.06	0.21
	Operation	2964	0	0	0	0.00	0.00	0.01	0.00
	Vehicle	1030	203	80	84	0.31	0.12	0.05	0.37
Grid Independent SI HEV	Feedstock	203	56	15	25	0.02	0.13	0.00	0.05
	Fuel	870	386	59	62	0.11	0.12	0.02	0.09
	Operation	4607	4540	354	358	0.22	0.44	0.02	0.01
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Grid Dependent SI HEV	Feedstock	203	61	15	27	0.02	0.12	0.06	0.05
	Fuel	1736	293	199	202	0.08	0.31	0.02	0.61
	Operation	3836	3077	237	240	0.15	0.29	0.02	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30

TABLE D-5 GREET Energy and Emission Factors for Light-Duty Trucks 2 in 2005

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NOx g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
RFG SI Autos (Conventional Oil)	Feedstock	324	89	8	25	0.03	0.20	0.01	0.07
	Fuel	1730	637	100	107	0.18	0.24	0.03	0.16
	Operation	7329	7021	562	567	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SI Autos (Tar Sands)	Feedstock	1189	86	70	89	0.03	0.20	0.01	0.08
	Fuel	1805	637	101	108	0.18	0.24	0.03	0.16
	Operation	7329	7021	562	567	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Conventional Oil)	Feedstock	328	90	24	41	0.03	0.20	0.01	0.07
	Fuel	1403	623	95	99	0.18	0.20	0.03	0.14
	Operation	7433	7326	571	576	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Tar Sands)	Feedstock	1206	88	87	106	0.03	0.20	0.01	0.08
	Fuel	1476	623	95	100	0.18	0.20	0.03	0.15
	Operation	7433	7326	571	576	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Conventional Oil)	Feedstock	324	89	8	25	0.03	0.20	0.01	0.07
	Fuel	1730	637	100	107	0.18	0.24	0.03	0.16
	Operation	7329	7021	562	567	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Tar Sands)	Feedstock	1189	86	70	89	0.03	0.20	0.01	0.08
	Fuel	1805	637	101	108	0.18	0.24	0.03	0.16
	Operation	7329	7021	562	567	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Low Sulfur)	Feedstock	269	74	26	40	0.02	0.17	0.01	0.06
	Fuel	854	430	64	66	0.03	0.13	0.02	0.10
	Operation	6108	6108	483	487	0.30	1.03	0.08	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Fischer Tropsch)	Feedstock	391	26	30	49	0.03	0.15	0.00	0.07
	Fuel	4016	95	148	159	0.05	0.35	0.09	0.13
	Operation	6108	0	466	470	0.30	1.03	0.07	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel	Feedstock	595	297	-42	-18	0.04	0.32	0.02	0.18

(Soy BD20)	Fuel	13146	19	17	7	0.38	-0.05	0.00	-0.08	
	Operation	6108	4955	480	483	0.30	1.03	0.08	0.05	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
NG	Feedstock	607	34	43	90	0.05	0.23	0.00	0.10	
	Fuel	578	27	48	50	0.00	0.08	0.02	0.17	
	Operation	7825	0	463	480	0.54	1.03	0.02	0.00	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
E85 (Dry Corn)	Feedstock	1146	319	-314	-242	0.09	0.58	0.03	0.26	
	Fuel	8747	480	101	114	0.36	0.69	0.07	0.26	
	Operation	7433	1967	561	565	0.78	1.03	0.02	0.00	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
E85 (Wet Corn)	Feedstock	1252	693	-295	-200	-0.19	0.81	0.04	0.41	
	Fuel	8899	279	308	324	0.35	0.58	0.16	0.55	
	Operation	7433	1967	561	565	0.78	1.03	0.02	0.00	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
E85 (Herbaceous)	Feedstock	794	301	-392	-330	0.08	0.40	0.02	0.08	
	Fuel	6436	249	5	21	0.26	0.63	0.04	-0.03	
	Operation	7433	1967	561	565	0.78	1.03	0.02	0.00	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
E85 (Corn Stover)	Feedstock	567	320	-367	-364	0.05	0.33	0.02	0.15	
	Fuel	5861	249	5	20	0.26	0.60	0.04	-0.03	
	Operation	7433	1967	561	565	0.78	1.03	0.02	0.00	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
E10 (Dry Corn)	Feedstock	400	110	1	23	0.03	0.24	0.01	0.09	
	Fuel	1871	599	92	96	0.19	0.22	0.03	0.15	
	Operation	7433	6954	570	575	0.82	1.03	0.02	0.01	
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15	
E10 (Wet Corn)	Feedstock	409	143	3	27	0.01	0.26	0.01	0.10	
	Fuel	1884	582	110	114	0.19	0.21	0.04	0.17	
	Operation	7433	6954	570	575	0.82	1.03	0.02	0.01	
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14	

(Continued)

TABLE D-5 Continued

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NOx g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
E10 (Herbaceous)	Feedstock	369	109	-5	16	0.03	0.22	0.01	0.07
	Fuel	1668	579	83	88	0.18	0.21	0.02	0.12
	Operation	7433	6954	570	575	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Corn Stover)	Feedstock	349	110	-3	13	0.03	0.22	0.01	0.08
	Fuel	1618	579	83	87	0.18	0.21	0.02	0.12
	Operation	7433	6954	570	575	0.82	1.03	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Electric	Feedstock	221	78	17	35	0.04	0.12	0.18	0.06
	Fuel	3810	112	529	531	0.01	0.74	0.02	1.83
	Operation	2478	117	0	0	0.00	0.00	0.01	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Hydrogen (Gaseous)	Feedstock	269	15	19	40	0.02	0.10	0.00	0.04
	Fuel	2305	43	364	375	0.02	0.21	0.07	0.24
	Operation	3474	0	0	0	0.00	0.00	0.01	0.00
	Vehicle	1030	203	80	84	0.31	0.12	0.05	0.37
Grid Independent SI HEV	Feedstock	234	64	17	29	0.02	0.15	0.01	0.05
	Fuel	1002	445	68	71	0.13	0.14	0.02	0.10
	Operation	5310	5233	408	412	0.75	0.80	0.02	0.01
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Grid Dependent SI HEV	Feedstock	230	69	17	31	0.03	0.14	0.06	0.05
	Fuel	1929	335	220	223	0.09	0.34	0.02	0.67
	Operation	4375	3545	273	276	0.50	0.54	0.02	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30

