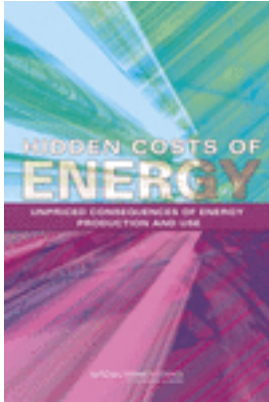


Free Executive Summary



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; National Research Council

ISBN: 978-0-309-14640-1, 466 pages, 6 x 9, paperback (2009)

This free executive summary is provided by the National Academies as part of our mission to educate the world on issues of science, engineering, and health. If you are interested in reading the full book, please visit us online at <http://www.nap.edu/catalog/12794.html>. You may browse and search the full, authoritative version for free; you may also purchase a print or electronic version of the book. If you have questions or just want more information about the books published by the National Academies Press, please contact our customer service department toll-free at 888-624-8373.

For multi-user PDF licensing, please contact customer service. Despite the many benefits of energy, most of which are reflected in energy market prices, the production, distribution, and use of energy causes negative effects. Many of these negative effects are not reflected in energy market prices. 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 recognition of these external or hidden costs. Hidden Costs of Energy defines and evaluates key external costs and benefits that are associated with the production, distribution, and use of energy, but not reflected in market prices. In aggregate, the damage estimates presented here are substantial, and reflect damages from air pollution associated with electricity generation, motor vehicle transportation, and heat generation. The book also considers other effects not quantified in dollar amounts, such as damages from climate change, effects of some air pollutants such as mercury, and risks to national security. While not a comprehensive guide to policy, this analysis indicates that major initiatives to further reduce other emissions, improve energy efficiency, or shift to a cleaner electricity-generating mix could substantially reduce the damages of external effects. A first step in minimizing the adverse consequences of new energy technologies is to better understand these external effects and damages. Hidden Costs of Energy will therefore be a vital informational tool for government policy makers, scientists, and economists in even the earliest stages of research and development on energy technologies.

This executive summary plus thousands more available at www.nap.edu.

Copyright © National Academy of Sciences. All rights reserved. Unless otherwise indicated, all materials in this PDF file are copyrighted by the National Academy of Sciences. Distribution or copying is strictly prohibited without permission of the National Academies Press <http://www.nap.edu/permissions/> Permission is granted for this material to be posted on a secure password-protected Web site. The content may not be posted on a public Web site.

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

Prepublication Copy—Subject to Further Editorial Correction

Copyright National Academy of Sciences. All rights reserved.

This executive summary plus thousands more available at <http://www.nap.edu>

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

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

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 (SO₂), 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.

¹Criteria 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.

²Hazardous 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.

³Greenhouse 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.

Summary

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 SO₂, 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.

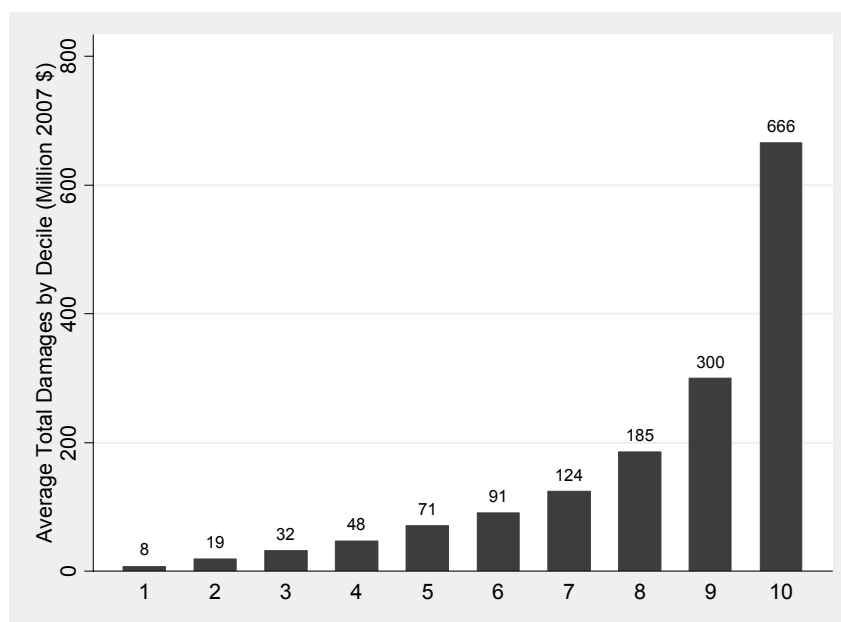


Figure S-1 Distribution of aggregate damages among the 406 coal-fired power plants analyzed in this study. In computing this chart, plants were sorted from smallest to largest based on damages associated with each plant. The lowest decile (10% increment) represents the 40 plants with the smallest damages 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 SO₂, NO_x, and PM. Damages related to climate-change effects are not included.

⁴Costs are reported in 2007 dollars.

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

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 SO₂ 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 SO₂ 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 SO₂, 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

⁵When 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.

⁶When 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.

Summary

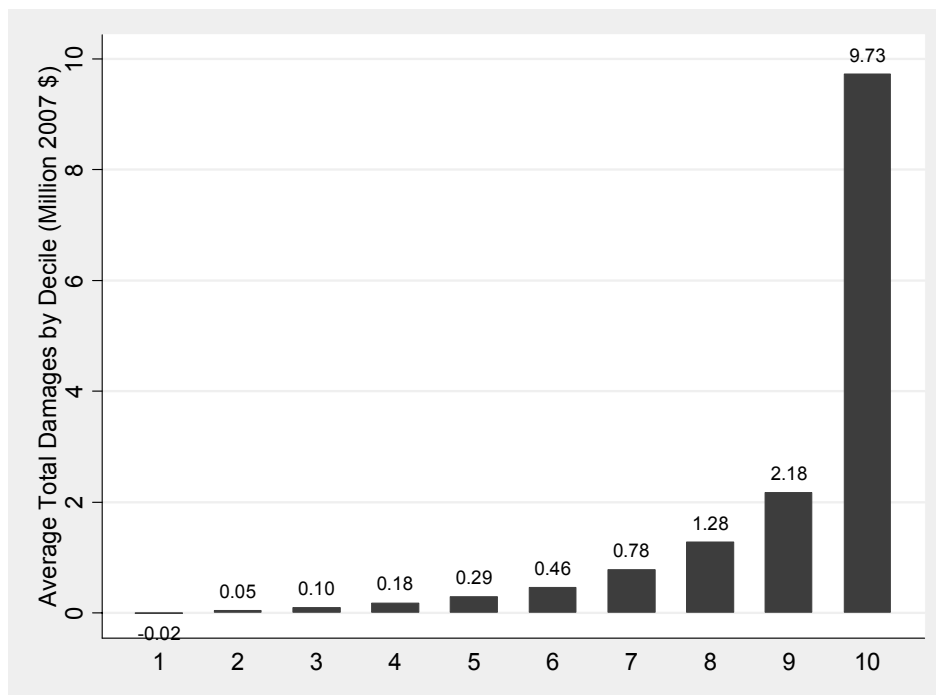


Figure S-2 Distribution of aggregate damages among the 498 natural gas-fired power plants analyzed in this study. In computing this chart, plants were sorted from smallest to largest based on damages associated with each plant. The lowest decile (10% increment) represents the 50 plants with the smallest 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 SO₂, 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

⁷The 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.

