U.S. Department of
ENERGY

Department of Energy
Quadrennial Technology Review
Framing Document

http://energy.gov/QTR

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The United States Department of Energy (DOE) has initiated a review of its energy technology activities (Quadrennial Technology Review, or QTR). This framing document is a principal means of facilitating stakeholder engagement in that process. It describes the nation's energy landscape and challenges, identifies important research, development, and demonstration (RD&D) policy choices to be made, and summarizes the current status of selected energy technologies and DOE technology program goals. It is intended to serve as the common framework for stakeholder engagement through advisory committees, workshops, and expert discussion groups. Successive drafts of the DOE-QTR will be circulated among U.S. Government stakeholders.

The Department especially seeks input on the questions posed throughout this document, which correspond to those in the Request for Information published in the Federal Register (Ref. 2011-5794). Instructions on submitting comments can be found at http://energy.gov/QTR.

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1 Introduction

The DOE-QTR will provide a context and framework for the Department's energy programs, as well as principles by which to establish program plans with a five-year horizon. It stems most immediately from recommendations in a recent report by the President's Council of Advisors on Science and Technology (PCAST), *Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy*, which echo and amplify numerous prior calls for better prioritization and planning in DOE's energy activities[1]. PCAST recommended a government-wide Quadrennial Energy Review. However, recognizing the scope and challenge of that task, they also recommended beginning with a more limited review centered on DOE activities. Secretary Chu initiated the DOE-QTR in February of 2011, and tasked Under Secretary for Science Steven Koonin with leading the process.

Given DOE's mission and capabilities, the DOE-QTR is concerned primarily with activities to develop and demonstrate new energy technologies in support of national energy goals. These are multi-year efforts in which science, technology, economics, and energy policy intertwine. In view of the multitude of technologies that *could* be developed and demonstrated, analytically-based priorities and coordination of RD&D efforts with policy are essential to facilitate deployment by the for-profit sector.

The scope of the DOE-QTR will include a discussion of the roles of government, industry, national laboratories, and universities in energy system transformation, as a function of technological area. It will describe summary roadmaps for advancing key energy technologies, systems, and sectors, including current status, historical pace of development and market diffusion, technological potential, factors affecting their market prospects, and research and demonstration milestones. The objective will be to include enough detail to enable the other objectives of the DOE-QTR, not to lay out detailed programmatic or technological roadmaps for wider application. The DOE-QTR will also establish principles by which the Department can judge the priority of various technology efforts. Rather than an ordered prioritization of technologies or activities, these principles will be useful to guide the budget process, which is the appropriate mechanism to set priorities. This will include the principles DOE will use to determine which demonstration projects to support. Last, the DOE-QTR will describe the connections between energy technology innovation and energy policy. While the document will be focused on the activities within DOE's purview, it will also identify critical DOE analytical assets that can inform policy making by others.

The DOE draft Strategic Plan, which was recently released for public comment, is a coherent plan for all of the Department's activities, including nuclear security, environmental management, and basic research. It does not have a singlular focus on the energy porfolio. The Plan does include energy goals:

> "Petroleum use will be decreased by raising fuel economy standards, gradual electrification of the vehicle fleet, and increasing production of advanced biofuels. Greenhouse gas emissions will be reduced through improved efficiency, accelerated deployment of low-carbon energy

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[1] For example, see the National Academy of Science *America's Energy Future* report, the National Commission on Energy Policy *Ending the Energy Stalemate* report, and the American Energy Innovation Council's *Business Plan for America's Energy Future*.

> generation technologies (including conventional renewable, nuclear, and carbon capture and storage), modernization of the electricity grid, and public policy."

This DOE-QTR will discuss more deeply the substance and process of DOE energy technology programs that can accelerate progress toward those goals; the Department's nuclear security, environmental management, and basic science are addressed to the extent that they relate to and inform the energy portfolio.

Coherent multi-year planning through reviews such as the Quadrennial Defense Review (QDR) has been important to success in other government missions. While this DOE-QTR follows the purpose and spirit of other federal "QXRs" (beyond the QDR already mentioned, there is the QDDR for Diplomacy and Development and QHSR for Homeland Security), it is fundamentally different because defense, diplomacy, and homeland security are almost entirely governmental functions that are directly shaped by public spending decisions and policies. In contrast, the deployment, ownership, and operations of energy technologies are almost entirely nongovernmental functions that are determined by government policies and investments. Many government agencies beyond DOE have significant roles to play in establishing those policies. As a result, broad nongovernmental and intra-governmental engagement is central to creating the DOE-QTR. In addition, full transparency of input to the drafting team is an important guiding principle.

This framing document and its accompanying Request For Information (RFI) begin a process that the Department believes will lead to robust, effective technology portfolio to accelerate energy transformation and meet our Nation's energy challenges. We welcome written comments responding to the questions raised in the RFI and in this document throughout the public comment period, lasting from March 14 to April 15, 2011.

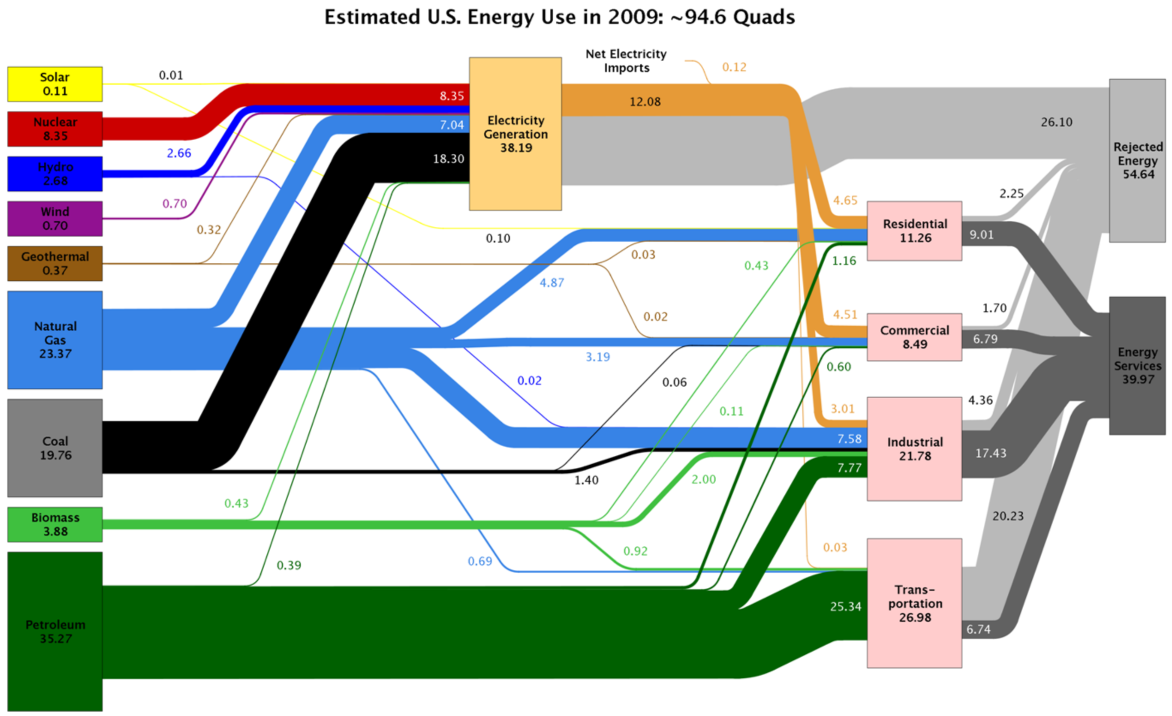
Following the close of that comment period, DOE will analyze comments received in preparation for a series of workshops. These will draw on the expertise of the private sector, academia, non-governmental organizations, DOE, and the national laboratories to delve into the questions raised here, as well as additional topics as might arise in response to the RFI. Each workshop will bring together experts and stakeholders to share their individual views on one or more of the six strategies we have described.

In keeping with the Administration's commitment to open government, the names, materials discussed, and subject matter (including transcripts or detailed notes where appropriate), for all of these meetings will be posted on the QTR website. DOE anticipates that vibrant discussion of the technology and policy questions relevant to our technology programs will help us produce a better Quadrennial Technology Review.

This document is organized as follows. Section 2 is a factual description of the national energy landscape and its near-term evolution. Section 3 describes the three challenges that drive the need for a prompt and substantial transformation of the nation's energy system. Section 4 is about the policies and capabilities within the Department's sphere of influence. Section 5 presents crosscutting questions for comment regarding how to allocate resources for DOE RD&D activities. Section 6 describes six thematic strategies that categorize the approaches to transforming our energy landscape.

2 U.S. Energy Context

Addressing our energy challenges, whether through technology or policy, requires that they be understood. This section provides a brief overview of the U.S. energy context, emphasizing those aspects most relevant to the challenges we face. A more detailed exposition can be found at the Energy Information Administration (EIA) website.



Estimated U.S. Energy Use in 2009: ~94.6 Quads

Figure 1. U.S. energy flow (Lawrence Livermore National Laboratory). Data in quadrillion British thermal units (Quads).

The energy sector is a large, complex *system* that touches every aspect of modern life and comprises 9% of gross domestic product (GDP) while enabling the rest of the economy. Figure 1 shows the flow of energy from supply to demand, scaled to show the relative amounts of energy produced from each energy source and consumed by use. Several salient points can be taken from Figure 1 and other data on the energy system.

