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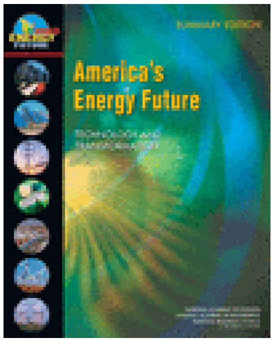


## America's Energy Future: Technology and Transformation: Summary Edition

Committee on America's Energy Future; National Academy of Sciences; National Academy of Engineering; National Research Council

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# Executive Summary

This report of the Committee on America's Energy Future addresses a potential new portfolio of energy-supply and end-use technologies—their states of development, costs, implementation barriers, and impacts—both at present and projected over the next two to three decades. The report's aim is to inform policy makers about technology options for transforming energy production, distribution, and use to increase sustainability, support long-term economic prosperity, promote energy security, and reduce adverse environmental impacts. Among the wide variety of technologies under development that *might* become available in the future, this report focuses on those with the best prospects of fully maturing during the three time periods considered: 2008–2020, 2020–2035, and 2035–2050.

Eight key findings emerge.

**First, with a sustained national commitment, the United States could obtain substantial energy efficiency improvements, new sources of energy, and reductions in greenhouse gas emissions through the accelerated deployment of existing and emerging energy-supply and end-use technologies.** These options are described in more detail below and in Chapter 2. Mobilization of the public and private sectors, supported by sustained long-term policies and investments, will be required for the decades-long effort to develop, demonstrate, and deploy these technologies. Moreover, actions taken between now and 2020 to develop and demonstrate several key technologies will largely determine options for many decades to come. Therefore, it is imperative that the technology development and demonstration activities identified in this report be started soon, even though some will be expen-



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sive and not all will be successful: some may fail, prove uneconomic, or be overtaken by better technologies.

**Second, the deployment of existing energy efficiency technologies is the nearest-term and lowest-cost option for moderating our nation's demand for energy, especially over the next decade. The potential energy savings available from the accelerated deployment of existing energy efficiency technologies in the buildings, transportation, and industrial sectors could more than offset the U.S. Energy Information Administration's (EIA's) projected increases in energy consumption through 2030.** In fact, the full deployment of cost-effective energy efficiency technologies in buildings alone could eliminate the need to construct any new electricity-generating plants in the United States except to address regional supply imbalances, replace obsolete power generation assets, or substitute more environmentally benign electricity sources—assuming, of course, that these efficiency savings are not used to support increased use of electricity in other sectors. Accelerated deployment of these technologies in the buildings, transportation, and industrial sectors could reduce energy use by about 15 percent (15–17 quads, that is, quadrillions of British thermal units) in 2020, relative to the EIA's "business as usual" reference case projection, and by about 30 percent (32–35 quads) in 2030 (U.S. energy consumption in 2007 was about 100 quads). Even greater energy savings would be possible with more aggressive policies and incentives. Most of these energy efficiency technologies are cost-effective now and are likely to continue to be competitive with any future energy-supply options; moreover, additional energy efficiency technologies continue to emerge.

**Third, the United States has many promising options for obtaining new supplies of electricity and changing its supply mix during the next two to three decades, especially if carbon capture and storage and evolutionary nuclear plants can be deployed at required scales. However, the deployment of these new supply technologies is very likely to result in higher consumer prices for electricity.**

- Renewable-energy sources could provide about an additional 500 TWh (500 trillion kilowatt-hours) of electricity per year by 2020 and about an additional 1100 TWh per year by 2035 through new deployments in favorable resource locations (total U.S. electricity consumption at present is about 4000 TWh per year).

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- Coal-fired plants with carbon capture and storage (CCS) could provide as much as 1200 TWh of electricity per year by 2035 through repowering and retrofits of existing plants and as much as 1800 TWh per year by 2035 through new plant construction. In combination, the entire existing coal power fleet could be replaced by CCS coal power by 2035.
- Nuclear plants could provide an additional 160 TWh of electricity per year by 2020, and up to 850 TWh by 2035, by modifying current plants to increase their power output and by constructing new plants.
- Natural gas generation of electricity could be expanded to meet a substantial portion of U.S. electricity demand by 2035. However, it is not clear whether adequate supplies of natural gas will be available at competitive prices to support substantially increased levels of electricity generation, and such expansion could expose the United States to greater import dependence and result in increased emissions of carbon dioxide ($CO_2$).