TABLE D-6 GREET Energy and Emission Factors for Light-Duty Autos in 2020

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
RFG SI Autos (Conventional Oil)	Feedstock	314	57	13	25	0.02	0.11	0.00	0.04
	Fuel	1125	410	64	69	0.12	0.11	0.01	0.06
	Operation	4753	4553	365	369	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
RFG SI Autos (Tar Sands)	Feedstock	913	55	60	73	0.02	0.12	0.01	0.04
	Fuel	1177	410	65	70	0.12	0.11	0.01	0.06
	Operation	4753	4553	365	369	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
CG SI Autos (Conventional Oil)	Feedstock	314	57	13	25	0.02	0.11	0.00	0.04
	Fuel	1125	410	64	69	0.12	0.11	0.01	0.06
	Operation	4753	4553	365	369	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
CG SI Autos (Tar Sands)	Feedstock	913	55	60	73	0.02	0.12	0.01	0.04
	Fuel	1177	410	65	70	0.12	0.11	0.01	0.06
	Operation	4753	4553	365	369	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
RFG SIDI Autos (Conventional Oil)	Feedstock	273	50	12	21	0.01	0.09	0.00	0.03
	Fuel	979	357	56	60	0.10	0.10	0.01	0.06
	Operation	4133	3959	317	321	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
RFG SIDI Autos (Tar Sands)	Feedstock	794	48	52	63	0.02	0.10	0.01	0.03
	Fuel	1023	357	57	60	0.10	0.10	0.01	0.06
	Operation	4133	3959	317	321	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Diesel (Low Sulfur)	Feedstock	262	48	24	33	0.01	0.09	0.00	0.03
	Fuel	560	279	42	43	0.02	0.06	0.01	0.04
	Operation	3961	3961	313	317	0.06	0.08	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14

(Continued)

TABLE D-6 Continued

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO₂ g/VMT	CO₂ₑ g/VMT	VOC g/VMT	NOₓ g/VMT	PM₂.₅ g/VMT	SOₓ g/VMT
Diesel (Fischer Tropsch)	Feedstock	254	17	20	32	0.02	0.07	0.00	0.04
	Fuel	2345	61	85	91	0.03	0.19	0.05	0.08
	Operation	3961	0	302	306	0.06	0.08	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Diesel (Soy BD20)	Feedstock	454	189	-22	-6	0.02	0.14	0.01	0.09
	Fuel	8561	66	18	11	0.23	-0.05	0.00	-0.07
	Operation	3961	3218	314	318	0.06	0.08	0.02	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
CNG	Feedstock	352	19	25	52	0.03	0.09	0.00	0.05
	Fuel	332	14	27	29	0.00	0.03	0.01	0.05
	Operation	4527	0	269	275	0.12	0.07	0.01	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Dry Corn)	Feedstock	730	208	-204	-163	0.04	0.22	0.01	0.11
	Fuel	5621	265	61	70	0.22	0.35	0.03	0.09
	Operation	4753	1245	358	362	0.14	0.07	0.01	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Wet Corn)	Feedstock	737	399	-198	-146	-0.12	0.34	0.02	0.19
	Fuel	5770	182	200	211	0.22	0.25	0.09	0.13
	Operation	4753	1245	358	362	0.14	0.07	0.01	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Herbaceous)	Feedstock	477	169	-252	-217	0.04	0.16	0.01	0.03
	Fuel	3122	163	5	15	0.17	0.35	0.02	0.00
	Operation	4753	1245	358	362	0.14	0.07	0.01	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E85 (Corn Stover)	Feedstock	342	170	-239	-237	0.02	0.11	0.01	0.06
	Fuel	2805	163	5	14	0.17	0.34	0.02	0.00
	Operation	4753	1245	358	362	0.14	0.07	0.01	0.00
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Dry Corn)	Feedstock	350	70	8	22	0.02	0.12	0.01	0.04
	Fuel	1200	379	58	61	0.12	0.11	0.01	0.06
	Operation	4753	4446	365	368	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10	Feedstock	351	87	9	24	0.00	0.13	0.01	0.05

(Wet Corn)	Fuel	1212	372	70	73	0.12	0.10	0.02	0.06
	Operation	4753	4446	365	368	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Herbaceous)	Feedstock	328	67	4	17	0.02	0.11	0.00	0.04
	Fuel	981	370	53	56	0.11	0.11	0.01	0.05
	Operation	4753	4446	365	368	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Corn Stover)	Feedstock	317	67	5	16	0.02	0.11	0.00	0.04
	Fuel	953	370	53	56	0.11	0.10	0.01	0.05
	Operation	4753	4446	365	368	0.15	0.07	0.01	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
Electric	Feedstock	126	41	9	20	0.02	0.04	0.09	0.03
	Fuel	2061	53	283	285	0.00	0.23	0.01	0.53
	Operation	1358	58	0	0	0.00	0.00	0.01	0.00
	Vehicle	645	122	50	52	0.21	0.08	0.03	0.23
Hydrogen (Gaseous)	Feedstock	153	8	11	23	0.01	0.04	0.00	0.02
	Fuel	1233	21	201	207	0.01	0.08	0.04	0.08
	Operation	1964	0	0	0	0.00	0.00	0.01	0.00
	Vehicle	792	160	62	65	0.21	0.09	0.04	0.29
Grid Independent SI HEV	Feedstock	207	38	9	16	0.01	0.07	0.00	0.02
	Fuel	740	270	42	45	0.08	0.07	0.01	0.04
	Operation	3127	2996	240	244	0.11	0.06	0.01	0.00
	Vehicle	645	122	50	52	0.21	0.08	0.03	0.23
Grid Dependent SI HEV	Feedstock	187	41	10	18	0.02	0.06	0.04	0.03
	Fuel	1289	201	137	140	0.05	0.14	0.01	0.23
	Operation	2618	2029	161	163	0.07	0.04	0.01	0.00
	Vehicle	645	122	50	52	0.21	0.08	0.03	0.23