2.1 Different Fuels for Different Uses

Fossil fuels currently provide 83% of U.S. primary energy, with coal used almost exclusively (93%) for power and oil used largely (72%) for transport. Natural gas (methane) is a flexible fossil fuel source that is used for power and heat across multiple sectors of the economy. Transport is fueled almost exclusively by petroleum-derived liquids (gasoline and diesel), while electricity is fed by many sources beyond fossil fuels, most significantly nuclear fission and hydropower. Other renewable sources supply less than 4% of U.S. electricity.

The energy system divides between transport and stationary (i.e., electricity and power/heat), with each further partitioned into the supply, intermediate, and demand sectors. These sectors are a useful framework for discussing the energy system and each has its own unique context, challenges, and opportunities.

2.2 Energy Efficiency

Nearly 60% of energy is lost due to waste heat (labeled “Rejected Energy” in Figure 1). Both electrical generation and transport make use of less than one-third of their primary energy inputs. While efficiency is bound by thermodynamic limits, there is significant potential to reduce energy consumption by increasing the efficiency of power plants and vehicles. The movement of goods and people, the least efficient energy use, can be made more efficient by technological changes to engines and vehicles, and by societal changes (e.g., greater use of public transport). Power generation can be improved by progressing to more efficient generating technologies and harnessing the waste heat for useful applications, such as heating water. Importantly, the 80% efficiency depicted in Figure 1 for residential, commercial, and industrial energy use is misleading; there is no rigorous way to measure absolute efficiency in end-use service delivery (relative efficiency can be rigorously measured). Significant opportunities also exist to reduce energy consumption in these sectors via improved building, device, and industrial process efficiencies.

Implementation of efficiency measures generally incurs an up-front capital cost that is offset by reduced ongoing energy costs, although cases do exist in which significant efficiencies can be achieved with little or no capital costs. A number of market failures prevent full utilization of these efficiency measures. For example, consumers and professionals alike often lack the necessary information to choose the best product to meet their needs at the lowest life cycle cost, and there is ample evidence that investment decisions, particularly by individual consumers, are driven by first-cost considerations rather than life-cycle cost analysis. Another notable market failure is the principal-agent problem, which occurs when one person acts on behalf of another, but acts contrary to that person’s best interests. For example, this commonly occurs in energy use between landlords and renters.

Energy efficiency reduces energy consumption and expense for the service delivered, allowing that money to be spent elsewhere, including increased use of the more efficient service (direct rebound). In addition, improved energy productivity spurs economic growth, with some associated increase in energy demand in all sectors (indirect rebound). The magnitudes of these rebound effects are topics of active research.

2.3 Stationary vs. Transport Supply

The energy needs of the residential and commercial sectors of the economy, about 40% of our national energy consumption, are met primarily by electricity and natural gas. The industrial sector consumes another 30% of the nation’s energy, supplied by diverse feedstocks. New energy technologies that supply these stationary energy consumers must compete against existing infrastructure that delivers energy reliably and at low cost.

Approximately 94% of transportation services are fueled by petroleum (see Figure 1). The growing price and price volatility of current fuels provide a significant opportunity for making current technologies more efficient, as well as for competing technologies to gain acceptance. However, new fuels must compete against the extraordinary energy density and marginal production costs of petroleum-based fuels and adapt to, or compete with, the established fuel distribution infrastructure.

2.4 Supply Changes Slowly, Demand Rapidly

Throughout U.S. history new energy resources have taken many decades to achieve scale and penetrate markets, often requiring 50 years or more. The timescale of supply change is dominated by long-lived infrastructure and the continual growth in energy consumption that has allowed new technologies to supplement rather than replace existing energy sources. In addition, energy is a commodity, where intermediaries (including refineries, utilities, and other electric power producers) operate on thin margins. Still, significant opportunities for greater efficiency with existing technologies and the introduction of new technologies exist due to the age of current U.S. infrastructure.

In contrast to large, long-lived energy supply assets, energy-consuming devices and vehicles are relatively inexpensive and replaced more frequently. Typical lifetimes for vehicles and home appliances are under 20 years, while consumer electronics and lighting technologies can have significantly shorter lifetimes. New demand-side technologies can therefore enter and dominate the market within a few years.

2.5 Scale

For both the transport and stationary sectors, there is a million-fold difference in the number of energy users and energy producers. This disparity in scale is at the root of the different challenges in transforming the energy system. The current energy supply paradigm is dominated by large, centralized supply facilities that are expensive to replace and affect the overall system when taken offline. Energy demand is the aggregated result of billions of individual end uses, each a miniscule fraction of total demand. Although the cumulative actions of energy consumers are the fundamental drivers of the energy system, the actions of any one end user do not materially affect the overall system.

2.6 Private Sector Dominance

By any measure, the U.S. energy system is in the hands of the private sector, which makes decisions based on cost and profit considerations. It designs, constructs, and operates the overwhelming majority of energy production and transmission facilities. On the supply side, all domestic refineries are owned by the private sector. The power marketing administrations, Tennessee Valley Authority, public utilities, and cooperative utilities combined are less than 25% of national generating capacity and 20% of transmission (and even these generally function like private-sector organizations in striving to serve customer loads reliably at lowest cost). On the demand side, while the federal government is the nation's largest single user of energy, it represents less than 2% of total demand (almost 90% of federal energy use is in the Department of Defense).

2.7 Current Policy Context

The U.S. energy system is regulated and subsidized by many players including the DOE at all levels of government. Incentives, standards, trade policies, and direct government investment shape the markets for fuels, electricity, and demand technologies. More than half of U.S. state governments have instituted renewable portfolio standards (RPS) that require certain fractions of the electricity sold in their states to be generated by renewable technologies. While portfolio standards create a certain level of market access for renewable fuels (federal renewable fuel standards) and renewable power (state RPSs), energy efficiency standards (set by the Department of Energy) and building codes (set by states) establish minimum performance standards that apply to entire markets, with the long-term goal of driving out the most wasteful products in a specific set of end-uses.

In addition, providers of energy are subject to a wide range of consumer-protection and environmental regulation. The electricity industry is owned and regulated by a diverse set of stakeholders. This structure varies across states and regions, and many combinations of roles exist for different entities within the system. The Federal Energy Regulatory Commission (FERC) regulates interstate transmission and sale of electricity, natural gas, and oil. Retail electricity regulation and infrastructure siting is largely controlled by the states, usually by public utility commissions. Natural gas for commercial and residential uses is generally subject to state regulation in a manner similar to electricity.

Environmental regulation affects both the transport and stationary energy sectors. There are federal regulations for criterion air pollutants from both sectors, and since finding that carbon dioxide (CO_2) also endangers public health, the Environmental Protection Agency (EPA) has established standards for CO_2 emissions that apply to light duty vehicles. Some states have taken additional action to curb CO_2 emissions through a wide range of policies and measures. Federal and state vehicle efficiency and emission standards address the emission of CO_2 and other pollutants. Federal regulations exist regarding the custody and disposition of fuel and waste from nuclear generation.

2.8 The U.S. Energy Industry

The U.S. energy industry is large and multifaceted, with activities that can be broadly categorized as deployment, manufacturing, or innovation. In deployment, modest increases in electrical demand and replacement of aging capacity resulted in approximately 16.4 gigawatts (GW) of capacity in new generators added in 2010, corresponding to some tens of billions of dollars in added capital. This deployment is less than 2% of total capacity and will provide an even smaller percentage of total electricity given the associated technology capacity factors. In contrast, more than 100 GW of capacity was added each year in non-Organisation for Economic Co-operation and Development (OECD) countries from 2004-2008, a 6% annual growth rate. While the petroleum refining capacity in the U.S. has plateaued over the last five years, the utilization of that capacity has fallen over the same time period, so major investments in fuel refining necessary to transition to new feedstocks or products will not happen under business-as-usual.

The conservatism of the energy system is reflected in research and development (R&D) investments; U.S. companies invested approximately $3 billion in energy supply R&D in 2010, about 0.3% of total revenue, a small proportion compared to non-commodity sectors, such as pharmaceuticals (18.7%) and computers and electronics (7.9%). Federal investment in energy RD&D was $4.3 billion in 2010, one-third of benchmark commonly articulated target for developed nations (1% of sector's portion of GDP).

Manufacturing related to energy technologies varies widely. In general, manufacturing facilities for mature technologies are built where the cost of manufacturing is lowest, and those for innovative technologies are built near the site of invention. Decisions regarding manufacturing capacity are also related to the cost of transport of the products. For example, a 2005 study suggested that U.S. suppliers will have inadequate production capacity for the predicted nuclear energy deployment, partially due to the inactivity in the U.S. nuclear market over the last several decades and the emergence of markets abroad. Similarly, while only 6% of solar photovoltaic modules were manufactured in the U.S. in 2008, the U.S. dominated production of innovative thin-film modules, which have been the recent focus of domestic RD&D. Beyond energy supply, end-use technologies responsible for consumer energy demand are manufactured world-wide and subject to vigorous global trade. Manufacturing of energy system components, including end-use technologies, is itself a significant energy consumer.

3 Challenges Posed by Today's Energy Landscape

Access to affordable, secure, and reliable energy has been the cornerstone of America's economic growth. However, the nation's physical and social systems that produce, store, transmit, and use energy remain deficient in several important dimensions.

3.1 Energy Security

The movement of goods and people is essential to our economy, and 94% of the energy used for domestic transportation comes from oil. When other sectors of our economy are considered as well, 37% of all U.S. primary energy is derived from oil, nearly half of which is imported. The crude import fraction has dropped from over 60% in 2005 and is expected to drop further to 42% in 2035; absolute imports are projected to decrease from 9 million barrels per day in 2009 to 8.5 in 2035.