**Fourth, expansion and modernization of the nation's electrical transmission and distribution systems (i.e., the power grid) are urgently needed. Expansion and modernization would enhance reliability and security, accommodate changes in load growth and electricity demand, and enable the deployment of new energy efficiency and supply technologies, especially intermittent wind and solar energy.**

**Fifth, petroleum will continue to be an indispensable transportation fuel during the time periods considered in this report. Maintaining current rates of domestic petroleum production (about 5.1 million barrels per day in 2007) will be challenging. There are limited options for replacing petroleum or reducing petroleum use before 2020, but there are more substantial longer-term options that could begin to make significant contributions in the 2030–2035 timeframe.** Options for obtaining meaningful reductions in petroleum use in the transportation sector include the following:

- *Improving vehicle efficiency.* Technologies to improve vehicle efficiency are available for deployment now, and new technologies continue to emerge.
- *Developing technologies for the conversion of biomass and coal-to-liquid fuels.* By 2035, cellulosic ethanol and coal-and-biomass-

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to-liquid fuels with CCS could replace about 15 percent of the fuel currently consumed in the transportation sector (1.7–2.5 million barrels per day of gasoline equivalent) with near-zero life-cycle $CO_2$ emissions. Coal-to-liquid fuels with CCS could replace about 15–20 percent of current fuel consumption in the transportation sector (2–3 million barrels per day; the lower estimate holds if coal is also used to produce coal-and-biomass-to-liquid fuels) and would have life-cycle $CO_2$ emissions similar to those of petroleum-based fuels. However, these levels of production would require the annual harvesting of 500 million dry tonnes (550 million dry tons) of biomass and an increase in coal extraction in the United States by 50 percent over current levels, resulting in a range of potential environmental impacts on land, water, air, and human health—including increased $CO_2$ emissions to the atmosphere from coal-to-liquid fuels unless process $CO_2$ from liquid-fuel production plants is captured and stored geologically. Commercial demonstrations of the conversion technologies integrated with CCS will have to be pursued aggressively and proven economically viable by 2015 if these technologies are to be commercially deployable before 2020. The development of advanced biomass-conversion technologies will require fundamental advances in bioengineering and biotechnology.

- *Electrifying the light-duty vehicle fleet through expanded deployment of plug-in hybrids, battery electric vehicles, and hydrogen fuel-cell vehicles.* Such a transition would require the development of advanced battery and fuel-cell technologies as well as modernization of the electrical grid to manage the increased demand for electricity.

**Sixth, substantial reductions in greenhouse gas emissions from the electricity sector are achievable over the next two to three decades through a portfolio approach involving the widespread deployment of energy efficiency technologies; renewable energy; coal, natural gas, and biomass with carbon capture and storage; and nuclear technologies. Achieving substantial greenhouse gas reductions in the transportation sector over the next two to three decades will also require a portfolio approach involving the widespread deployment of energy efficiency technologies, alternative liquid fuels with low life-cycle $CO_2$ emissions, and light-duty vehicle electrification technologies.**

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To enable this portfolio approach in the electricity sector, the viability of two key technologies must be demonstrated during the next decade to allow for their widespread deployment starting around 2020:

- Demonstrate whether CCS technologies for sequestering carbon from the use of coal and natural gas to generate electricity are technically and commercially viable for application to both existing and new power plants. This will require the construction before 2020 of a suite (~15–20) of retrofit and new demonstration plants with CCS featuring a variety of feedstocks, generation technologies, carbon capture strategies, and geologic storage locations.
- Demonstrate whether evolutionary nuclear plants are commercially viable in the United States by constructing a suite of about five plants during the next decade.

A failure to demonstrate the viability of these technologies during the next decade would greatly restrict options to reduce the electricity sector's $CO_2$ emissions over succeeding decades. The urgency of getting started on these demonstrations to clarify future deployment options cannot be overstated.

Reducing greenhouse gas emissions from the liquid-fuel-based transportation sector in the 2020–2035 timeframe will also require a portfolio approach that includes cellulosic ethanol and coal-and-biomass-to-liquid fuels. Coal-and-biomass-to-liquid fuels can be produced in quantity starting around 2020 but will not have low carbon emissions unless geologic storage of $CO_2$ is demonstrated to be safe and commercially viable by 2015. Further reductions in greenhouse gas emissions could potentially be achieved in the transportation sector through electrification of the light-duty vehicle fleet, together with the production of electricity and hydrogen in ways that emit little or no $CO_2$, assuming the availability of suitable batteries or fuel cells. Although substantial reductions in emissions via these pathways are not likely until late in the 2020–2035 period and beyond, the widespread deployment of hydrogen fuel-cell vehicles during that time also holds some hope for more substantial long-term emission reductions in the transportation sector.