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

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 CO₂ from coal-fired power plants are the largest single source of GHGs in the United States. CO₂ emissions vary; their average is about 1 ton of CO₂ 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 CO₂ from gas-fired power plants also are significant, with an average of about 0.5 ton of CO₂ per MWh generated and a 5th-to-95th-percentile range of 0.3–1.1 tons. Life-cycle CO₂ 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

Summary

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 CO₂. Methane, the major component of natural gas, is a GHG itself and has a global-warming potential about 25 times that of CO₂. 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. CO₂-equivalent (CO₂-eq) emissions⁹ (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 CO₂-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 CO₂-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.

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

⁹CO₂-equivalent (noted as CO₂-eq) expresses the global warming potential of a given stream of greenhouse gases, such as methane, in terms of CO₂ quantities.

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

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.

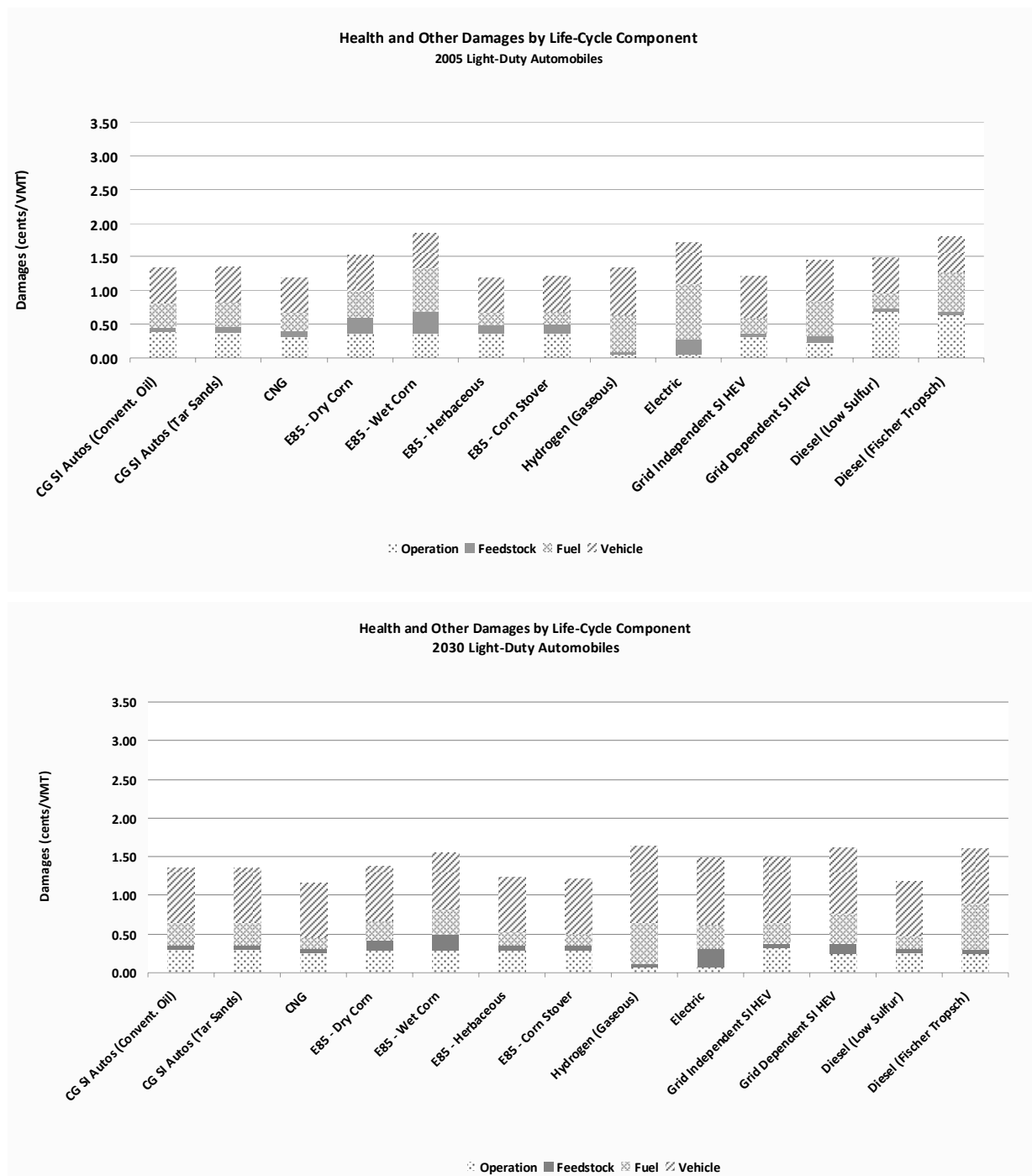
Compressed natural gas had lower damages than other options, as the technology’s operation and fuel produce very few emissions.

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.

¹⁰The 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.

¹¹Indirect 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.

Summary



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.

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

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 fuels¹² had the highest life-cycle GHG emissions among all fuel/vehicle combinations considered. Vehicles using cellulosic 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 CO₂ 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

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

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

¹⁴In 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.