Crude imports at current prices add nearly $1 billion per day to the national trade deficit. In addition, the world relies on OPEC countries for approximately 40% of it oil supply, much of which is produced in regions and countries subject to disruptions. This circumstance shapes U.S. foreign policy and engenders economic vulnerability. Further, there is effectively one global price for oil set by global supply and demand, modulated slightly based on geographic and quality differences in the crude. That price may well continue to be higher than historic norms due to increasing demand in developing economies and concentration of low-cost supply in a few countries. Continued reliance on transportation fuels fungible with oil implies continued U.S. coupling to the global oil price and the drawbacks that entails. However, any reduction in oil use through efficiency would diminish the economic harm of high prices and price volatility.

Security concerns associated with the U.S. energy system extend beyond oil. The security and management of the nuclear fuel cycle will be of critical importance to increased deployment of nuclear energy technologies in the U.S. and abroad. National policy and international agreements are elements of ensuring the availability of the required fuel supply. Effective and credible international nuclear safeguards, export controls as well as R&D will be required to ensure that future nuclear power systems can be deployed safely and securely with appropriate mitigation of risks from terrorism and proliferation. The nation's electric grid must be more secure and reliable to minimize the impact of potential natural and man-made disruptions.

3.2 U.S. Competitiveness

American leadership in clean energy technologies can be a foundation for future economic growth. The market for clean energy technologies is expected to grow because of global economic development, which is driving dramatic increases in energy demand, and increasing international focus on environmental concerns. The economic opportunities in the clean energy technology market are driving innovation, manufacturing, and deployment worldwide. To participate in that market, the U.S. must have a robust energy technology industry and well-developed supply chains.

3.2.1 Innovation

Innovation has historically been the nation's economic engine, and is an area accessible for continued U.S. leadership. The U.S. has led in innovation because of a culture of creativity and entrepreneurship coupled with investment in basic and applied research by both the government and the private sector. However, the U.S. is out-spent in RD&D as a fraction of GDP by Japan, and China's investments are rising steadily. In energy RD&D, the U.S. is out-spent by its major trading partners (i.e., Japan, Korea, France, and China). Innovation is correlated with RD&D funds, as illustrated by national statistics for patent filings.

3.2.2 Manufacturing

Reversing the decline in domestic manufacturing is often cited as necessary for U.S. economic competitiveness. While the U.S. has steadily shed manufacturing jobs since 2000, manufacturing output and wages have increased over the same period. Although increased manufacturing productivity can be a hazard to individual manufacturing jobs, the associated economic growth benefits the economy as a whole. Investment in manufacturing facilities not only creates immediate capabilities, it facilitates future manufacturing efforts because the existing capital can be updated to accommodate new needs.

Historically, U.S. leadership in innovation enabled its leadership in manufacturing highly differentiated products, since close collaboration between researchers, engineers, and manufacturers is useful for burgeoning technologies. However, once a product becomes a commodity in the broader market, premiums can no longer be garnered by domestically-produced materials and local pools of talent, and manufacturing will shift to where it is economically optimal. Innovation in manufacturing processes, in addition to the invention of new and better products, enables increased productivity and output and creates competitive advantage. Manufacturers in the developing world are becoming ever-more sophisticated; Chinese high-tech manufacturing value-added quadrupled from 1997–2007. Private-sector decisions regarding the location of manufacturing facilities are shaped by a variety of factors, including access to capital, tax incentives, regulatory hurdles, market access, and labor force productivity.

3.2.3 Deployment

Large developing economies are just now building the bulk of their infrastructure and are well suited to adopt new clean energy technologies as they build out a modern energy infrastructure for the first time. This rapid growth abroad is a market opportunity for U.S.-developed clean energy technologies. While the U.S. is unlikely to lead the world in the absolute numbers of clean energy technologies deployed simply because the U.S. energy market is a mature market dominated by replacement and modest demand growth, widely deploying clean energy technologies domestically is attractive for economic competitiveness for several reasons. These include the benefit of the technology itself (e.g., decreased energy costs with efficiency technologies), decreased cost of the technology from lessons learned through deployment, as well as the associated jobs that cannot be outsourced for the sale, installation, operation, and maintenance of the technology.

The president has set a goal of increasing the share of America's electricity supplied by clean energy sources to 80% by 2035.

3.3 Environmental Impacts

Conventional energy production and consumption cumulatively can have significant environmental impacts. Among these are the emission of greenhouse gasses (GHGs) and other airborne pollutants, the production of solid wastes, and ecological impacts due to the use and consumption of significant quantities of water.

The use of fossil fuels is a major source of CO_2 accumulation in the atmosphere, which is perturbing the climate. Global temperatures during the last thirty years have risen about 0.6 °C, consistent with expectations. Substantial climate change over the next 90 years would have a serious impact on society, and could lead to global instabilities if water supplies are threatened or if a substantial rise in sea levels displaces populations. Energy and water are linked; the production of energy requires large volumes of water while the treatment and distribution of water is equally dependent upon readily available, low-cost energy. Climate changes may affect water run-off in the U.S. and elsewhere.

Other pollutants have environmental impacts. For example, highly radioactive and toxic used nuclear fuel is produced and stored at the current fleet of nuclear plants, and presents a future problem for centennial-scale storage. The burning of fuels can lead to other types of solid or airborne waste that may contain mercury, ozone, sulfur oxides, nitrogen oxides, and heavy elements. Extraction of fossil fuels can have significant environmental effects at the location of the extraction.

Significant deployment of any energy technology will have environmental impact simply because of the required scale. Some environmental impacts of large wind or solar farms have been discussed; biomass production can have both direct and indirect environmental impacts

4 DOE Activities

An effective plan for the Department's energy technology programs requires both knowledge of the energy landscape and challenges reviewed in the previous sections together with a realistic understanding of the government's and DOE's role in shaping the energy system. Since that system is largely in the hands of the private sector, the government can effect change through the pre-competitive RD&D it supports and through its policies that affect the rate of deployment, including market incentives and penalties, regulation, and finance.

As outlined in Section 2.7, nearly every governmental entity defines some policies related to the energy sector. Even within the federal government, many of the regulations and incentives that shape the energy system are not administered by the DOE. The EPA is home to emissions and environmental regulations; all tax incentives are the purview of the Treasury; the Department of Transportation sets the Corporate Average Fuel Economy (CAFE) standards; the Department of the Interior regulates fossil fuel extraction and siting of energy projects on federal lands; the Department of Agriculture regulates and subsidizes the feedstocks for most biofuels; FERC regulates interstate energy transmission; the Nuclear Regulatory Commission (NRC) regulates nuclear power; many federal agencies are involved in the siting of off-shore energy projects; the Department of Defense (DoD) funds energy RD&D for its own substantial, and often unique, energy needs; the Department of Labor regulates worker safety and compensation for energy projects; and the list goes on.

The federal government's direct participation in the energy system as a provider or purchaser of energy is limited. Its major influence is instead exerted by joining with state and local governments to modulate private-sector decisions through policies that set the terms of operation and trade in the energy sector. DOE contributes in part to private sector decisions by developing and maturing technology options that could be rewarded in evolving market conditions.

The Department of Energy's RD&D programs include the Offices of Science, Energy Efficiency and Renewable Energy, Electricity Delivery and Energy Reliability, Nuclear Energy, Fossil Energy, and Nuclear Nonproliferation. The Office of Science is the single largest funder of basic research in the physical sciences in the country. The other Offices primarily support applied research and development in technology-specific areas. In addition, the Advanced Research Projects Agency – Energy (ARPA-E) funds the development of high-risk, high-payoff clean energy technologies. As a whole, the Department's programs are a major U.S. innovation engine, supporting mission-related research in academia, the DOE complex of national laboratories and user facilities, and the for-profit sector. The Department is home to some of the world's most powerful scientific computers and leads the world in simulation capabilities that couple computer modeling with experimental validation. A strategic combination of applied research, test beds and simulation has the potential to decrease risks associated with new technologies, accelerate technological progress, and can catalyze private-sector investment for the wide deployment of clean energy technologies.

The Department's core strength lies in its science and technology efforts, which have led to technology improvements and breakthroughs, and these efforts are the focus of this DOE-QTR process. However, these are not the Department's only responsibilities and policy tools. DOE has some regulatory (e.g., appliance efficiency standards) and financial authorities (e.g., loan guarantees) and its techno-economic analyses play a unique role in informing and shaping energy and related environmental policies and investments.

The *American Recovery and Reinvestment Act* (Recovery Act) channeled an unprecedented amount of funds through the Department in record time. The Recovery Act funding and an increased fiscal year 2009 appropriation provided the opportunity for new, extensive projects. In energy, projects include tax credits, construction of advanced vehicle technology battery manufacturing facilities, and energy efficiency grants available to every state, county, and large city. These projects will help inform future investments in energy technology research, development, demonstration, and deployment (RDD&D).

The Department serves as a repository and disseminator of technical information and best practices for energy consumers, from individuals to industries to the federal government. For example, the Federal Energy Management Program (FEMP) facilitates the federal government's implementation of sound, cost-effective energy management and investment practices to enhance the nation's energy security and environmental stewardship. DOE has the authority to set mandatory minimum energy efficiency standards for a range of residential, commercial, and industrial appliances, including lighting, refrigerators, heating and cooling systems, and motors.

The Department works with dozens of foreign governments and international organizations to promote best practice policies and programs, including appliance standards, to accelerate technology innovation and clean energy deployment. Through leadership in the Clean Energy Ministerial and the Energy & Climate Partnership of the Americas, DOE is catalyzing an array of cooperative activities with countries that account for the vast majority of the world's energy use. With most of the growth in future energy use expected to occur in developing countries, DOE also supports strong strategic bilateral partnerships with both China and India, where the rapid speed and large scale of new energy technology deployment is an important driver for innovation.