**Seventh, to enable accelerated deployments of new energy technologies starting around 2020, and to ensure that innovative ideas continue to be explored, the**

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**public and private sectors will need to perform extensive research, development, and demonstration over the next decade.** Given the spectrum of uncertainties involved in the creation and deployment of new technologies, together with the differing technological needs and circumstances across the nation, a portfolio that supports a broad range of initiatives from basic research through demonstration will likely be more effective than targeted efforts to identify and select technology winners and losers. High-priority technology demonstration opportunities during the next decade include CCS, evolutionary nuclear power technologies, cellulosic ethanol, and advanced light-duty vehicles. Research and development opportunities during the next decade include advanced batteries and fuel cells, advanced large-scale storage for electrical load management, enhanced geothermal power, and advanced solar photovoltaic technologies.

**Eighth, a number of current barriers are likely to delay or even prevent the accelerated deployment of the energy-supply and end-use technologies described in this report. Policy and regulatory actions, as well as other incentives, will be required to overcome these barriers.** For technologies to be accepted in the market they must be clearly attractive—in terms of their performance, convenience, and cost—to investors, purchasers, and users. Regulations and standards that target performance characteristics can do a great deal to spur technological development and help improve market attractiveness.

Although the committee has done its best to identify those technologies likely to be available over the next two to three decades, many uncertainties remain on the scientific, technological, and policy frontiers and in energy markets. Consequently, the technology options identified in this report should be considered as important first-step technology assessments rather than as forecasts.

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# America's Energy Future

## TECHNOLOGY AND TRANSFORMATION

## SUMMARY EDITION

Committee on America's Energy Future

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NATIONAL ACADEMY OF ENGINEERING
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# Foreword

Energy, which has always played a critical role in our country's national security, economic prosperity, and environmental quality, has over the last two years been pushed to the forefront of national attention as a result of several factors:

- World demand for energy has increased steadily, especially in developing nations. China, for example, saw an extended period (prior to the current worldwide economic recession) of double-digit annual increases in economic growth and energy consumption.
- About 56 percent of the U.S. demand for oil is now met by depending on imports supplied by foreign sources, up from 40 percent in 1990.
- The long-term reliability of traditional sources of energy, especially oil, remains uncertain in the face of political instability and limitations on resources.
- Concerns are mounting about global climate change—a result, in large measure, of the fossil-fuel combustion that currently provides most of the world's energy.
- The volatility of energy prices has been unprecedented, climbing in mid-2008 to record levels and then dropping precipitously—in only a matter of months—in late 2008.
- Today, investments in the energy infrastructure and its needed technologies are modest, many alternative energy sources are receiving insufficient attention, and the nation's energy supply and distribution systems are increasingly vulnerable to natural disasters and acts of terrorism.



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All of these factors are affected to a great degree by the policies of government, both here and abroad, but even with the most enlightened policies the overall energy enterprise, like a massive ship, will be slow to change course. Its complex mix of scientific, technical, economic, social, and political elements means that the necessary transformational change in how we generate, supply, distribute, and use energy will be an immense undertaking, requiring decades to complete.

To stimulate and inform a constructive national dialogue about our energy future, the National Academy of Sciences and the National Academy of Engineering initiated a major study in 2007, "America's Energy Future: Technology Opportunities, Risks, and Tradeoffs." The America's Energy Future (AEF) project was initiated in anticipation of major legislative interest in energy policy in the U.S. Congress and, as the effort proceeded, it was endorsed by Senate Energy and Natural Resources Committee Chair Jeff Bingaman and former Ranking Member Pete Domenici.

The AEF project evaluates current contributions and the likely future impacts, including estimated costs, of existing and new energy technologies. It was planned to serve as a foundation for subsequent policy studies, at the Academies and elsewhere, that will focus on energy research and development priorities, strategic energy technology development, and policy analysis.

The AEF project has produced a series of five reports, plus this *Summary Edition*, designed to inform key decisions as the nation begins a comprehensive examination of energy policy issues this year. Numerous studies conducted by diverse organizations have benefited the project, but many of those studies disagree about the potential of specific technologies, particularly those involving alternative sources of energy such as biomass, renewable resources for generation of electric power, advanced processes for generation from coal, and nuclear power. A key objective of the AEF series of reports is thus to help resolve conflicting analyses and to facilitate the charting of a new direction in the nation's energy enterprise.

The AEF project, outlined in Appendix C, included a study committee and three panels that together have produced an extensive analysis of energy technology options for consideration in an ongoing national dialogue. A milestone in the project was the March 2008 "National Academies Summit on America's Energy Future" at which principals of related recent studies provided input to the AEF study committee and helped to inform the panels' deliberations. A report chronicling the event, *The National Academies Summit on America's Energy Future:*

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*Summary of a Meeting* (Washington, D.C.: The National Academies Press), was published in October 2008.