Summary

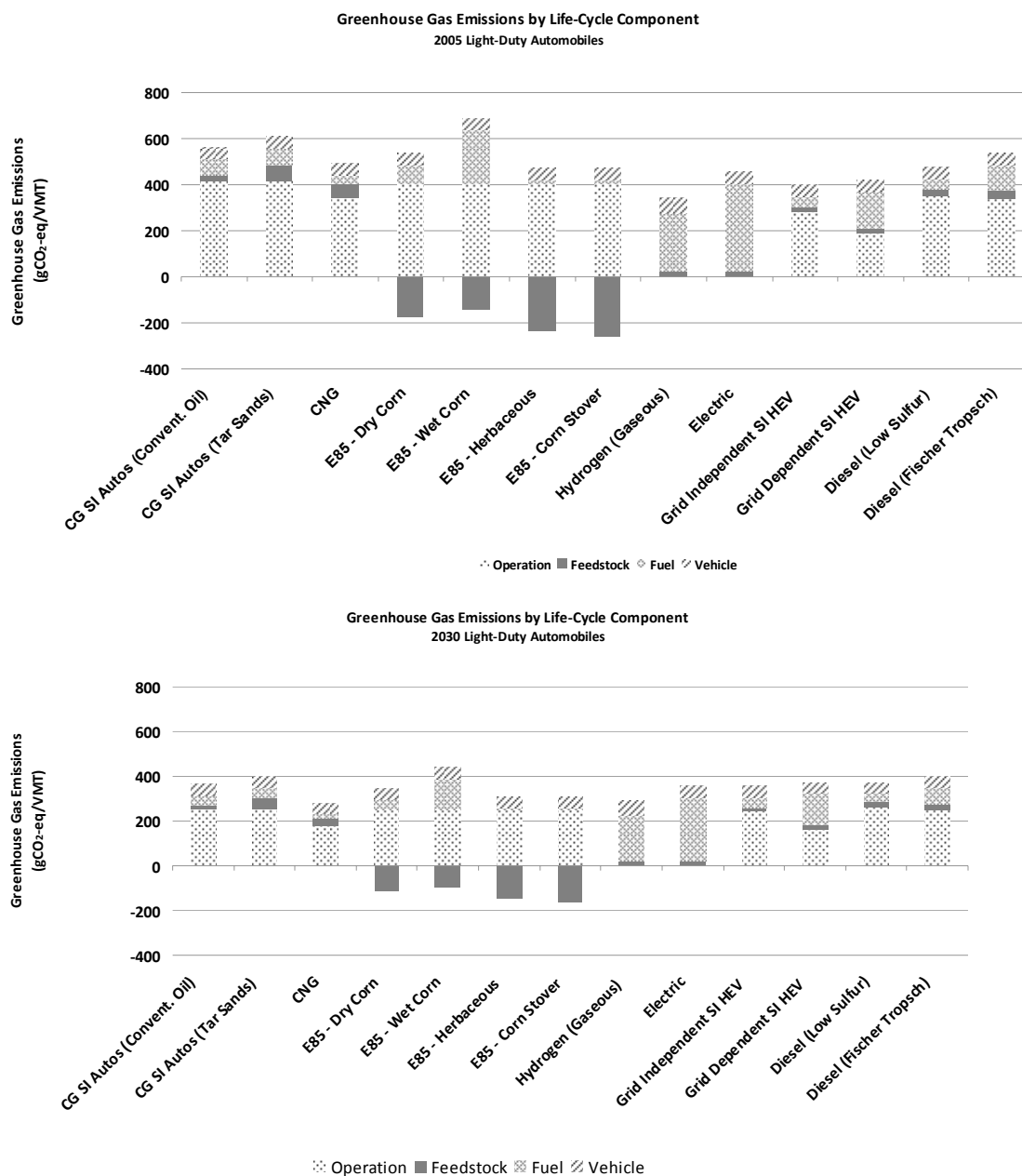


FIGURE S-4 GHG emissions (grams CO₂-eq)/VMT by life-cycle component for different combinations of fuels and light-duty automobiles in 2005 (top) and 2030 (bottom). Going from bottom to top of each bar, damages are shown for life-cycle stages as follows, vehicle operation, feedstock production, fuel refining or conversion, and vehicle manufacturing. One exception is ethanol fuels for which feedstock production exhibits negative values due to CO₂ uptake. The amount of CO₂ 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

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

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 CO₂-eq emitted into the atmosphere. Estimating these marginal damages depends on the temperature increase in response to a unit increase in CO₂-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 CO₂-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 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 CO₂-eq emitted. For example, coal-fired electricity plants were estimated to emit an average of about 1 ton of CO₂ per MWh (or 2 lb/kWh). Multiplying that emission rate by an assumed marginal damage value of \$30/ton CO₂-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 CO₂-eq is provided for illustrative purposes and is not a recommendation of the committee.

Summary

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 CO₂-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 CO₂-eq. If the marginal climate damage was less than \$30/ton CO₂-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 CO₂-eq.

Overall: All of the model results available to the committee estimated that the climate-related damages per ton of CO₂-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 CO₂-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.

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

- 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		

¹⁵These are damages related principally to emissions of NO_x, SO₂, and PM relative to a baseline of zero emissions from energy-related sources for the effects considered in this study.

PREPUBLICATION COPY

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

Division on Engineering and Physical Sciences

Board on Science, Technology, and Economic Policy

Policy and Global Affairs Division

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS

500 Fifth Street, NW

Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This project was supported by Contract No. TOS-08-038 between the National Academy of Sciences and the U.S. Department of the Treasury. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for this project.

Additional copies of this report are available from

The National Academies Press
500 Fifth Street, NW
Box 285
Washington, DC 20055

800-624-6242
202-334-3313 (in the Washington metropolitan area)
<http://www.nap.edu>

Copyright 2009 by the National Academy of Sciences. All rights reserved.

Printed in the United States of America.

Prepublication Copy

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

**COMMITTEE ON HEALTH, ENVIRONMENTAL, AND OTHER EXTERNAL COSTS AND
BENEFITS OF ENERGY PRODUCTION AND CONSUMPTION**

Members

JARED L. COHON (*Chair*), Carnegie Mellon University, Pittsburgh, PA
MAUREEN L. CROPPER (*Vice Chair*), University of Maryland, College Park
MARK R. CULLEN, Stanford University School of Medicine, Stanford, CA
ELISABETH M. DRAKE (retired), Massachusetts Institute of Technology, Auburndale, MA
MARY ENGLISH, University of Tennessee, Knoxville
CHRISTOPHER B. FIELD, Carnegie Institution of Washington, Stanford, CA
DANIEL S. GREENBAUM, Health Effects Institute, Boston, MA
JAMES K. HAMMITT, Harvard University Center for Risk Analysis, Boston, MA
ROGENE F. HENDERSON, Lovelace Respiratory Research Institute, Albuquerque, NM
CATHERINE L. KLING, Iowa State University, Ames
ALAN J. KRUPNICK, Resources for the Future, Washington, DC
RUSSELL LEE, Oak Ridge National Laboratory, Oak Ridge, TN
H. SCOTT MATTHEWS, Carnegie Mellon University, Pittsburgh, PA
THOMAS E. MCKONE, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA
GILBERT E. METCALF, Tufts University, Medford, MA
RICHARD G. NEWELL,¹ Duke University, Durham, NC
RICHARD L. REVESZ, New York University School of Law, New York
IAN SUE WING, Boston University, Boston, MA
TERRANCE G. SURLS, University of Hawaii at Manoa, Honolulu, HI

Consultants

TODD D. CAMPBELL, Iowa State University, Ames
MIKHAIL V. CHESTER, University of California, Berkeley
PHILIP W. GASSMAN, Iowa State University, Ames
NICHOLAS Z. MULLER, Middlebury College, Middlebury, VT

Staff

RAYMOND WASSEL, Project Director, Board on Environmental Studies and Toxicology
STEVE MERRILL, Director, Board on Science, Technology, and Economic Policy
JAMES ZUCCHETTO, Director, Board on Energy and Environmental Systems
DAVID POLICANSKY, Scholar
KEEGAN SAWYER, Associate Program Officer
RUTH CROSSGROVE, Senior Editor
STEVEN MARCUS, Editor
MIRSADA KARALIC-LONCAREVIC, Manager, Technical Information Center
RADIAH ROSE, Editorial Projects Manager
JOHN BROWN, Program Associate