In addition, the Department has a core competency in providing unbiased, technically rigorous information for policymakers. The EIA is the nation’s premier source of independent statistical information about energy production and use. The power marketing administrations, DOE independent agencies, offer experience in power generation and transmission activities and can demonstrate and deploy new technologies and capabilities into the electrical grid. The Department collaborates with other federal agencies to leverage expertise, advance research, development, demonstration, and deployment programs, reduce redundancy in energy research programs, and leverage government purchasing power to facilitate commercialization and initial deployment. One example is the Department’s work with the Departments of Agriculture, Commerce, and Transportation on biofuels from farm to certification. The DoD, with whom the DOE has a memorandum of understanding regarding early deployment of new energy technologies, will be an important early adopter of new and improving clean energy technologies, and the information DoD generates from trials at installations can inform DOE’s technology programs.

5 Crosscutting Questions

With the above framework in mind, the Department has a series of questions for which it seeks public input.

5.1 Mission

1) What do you think of the following mission statement for DOE energy research?

To facilitate the invention, refinement, and early deployment of meaningful technologies that enable options for scaling by the private sector toward national energy goals.

The words in this statement are carefully chosen:

- to facilitate – we convene and fund various entities – as well as support the basic research that underpins invention and refinement
- invention, refinement – we work on both revolutionary and evolutionary technologies
- early deployment – we support some activities beyond first commercial demonstration
- meaningful technologies – we pursue technologies that could have a material impact when deployed; accordingly, scale, economics, and timeliness are important criteria
- enable options – we do not pick commercial winners and losers; the markets make those choices
- scaling by the private sector – we support commercialization as an essential part of what we do
- toward national energy goals – we cannot and will not pursue all technologies; only those that enhance energy and national security, reduce environmental impacts, and increase U.S. competitiveness

5.2 Technology Policy

5.2.1 Clean Energy Leadership

U.S. leadership in clean energy technologies can help promote their diffusion around the world and contribute to the nation’s economic competitiveness. The Department has long supported RD&D to catalyze energy innovation. Some programs drive entire clean energy fields, while others are focused on specific technical hurdles; we fund individual researchers as well as interdisciplinary teams of investigators addressing a common problem; we fund research at national laboratories, universities, and in the private sector. The Department supports a broad set of basic research in the physical sciences, with world-leading programs in materials science and engineering and in simulation, since these areas are critical to progress not only in energy, but also in our security, environmental, and science missions.

The Department has a number of mechanisms to support the manufacturing of clean energy technologies. The loan guarantee program supports manufacturing of innovative technologies that will avoid, reduce, or sequester GHG emissions. The Industrial Technologies Program funds R&D and provides technical assistance to make manufacturing processes more efficient.

The Department has neither the authority nor resources to significantly deploy technologies itself. However, DOE can facilitate private investment to deploy clean energy technologies. For example, working with the Department of the Interior, DOE is participating in studies to identify resources that will help developers of renewable energy generation projects. In addition, the loan guarantee program leverages private resources to support renewable energy generation projects that have difficulty finding traditional financing.

As the greatest energy challenges are global in nature, partnering internationally to develop and demonstrate new technologies is both essential and attractive. Other countries can have technical capabilities that complement our own, and greater demand, pace, and/or risk tolerance in energy innovation. International partnerships could offer more diverse projects to increase learning rates, promote the global adoption of clean energy technologies, and perhaps ease foreign market entry for U.S. firms. However, international partnerships require careful management of intellectual property and competitiveness issues.

2) **How can DOE activities best support U.S. leadership in clean energy innovation? In clean energy manufacturing? In clean energy deployment? How do we balance international competitiveness against international cooperation?**

5.2.2 Program Definition and Management

Focusing programs on eliminating the most significant problems and barriers allows the most rapid progress toward our goals. All programs have many more good ideas to fund than resources available to pursue them, and constantly churning priorities, the pursuit of quick wins, or the dilution of resources in the face of too many options sap the effectiveness of our efforts. Programs that ramp up and down before the hard work can be carried out to test an idea, develop an essential tool, or prove a technology cannot effectively deliver results.

The active participation of multiple technologies or resources in a market is frequently beneficial. Competition exerts downward pressure on prices, while diversity reduces the risks associated with technical, economic, or supply chain complications and disruptions. Yet the strategic and economic value of diversity is often difficult to balance against other metrics, and a portfolio guided only by diversity can dilute investments and diminish the likelihood of success.

Clear-cut, baseline standards for entry into the DOE portfolio are useful tools for program definition. The DOE draft Strategic Plan says we will “focus on technologies that can confidently be predicted to enter commercial application at a minimum of 1 Quad annually by 2030 (about 1% of current U.S. primary energy).” Analogous thresholds for technologies that don’t supply energy (e.g., carbon capture and storage or efficiency technologies) are more difficult to capture in this way. However, such standards cannot be the sole guide to program definition or budgeting, as mere technical possibility is too low a threshold; they do not capture the readiness of the technology for deployment, the maturity of the industry involved, or the RD&D involvement of outside parties. Furthermore, such standards do not provide guidance for how RD&D efforts should evolve as the technology is deployed and gains market share.

The Department can also use targets to guide its activities in different technologies. For example, the SunShot program aims to achieve a $1/Watt cost for installed utility-scale solar power by 2020. ARPA-E, too, cites specific parameters that technologies must plan to achieve in their funding opportunity announcements. These targets can be useful in that they provide concrete, tangible goals to work towards without prescribing the specific technological pathway to achieve them. On the other hand, finding the right targets is challenging since the relationship between technical targets within an R&D setting and scaled production can be difficult to determine rigorously, and inappropriate targets can hamper technology development. For example, if DOE targets are underambitious, there is little incentive for the private sector to help the Department increase the aggressiveness of its targets. However, without input from industry, the Department runs the risk of recalibrating targets to unrealistic levels.

These challenges might be addressed by planning that is grounded by rigorous analysis, clear priorities established with broad input from stakeholders, and decisions based upon rigorous peer review. In addition, achieving even the most ambitious targets does not guarantee adoption and deployment by the private sector, as there are many non-technological barriers to technology commercialization.

3) **What principles should the Department follow for allocating resources among technologies of disparate maturity and potential time to impact?**

    a) **What should be the criteria for including a technology in the DOE portfolio? What should be the criteria for removing a technology from the DOE portfolio? How should programs be structured and managed to accommodate entry and exit of technologies within the DOE portfolio?**[2]
    b) **How do we balance the diversity of technology options the Department could provide for the private sector against timeliness, scale, and cost-effectiveness?**
    c) **How can DOE be more effective at each stage of the innovation chain?**
    d) **What are useful metrics to guide DOE technology activities?**

5.2.3 Private Sector Partnership

Since the Government is not the primary driver of either energy supply or use, all DOE energy activities must have the ultimate goal of catalyzing action by the private sector. In general, basic research is conducted solely at universities and national laboratories with funding by the government. As a technology moves through development and demonstration and associated risks lessen, it gains more attention and support from the private sector. Venture capital and small businesses have a higher risk tolerance than large corporations, who deploy technology at scale. To promote commercialization, the Department must partner with the private sector and other federal agencies to move technologies from proof-of-concept to full-scale deployment.

Progress towards an improved energy system in the U.S. will require both basic research and applied technology development. Historically, the feedback loop between science and technology has been a critical part of how progress is made; the more active the feedback loop, the higher the likelihood of rapid progress. To this end, we have developed a portfolio of new research efforts that augment our base programs to provide integration across disciplinary boundaries as well as across multiple phases of

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[2] This question appears in the RFI as: "What should the threshold be for entry of a technology into the DOE portfolio? Does every technology deserve a program? Conversely, when should we declare 'mission accomplished' for a government RD&D effort, or cease efforts on a program whose costs may outweigh its benefits?"

RD&D. These include Energy Innovation Hubs, Energy Frontier Research Centers, Bioenergy Research Centers, and ARPA-E.

One of the Department's successful partnering mechanisms is its model of scientific user facilities. These facilities allow researchers to do experiments on large, capital-intensive DOE-owned scientific instruments. To ensure the Department's experimental facilities are used most effectively, proposals to use these facilities undergo rigorous peer review by researchers in academia and the national laboratories. To ensure that the knowledge from experiments is widely disseminated, users must either publish their results or pay for the use of the facility. A similar model could be imagined for clean energy technologies; for example, the Department could create and operate national technology test beds with greater experimental capability than could be developed by the private-sector in order to validate novel energy technologies and explore their system-level performance. While DOE national laboratories have similar capabilities for some technologies (e.g., the National Wind Technology Test Site and the Biomass Process Facility), these facilities are generally not operated under the paradigm described above. In the experience of the DOE, the user-facility model of open-calls for proposals and peer-reviewed selection have resulted in a diverse, high-quality set of research projects. This model may also apply in the arena of technology development. However, the translation of that model to energy technologies may be imperfect, as the majority of the users of these facilities will likely be for-profit and more likely to pay for their time and want to hold the results proprietary.

Energy RD&D management and planning will be most effective when fully informed about the actions of all relevant parties. The private sector is most knowledgeable about the status of commercial technologies and their likely evolution, yet competitiveness concerns may inhibit complete sharing, particularly for commodity products. The Department's current mechanisms to gather information on private sector innovation in clean energy technologies include invention disclosures of innovations that were made with DOE resources (e.g., through partnering with a DOE national laboratory), and efforts by the applied technology programs to hold workshops, read proposals submitted to solicitations, attend technology conferences, tour manufacturing plants, read market reports, and commission technology studies. However, these are imperfect and incomplete.