TABLE D-7 GREET Energy and Emission Factors for Light-Duty Trucks 1 in 2020

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO_2 g/VMT	CO_{2e} g/VMT	VOC g/VMT	NO_x g/VMT	$PM_{2.5}$ g/VMT	SO_x g/VMT
RFG SI Autos (Conventional Oil)	Feedstock	373	68	16	29	0.02	0.13	0.01	0.04
	Fuel	1338	488	76	82	0.14	0.13	0.02	0.08
	Operation	5652	5414	434	438	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SI Autos (Tar Sands)	Feedstock	1086	66	71	87	0.02	0.14	0.01	0.04
	Fuel	1399	488	77	83	0.14	0.13	0.02	0.08
	Operation	5652	5414	434	438	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Conventional Oil)	Feedstock	373	68	16	29	0.02	0.13	0.01	0.04
	Fuel	1338	488	76	82	0.14	0.13	0.02	0.08
	Operation	5652	5414	434	438	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Tar Sands)	Feedstock	1086	66	71	87	0.02	0.14	0.01	0.04
	Fuel	1399	488	77	83	0.14	0.13	0.02	0.08
	Operation	5652	5414	434	438	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Conventional Oil)	Feedstock	325	59	14	26	0.02	0.11	0.00	0.04
	Fuel	1164	424	66	71	0.12	0.12	0.02	0.07
	Operation	4915	4708	377	381	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Tar Sands)	Feedstock	944	57	62	75	0.02	0.12	0.01	0.04
	Fuel	1217	424	67	72	0.12	0.12	0.02	0.07
	Operation	4915	4708	377	381	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Low Sulfur)	Feedstock	311	57	28	39	0.02	0.10	0.00	0.04
	Fuel	666	331	50	51	0.02	0.07	0.01	0.05
	Operation	4710	4710	372	376	0.06	0.12	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Fischer Tropsch)	Feedstock	302	20	23	38	0.03	0.08	0.00	0.05
	Fuel	2789	72	101	109	0.03	0.23	0.06	0.09

	Operation	4710	0	359	363	0.06	0.12	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Soy BD20)	Feedstock	540	224	-26	-7	0.02	0.16	0.01	0.11
	Fuel	10179	78	21	13	0.28	-0.06	0.00	-0.09
	Operation	4710	3827	373	377	0.06	0.12	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CNG	Feedstock	418	23	30	62	0.03	0.11	0.00	0.06
	Fuel	395	17	33	34	0.00	0.03	0.01	0.06
	Operation	5383	0	319	326	0.15	0.10	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Dry Corn)	Feedstock	868	247	-243	-193	0.05	0.27	0.01	0.13
	Fuel	6683	316	72	83	0.26	0.41	0.04	0.11
	Operation	5652	1480	426	430	0.17	0.10	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Wet Corn)	Feedstock	876	475	-236	-174	-0.14	0.40	0.02	0.22
	Fuel	6861	217	237	251	0.26	0.30	0.10	0.16
	Operation	5652	1480	426	430	0.17	0.10	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Herbaceous)	Feedstock	567	201	-300	-258	0.05	0.19	0.01	0.03
	Fuel	3712	194	6	17	0.20	0.42	0.03	0.00
	Operation	5652	1480	426	430	0.17	0.10	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Corn Stover)	Feedstock	407	202	-284	-281	0.02	0.13	0.01	0.08
	Fuel	3336	194	6	17	0.20	0.40	0.03	0.00
	Operation	5652	1480	426	430	0.17	0.10	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Dry Corn)	Feedstock	417	84	10	26	0.02	0.14	0.01	0.05
	Fuel	1426	451	69	72	0.14	0.13	0.02	0.07
	Operation	5652	5287	434	437	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15

(Continued)

TABLE D-7 Continued

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
E10 (Wet Corn)	Feedstock	417	104	10	28	0.01	0.15	0.01	0.06
	Fuel	1442	442	84	87	0.14	0.12	0.02	0.07
	Operation	5652	5287	434	437	0.18	0.10	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Herbaceous)	Feedstock	390	80	5	21	0.02	0.13	0.01	0.04
	Fuel	1166	440	64	66	0.14	0.13	0.02	0.06
	Operation	5652	5287	434	437	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Corn Stover)	Feedstock	376	80	6	19	0.02	0.13	0.01	0.05
	Fuel	1134	440	64	66	0.14	0.12	0.02	0.06
	Operation	5652	5287	434	437	0.18	0.10	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Electric	Feedstock	150	48	11	23	0.03	0.05	0.10	0.03
	Fuel	2450	62	337	339	0.01	0.28	0.01	0.63
	Operation	1615	69	0	0	0.00	0.00	0.01	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Hydrogen (Gaseous)	Feedstock	181	10	13	27	0.01	0.05	0.00	0.03
	Fuel	1466	26	238	246	0.01	0.10	0.04	0.09
	Operation	2335	0	0	0	0.00	0.00	0.01	0.00
	Vehicle	1030	203	80	84	0.31	0.12	0.05	0.37
Grid Independent SI HEV	Feedstock	246	45	10	19	0.01	0.08	0.00	0.03
	Fuel	880	321	50	54	0.09	0.09	0.01	0.05
	Operation	3718	3562	285	289	0.13	0.08	0.02	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Grid Dependent SI HEV	Feedstock	222	49	11	22	0.02	0.07	0.04	0.03
	Fuel	1533	239	163	166	0.06	0.17	0.01	0.28
	Operation	3113	2413	191	194	0.09	0.06	0.01	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30

TABLE D-8 GREET Energy and Emission Factors for Light-Duty Trucks 2 in 2020

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
RFG SI Autos (Conventional Oil)	Feedstock	436	80	19	34	0.02	0.15	0.01	0.05
	Fuel	1564	570	89	96	0.16	0.16	0.02	0.09
	Operation	6605	6327	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SI Autos (Tar Sands)	Feedstock	1269	77	83	101	0.03	0.16	0.01	0.05
	Fuel	1635	570	90	97	0.16	0.16	0.02	0.09
	Operation	6605	6327	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Conventional Oil)	Feedstock	436	80	19	34	0.02	0.15	0.01	0.05
	Fuel	1564	570	89	96	0.16	0.16	0.02	0.09
	Operation	6605	6327	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CG SI Autos (Tar Sands)	Feedstock	1269	77	83	101	0.03	0.16	0.01	0.05
	Fuel	1635	570	90	97	0.16	0.16	0.02	0.09
	Operation	6605	6327	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Conventional Oil)	Feedstock	379	69	16	30	0.02	0.13	0.01	0.04
	Fuel	1360	496	78	83	0.14	0.14	0.02	0.08
	Operation	5743	5502	441	445	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
RFG SIDI Autos (Tar Sands)	Feedstock	1103	67	72	88	0.03	0.14	0.01	0.04
	Fuel	1422	496	79	84	0.14	0.14	0.02	0.08
	Operation	5743	5502	441	445	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Low Sulfur)	Feedstock	363	66	33	46	0.02	0.12	0.01	0.04
	Fuel	778	387	58	60	0.02	0.09	0.01	0.06
	Operation	5504	5504	435	439	0.07	0.17	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15