Sponsor

U.S. DEPARTMENT OF THE TREASURY

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

BOARD ON ENVIRONMENTAL STUDIES AND TOXICOLOGY

Members

ROGENE F. HENDERSON (*Chair*), Lovelace Respiratory Research Institute, Albuquerque, NM
RAMÓN ALVAREZ, Environmental Defense Fund, Austin, TX
TINA BAHADORI, American Chemistry Council, Arlington, VA
JOHN M. BALBUS, George Washington University, Washington, DC
MICHAEL J. BRADLEY, M.J. Bradley & Associates, Concord, MA
DALLAS BURTRAW, Resources for the Future, Washington, DC
JAMES S. BUS, Dow Chemical Company, Midland, MI
JONATHAN Z. CANNON, University of Virginia, Charlottesville
GAIL CHARNLEY, HealthRisk Strategies, Washington, DC
RUTH DEFRIES, Columbia University, New York, NY
RICHARD A. DENISON, Environmental Defense Fund, Washington, DC
H. CHRISTOPHER FREY, North Carolina State University, Raleigh
J. PAUL GILMAN, Covanta Energy Corporation, Fairfield, NJ
RICHARD M. GOLD, Holland & Knight, LLP, Washington, DC
LYNN R. GOLDMAN, Johns Hopkins University, Baltimore, MD
JUDITH A. GRAHAM (retired), Pittsboro, NC
HOWARD HU, University of Michigan, Ann Harbor
ROGER E. KASPERSON, Clark University, Worcester, MA
TERRY L. MEDLEY, E. I. du Pont de Nemours & Company, Wilmington, DE
DANNY D. REIBLE, University of Texas, Austin
JOSEPH V. RODRICKS, ENVIRON International Corporation, Arlington, VA
ROBERT F. SAWYER, University of California, Berkeley
KIMBERLY M. THOMPSON, Harvard School of Public Health, Boston, MA
MARK J. UTELL, University of Rochester Medical Center, Rochester, NY

Senior Staff

JAMES J. REISA, Director
DAVID J. POLICANSKY, Scholar
RAYMOND A. WASSEL, Senior Program Officer for Environmental Studies
EILEEN N. ABT, Senior Program Officer for Risk Analysis
SUSAN N.J. MARTEL, Senior Program Officer for Toxicology
KULBIR S. BAKSHI, Senior Program Officer
ELLEN K. MANTUS, Senior Program Officer
RUTH E. CROSSGROVE, Senior Editor

BOARD ON ENERGY AND ENVIRONMENTAL SYSTEMS

Members

DOUGLAS M. CHAPIN (*Chair*), MPR Associates, Inc., Alexandria, VA
ROBERT W. FRI (*Vice Chair*), Resources for the Future, Bethesda, MD
RAKESH AGRAWAL, Purdue University, West Lafayette, IN
WILLIAM F. BANHOLZER, the Dow Chemical Company, Midland, MI
ALLEN J. BARD, University of Texas, Austin, TX
ANDREW BROWN, JR., Delphi Corporation, Troy, Michigan
MARILYN BROWN, Oak Ridge National Laboratory, Oak Ridge, TN, and Georgia Institute of Technology, Atlanta, GA
MICHAEL L. CORRADINI, University of Wisconsin, Madison
PAUL A. DECOTIS, Long Island Power Authority, Albany, NY
E. LINN DRAPER, JR., (retired) American Electric Power, Inc., Lampasas, TX
CHARLES H. GOODMAN (retired), Southern Company Services, Inc., Birmingham, AL
SHERRI GOODMAN, CNA, Alexandria, VA
NARAIN HINGORANI, Consultant, Los Altos Hills, CA
WILLIAM F. POWERS (retired), Ford Motor Company, Ann Arbor, MI
MICHAEL P. RAMAGE (retired), ExxonMobil Research and Engineering Company, Moorestown, NJ
DAN REICHER, Google.org, Warren, VT
MAXINE L. SAVITZ (retired), Honeywell, Inc., Los Angeles, CA
MARK H. THIEMENS, University of California, San Diego
SCOTT W. TINKER, University of Texas, Austin

Senior Staff

JAMES ZUCCHETTO, Director
DUNCAN BROWN, Senior Program Officer
DANA CAINES, Financial Associate
ALAN CRANE, Senior Program Officer
K. JOHN HOLMES, Senior Program Officer
LANITA JONES, Administrative Coordinator
JASON ORTEGO, Senior Program Assistant
MADELINE WOODRUFF, Senior Program Officer
JONATHAN YANGER, Senior Program Assistant

BOARD ON SCIENCE, TECHNOLOGY, AND ECONOMIC POLICY

Members

EDWARD E. PENHOET (*Chair*), Alta Partners, San Francisco, CA

LEWIS W. COLEMAN, DreamWorks Animation, Glendale, CA

MARY L. GOOD, University of Arkansas, Little Rock

RALPH E. GOMORY, president emeritus, Alfred P. Sloan Foundation; New York University,
New York, NY

AMORY ‘AMO’ HOUGHTON, JR. (former member of U.S. Congress), Cohasset, MA

DAVID T. MORGENTHALER, Morgenthaler Ventures, Cleveland, OH

JOSEPH P. NEWHOUSE, Harvard University, Boston, MA

ARATI PRABHAKAR, U.S. Venture Partners, Menlo Park, CA

WILLIAM J. RADUCHEL, independent director and investor, Great Falls, VA

JACK W. SCHULER, Crabtree Partners, Chicago, IL

ALAN WILLIAM WOLFF, Dewey & LeBoeuf LLP, Washington, DC

Senior Staff

STEVE MERRILL, Director

DANIEL MULLINS, Senior Program Associate

**OTHER REPORTS OF THE
BOARD ON ENVIRONMENTAL STUDIES AND TOXICOLOGY**

Contaminated Water Supplies at Camp Lejeune—Assessing Potential Health Effects (2009)
Review of the Federal Strategy for Nanotechnology-Related Environmental, Health, and Safety Research (2009)
Science and Decisions: Advancing Risk Assessment (2009)
Phthalates and Cumulative Risk Assessment: The Tasks Ahead (2008)
Estimating Mortality Risk Reduction and Economic Benefits from Controlling Ozone Air Pollution (2008)
Respiratory Diseases Research at NIOSH (2008)
Evaluating Research Efficiency in the U.S. Environmental Protection Agency (2008)
Hydrology, Ecology, and Fishes of the Klamath River Basin (2008)
Applications of Toxicogenomic Technologies to Predictive Toxicology and Risk Assessment (2007)
Models in Environmental Regulatory Decision Making (2007)
Toxicity Testing in the Twenty-first Century: A Vision and a Strategy (2007)
Sediment Dredging at Superfund Megsites: Assessing the Effectiveness (2007)
Environmental Impacts of Wind-Energy Projects (2007)
Scientific Review of the Proposed Risk Assessment Bulletin from the Office of Management and Budget (2007)
Assessing the Human Health Risks of Trichloroethylene: Key Scientific Issues (2006)
New Source Review for Stationary Sources of Air Pollution (2006)
Human Biomonitoring for Environmental Chemicals (2006)
Health Risks from Dioxin and Related Compounds: Evaluation of the EPA Reassessment (2006)
Fluoride in Drinking Water: A Scientific Review of EPA's Standards (2006)
State and Federal Standards for Mobile-Source Emissions (2006)
Superfund and Mining Megsites—Lessons from the Coeur d'Alene River Basin (2005)
Health Implications of Perchlorate Ingestion (2005)
Air Quality Management in the United States (2004)
Endangered and Threatened Species of the Platte River (2004)
Atlantic Salmon in Maine (2004)
Endangered and Threatened Fishes in the Klamath River Basin (2004)
Cumulative Environmental Effects of Alaska North Slope Oil and Gas Development (2003)
Estimating the Public Health Benefits of Proposed Air Pollution Regulations (2002)
Biosolids Applied to Land: Advancing Standards and Practices (2002)
The Airliner Cabin Environment and Health of Passengers and Crew (2002)
Arsenic in Drinking Water: 2001 Update (2001)
Evaluating Vehicle Emissions Inspection and Maintenance Programs (2001)
Compensating for Wetland Losses Under the Clean Water Act (2001)
A Risk-Management Strategy for PCB-Contaminated Sediments (2001)
Acute Exposure Guideline Levels for Selected Airborne Chemicals (seven volumes, 2000-2009)
Toxicological Effects of Methylmercury (2000)
Strengthening Science at the U.S. Environmental Protection Agency (2000)
Scientific Frontiers in Developmental Toxicology and Risk Assessment (2000)
Ecological Indicators for the Nation (2000)
Waste Incineration and Public Health (2000)
Hormonally Active Agents in the Environment (1999)
Research Priorities for Airborne Particulate Matter (four volumes, 1998-2004)
The National Research Council's Committee on Toxicology: The First 50 Years (1997)
Carcinogens and Anticarcinogens in the Human Diet (1996)
Upstream: Salmon and Society in the Pacific Northwest (1996)