4) **What are the optimal roles for the private sector, government laboratories, citizens and academia in accelerating technology innovation?**

    a) **How can DOE best coordinate activities between and among these types of organizations (including the wide variety of institutions within each class)? How should we gauge the effectiveness of this coordination? How can the basic-applied coupling be optimized? Are there examples in other sectors or other countries that can serve as models?**

    b) **What are the design principles for an effective 'technology user facility'?**[3]

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[3] This question appears in the RFI as: "Are 'technology user facilities' analogous to the Department's scientific user facilities possible, or even desirable? If so, what would be the most effective model for their operation?"

   c) **How can the Department best gather technology market information? How can information on private sector innovation be captured without compromising competitive advantage?**

5.2.4 Technology Demonstration

Reducing the risks associated with new technologies is a critical component of government engagement with the private sector. The commercialization, broad diffusion, and regulatory approval of a new energy technology require high confidence in its performance. Uncertainty in operation at scale or in system-integrated operation increases early adopter risk and slows market penetration.

The DOE collaborates with industry on demonstration projects to help catalyze large-scale adoption of promising energy technologies. In order to ensure these efforts have the largest possible impact, DOE is interested in ideas to improve the process for selecting when and under what circumstances to sponsor technology demonstrations with industry, as well as how to best disseminate the results so as to have the largest market impact. To ensure relevance and application beyond the direct participants, learning must be widely disseminated so that test bed and demonstration activities can benefit entire industries. Such practices will require a careful balance of promulgating information for broadest impact against non-disclosure agreements and intellectual property protection necessary for private sector participation. However, specifics of how to chose and operate demonstration projects are unclear.

Failure is a common, and beneficial, fact of experimentation. The Department's R&D programs expect a certain proportion of failed research ideas, although contingency plans are integral to good program management. In contrast, the Department's Loan Guarantee Program is operated such that every funded project has a high likelihood of success (defined as a reasonable prospect of loan repayment). The risk associated with demonstration projects falls somewhere between R&D and commercial viability. Assessing and planning for risk will be essential to demonstration projects the DOE undertakes.

5) **What are principles and best practices in performing large-scale demonstration projects?**

   a) **How close to commercial viability does a demonstration have to be? What are the optimal cost sharing arrangements? How might demonstrations be coordinated with DOE financing activities?**
   b) **How can demonstration projects better benefit all stakeholders beyond the immediate participants? How are lessons-learned best captured and promoted, and how is intellectual property best handled?**
   c) **How should DOE determine whether demonstrations adequately address technical and operation risks?**
   d) **What defines failure or success in the demonstration phase?**

5.2.5 Non-Technical Barriers

DOE is but one of the many entities whose actions impact the energy system; while the energy sector is heavily regulated, few of those regulations are in the control of the Department. Integrated planning at the federal and international levels is essential to accelerating the deployment of new energy technologies. Standards, siting, and permitting are examples of the many issues that require multiple agency participation. Establishing common understanding and prioritization regarding land or other resource use, and accelerating the process by which applications are considered across multiple agencies, would enable more rapid deployment of clean energy technologies. Other methods for addressing non-technical barriers include voluntary technical standards (like the work of ASTM International and the American National Standards Institute), dissemination of information crucial to market function, and support for workforce skills and availability.A comprehensive discussion of federal policies for addressing non-technical barriers to deployment would be the subject of the government-wide Quadrennial Energy Review suggested in the PCAST report, not this DOE-QTR. However, the Department is interested in comments regarding its role in addressing these barriers.

6) **A number of non-technical barriers—including federal, state, and local regulations, market failures, and non-technical risks—impact the rate of deployment of energy technologies. What, if any, role should the Department have in addressing these barriers?**

6 Six Strategies

The recently released DOE draft Strategic Plan (February, 2011) outlines three important Departmental goals:

- Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.
- Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity, with clear leadership in strategic areas.
- Enhance nuclear security through defense, nonproliferation, and environmental efforts.

President Obama has articulated broad goals for reducing our dependence on oil, reducing pollution, and investing in RD&D of clean energy technologies in the United States to create jobs. These include:

- Reduce energy-related greenhouse gas emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline.
- By 2035, 80% of America's electricity will come from clean energy sources.
- Support deployment of 1 million electric vehicles (EVs) on the road by 2015.

There are six more or less independent strategies that are both necessary and sufficient to address the Administration's goals (see Figure 2) and enhance our energy, economic, and environmental security. These six divide into two trios: one for stationary energy (heat and power), and another for transport. Each trio has supply, efficiency, and "intermediate" strategies.

Implementation of any one of these strategies is a complex undertaking involving policies, economics, and technologies; this DOE-QTR is concerned with DOE's efforts in the latter.

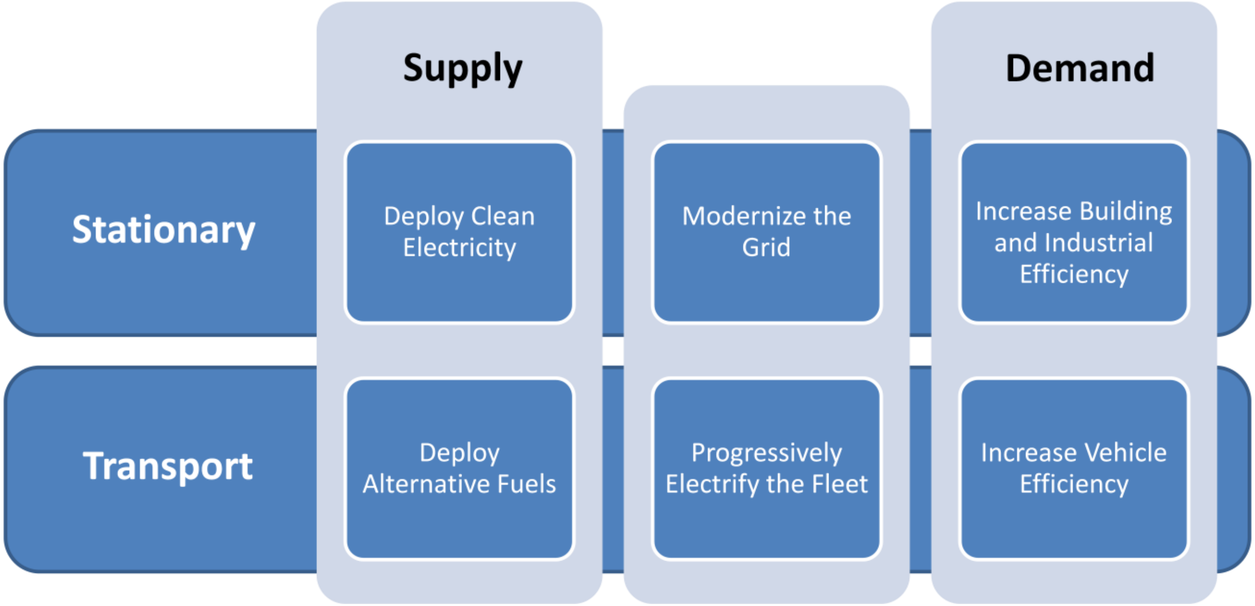

Figure 2. Six Strategies

7) **Have we correctly identified and structured these six strategies?**

The remainder of this framing document describes each strategy and its context, together with summaries of technologies we believe are important to that strategy. In each of the transportation and stationary sectors we begin with end-use efficiency, since improvements here will have the most immediate impact.

These sections are meant to solicit input on state-of-the-art, learning curves, and potential of each technology. In developing technology and policy priorities, future opportunities must compete on the quality of their ideas, the rigor of their technical approach, and the value of their knowledge return. Because of their importance in prioritization, technology assessments must be made within a systems context under realistic assumptions of scale, technology headroom, and economics. We believe the technologies and strategies discussed below meet the criteria of timeliness, and scale and should be central to DOE efforts going forward. Since we believe DOE's efforts best leverage the private sector in immature industries, our selection deemphasizes established energy sources such as conventional hydroelectric power and fossil fuels without carbon capture and sequestration. We welcome comment on our technology selection.

For each strategy or technology, we list source documents we intend to draw upon in assessing a technology's potential and in developing summary roadmaps towards its realization. In addition to the technology-specific reports listed in each section below, we will draw upon a number of cross-cutting reports and data: the National Academies of Science *America's Energy Future* reports, historical data from the EIA, the European Commission on Energy's *Strategic Energy Technology Plan*, and the *Global Energy Assessment*, when it becomes available.

8) We welcome comment on the selection of these technologies and sources, as well as suggestions of alternate technologies and sources, and updated technology, cost, and forecast data, particularly in rapidly-moving fields.

6.1 Transport

6.1.1 Increase Vehicle Efficiency

Powered almost exclusively by petroleum, U.S. road vehicles travelled three trillion miles in 2009 and consumed more than 150 billion gallons of liquid fuel. Vehicle miles traveled are projected to increase by 50% through 2035, although energy consumption by the fleet is projected to grow by only 20%.

U.S. fuel-economy in cars and light trucks (Light Duty Vehicles, or LDV) has been constant for 25 years, with continuously improving engine efficiency offset by growth in vehicle size, performance, and accessories. During this same period, European and Japanese fuel economics have improved steadily, so that their fleets are now 60% more fuel efficient than the U.S. fleet.

Significant opportunities remain for improving vehicle efficiency and fuel economy without adversely impacting performance, size, and other characteristics. Advanced internal combustion engines (ICEs) could improve efficiency by nearly 50% over today’s gasoline engines, and additional opportunities to improve the fuel economy of vehicles with conventional ICEs abound (e.g., improved transmission gearing and reduced vehicle weight).