(Continued)

TABLE D-8 Continued

		Total Energy Btu/VMT	Petroleum Btu/VMT	CO$_2$ g/VMT	CO$_{2e}$ g/VMT	VOC g/VMT	NO$_x$ g/VMT	PM$_{2.5}$ g/VMT	SO$_x$ g/VMT
Diesel (Fischer Tropsch)	Feedstock	353	23	27	44	0.03	0.09	0.00	0.06
	Fuel	3259	84	118	127	0.04	0.27	0.08	0.11
	Operation	5504	0	420	424	0.07	0.17	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Diesel (Soy BD20)	Feedstock	631	262	-30	-8	0.03	0.19	0.01	0.13
	Fuel	11895	92	25	16	0.32	-0.07	0.00	-0.10
	Operation	5504	4472	436	440	0.07	0.17	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
CNG	Feedstock	489	27	35	72	0.04	0.13	0.00	0.07
	Fuel	461	20	38	40	0.00	0.04	0.01	0.07
	Operation	6290	0	373	381	0.18	0.14	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Dry Corn)	Feedstock	1014	288	-284	-226	0.06	0.31	0.01	0.15
	Fuel	7810	369	85	97	0.31	0.48	0.05	0.13
	Operation	6605	1730	498	502	0.20	0.14	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Wet Corn)	Feedstock	1024	555	-275	-203	-0.17	0.47	0.02	0.26
	Fuel	8018	253	278	293	0.31	0.35	0.12	0.18
	Operation	6605	1730	498	502	0.20	0.14	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Herbaceous)	Feedstock	663	234	-351	-302	0.05	0.22	0.01	0.04
	Fuel	4337	227	7	20	0.23	0.49	0.03	0.00
	Operation	6605	1730	498	502	0.20	0.14	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E85 (Corn Stover)	Feedstock	475	236	-332	-329	0.03	0.15	0.01	0.09
	Fuel	3898	227	7	20	0.23	0.47	0.03	0.00
	Operation	6605	1730	498	502	0.20	0.14	0.02	0.00
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Dry Corn)	Feedstock	487	98	11	31	0.03	0.16	0.01	0.06
	Fuel	1667	527	81	84	0.17	0.15	0.02	0.08

	Operation	6605	6178	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Wet Corn)	Feedstock	488	121	12	33	0.01	0.17	0.01	0.07
	Fuel	1685	517	98	101	0.17	0.14	0.03	0.08
	Operation	6605	6178	507	511	0.22	0.14	0.02	0.01
	Vehicle	633	126	47	50	0.21	0.08	0.03	0.14
E10 (Herbaceous)	Feedstock	456	93	6	24	0.03	0.15	0.01	0.05
	Fuel	1363	514	74	78	0.16	0.15	0.02	0.07
	Operation	6605	6178	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
E10 (Corn Stover)	Feedstock	440	93	7	22	0.02	0.15	0.01	0.05
	Fuel	1325	514	74	78	0.16	0.15	0.02	0.07
	Operation	6605	6178	507	511	0.22	0.14	0.02	0.01
	Vehicle	730	140	54	57	0.31	0.08	0.04	0.15
Electric	Feedstock	176	56	13	27	0.03	0.06	0.12	0.04
	Fuel	2863	73	394	396	0.01	0.32	0.01	0.74
	Operation	1887	80	0	0	0.00	0.00	0.01	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Hydrogen (Gaseous)	Feedstock	232	13	16	34	0.02	0.06	0.00	0.03
	Fuel	1875	33	305	314	0.02	0.13	0.05	0.12
	Operation	2989	0	0	0	0.00	0.00	0.01	0.00
	Vehicle	1030	203	80	84	0.31	0.12	0.05	0.37
Grid Independent SI HEV	Feedstock	305	56	13	24	0.02	0.10	0.00	0.04
	Fuel	1094	399	62	67	0.11	0.11	0.01	0.06
	Operation	4619	4424	354	358	0.20	0.11	0.02	0.01
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30
Grid Dependent SI HEV	Feedstock	272	59	14	27	0.02	0.09	0.05	0.04
	Fuel	1835	295	193	197	0.08	0.20	0.01	0.32
	Operation	3821	2995	238	240	0.13	0.07	0.02	0.00
	Vehicle	840	146	65	68	0.31	0.10	0.04	0.30

GREET allows for the adjustment of many vehicle and fuel parameters, however, certain critical parameters are adjusted some of the vehicle-fuel combinations to estimate life cycle emissions. For reformulated gasoline vehicles, GREET's share of reformulated gasoline in total gasoline factor was set to 100%. For conventional and reformulated gasoline vehicles using petroleum derived from tar sands oil, GREET's share of oil sands products in crude oil refineries was set to 100%. GREET assumes that in 2005 an 80% share of dry mill corn ethanol production (this increases to 90% by 2020). In evaluating E10 and E85 fueled vehicles from corn ethanol feedstock, this percentage was adjusted. For E10 and E85 from dry corn this was set to 100% while from wet corn, to 0% (or 100% wet milling plants). To evaluate the compression ignition direct injection low sulfur diesel combination, the share of low sulfur diesel in total diesel use was specified as 100% for 2005. For the other vehicle-fuel combinations, default GREET values were left unchanged. The ethanol yield factors were verified against existing literature and electricity mixes for the two time periods received slight adjustments based on the US Energy Information Administration's Annual Energy Outlook. The energy and emission factors for the different vehicle types (LDA, LDT1, and LDT2) in 2005 are shown in Table D-3, Table D-4, and Table D-5 and for 2020 in Table D-6, Table D-7, and Table D-8.