Science and the Endangered Species Act (1995)
Wetlands: Characteristics and Boundaries (1995)
Biologic Markers (five volumes, 1989-1995)
Science and Judgment in Risk Assessment (1994)
Pesticides in the Diets of Infants and Children (1993)
Dolphins and the Tuna Industry (1992)
Science and the National Parks (1992)
Human Exposure Assessment for Airborne Pollutants (1991)
Rethinking the Ozone Problem in Urban and Regional Air Pollution (1991)
Decline of the Sea Turtles (1990)

*Copies of these reports may be ordered from the National Academies Press
(800) 624-6242 or (202) 334-3313
www.nap.edu*

OTHER REPORTS OF THE BOARD ON ENERGY AND ENVIRONMENTAL SYSTEMS

- Letter Report on Review of Site and Full-Fuel-Cycle Measurement Approaches to DOE/EERE Building Appliance Energy-Efficiency Standards (2009)
- Assessing Economic Impacts of Greenhouse Gas Mitigation: Summary of a Workshop (2009)
- Review of the 21st Century Truck Partnership (2008)
- Review of the Research Program of the FreedomCAR and Fuel Partnership, Second Report (2008)
- Transitions to Alternative Transportation Technologies—A Focus on Hydrogen (2008)
- Letter Report: Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy (2008)
- Review of DOE's Nuclear Energy Research and Development Program (2007)
- Alternatives to the Indian Point Energy Center for Meeting New York Electric Power Needs (2006)
- Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two) (2006).
- Trends in Oil Supply and Demand, Potential for Peaking of Conventional Oil Production, and Possible Mitigation Options: A Summary Report of the Workshop (2006)
- Review of the Research Program of the FreedomCAR and Fuel Partnership, First Report (2005).
- Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look Forward (2005).
- Letter Report: Methodology for Estimating Prospective Benefits of Energy Efficiency and Fossil Energy R&D (2004)
- The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs (2004)
- Final Letter Report by the National Research Council Committee on Novel Approaches to Management of Greenhouse Gases from Energy Systems (2004)
- Workshop Report: Novel Approaches to Carbon Management: Separation, Capture, Sequestration, and Conversion to Useful Products (2003)
- Letter Report: Strategies and Alternatives for Future Hydrogen Production and Use (2003)
- Letter Report: Critique of the Sargent and Lundy Assessment of Cost and Performance Forecasts for Concentrating Solar Power Technology (2002)
- Making the Nation Safer, The Role of Science and Technology in Countering Terrorism: Panel on Energy Facilities and Cities (2002)
- Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards (2002)
- Review of the DOE's Vision 21 Research and Development Program—Phase I (2002)
- The Disposition Dilemma: Controlling the Release of Solid Materials from Nuclear Regulatory Commission-Licensed Facilities (2002)
- Energy Research at DOE: Was It Worth It?: Energy Efficiency and Fossil Energy Research 1978 to 2000 (2001)
- Review of the Research Program of the Partnership for a New Generation of Vehicles, Seventh Report (2001)
- Review of the Research Program of the Partnership for a New Generation of Vehicles, Sixth Report (2000)
- Review of the U.S. Department of Energy's Office of Heavy Vehicle Technologies Program (2000)
- Vision 21: Fossil Fuel Options for the Future (2000)
- Renewable Power Pathways: A Review of the U.S. Department of Energy's Renewable Energy Programs (2000)
- Letter Report on Recent Initiatives by the Office of Energy Efficiency & Renewable Energy and the Office of Power Technologies (2000)
- Review of DOE's Office of Fossil Energy's Research Plan for Fine Particulates (1999)
- Review of the Research Strategy for Biomass-Derived Transportation Fuels (1999)
- Review of the Research Program of the Partnership for a New Generation of Vehicles, Fifth Report (1999)

Review of the Research Program of the Partnership for a New Generation of Vehicles, Fourth Report (1998)
Review of the R&D Plan for the U.S. Department of Energy's Office of Advanced Automotive Technologies (1998)
Effectiveness of the United States Advanced Battery Consortium as a Government-Industry Partnership (1998)
Review of the Research Program of the Partnership for a New Generation of Vehicles, Third Report (1997)
Application of Digital Instrumentation and Control Technology to Nuclear Power Plant Operations and Safety (Phase 1, 1995; Phase 2, 1997)
Review of the Research Program of the Partnership for a New Generation of Vehicles, Second Report (1996)
Decontamination & Decommissioning of Uranium Enrichment Facilities (1996)
Separations Technology and Transmutation Systems (1995)
Coal: Energy for the Future (1995)
Review of the Research Program of the Partnership for a New Generation of Vehicles, First Report (1994)
Review of the Strategic Plan of the U.S. Department of Energy's Office of Conservation and Renewable Energy (1993)
Nuclear Power: Technical and Institutional Options for the Future (1992)
Automotive Fuel Economy: How Far Should We Go? (1992)
The National Energy Modeling System (1992)
Potential Applications of Concentrated Solar Photons (1991)
Assessment of Research Needs for Wind Turbine Rotor Materials Technology (1991)
Alternative Applications of Atomic Vapor Laser Isotope Separation Technology (1991)
Fuels to Drive Our Future (1990)
Confronting Climate Change: Strategies for Energy Research and Development (1990)
Nuclear Engineering Education: Status and Prospects (1990)
University Research Reactors in the United States—their Role and Value (1988)