Beyond the fuel consumption by LDVs, medium- and heavy-duty vehicles (HDVs)—particularly freight trucks—consume an additional 30 billion gallons of diesel fuel per year. There are opportunities to reduce fuel consumption by up to 50% in these vehicles using conventional technologies, at a break-even fuel price of just over $1 per gallon. Given the rapid turnover of HDV stock, the freight sector can effect a significant near-term reduction of petroleum consumption.

The cross-cutting questions described in Section 5 should be considered while reviewing these technologies. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America’s Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

In developing roadmaps for all vehicle efficiency technologies, we will draw upon the following sources:

- DOE Vehicle Technologies Program, *Multi-Year Program Plan, 2011-2015*, 2010
- DOE EERE, *2008 Vehicle Technologies Market Report*, 2009
- National Research Council, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, 2011
- National Research Council, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*, 2010

6.1.1.1 Light-weight Materials

Light-weight materials like magnesium, aluminum, high-strength steel, and polymer composites can replace the cast-iron and traditional steel in vehicles to significantly increase fuel economy while maintaining safety, performance, and reliability. A 10% reduction in vehicle weight can increase fuel economy by 6–8%. Moreover, replacing traditional components with lightweight materials allows vehicles to carry advanced emissions control equipment, safety devices, power systems, and integrated electronic systems without an overall increase in weight.

For passenger vehicles, DOE is working to validate a cost-effective weight reduction of 50% in body and chassis systems by 2015 compared to a 2002 baseline, while maintaining safety, performance, and reliability. DOE funds research on a variety of lightweight materials, focusing on carbon fiber composites and magnesium. Through these activities, DOE aims to lower the cost of carbon fiber from the current $10–20 per pound to less than $5 per pound.

In developing roadmaps for lightweighting technologies, we will draw upon the following source:

- DOE Vehicle Technologies Program, *2009 Annual Progress Report for Lightweighting Materials*, 2009

6.1.1.2 Internal Combustion Engine Performance

ICEs power 240 million cars and light trucks on our nation's roads, and nearly all of the 10–17 million new vehicles sold each year. Many vehicles of the future, whether traditional combustion, hybrid-electric, or plug-in hybrid, will continue to rely on ICEs because of their relatively low cost, high performance, and ability to use diverse liquid fuels. Increasing the efficiency of ICEs is one of the most promising and cost-effective approaches to improving the fuel economy of our nation's vehicle fleet in the near- to mid-term. ICE thermal efficiency and emission reduction are being driven by innovations in low temperature combustion strategies, emission controls, and fuel injection. Key developments in combustion and emission controls plus low-sulfur fuel have enabled manufacturers to achieve the necessary emissions levels and introduce additional diesel-powered LDV models to the U.S. market.

DOE aims to facilitate improvement of LDV gasoline fuel economy by 25% by 2015 and of LDV diesel by 40% compared to a baseline 2009 gasoline vehicle. The program also aims to improve heavy truck fuel economy by 20% by 2015 and by 30% by 2018.

In developing roadmaps for combustion engine technologies, we will draw upon the following source:

- DOE Vehicle Technologies Program, *2009 Annual Progress Report for Advanced Combustion Engine Research and Development*, 2009

6.1.2 Progressive Electrification of the Vehicle Fleet

Electrification of the transportation sector is a significant opportunity to reduce petroleum consumption, lower GHG emissions, and reduce air pollution. Degrees of electrification range from mild and strong hybrid electric vehicles (HEVs), through plug-in hybrid electric vehicles (PHEVs), to battery electric vehicles (BEVs). More than 1.5 million HEVs have been sold in the U.S. since their introduction in 2005 and new hybrid models are introduced every year.

HEV powertrains are at least 50% more efficient than current gasoline internal combustion engines (ICEs), and do not require infrastructure upgrades. Grid-connected vehicles (PHEVs and BEVs) that further minimize fuel consumption have recently come to market. The first mass produced PHEV (Chevy Volt) and BEV (Nissan Leaf) began delivery in late 2010, and DOE has estimated that auto manufacturers will have the capacity to produce more than one million EVs by 2015. DOE is also supporting large demonstrations of 13,000 PHEVs and BEVs and 23,000 chargers in more than 20 cities around the country.

Partial electrification of the vehicle fleet combined with improvement in conventional vehicles could reduce domestic fuel consumption by more than 80 billion gallons per year in 2035. Estimating GHG reductions becomes more problematic as integration with the electric grid grows and the carbon footprint of future electric power becomes important.

The principal challenge to vehicle electrification continues to be the cost, performance, and physical characteristics of batteries. Other challenges include the supply of rare-earth elements for motors, local barriers to installing charging infrastructure, long charging times, and standardization of chargers and the grid interface. PHEVs and BEVs are both a challenge and opportunity for the grid. Large numbers of EVs could burden residential distribution transformers and reduce grid reliability. High EV penetration combined with smart charging could also provide distributed grid storage that enhances grid operability and reliability and allows for greater integration of renewable power.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

In developing roadmaps for all vehicle electrification technologies, we will draw upon the following sources:

- National Research Council, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, 2011
- DOE Vehicle Technologies Program, *Multi-Year Program Plan, 2011-2015*, 2010

6.1.2.1 Batteries

The cost and performance of batteries are key factors determining the growth of electric drive. In 2010, more than 95% of lithium-ion batteries were made in Japan, China, and South Korea. The worldwide market for EV batteries is projected to grow to $8 billion by 2015. The Recovery Act included grants that are enabling companies to build the capacity to produce 50,000 EV batteries annually by the end of 2011 and 500,000 EV batteries annually by December 2014. This represents capacity sufficient to meet the requirements for projected U.S. EV production.

DOE's goal is to drive reduction in the cost of battery storage to $300 per kilowatt hour (kWh) by 2014, roughly half of current costs. This is being done through investments in RD&D of battery chemistries, including both the mature family of lithium-ion batteries and other less mature chemical systems such as lithium metal polymer batteries and lithium sulfur batteries. ARPA-E supports 14 battery projects. The Recovery Act supported 30 new battery, electric drive, and electric vehicle manufacturing plants, and supported construction of more than 10,000 charging locations.

In developing roadmaps for battery technologies, we will draw upon the following source:

- International Energy Agency, *Technology Roadmap: Electric and plug-in hybrid electric vehicles*, 2009

6.1.2.2 Motors

Electric propulsion components can add significant price to vehicles that require 80–180 kilowatt (kW) motors. An electric motor and inverter, critical components of the electric drive power train, use the energy in the battery to move the EV. Permanent magnet motors are the most popular for EVs because of their high power density, specific power, and efficiency. These permanent magnets require rare earth metals, the supply and cost of which present a potential barrier to wide deployment of EVs.

The DOE aims to facilitate a reduction in the cost of an electric drive system to $12/kW ($7/kW for the motor) in 2015 and $8/kW ($4.70/kW for the motor) in 2020 with specific requirements and targets including power density, efficiency and lifetime. To achieve these metrics, DOE is supporting research, development, and demonstration to decrease cost, weight, volume, and improve thermal management of power electronics (inverters and capacitors) and electric motors.

In developing roadmaps for electric motor technologies, we will draw upon the following source:

- DOE FreedomCAR and Fuel Partnership, *Electrical and Electronics Technical Team Roadmap*, 2010

6.1.3 Alternative Fuels

For reasons of energy density, cost of production, and ease of transport and use, petroleum-derived gasoline and diesel dominate both domestically and globally. Despite improving vehicle efficiencies and progressive electrification, the U.S. is projected to continue to rely on liquid fuels for the foreseeable future, and certain segments of the transportation sector (e.g. HDVs, airplanes, and civilian ships) require the energy density of liquid fuels for effective operation. Use of alternative (non-crude-derived) liquid or gaseous fuels is therefore another strategy to reduce oil consumption.

The existing petroleum fleet is supported by an extensive infrastructure. Substitution of other fuels for petroleum products is therefore a significant challenge, as diverse alternative chemistries face a range of complications. Certain fuels are incompatible with existing infrastructure, and so require new infrastructures to be deployed, an expensive proposition for a sector that includes 250 million vehicles. Other fuels require significant resources and technology advances to achieve production at scale, and still others suffer from low energy density relative to petroleum-derived incumbents. Drop-in compatible alternative fuels (i.e., fuels that can be easily blended with or substituted for their petroleum-derived counterparts) therefore have a structural advantage.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* report on liquid fuels. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

6.1.3.1 Advanced Biofuels

Biofuels are substitutes for petroleum-based transportation fuels made by biologically or chemically converting renewable biological feedstock. In 2010, the U.S. produced an estimated 13 billion gallons of ethanol from corn grain, an 800% increase from 2000. The total global ethanol supply was estimated to be 22.5 billion gal in 2010. Biodiesel produced from oilseed crops peaked in 2008 at 691 million gallons and has declined since. These first-generation commercial biofuels total less than 5% of the fuels consumed for U.S. transportation, and interact significantly with food and feed markets.

Lignocellulosic biomass, on the other hand, derives from agricultural and forestry residues or dedicated energy crops. It is estimated that over 400 million tons of U.S. biomass annually is sustainably available today, and that the sustainable resource potential is over 1 billion tons annually. This estimate does not include potentially significant sources of non-terrestrial biomass such as algae. More than 35 biorefineries for lignocellulosic biomass are being designed and/or constructed in the U.S at pilot-, demonstration-, and commercial scales.

Possible biofuels include alcohols, other oxygenates, and drop-in hydrocarbons. There are multiple conversion pathways, including biochemical approaches that use a combination of chemical pretreatment, enzymatic hydrolysis and fermentation; gasification to convert biomass to synthesis gas intermediates; and pyrolysis and other liquefaction that convert biomass to liquid bio-oil intermediates.