2030 Fuel Economy and Emission Factor Adjustments

The implementation of 35 miles per gallon fuel economy standards for 2030 requires an adjustment to GREET default 2020 emission factors. The GREET model assumes fuel economies between 20 and 30 miles per gallon for conventional gasoline and E85 light-duty automobiles in 2020. For light-duty trucks the fuel economy ranges are even lower (20-24 miles per gallon for LDT1 and 17-20 miles per gallon for LDT2). For 2030, all energy and emission factors are adjusted based on the GREET default fuel economies and the expected 35 miles per gallon standard. Fuel and feedstock factors from GREET are reduced by the percentage reduction of default and 35 mile per gallons economies (e.g., if the 2020 fuel economy is specified as 24 miles per gallon then the fuel and feedstock emission factors for 2020 are multiplied by 24/35 to determine the adjusted 2030 factors). This is based on the assumption that with an increase in fuel economy, a proportional reduction is needed in fuel production which results in lower feedstock requirements. Vehicle operation combustion factors are also reduced using the same methodology. VOC evaporative losses and PM tire and brake wear factors were left unchanged from GREET default values as well as vehicle manufacturing. Both automobiles and light-duty trucks were assessed the adjusted factors. Trucks show the largest changes from default to the 35 miles per gallon standard due to relatively low GREET estimated 2020 fuel economies. All vehicles that had fuel economies greater than 35 miles per gallon in GREET in 2020 were not adjusted.

Mobile 6.2 Heavy-duty Truck Energy and Emissions Factors

The operational factors for heavy-duty vehicles were determined with Mobile 6.2 and are shown in Table D-9 and Table D-10. Default Mobile 6.2 values were used for these vehicles.

GREET and Mobile 6.2 Comparison

The GREET vehicle operation factors can be compared against Mobile 6.2's to evaluate the accuracy of particular vehicles. GREET assumes default emission factors for conventional gasoline and diesel vehicles and the operating conditions of the vehicles is not transparent. Mobile 6.2 is designed to model emissions from conventional fuel vehicles and low level ethanol blends and provides the ability to adjust many vehicle operation and fuel characteristics in determining emission factors. Table D-11 and Table D-12 compare the GREET default conventional gasoline and diesel vehicle emissions against Mobile 6.2.

TABLE D-9 Mobile 6.2 Energy and Emission Factors for Heavy-Duty Vehicles in 2005

	Total Energy	CO2	VOC	NOx	PM2.5	SOx
	Btu/VMT	g/VMT	g/VMT	g/VMT	g/VMT	g/VMT
HDGV2A	12500	888	1.79	4.13	0.07	0.05
HDGV2B	12500	888	1.79	4.13	0.07	0.05
HDGV3	13587	963	2.47	4.71	0.08	0.06
HDGV4	14205	1005	5.30	5.90	0.07	0.06
HDGV5	15823	1124	3.10	5.40	0.06	0.06
HDGV6	15823	1119	2.91	5.30	0.07	0.07
HDGV7	17123	1217	3.43	6.09	0.07	0.07
HDGV8A	18382	1296	4.05	6.79	0.00	0.00
HDDV2A	10195	795	0.23	3.99	0.12	0.01
HDDV2B	10195	795	0.23	3.99	0.12	0.01
HDDV3	11250	879	0.25	4.44	0.13	0.01
HDDV4	12921	1004	0.31	5.41	0.11	0.01
HDDV5	13316	1036	0.32	5.68	0.25	0.01
HDDV6	15000	1176	0.47	7.99	0.26	0.01
HDDV7	17400	1354	0.58	9.94	0.33	0.01
HDDV8A	20077	1561	0.56	12.89	0.36	0.02
HDDV8B	21048	1647	0.66	15.10	0.36	0.02

TABLE D-10 Mobile 6.2 Energy and Emission Factors for Heavy-Duty Vehicles in 2030

	Total Energy	CO2	VOC	NOx	PM2.5	SOx
	Btu/VMT	g/VMT	g/VMT	g/VMT	g/VMT	g/VMT
HDGV2A	12376	876	0.35	0.18	0.02	0.02
HDGV2B	12376	876	0.35	0.18	0.02	0.02
HDGV3	13298	945	0.76	0.23	0.02	0.02
HDGV4	13298	949	0.82	0.21	0.02	0.02
HDGV5	15625	1107	0.91	0.24	0.02	0.02
HDGV6	15432	1090	0.90	0.24	0.02	0.02
HDGV7	16779	1191	0.95	0.27	0.03	0.02
HDGV8A	17606	1255	1.00	0.28	0.00	0.00
HDDV2A	10038	785	0.10	0.25	0.01	0.01
HDDV2B	10038	785	0.10	0.25	0.01	0.01
HDDV3	11154	873	0.12	0.26	0.02	0.01
HDDV4	12794	998	0.14	0.41	0.02	0.01
HDDV5	13182	1030	0.15	0.44	0.02	0.01
HDDV6	15000	1169	0.19	0.47	0.02	0.01
HDDV7	17400	1352	0.23	0.58	0.03	0.01
HDDV8A	19773	1544	0.26	0.64	0.03	0.02
HDDV8B	20714	1616	0.29	0.75	0.03	0.02

TABLE D-11 Comparison of Emission Factors (g/VMT) for a Light-Duty Gasoline Automobile in 2005

	VOC Exhaust	VOC Evap	NOX	PM2.5 Exhaust	PM2.5 TBW	SOX
GREET	0.15	0.07	0.3	0.008	0.007	0.01
Mobile 6.2	0.27	0.87	0.8	0.005	0.007	0.02

TABLE D-12 Comparison of Emission Factors (g/VMT) for a Light-Duty Diesel Automobile in 2005

	VOC Exhaust	NOX	PM2.5 Exhaust	PM2.5 TBW
GREET	0.09	0.3	0.07	0.007
Mobile 6.2	0.33	1.3	0.15	0.007

The lack of transparency in the vehicle and operating characteristics used to generate GREET factors results in some difficulty in verification using Mobile 6.2. GREET assumes low sulfur concentrations in 2005 of 26 ppm in gasoline and 200 ppm in conventional diesel. GREET further specifies sulfur contents for low sulfur diesel. Outside of fuel sulfur levels, vehicle emission factors are fixed based on inputs and assumptions from 1990 through 2020.