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# Preface

The security and sustainability of our nation's energy system have been perennial concerns since World War II. Indeed, all postwar U.S. presidents have focused some attention on energy-supply issues, especially our growing dependence on imported petroleum and the environmental impacts of fossil-fuel combustion—the latter including the direct effects of pollutant emissions on human health and, more recently, the impacts of greenhouse gases, particularly carbon dioxide ($CO_2$), on global warming.

The United States has made a great deal of progress in reducing traditional gaseous and particulate emissions (e.g., $SO_x$, $NO_x$) through regulatory controls and the technology improvements that have followed. But greenhouse gas emissions are only beginning to be addressed in any meaningful way. The United States also needs to lower its dependence on fragile supply chains for some energy sources, particularly petroleum at present and possibly natural gas in the future, and to avoid the impacts of this dependence on our nation's economy and national security.

As a result of these and other factors (described in Chapter 1), such as the nation's increasingly vulnerable transmission and distribution systems, there has been a steadily growing consensus[1] that our nation must fundamentally transform the ways in which it produces, distributes, and consumes useful energy. Given the size and complexity of the U.S. energy system and its reach into all aspects of

[1]See, for example: *Lighting the Way: Toward a Sustainable Energy Future*, published by the InterAcademy Council in 2007 (www.interacademycouncil.net/?id=12161); *Ending the Energy Stalemate*, published by the National Commission on Energy Policy in 2007 (www.energycommission.org/ht/d/sp/i/492/pid/492); and *Facing the Hard Truths About Energy*, published by the National Petroleum Council in 2007 (www.npchardtruthsreport.org).



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American life, this transformation will be an enormous undertaking; it will require fundamental changes, structural as well as behavioral, among producers and consumers alike. This report lays out the technical opportunities, the uncertainties, and some of the costs and benefits of initiating this transformation in earnest.

Given the massive installed base of long-lived energy production and distribution assets, together with a certain inertia—caused by uncertainties with respect to new technologies and regulations and by the generally slow pace of change in existing industrial practices, public policies, and consumer habits—the challenge that the nation faces not only is great but also will not be met overnight. *As a result, a meaningful and timely transformation to a more sustainable and secure energy system will likely entail a generation or more of sustained efforts by both the public and the private sectors.*

"Business as usual" approaches for obtaining and using energy will be inadequate for achieving the needed transformation. The efforts required will involve not only substantial new investments by the public and private sectors in research, development, demonstration, and deployment—in virtually all aspects of the energy infrastructure—but also new public policies and regulations on energy production, distribution, and use. Our energy system is, after all, much more than a set of technological arrangements; it is also a deep manifestation of society's economic, social, and political arrangements.

The America's Energy Future (AEF) Committee began this study at a moment of rapidly rising prices both in crude oil and in other raw materials that underpin the infrastructure that produces and delivers useful energy. As the study progressed, these prices reached a peak, began to fall steeply in the face of a global recession, and then began to rise again. Because it is virtually impossible to forecast future prices, this report makes no attempt to do so. Nevertheless, it is clear to the committee that market incentives for businesses and individuals to both invest in and deploy new energy technologies will depend most crucially, though not solely, on such prices. The technologies to be deployed must have adequate maturity, market appeal, and capability to meet the desired demands, and their development must be supported by appropriate public policies and regulations governing energy production, distribution, and use.[2]

[2]Any substantial change in the demand for key inputs, whether of primary energy stocks or of the resources required to transport and transform them, will strain the existing infrastructure and limit the pace of change.

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The committee carefully considered existing and emerging technologies alike, some of which are now fairly well understood in principle though not necessarily deployable at scale or competitive in the marketplace, and it assessed how the deployment of such technologies might enable the nation to achieve meaningful transformation of the energy system over the next few decades. The committee did not, however, consider the opportunities available through conservation efforts or other opportunities through changes in policy or other socioeconomic initiatives. One of the committee's conclusions is that there is no technological "silver bullet" at present that could transform the U.S. energy system through a substantial new source of clean and reasonably priced domestic energy. Instead, the transformation will require a balanced portfolio of existing (though perhaps modified) technologies, multiple new energy technologies, and new energy-efficiency and energy-use patterns. This will in turn require a sustained national will and commitment of resources to develop and deploy these assets where needed.