DOE's program supports R&D to make cellulosic biofuels cost competitive with petroleum-based fuels. The Energy Independence and Security Act set a goal of 36 billion gallons per year of renewable transportation fuels by 2022, of which at most 12 billion may be corn ethanol. The Recovery Act supported the construction of 19 pilot, demonstration, and commercial-scale bio-refineries.

In developing roadmaps for advanced biofuel technologies, we will draw upon the following sources:

- DOE and U.S. Department of Agriculture, *Biomass as Feedstock for a Bioenergy and BioProducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. ORNL/TM-2005/06, 2005
- DOE, *Biomass Program Multi-Year Program Plan*, 2010

6.1.3.2 Alternative Fossil Fuels

Both coal and natural gas can substitute for petroleum in transportation applications. The abundant domestic supply of both fossil fuels can address challenges associated with oil, although as with all forms of energy, there are environmental aspects to be managed and balanced.

In 2008, 150,000 vehicles (mostly buses and corporate-fleet vehicles) were powered by compressed natural gas (CNG) in the U.S. Natural gas must be compressed to meet the volume requirements of mobile applications, but even CNG takes considerable space in vehicles. Advantages for CNG as a substitute for petroleum include engine efficiencies greater than those for gasoline and and the existing natural gas infrastructure for domestic and industrial applications.

Coal (with or without added biomass) and natural gas can be converted to syngas, which can be subsequently catalyzed into gasoline components, alternative diesel components, methanol, or dimethyl ether (DME) through a variety of proven chemical processes. Commercial deployment of methanol would require considerable new infrastructure, and methanol's corrosive and toxic properties raise environmental and health concerns. DME is a clean-burning drop-in substitute for diesel, but like other alternative fuels would require upgrades in infrastructure. Coal can also be liquefied directly to synthetic crude oil for subsequent refining.

The primary barriers to all of these conversion processes are scale, capital intensity, and environmental impact. Opportunities for technical improvement include gasification units, separation processes, catalysts, and CCS.

DOE currently has no activities related to alternative liquid transportation fuels from fossil feedstocks.

In developing roadmaps for alternative fossil transportation fuel technologies, we will draw upon the following source:

- California Institute for Energy and the Environment, *Natural Gas Vehicle Research Roadmap*, 2008

6.2 Stationary

6.2.1 Building and Industrial Efficiency

Industry consumes some 30% of U.S. energy, with residential and commercial buildings accounting for a further 40%. Energy efficiency improvements, whereby the same or better services are provided to the end user while consuming less energy, could therefore dramatically reduce energy demand, often with net economic benefit to the end user.

Changes in electrical energy demand directly affect the entire grid system, and can have benefits well beyond the economic value of reduced energy consumption for the consumer. By reducing energy demand, efficiency improvements enable utilities to serve more customers with the same infrastructure, thereby deferring large-capital upgrades to the bulk and distribution power systems. Demand response, where device power consumption is adjusted in response to the state of a larger system, can target efficiency to periods of peak stress where the operational value is often highest and opportunities for revenue generation are greatest.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* report on efficiency. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment. The many and varied end uses of energy present a challenge to prioritization, and DOE particularly welcomes input on Question 3 in Section 5.2.2 with respect to efficiency technologies and priorities.

6.2.1.1 Efficiency in Buildings

Residential and commercial buildings currently use about 40% of U.S. primary energy and 72% of U.S. electricity each year. Building energy use is dominated by heat generation (for air or water), moving heat from one place to another (air conditioning or refrigeration), and lighting. However, end-use devices account for a growing fraction of building electricity use. Direct fossil fuel (primarily natural gas and fuel oil) use in buildings is overwhelmingly for conditioning air and heating water.

Significant energy savings (likely over 20%) would be possible by deploying currently cost-effective technologies. However, the interdependence of building components makes it harder to estimate the potential for energy efficiency. For example, the building envelope, windows, and control systems impact the energy use required for heating, ventilation, and air conditioning (HVAC), and windows have a direct impact on lighting demand.

Building codes and standards govern building construction and have historically been concerned primarily with safety. Recent building codes and voluntary programs have increased attention on energy-efficient design and building operation. Equipment and appliance standards set minimum energy efficiency limits. Technology development and building codes and standards can work together to create beneficial feedback loops.

Building energy use can have two key interactions with the other stationary energy strategies described in this DOE-QTR. Some clean electricity technologies (particularly solar PV) can be installed in or on buildings to provide energy directly. This distributed energy generation changes the nature of the demands on the transmission and distribution grids. In addition, a modern grid system could implement demand response technologies that shed load rather than increase generation at times of high demand or decreases in production (such as from intermittent sources). Many building loads are well suited to participate in demand response.

DOE has identified five key technologies and loads in improving building efficiency.

6.2.1.1.1 Whole Building Design

Integrated approaches to whole building design that incorporate architecture/design, engineering, and construction for new commercial buildings have demonstrated up to 50% energy savings compared with current building codes. In 2006, the U.S. market for the construction and renovation of new and existing residential and commercial buildings was estimated to be approximately $1.22 trillion, which is over 69% of the value of all U.S. construction and over 9% of U.S. GDP.

DOE uses a systems engineering approach to assess and improve the efficiency of residential homes through its Building America program. Additionally, DOE is working with the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and other stakeholders in commercial buildings to develop advanced energy design guides for commercial buildings that are 50% more efficient than minimum code requirements.

6.2.1.1.2 Energy Management Systems

A system-wide approach to reducing a building's energy consumption combines sensors, controls, feedback loops, and software that integrate information from smart end-use technologies with an intelligent grid. The building control systems market grew from $3.1 billion in the U.S. in 2001 to $4.3 billion in North America in 2008, while remaining approximately one third of the global market for building controls.

Within the U.S., centralized energy management and control systems operate in about 33% of commercial building floor space, all of which is contained within about 10% of commercial buildings.

Automated demand response (ADR) allows smart buildings to adjust energy consumption in response to changing energy prices from a smart grid. ADR has been enhanced by open protocols and wireless technologies, both of which have contributed to the ability of service providers to integrate systems and provide clients with valuable data. ADR has been successfully demonstrated.

DOE is supporting work across several technical pathways including commissioning, standards development, sensors, algorithms for automation systems, integration with existing buildings, and integration with the design and construction of new buildings.

6.2.1.1.3 HVAC and Water Heating

HVAC accounts for 32% of building energy use. U.S. shipments of central air conditioners and air-source heat pumps make up about 10% of the global market. Unitary air conditioners and heat pumps have improved in energy efficiency by more than 13% since 2005. DOE has a goal of driving a reduction of 80% in the energy consumption of commercial HVAC between 2004 and 2020.

Water heating accounts for 9% of building energy use. Efficient water heating includes solar and heat pump devices. These currently comprise about 0.25% of the 8–10 million water heaters installed each year, and about 1% of the 100 million installed in the U.S. Heat pump water heaters have very low global penetration. In solar water heating, however, China leads the world, followed by Australia and New Zealand, Europe, Japan, and the U.S. and Canada. DOE has a goal of driving a reduction of energy use for hot water service by 50% between 2005 and 2015.

6.2.1.1.4 Lighting

Lighting accounts for 14% of building energy use. Compact fluorescent (CFL) shipments increased from about 21 million units in 2000 to 400 million units in 2007, causing CFLs to account for the majority of "light service" sold in 2007. Though light-emitting diodes (LEDs) are still in early deployment stages, DOE projections indicate that a 1000-lumen LED source could cost $2 in 2015. DOE is supporting development of solid state lighting across two main pathways—LEDs and organic LEDs—and across the innovation chain via core technology research, product development, and manufacturing support. DOE's goal is to improve lighting costs from 22 to 118 lumens per dollar and increase lighting output from 78 to 154 lumens per watt by 2015. The Recovery Act supported 17 projects that advanced core technology research, product development, and manufacturing of solid-state lighting.

6.2.1.1.5 Building Envelope and Windows

The windows, roofs, attic, and insulation of a building forms an envelope that determines about 36% of overall building energy use through loss of heating and cooling energy. Efficient windows can reduce a building's heating and cooling demand by up to 35%. From 2005 to 2009, energy efficient windows with low-e (R-3) glass increased from 58% to 74% of all units sold in the residential market and from 37% to 54% of the commercial market. R-5 windows, as well as dynamic windows, are available and could enable system effects such as downsizing HVAC capacity. DOE is supporting activities to lower the cost of R-10 windows to $\$3/\text{ft}^2$ price premium by 2020, as well as aiming to improve foam insulation performance by 25-40% by 2015 and enable dynamic thermal response of attics and walls at no extra life cycle cost by 2015.

Cool roofs can reduce a building's heating and cooling demand by up to 15%. Cool roofs for commercial buildings have achieved widespread use in California and will be mandatory in hot climates (zones 1-3) after upcoming changes to the ASHRAE 90.1 standard. Cool roofs for residential buildings currently have a very low market share due to high price premiums.

In developing roadmaps for building efficiency technologies, we will draw upon the following sources:

- Interlaboratory Working Group, *Scenarios for a Clean Energy Future*, ORNL/CON-476 and LBNL-44029, 2000
- Dirks, J.A., et al., *Lost Opportunities in the Buildings Sector: Energy-Efficiency Analysis and Results*, PNNL-17623, 2008

6.2.1.2 Industrial Efficiency

The energy requirements of the industrial sector are significant and diverse, consuming about one-third of all energy produced in the U.S. Approximately two-thirds of the end-use energy is consumed by relatively few energy intensive subsectors including chemicals, refining, pulp and paper, iron and steel, glass, aluminum, metal-casting, and cement. Manufacturing remains a leading contributor to the U.S. economy; in 2009 it accounted for 11% of GDP and directly employed 14 million people, supplied 60% of U.S. exports, and produced nearly 20% of the world's output.