**OTHER REPORTS OF THE
BOARD ON SCIENCE, TECHNOLOGY, AND ECONOMIC POLICY**

- 21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change: Report of a Symposium (2009)
- Innovative Flanders: Innovation Policies for the 21st Century: Report of a Symposium (2008)
- Innovation in Global Industries: U.S. Firms Competing in a New World (Collected Studies) (2008)
- India's Changing Innovation System: Achievements, Challenges, and Opportunities for Cooperation: Report of a Symposium (2007)
- Innovation Policies for the 21st Century: Report of a Symposium
- Committee on Comparative Innovation Policy: Best Practice for the 21st Century (2007)
- Innovation Inducement Prizes at the National Science Foundation (2007)
- Enhancing Productivity Growth in the Information Age: Measuring and Sustaining the New Economy (2007)
- The Telecommunications Challenge: Changing Technologies and Evolving Policies - Report of a Symposium (2006)
- Aeronautics Innovation: NASA's Challenges and Opportunities (2006)
- Measuring and Sustaining the New Economy, Software, Growth, and the Future of the U.S Economy: Report of a Symposium (2006)
- Reaping the Benefits of Genomic and Proteomic Research: Intellectual Property Rights, Innovation, and Public Health (2006)
- Deconstructing the Computer: Report of a Symposium (2005)
- Partnering Against Terrorism: Summary of a Workshop (2005)
- Research and Development Data Needs: Proceedings of a Workshop (2005)
- Productivity and Cyclicity in Semiconductors: Trends, Implications, and Questions -- Report of a Symposium (2005)
- A Patent System for the 21st Century (2004)
- Patents in the Knowledge-Based Economy (2003)
- Securing the Future: Regional and National Programs to Support the Semiconductor Industry (2003)
- Government-Industry Partnerships for the Development of New Technologies (2002)
- Partnerships for Solid-State Lighting: Report of a Workshop (2002)
- Using Human Resource Data to Track Innovation: Summary of a Workshop (2002)
- Medical Innovation in the Changing Healthcare Marketplace: Conference Summary (2002)
- Measuring and Sustaining the New Economy: Report of a Workshop (2002)
- Trends in Federal Support of Research and Graduate Education (2001)
- The Advanced Technology Program: Assessing Outcomes (2001)
- A Review of the New Initiatives at the NASA Ames Research Center: Summary of a Workshop (2001)
- Capitalizing on New Needs and New Opportunities: Government - Industry Partnerships in Biotechnology and Information Technologies (2001)
- Building a Workforce for the Information Economy (2001)

*Copies of these reports may be ordered from the National Academies Press
(800) 624-6242 or (202) 334-3313
www.nap.edu*

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

Preface

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

Contents

SUMMARY	3
1 INTRODUCTION	17
Genesis of the Study, 17	
Statement of Task, 17	
Related Studies, 19	
Defining and Measuring Externalities, 22	
Selecting Energy Sources and Uses for This Study, 26	
Framework for Evaluating External Effects, 32	
The Policy Context for This Study, 39	
Some Methodological Issues: Space, Time, and Uncertainty, 41	
Organization of the Report, 45	
2 ENERGY FOR ELECTRICITY	47
Background, 47	
Electricity Production from Coal, 52	
Electricity Production from Natural Gas, 81	
Electricity Production from Nuclear Power, 93	
Electricity Production from Wind, 101	
Electricity Production from Solar Power, 105	
Electricity Production from Biomass, 107	
Transmission and Distribution of Electricity, 108	
Summary, 109	
3 ENERGY FOR TRANSPORTATION	113
Background, 113	
Approach to Analyzing Effects and Externalities of Transportation Energy Use, 115	
Production and Use of Petroleum-Based Fuels, 121	
Production and Use of Biofuels, 132	
Electric Vehicles, 143	
Natural Gas, 147	
Hydrogen Fuel Cell Vehicles, 149	
Summary and Conclusions, 150	
4 ENERGY FOR HEAT	161
Background, 161	
Heat in Residential and Commercial Buildings, 164	
Heat in the Industrial Sector, 165	
Estimates of Externalities Associated with Energy Use for Heat, 168	
Emissions of Greenhouse Gases, 173	
Potential Damages Reductions in 2030, 174	
Summary, 178	

Contents

5	CLIMATE CHANGE	179
	Overview of Quantifying and Valuing Climate Change Impacts, 179	
	Impacts on Physical and Biological Systems, 188	
	Impacts on Human Systems, 192	
	Economic Damage from Irreversible and Abrupt Climate Change, 208	
	Aggregate Impacts of Climate Change, 211	
	Marginal Impacts of Greenhouse Gas Emissions, 213	
	Research Recommendations, 220	
6	INFRASTRUCTURE AND SECURITY	222
	Introduction, 222	
	Disruption Externalities in the Electricity Grid, 222	
	Facility Vulnerability to Accidents and Attacks, 226	
	External Costs of Oil Consumption, 233	
	Security of Energy Supply, 236	
	National Security Externalities, 237	
	Conclusion, 240	
7	OVERALL CONCLUSIONS AND RECOMMENDATIONS	241
	The Committee’s Analyses, 241	
	Limitations in the Analyses, 242	
	Electricity Generation, 242	
	Transportation, 250	
	Heat Generation, 258	
	Climate Change, 259	
	Comparing Climate and Non-Climate Damage Estimates, 260	
	Overall Conclusions and Implications, 261	
	Research Recommendations, 265	
	REFERENCES	269
	ABBREVIATIONS	296
	COMMON UNITS AND CONVERSIONS	299

APPENDIXES

A	BIOGRAPHICAL INFORMATION ON THE COMMITTEE ON HEALTH, ENVIRONMENTAL, AND OTHER EXTERNAL COSTS AND BENEFITS OF ENERGY PRODUCTION AND CONSUMPTION	305
B	A SIMPLE DIAGRAMMATIC EXAMPLE OF AN EXTERNALITY	311
C	DESCRIPTION OF APEEP MODEL AND ITS APPLICATION	313
D	DESCRIPTION OF GREET AND MOBILE6 MODELS AND THEIR APPLICATION	319
E	SUPPLEMENTAL INFORMATION ON LAND USE EXTERNALITIES FROM BIOFUELS: A CASE STUDY OF THE BOONE RIVER WATERSHED	348

Contents

BOXES, FIGURES AND TABLES

BOXES

- 1-1 Statement of Task, 18
- 1-2 Definitions of Key Terms, 23
- 2-1 Airborne Particulate Matter, 50
- 2-2 Entrainment and Impingement of Aquatic Organisms by Thermal Power Plants, 98
- 4-1 Definition of Residential, Commercial, and Industrial Sectors, 162
- 4-2 Energy for Heat in Steel Manufacture, 166
- 4-3 Zero-Energy Concept Home, 175
- 5-1 Estimating the Impacts of Climate Change on Agriculture, 203
- 5-2 Discounting and Equity Weighting, 217