The differences between GREET and Mobile 6.2 emission factors are most likely due to the variations in vehicle operation and fuel input parameters. This could include cold start and warm running, fuel vapor pressure, summer or winter fuel mix, and vehicle model assumptions. While the Mobile 6.2 factors tend to be larger than the GREET factors, it is assumed that the GREET factors are reasonable given the uncertainty in vehicle and fuel parameters and that they are within the bounds of Mobile 6.2 estimates for the year.

EPA Mobile 6 Ammonia Emissions Factors

Ammonia emissions, which ultimately contribute to particulate formation, are evaluated by APEEP but not included in the default transportation damage assessment. GREET does not evaluate ammonia emissions but Mobile 6.2 does for a subset of vehicle-fuel combinations included in GREET. Table D-13 summarizes the Mobile 6.2 ammonia emission factors for 2005 and 2030.

For light-duty gasoline vehicles, the ammonia factors are around 0.1 g/VMT while for light-duty diesel vehicles they range from 0.01-0.03 g/VMT for both years. The heavy-duty gasoline and diesel vehicle factors are 0.05 and 0.03 g/VMT.

Applying GREET Feedstock and Fuel Production Factors to Heavy-duty Vehicles

Feedstock and fuel production factors from GREET are used to supplement the Mobile 6.2 heavy-duty vehicle operational emissions. Because Mobile 6.2 evaluates only the operational phase of heavy-duty vehicles, there is a need to supplement this component with feedstock and fuel production requirements so that results are commensurate with light-duty vehicles evaluated in GREET. To do this, the GREET feedstock and fuel production factors from reformulated gasoline and low sulfur diesel light-duty vehicles are used. Using the energy content of gasoline or diesel consumed during vehicle operation, the corresponding GREET feedstock and fuel production factors are prorated and assessed to the heavy-duty vehicles. This is done across all of the energy and emissions factors for each of the heavy-duty vehicles assessed with Mobile 6.2.

Heavy-duty vehicle manufacturing factors are not included in the assessment. Unlike feedstock and fuel production processes which are specific to a fuel (which is the same for both light and heavy

TABLE D-13 Mobile 6.2 Ammonia Emissions (g/VMT)

	2005	2030
HDGV2B	0.045	0.045
HDGV3	0.045	0.045
HDGV4	0.045	0.045
HDGV5	0.045	0.045
HDGV6	0.045	0.045
HDGV7	0.045	0.045
HDDV2B	0.027	0.027
HDDV3	0.027	0.027
HDDV4	0.027	0.027
HDDV5	0.027	0.027
HDDV6	0.027	0.027
HDDV7	0.027	0.027
HDDV8A	0.027	0.027
HDDV8B	0.027	0.027
LDGV	0.100	0.102
LDGT1	0.100	0.102
LDGT2	0.097	0.102
LDGT3	0.097	0.102
LDDV	0.007	0.007
LDDT	0.027	0.027
LDDT12	0.007	0.007

duty vehicles), vehicle manufacturing processes are unique. No known information exists that estimates the energy requirements and resulting emissions of manufacturing heavy-duty gasoline and diesel fuels of different classes. As a result, this component was excluded from the assessment.

COUNTY-LEVEL DAMAGE CALCULATIONS

The vehicle feedstock, fuel, operation, and manufacturing per VMT emission factors are used in conjunction with APEEP unit damage county factors to determine county resolution total damages. For each of the life cycle components, particular assumptions were made in performing the calculations. APEEP has county level pollutant unit damages for all states except Alaska and Hawaii. For every county, APEEP reports ground level and various heights unit emission damages ($ per metric tonne emitted) for VOCs, NO_X, $PM_{2.5}$, SO_2, and NH_3 (ammonia).

Feedstock Production Damages

The location of feedstock production and associated emissions is not clear for the various fuel energy inputs. From crude oil to corn to coal, the identification of feedstock production locations is not transparent. Feedstock can be produced internationally (e.g., conventional crude oil from overseas or tar sands crude oil from Canada) or domestically (e.g., coal or corn) and transport of raw energy inputs can occur between. The difficulty of estimating feedstock production and transport locations resulted in the assignment of these emissions to the county where travel occurs. The feedstock emissions are assessed the lowest level above ground level height in APEEP.

Fuel Production Damages

Fuel production damages are assessed to particular geographic regions based on petroleum refinery and ethanol plant locations. PADD (Petroleum Administration for Defense Districts) regions are used to identify five geographic areas of the United States for petroleum production and consumption statistics. The regions are East Coast, Midwest, Gulf Coast, Rocky Mountain, and West Coast, and serve as a common resolution for petroleum data. The U.S. Energy Information Administration reports petroleum refinery locations and production capacity[4]. Using these locations, associated counties could be determined for assessment of APEEP damage factors for conventional fueled vehicles. Without knowing which refinery produces the fuel for a VMT in another county, PADD resolution was used to assess fuel production unit damages. For each PADD, a weighted average APEEP fuel factor (further referred to as $APEEP_{FUEL}$) was determined from the percentage of PADD fuel production capacity for each refinery and the corresponding county. This produced five $APEEP_{FUEL}$ pollutant damage factors, one for each PADD. The $APEEP_{FUEL}$ damage factors were assessed to each county in the United States based on its PADD location. The fuel production life cycle emissions were used in conjunction with the $APEEP_{FUEL}$ factors to determine fuel production damages for each county given a specific vehicle's per VMT emissions.

A PADD-based resolution approach was also used for ethanol fuel production. Using ethanol refinery locations[5], $APEEP_{FUEL}$ factors were determined for ethanol production for each of the five PADD regions. Given the mix of ethanol in the fuel (i.e., 10% or 85%), this fraction was multiplied by the $APEEP_{FUEL}$ ethanol factor and the remainder by the $APEEP_{FUEL}$ gasoline factor. For example, for an E10 vehicle operating in a county in PADD 1, 10% × $APEEP_{FUEL,ETHANOL}$ and 90% × $APEEP_{FUEL,GASOLINE}$ are added and assessed to that county. This mixed $APEEP_{FUEL}$ factor for each pollutant is then multiplied by the corresponding fuel production emissions for an E10 vehicle. Similar to feedstock production, the fuel production APEEP factors are based on the lowest level height above ground level.