Throughout this study the committee also paid close attention to the practical problems of developing and deploying new technologies, even assuming that there is the requisite national commitment to do so. An example is the integration of sizable new supplies of electricity from intermittent sources (e.g., wind and solar power) into the nation's electrical transmission and distribution systems. These systems need to be upgraded and continuously improved to enhance their reliability and security, to meet the needs of 21st-century electricity production technologies, and to provide for patterns of use that are more efficient.

Although this report focuses on the U.S. energy system, decision makers will need to take a wider view. It is clear that the country's economic, national security, and environmental goals, especially with respect to energy, cannot be fully achieved without collective international action.[3] Our nation's prosperity depends on global prosperity, our national security is tied to international security, and the achievement of our environmental goals depends on environmental protection actions taken elsewhere. In short, full realization of goals of the United States for transforming its energy sector requires that we find effective mechanisms for working with other nations, many of which face similar challenges. Maintaining an awareness of international developments and cooperating with other countries on research and development, pilot projects, and commercial demonstrations will be key to our own success.

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[3]Such collective action among nations is not easy to achieve, as it requires broad participation, consequential monitoring, and meaningful compliance by all.

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It is beyond the scope of this committee's charge to opine on the priority, relative to other national issues, of initiating and sustaining a national effort to transform our energy sector. However, I personally believe that despite the uncertainties before us, it is a truly urgent matter to begin such a transformation and, moreover, that the technology and knowledge for doing so are at hand. Indeed, the urgency for action to meet the nation's needs in the economic, environmental, and national security arenas as they relate to energy production and use are unique in our history, and delayed action could dramatically increase the challenges we face. But a timely transformation of the energy system is unlikely to happen without finally adopting a strategic energy policy to guide developments over the next decades. *Long-term problems require long-term solutions, and only significant, deliberate, stable, integrated, consistent, and sustained actions will move us to a more secure and sustainable energy system.*

I also believe that we should not allow short-term fluctuations, either in the prices of energy supplies or in geopolitical affairs, to distract us from this critical long-term effort. Creating a more sustainable and secure energy system will require leadership, courage, risk-taking, and ample support, both public and private, but in my view such investments will generate a significant stream of long-term dividends.

Harold T. Shapiro, *Chair*
Committee on America's Energy Future

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The committee initially organized itself into seven subgroups to facilitate information-gathering and, ultimately, the development of Chapters 4–9, which appear in Part 2 of this report:

- Alternative liquid transportation fuels (chaired and staffed, respectively, by Mike Ramage and Evonne Tang)
- Crosscutting and integration issues (Jim Sweeney and Madeline Woodruff)
- Electricity transmission and distribution (Jim Markowsky; Alan Crane and Sarah Case)
- Energy efficiency (Lester Lave; Madeline Woodruff, Greg Eyring, and Tom Menzies)
- Fossil-fuel energy (Lynn Orr and Greg Eyring)
- Nuclear energy (Dick Meserve and Sarah Case)
- Renewable energy (Larry Papay and K. John Holmes, assisted by Mirzayan Science and Technology Policy Graduate Fellows Amy Hee Kim, Dorothy Miller, and Stephanie Wolahan).



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I thank these chairs for their able leadership, and I thank the subgroup members, staff, and fellows for their good work. I also express my gratitude to study director Kevin Crowley, who worked tirelessly to keep the entire study moving forward and to help the committee develop and articulate its key findings, which appear in Part 1 of this report.

The subgroups held separate meetings to obtain presentations and to gather the information that now appears in the Part 2 chapters. On behalf of the entire committee, I thank the outside experts who participated in these meetings. They are too numerous to list in this short section but are identified in Appendix B.

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Oparaugo assisted with research and administrative tasks for the nuclear energy chapter. LaNita Jones and Jonathan Yanger provided critical logistical support of the committee's work. Consultant Steve Marcus edited the report. Stephen Mautner supervised the report's publication by the National Academies Press, Estelle Miller provided design and layout, and Susan Maurizi and Livingston Sheats took responsibility for production editing. All figures in the report were rendered by Danial James Studios of Golden, Colorado.

It has been a great pleasure to work with such a talented and committed group of people. We learned a great deal from our presenters, consultants, and each other during the course of this study. It is my hope that our collective efforts have produced a report that will inform decision making and help engender wise policies and actions among our nation's political and business leaders.

Harold T. Shapiro

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# Acknowledgment of Reviewers

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's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the 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 individuals for their participation in the review of this report:

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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 Elisabeth M. Drake, Massachusetts Institute of Technology, and Robert A. Frosch, Harvard University. 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 authoring committee and the institution.

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## APPENDIXES



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*Listed below are the chapters that constitute Part 2,*
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# PART 2



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