FIGURES

- S-1 Distribution of aggregate damages among the 406 coal-fired power plants analyzed in this study, 5
- S-2 Distribution of aggregate damages among the 498 natural gas-fired power plants analyzed in this study, 7
- 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 and 2030, 11
- S-4 GHG emissions (grams CO₂-eq)/VMT by life-cycle component for different combinations of fuels and light-duty automobiles in 2005 and 2030, 13
- 1-1 Marginal damage associated with sulfur dioxide emissions in a year (x-axis) and the marginal cost of emitting SO₂ in a year (y-axis) for a hypothetical power plant (Firm 1) emitting SO₂, 25
- 1-2 Sources and forms of energy that provide the ability to do useful work, 27
- 1-3 Energy flows in the U.S. economy, 2007, 28
- 1-4 U.S. consumption of primary energy sources in 2007, 28
- 1-5 U.S. consumption of energy by sector in 2007, 29
- 1-6 U.S. delivered energy consumption by end-use sector in 2007, 30
- 1-7 Life-cycle analysis for energy use, 33
- 2-1 Major coal producing regions in the United States (million short tons and percent change from 2006), 53
- 2-2 Methods of U.S. coal transport, 54
- 2-3 Injuries in U.S. coal mining operations from 2000 to 2008, 56
- 2-4 U.S. coal production 1949-2007, by mining method, 59
- 2-5 Distribution of aggregate damages in 2005 by decile: Coal plants, 65
- 2-6 Air pollution damages from coal generation for 406 plants, 2005 (2007 USD), 67
- 2-7 Distribution of air pollution damages per kWh for 406 coal plants, 2005 (USD 2007), 68
- 2-8 Regional distribution of air pollution damages from coal generation per kWh in 2005, (USD 2007), 69
- 2-9 Coal combustion product beneficial use versus production, 78
- 2-10 U.S. natural gas well average productivity, 82
- 2-11 Natural gas production, consumption, and imports in the United States, 82
- 2-12 U.S. fatalities in oil and gas extraction from 1992 to 2007, 85
- 2-13 Injuries and illnesses in U.S. oil and natural gas extraction operations, 85
- 2-14 Distribution of aggregate damages in 2005 by decile: Natural gas fired plants, 88
- 2-15 Criteria air pollution damages from gas generation for 498 plants, 2005 (USD 2007), 89
- 2-16 Distribution of criteria air pollution damages per kWh of emissions for 498 natural gas fired plants, 2005, 91
- 2-17 Regional distribution of criteria air pollution damages from gas generation per kWh, (2007 USD), 92
- 2-18 Locations of operating nuclear power reactors in the United States, 94
- 2-19 Locations of power reactor sites undergoing decommissioning in the United States, 94
- 3-1 U.S. transportation energy consumption by mode and vehicle in 2003, 114
- 3-2 Overview of petroleum consumption, production, and imports from 1949 to 2007, 121
- 3-3 Location of U.S. oil refineries, 122
- 3-4 Products made from one barrel of crude oil (gallons), 123
- 3-5 U.S. refinery and blender net production of refined petroleum products in 2007, 123
- 3-6 Conceptual stages of fuel life cycle, 125

Contents

- 3-7a Aggregate 2005 life-cycle damages of light-duty vehicles from air pollutant, excluding GHGs emissions (cents/VMT), 152
- 3-7b Aggregate 2030 life-cycle damages of light-duty vehicles from air pollutant, excluding GHGs emissions (cents/VMT), 152
- 3-8 GHG emissions (grams CO₂ equivalent)/VMT by life-cycle component for light-duty automobiles in 2005 and 2030, 156-157
- 3-9 Aggregate operation, feedstock, and fuel damages of heavy-duty vehicles from air pollutant emissions (excluding GHGs) (cents/VMT), 158
- 3-10 Aggregate operation, feedstock, and fuel damages of heavy-duty vehicles from GHG emissions (cents/VMT), 159
- 4-1 Total U.S. energy use by sector, 2008, 162
- 4-2 U.S. energy consumption by source and sector, 2008 (quadrillion Btu), 163
- 4-3 Energy use, energy intensity, output, and structural effects in the industrial sector, 1985-2004, 167
- 4-4 Manufacturing sector consumption of natural gas as a fuel by industry, 2002, 168
- 4-5 GHG emissions in the United States by sector, 174
- 5-1 Global anthropogenic GHG emissions, 180
- 5-2 Atmosphere-ocean general circulation model projections of surface warming, 182
- 5-3 Global CO₂ emissions for 1940 to 2000 and emissions ranges for categories of stabilization scenarios from 2000 to 2100; and the corresponding relationship between the stabilization target and the likely equilibrium global average temperature increase above pre-industrial, 184
- 5-4 Multi-model projected patterns of precipitation changes, 190
- 5-5 Examples of regional impacts of climate change, 195
- 5-6 Mid-Atlantic wetland marginalization and loss as a consequence of sea-level rise, 197
- 5-7 Impact of increased temperature and precipitation on agricultural productivity, 204
- 5-8 Irreversible precipitation changes by region, 210
- 5-9 Dependence of GHG damage on the amount of temperature change, 214
- 5-10 Dependence of GHG damage, as a percent of global gross domestic product, on the amount of temperature change, 215
- 6-1 Illustration of monopsony, 235
- 7-1 Distribution of aggregate damages by decile: Coal plants (2007 USD), 244
- 7-2 Air pollution damages from coal generation for 406 plants, 2005, 245
- 7-3 Distribution of air pollution damages per kWh for 406 coal plants, 2005 (2007 USD), 246
- 7-4 Distribution of aggregate damages by decile: gas plants (2007 USD), 246
- 7-5 Air pollution damages from gas generation for 498 plants, 2005, 247
- 7-6a-b Aggregate life-cycle damages of light-duty vehicles from air pollutants, excluding GHGs emissions (cents/VMT) for 2005 and 2030, 253-254
- 7-7a-b GHG emissions (grams CO₂-eq)/VMT by life-cycle component for light-duty automobiles in 2005 and 2030, 256-257
- B-1 Pollution abatement and cost per ton of abatement, 312
- E-1 The Boone River Watershed, 349

TABLES

- 1-1 Committee Study Approach for Energy Sources and Consumption Sectors, 30
- 1-2 Illustrative Impacts of Producing Electricity from Coal, 34
- 1-3 Illustrative Impact Categories Pathways, 37
- 2-1 Net Electricity Generation by Energy, 48
- 2-2 Energy for Electricity: Impacts and Externalities Discussed, Quantified, or Monetize, 51
- 2-3 Coal Classification by Type, 52
- 2-4 Five Leading Coal-Producing States, 2007, by Mine Type and Production (Thousand Short Tons), 54
- 2-5 Estimated Recoverable Reserves for the 10 States with the Largest Reserves, by Mining Method for 2005 (million short tons), 56
- 2-6 Estimated Injuries, Illnesses, and Fatalities during Rail Transport of Coal for Electricity Power, 2007, 58
- 2-7 Distribution of Criteria Air Pollution Damages Associated with Emissions from 406 Coal-Fired Power Plants in 2005 (USD 2007), 65