For electric vehicles, power plant emissions were assumed to occur according to petroleum PADD locations. Give the complexity of modeling electricity generation emissions given driving locations, fuel production emissions were assigned to the petroleum production locations and PADD regions.

Vehicle Operation Damages

Vehicle operation VMT are based on county populations which are assumed to be a reasonable metric for disaggregation of total state VMT. Given the GREET and Mobile 6.2 per VMT emissions factors, VMT estimates are needed for each U.S. county to determine total emissions in that county. State-level VMT is available but not any higher resolution[6]. Using U.S. census population estimates, state-level VMT is disaggregated to each county by the fraction of population. These county VMT are then multiplied by the GREET and Mobile 6.2 vehicle operational emission factors to determine total emissions for each county. The emissions of each pollutant are then joined with the APEEP ground-level pollutant county factors to determine total damages.

Vehicle Manufacturing Damages

Similar to fuel production, PADD regions are used to aggregate vehicle manufacturing APEEP costs. Vehicle, parts, and tire manufacturing facilities (including number of facilities, employee counts,

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[4]U.S. Energy Information Administration, Ranking of U.S. Refineries, http://www.eia.doe.gov/neic/rankings/refineries.htm

[5]Renewable Fuels Association, Biorefinery Locations, http://www.ethanolrfa.org/industry/locations/.

[6]U.S. Federal Highway Administration, Highway Statistics Series, http://www.fhwa.dot.gov/policy/ohpi/hss/index.cfm.

and county) were queried from census data. The census data details the location and employee count for over 8,000 facilities. For each county in the United States, the total number of employees from these industries was determined. A weighted average vehicle manufacturing APEEP factor (further referred to as APEEP$_{MANUFACTURING}$) was determined for each PADD based on the percentage of employees in each PADD's counties and the corresponding county's APEEP factor. Again, this was done because of lack of information that identifies if a vehicle is driven in a particular county, where it was manufactured. The PADD-based approach assumes that for a vehicle driven in a particular county, the manufacturing took place in that county's PADD and the weighted average APEEP$_{MANUFACTURING}$ factor is applied.

Total Life Cycle Damages

Total damages are determined from feedstock production, fuel production, vehicle operation, and vehicle manufacturing factors. This assessment was performed for each vehicle-fuel combination. Given a specific vehicle-fuel combination, the feedstock, fuel, operation, and manufacturing emission factors (in grams of VOC, NO$_X$, PM$_{2.5}$, and SO$_2$ per VMT) are multiplied by the APEEP county and pollutant factors (dollar damages per gram of pollutant which may be weighted averages for the PADD region). Furthermore, the APEEP factors are reported in dollars of damage of emission for mortality, morbidity and other damages (e.g., agricultural or visibility impairment). For each vehicle-fuel combination, the life cycle emission factors are joined with the APEEP pollutant damage factors for mortality, morbidity, and other, to determine total damages for each county. The result is a mortality, morbidity, and other dollar damages for each county and each vehicle type (light-duty autos, truck 1, and truck 2), in both 2005 and 2030.

Damages Related to Electric Vehicles and Grid-Dependent Hybrids

For the vehicle manufacturing component and the fuel feedstock (e.g., coal or natural gas) component of the lifecycles of electric vehicles (EVs) and grid-dependent hybrid vehicles (GD-HVs), the GREET model's estimates of emissions per vehicle mile traveled were paired with results from the APEEP model, which provided estimates of the physical health and other non-climate change related effects and monetary damages per ton of emissions that form criteria air pollutants. However, the allocation of electric utility-related damages to the vehicle operations and electricity-production components of the lifecycles, were approximated by applying a GREET-generated kWh/VMT and applying that to the estimated average national damages per kWh from the electricity analysis presented in Chapter 2.

We used 1.59 cents /kWh for 2005 and 0.79 cents/kWh for 2030 for the damages due to producing (not consuming) electricity for both EVs and GD-HEVs. Those values were obtained by determining the aggregate marginal damages for coal-fired and natural gas plants, based on their shares of net generation and the average marginal damages for each type of plant. For example, for 2005: [0.485 (coal share of net generation) × 3.2 cents/kWh] + [0.213 (natural gas share of net generation) × 0.16 cents/kWh] = 1.59 cents/kWh.

We estimated the fuel (electricity generation) component damages based on the damages associated with producing electricity at the rate of 0.52 kWh/VMT. So the fuel damages for 2005 were calculated as follows, 0.52 kWh/VMT × 1.59 cents/kWh = 0.83 cents/VMT. For 2030, the estimate for fuel damage is 0.31 cents/VMT. For the vehicle operation component, we estimated damage associated with a 10% loss of electricity over transmission and distribution lines (e.g., 0.05 kWh/VMT for 2005).[7]

A similar approach was used for estimating the electricity-relate damages for GD-HEVs. However, no more than 35% of energy supplied to GD-HEVs was estimated to come from the grid.

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[7]U.S. Department of Energy "Overview of the Electric Grid" http://sites.energetics.com/gridworks/grid.html, accessed September 4, 2009.

E

Supplemental Information on Land Use Externalities from Biofuels: A Case Study of the Boone River Watershed

We use the EPIC model in conjunction with detailed field-level data for the Boone River Watershed to evaluate a number of "scenarios" where each scenario is associated with a different possible land use constituting different crops grown and/or different management practices on the land. To begin, a baseline land use corresponding to the 2005 cropping pattern and land management is developed and an estimate of the externalities associated with the baseline is made. Then, various alternative land uses are proposed and evaluated using EPIC to predict the amount of nitrogen, phosphorous, sediments exported from each field as well as the amount of carbon sequestered. These levels can be aggregated to the watershed level and compared with the baseline. Additionally, we compute the amount of biofuels that the new landuse can produce so that the externalities can be considered relative to the amount of acreage used to grow the feedstock or to the amount of fuel produced, or both. Finally, using values from the literature we monetize the externality endpoints.

The land use conditions we evaluate include a baseline that represents 2005 cropping patterns and land use and the following counterfactual scenarios:

1. Continuous Corn: Convert the existing corn acreage that rotates with soybeans to continuous corn. The represents a change to about 90% of the acreage. As there is very little CRP or idle land in this watershed, this is the main way in which planting decisions in this watershed could respond to increased demand for corn usage via ethanol.