Contents

- 2-8 Distribution of Criteria Air Pollution Damages per Ton of Emissions from Coal-Fired Power Plants (USD 2007), 65
- 2-9 Distribution of Criteria Air Pollutant Damages per kWh Associated with Emissions from 406 Coal-Fired Power Plants in 2005 (2007 Cents), 66
- 2-10 NO_x and SO₂ Emissions (2002) from Coal-Fired Electricity Generation by Age of Power Plant, 70-71
 - a. 2002 NO_x Emissions and Share of Generation of Coal-Fired Capacity by Vintage, 70
 - b. 2002 SO₂ Emissions and Performance of Coal-Fired Capacity by Vintage, 70
 - c. 2002 NO_x Emissions and Share of Generation of Coal-Fired Capacity by NSPS, 70
 - d. 2002 SO₂ Emissions and Performance of Coal-Fired Capacity by NSPS, 71
- 2-11 Distribution of Pounds of Criteria-Pollutant Forming Emissions per MWh by Coal-Fired Power Plants, 2005, 72
- 2-12 2007 Coal Combustion Product (CCP) Production and Use Survey Results, 76
- 2-13 IPCC Range of Aggregate Costs for CO₂ Capture, Transport, and Geological Storage, 79
- 2-14 Distribution of Criteria Pollution Damages Associated with Emissions from 498 Gas-Fired Power Plants in 2005 (2007 USD), 87
- 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), 88
- 2-16 Distribution of Pounds of Criteria-Pollutant Forming Emissions per MWh by Gas-Fired Power Plants, 2005, 90
- 2-17 Distribution of Damages per Ton of Criteria-Pollutant Forming Emissions by Gas-Fired Power Plants (USD 2007), 90
- 2-18 U.S. Nuclear Power Reactors Undergoing Decommissioning, 95
- 3-1 Vehicle-Fuel Technologies in the Committee's Analysis, 118
- 3-2 Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances, 124
- 3-3 Health and Other Non-GHG Damages from a Series of Gasoline and Diesel Fuels Used in Light-duty Autos, 130
- 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), 131
- 3-5 Carbon Dioxide Equivalent (CO₂-eq) Emissions of Greenhouse Gases from a Series of Gasoline and Diesel Fuels, 131
- 3-6 Feedstocks Identified in AEF Report and Partial List of Their Externalities, 133
- 3-7 Water Quality and Externalities Estimated for Ethanol Scenarios, 139
- 3-8 Estimated Ethanol Production from Feedstocks in the Boone River Watershed, 140
- 3-9 Monetized Land-Use Damages of the Boone-River Case Study, 141
- 3-10 Comparison of Health and Other Non-GHG Damages from Conventional Gasoline to Three Ethanol Feedstocks, 142
- 3-11 Plausible LDV Market Shares of Advanced Vehicles by 2020 and 2035, 143
- 3-12 Energy Use During Vehicle Manufacturing and Disposal from AEF Report, 145
- 3-13 Comparison of Health and Other Non-GHG Damage Estimates for Hybrid and Electric Vehicle Types with Conventional Gasoline 2005 and 2030, 146
- 3-14 Health and Other Non-GHG Damages from CNG Light-Duty Autos and Trucks (Values Reported in Cents/VMT), 148
- 3-15 Carbon Dioxide equivalent (CO₂-eq) Emissions of Greenhouse Gases from CNG Autos and Light-Duty Trucks Compared to Reformulated Gasoline Vehicles (Grams/VMT), 149
- 3-16 Health and Other Non-GHG Damages from Hydrogen Fuel Cell Autos Compared to Reformulated Gasoline Autos, 149
- 3-17 Carbon Dioxide Equivalent (CO₂-eq) Emissions of Greenhouse Gases from Hydrogen Fuel Cell Autos Compared to Reformulated Gasoline Autos, 150
- 3-18 Relative Categories of Damages 2005 and 2030 for Major Categories of Light-Duty Fuels and Technologies, 151
- 3-19 Relative Categories of GHG Emissions 2005 and 2030 for Major Categories of Light-Duty Fuels and Technologies, 154
- 4-1 U.S. Non-Electric Energy Consumption by Source and End-Use Sector: Years 2007 and 2030 (EIA Estimates) (Quadrillion Btu), 165

Contents

- 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), 169
- 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 3,100 Counties), 170
- 4-4 Commercial Sector Natural Gas Use for Heat: National Damage Estimates from Air Pollutants (Excluding GHGs) (cents/MCF in 2007 USD), 171
- 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, 183
- 5-2 Climate-related Observed Trends of Various Components of the Global Freshwater Systems, 191
- 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, 194
- 5-4 Water Availability Effects from Climate Change for Selected Studies (Percent of Contemporaneous GDP Around 2100), 195
- 5-5 Values of the Benchmarking Parameter, 199
- 5-6 Benchmark Sea-Level Rise Estimates in FUND, 200
- 5-7 Estimates of Total Damage Due to Climate Change from Benchmark Warming (Percent Change in Annual GDP), 212
- 5-8 Marginal Global Damages from GHG Emissions: Estimates from Widely Used Models, 214
- 5-9 Indicative Marginal Global Damages from Current GHG Emissions (\$/Ton CO₂-eq), 218
- 5-10 Illustration of Ranges of Climate-related Damages for Selected Categories of Energy Use in the United States, 2005, 220
- 6-1 Net Stock of Energy-related Fixed Assets in 2007 (\$Billions), 223
- 6-2 Estimates of the Average Cost of Outages, 224
- 6-3 LNG Infrastructure and Safety Record, 228
- 6-4 Average Number and Volume of Oil Spills on U.S. Soil, 1990-1998, 230
- 6-5 Annual Averages for Significant Pipeline Incidents, 2002-2006, 231
- 6-6 Annual Averages for Pipelines Per Ton Miles, 2002-2006, 231
- 6-7 U.S. Oil Dependence, 234
- 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, 251
- 7-2 Relative Categories of GHG Emissions 2005 and 2030 for Major Categories of Light-Duty Fuels and Technologies, 255
- 7-3 Monetized Damages Per Unit of Energy-related Activity, 261
- C-1 Epidemiology Studies Employed in APEEP, 316
- C-2 Concentration-Response Studies Employed in APEEP, 316
- C-3 Value of Human Health Effects in APEEP, 316
- C-4 Value of Non-Market Impacts of Air Pollution, 317
- D-1 GREET 2.7a Vehicle Manufacturing Results for Cars, 322
- D-2 GREET 2.7a Vehicle Manufacturing Results for SUVs, 323
- D-3 GREET Energy and Emission Factors for Light-Duty Autos in 2005, 324
- D-4 GREET Energy and Emission Factors for Light-Duty Trucks 1 in 2005, 327
- D-5 GREET Energy and Emission Factors for Light-Duty Trucks 2 in 2005, 330
- D-6 GREET Energy and Emission Factors for Light-Duty Autos in 2020, 333
- D-7 GREET Energy and Emission Factors for Light-Duty Trucks 1 in 2020, 336
- D-8 GREET Energy and Emission Factors for Light-Duty Trucks 2 in 2020, 339
- D-9 Mobile 6.2 Energy and Emission Factors for Heavy-Duty Vehicles in 2005, 343
- D-10 Mobile 6.2 Energy and Emission Factors for Heavy-Duty Vehicles in 2030, 343
- D-11 Comparison of Emission Factors (g/VMT) for a Light-Duty Gasoline Automobile in 2005, 344
- D-12 Comparison of Emission Factors (g/VMT) for a Light-Duty Diesel Automobile in 2005, 344
- D-13 Mobile 6.2 Ammonia Emissions (g/VMT), 345
- E-1 Boone River Watershed Baseline Cropping Pattern, 350