2. Corn Stover: In this scenario, we assume that the stover is removed from the baseline acreage and used to produce ethanol. We consider three possible rates of removal: 50%, 80%, and 100%.

3. Continuous Corn and Corn Stover: This is a combination of the first two scenarios, all corn-soybean rotations are changes to continuous corn and then stover removals of 50%, 80%, and 100% are simulated.

4. Switch grass: In these scenarios, switchgrass acreage is randomly placed on the baseline acreage from the baseline in percentages of 25%, 50%, 75%, and the complete watershed (100%). A nitrogen fertilizer rate of 123 kg/ha was simulated for the switchgrass which is consistent with optimum rates reported by Vogel et al. (2002) and Heggenstaller et al. (2009) for Iowa switchgrass biofuel production.

The Boone River Watershed Model and Data. Our analysis draws heavily from the model and data sources developed by Gassman (2008) and we refer the interested reader to that document for substantially greater details on the data sources, collection methods, and assumptions. Here, we outline the basics of the model and summarize the externality estimates from the model. The Boone River Watershed covers over 500,000 acres in north central Iowa. Figure E-1 shows its location with the Upper Mississippi River Basin and the state. The watershed is dominated by corn and soybean production, which together account for nearly 90% of its land use. The watershed is also characterized by intensive

livestock production; land-applied manure from these livestock operations and commercial fertilizer applications are the primary sources of nutrients to the watershed stream system. However, manure applications were not accounted for in these simulations.

A key source of land use data for the Boone simulations is a field-level survey of cropping patterns and conservation practices undertaken by Mr. Charles Kiepe, formerly with the USDA-NRCS, who visually inspected all of the fields (common land units) in the Boone watershed during the spring of 2005. This highly detailed spatially explicit data provides the basic information to populate the EPIC model. Table E-1 summarizes the cropping pattern observed: the region is planted almost entirely to a corn and soybeans in a 1 year rotation. A few acres are in continuous corn or pasture and a few are enrolled in the Conservation Reserve Program and are planted to a perennial cover. Additional data sources include soils information from the Soil Survey Geographic Database and the Iowa Soil Properties and Interpretations Database, climate data from NOAA and the Iowa Environmental Mesonet, topographic information from the Iowa Digital Elevation Model, livestock operations from the Iowa Department of Natural Resources. Extensive additional details on these and other data sources used to populate the model can be found in Gassman (2008).
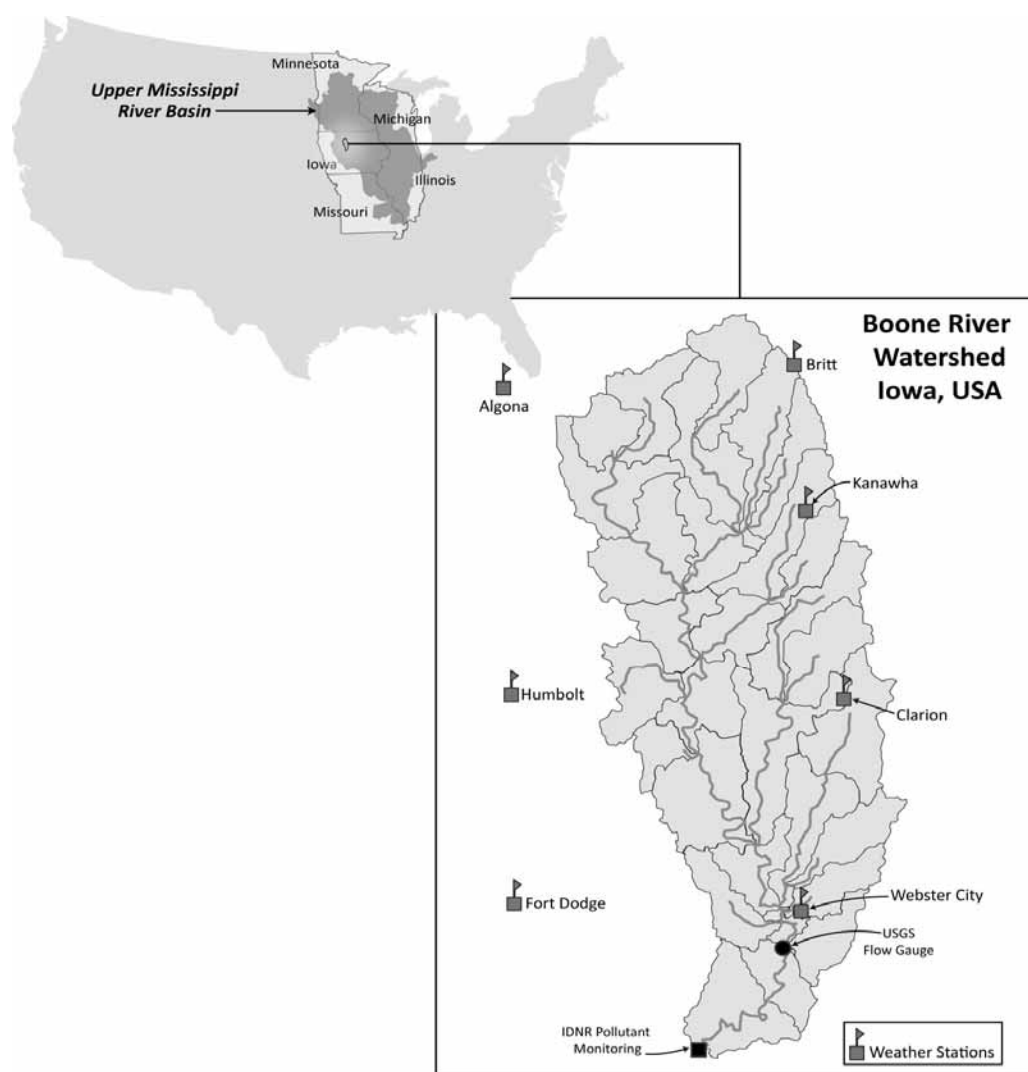
FIGURE E-1 The Boone River Watershed.

TABLE E-1   Boone River Watershed Baseline Cropping Pattern

	Acres	Percent of Watershed
Corn-Soybean Rotation	474,000	89
Continuous Corn Rotation	21,000	4
Pasture	16,000	3
Conservation Reserve Program	13,000	2
Other (mixture of other rotations and alfalfa)	9	<1
Total	533,000	100