Best practices and deployment of commercially-available state-of-the-art manufacturing technologies to improve efficiency are the fastest routes to improved industrial efficiencies. There is significant headroom both to improve the efficiency of existing processes and technologies (such as through the use of high-efficiency motor systems and combined heat and power) and to develop new processes and technologies that require significantly less energy to perform the same service (such as new fiber or plastic that can replace metals in some applications).

Many cost-effective energy efficient technologies have not been widely adopted due to barriers that include insufficient access to industry-specific energy efficiency expertise and workforce, slow capital stock turnover and uncertainty of energy prices, which deter corporate energy efficiency investments. The National Academies has surveyed a range of studies that estimate industrial energy savings of more than 16% through deploying existing and emerging technologies by 2020. Including the energy-savings potential of combined heat and power increases these estimates to more than 20%.

Next-generation materials and associated production technologies are intended to reduce costs, reduce energy use, reduce pollution, and improve product quality. DOE's industrial technology program includes efforts in coatings, thin films, electrochemicals that require functional surface interactions; ceramics, engineered polymers, and metallics that operate in extreme environments; composites and smart materials integrated in energy systems; and substitutes for magnetic materials containing rare earth elements.

Next-generation manufacturing processes improve efficiency by reducing steps required, developing alternative low-energy pathways, and developing entirely new processes and unit operations. Novel methods are required to produce such energy-intensive materials as steel, chemicals, titanium, and carbon fiber. DOE supports development of new production systems, including innovative bioprocessing techniques, high-performance catalysts and separations, nano-scale manufacturing and processing, next-generation computational tools (including simulation), advanced characterization, integrated sensor and process control systems, and smart process manufacturing.

In developing roadmaps for industrial efficiency technologies, we will draw upon the following sources:

- The Minerals, Metals, and Materials Society, Linking Transformational Materials and Processing for an Energy-Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization, *Vision Report of the Energy Materials Blue Ribbon Panel*, 2010, and *Opportunity Analysis for Materials Science and Engineering*, 2011
- Science and Technology Policy Institute, *The White Papers on Advanced Manufacturing Questions*, April 2010 draft

6.2.2 Modernize the Grid

The electrical grid is a large and complex system that moves 4 trillion kWh of electricity in the U.S. annually from more than 40,000 individual generating units through more than 150,000 miles of high voltage transmission lines to distribution systems that service more than 140 million customers. The physical nature of electricity links components together requiring real-time system balancing and every technology and action on the grid affects the rest of the system. Indeed, the utilities, independent power producers, system and transmission operators, and consumers all affect the same system, making forecasting the function, value, operation, and integration of new technologies in the system challenging, and leading to conservatism in the deployment of new technologies.

Much of the grid is based on an historical paradigm of large centralized generators connected to a bulk-energy transmission system, in which the distribution circuits that bring electricity into our homes and businesses are considered simple loads rather than integral components that contribute to overall system health. The system is designed for minimally acceptable operation at the extremes rather than the most efficient use of capital-intensive infrastructure. It is thus under-utilized and requires infrastructure upgrades despite having capacity to spare on most days. Additionally, because the grid evolved to accommodate generation and consumption technologies with physical characteristics different than those of today's technologies, power quality and reliability are compromised. The changing supply mix, increased demand requirements, and emerging vulnerabilities present unprecedented challenges to grid operation. Any transition toward the energy resources and technologies of the future will be enabled, or limited, by the grid.

The introduction of plug-in EVs will conjoin the transportation and stationary energy systems in an unprecedented manner (see 6.1.2), and distributed generation and actively managed distribution networks will require increased connectivity in both the electrical and telecommunications realms. Smart grid technologies are allowing system operation and engagement all the way to the customer, creating a distribution system with a level of flexibility not previously attainable. The ability to understand and control aspects of both the bulk power and distribution systems in real time will allow full exploitation of new technologies ranging from renewable generation, to efficiency and dynamic response of distribution networks, to EVs, all while supporting the power quality and reliability that is required by modern loads and consumers.

The broader objectives of “grid modernization” are to provide access to new energy resources while simultaneously increasing system utilization and flexibility. While specific needs may vary between the bulk power and distribution systems, the overall needs for improved system control and protection are common.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America’s Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, and non-technical barriers to deployment.

In developing roadmaps for all grid technologies, we will draw upon the following sources:

- DOE, *National Transmission Grid Study*, 2002, and associated the Issue Papers, particularly Section F: *Advanced Transmission Technologies*, 2002
- DOE Electricity Advisory Committee, *Keeping the Lights On in a New World – A Report by the Electricity Advisory Committee*, 2009

6.2.2.1 Monitoring, Modeling, and Control

Improving system flexibility across multiple timescales is important to enable system-wide improvements in asset utilization and to accelerate the integration of new technologies. New smart grid technologies that enable monitoring and control of critical electric system parameters are dramatically expanding visibility and flexibility throughout the system.

Phasor measurement units (PMUs) with data sampling rates in excess of 30 Hz, a 100x improvement of over legacy supervisory control and data acquisition systems, will allow users to observe and analyze the bulk power system in real-time. The deployment of advanced metering infrastructure could eventually turn each point of consumption into an active informational stream, thereby enhancing real-time grid monitoring capability. The Recovery Act supported the installation of 18 million smart meters and more than 850 PMUs.

The wealth of operational data provides significant opportunity to improve our models and understanding of the grid. The complexity and interdependencies associated with the electric system result in system-wide dynamic engagements that require improved knowledge and prediction of performance beyond today's capabilities. Modeling, simulation, and forecasting enable improved understanding of issues from operation through planning, and especially the interaction of the interconnected elements.

Leveraging advances in both monitoring and modeling to enable control points across the system will improve reliability and asset utilization. New real-time analysis tools and control protocols will be required, although attention must be paid to concerns over privacy and consumer preference.

In developing roadmaps for grid monitoring, modeling and control technologies, we will draw upon the following source:

- DOE and FERC, *Steps to Establish a Real-time Transmission Monitoring System for Transmission Owners and Operators Within the Eastern and Western Interconnections: A Report to Congress Pursuant to Section 1839 of the Energy Policy Act of 2005*, 2006

6.2.2.2 Power Electronics

New developments in power electronics devices, such as voltage control equipment and volt ampere reactive compensators will provide utilities with the ability to more effectively deliver power to their customers while increasing reliability of the bulk power system. Power electronics enable power flow control and energy conversion, critical to the efficient movement of electricity from generation resource to the consumer. Advances in power electronic devices include both technologies that are new to the grid and evolutionary improvements in existing technologies, both involving the development and deployment of new materials. Overcoming the limitations of silicon-based semiconductors (which include low voltage blocking capability, low switching speeds at high power, and limited junction operating temperature) would enable new technologies. DOE is supporting research in large-bandgap materials.

In developing roadmaps for power electronics technologies, we will draw upon the following source:

- L. M. Tolbert et al., *Power Electronics For Distributed Energy Systems and Transmission and Distribution Applications*, ORNL/TM-2005/230, 2005.

6.2.2.3 Energy Storage

The core function of energy storage is to bridge the gap between the characteristics of the generation, load, and control technologies. The physical characteristics of energy storage technologies govern their most useful applications, and despite the large number of technologies available for storing energy, each technology is best suited to a limited subset of applications and services.

Optimal deployment of storage will require assessment and analysis of technology characteristics, possible system configurations, and service value. Departmental goals in energy storage are to understand how to optimize system integration, to improve performance of storage systems relevant to their most appropriate application, and to develop the manufacturing innovations necessary for cost-effective storage technologies. The Recovery Act supported the development of two utility-scale energy storage facilities.

In developing roadmaps for energy storage technologies, we will draw upon the following sources:

- DOE Electricity Advisory Committee, *Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid – A Report by the Electricity Advisory Committee*, 2008
- DOE, *Electric Power Industry Needs for Grid-Scale Storage Applications*, 2010
- *Electric Power Research Institute and DOE, EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, 2003, and its sup*plement, EPRI-DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications*, 2004
- DOE, *Advanced Materials and Devices for Stationary Electrical Energy Storage*, 2010

6.2.3 Adoption and Deployment of Clean Electricity Supply

Approximately 50% of our electricity is generated from coal, 20% from nuclear, 20% from natural gas, and a further 10% from renewable resources such as hydropower and wind. The conventional fossil energy technologies that dominate the system (i.e. coal and natural gas) provide a variety of services, including base-load and grid regulation, and are simultaneously consistent and dispatchable to respond to changing loads. However, their environmental impacts can include particulate, mercury, and GHG emissions, and consumption of 27% of non-agricultural fresh water.

There are many alternative generation technologies, each with benefits and challenges relative to the incumbent mix. Renewable technologies such as wind and solar are non-polluting and require little water; successful deployment of carbon capture and storage (CCS) technologies would dramatically reduce the emissions associated with coal and gas. Because the final product of a new generation technology (power into the grid) is indistinguishable from that of legacy technologies, clean energy technologies face considerable hurdles in displacing incumbent technologies, ranging from cost to performance. Recent innovations in extraction, partially driven by DOE research contributions a decade ago, have made natural gas a low-cost power method, and it will likely set cost benchmarks going forward. The low energy density (both per unit area and per project) of renewable resources relative to fossil or nuclear plants requires expansive deployment, often elevating costs and regulatory hurdles beyond conventional technologies. The opportunity to deploy generation in a distributed manner presents opportunities to lower cost burdens to entry of new technologies and provide resilience compared to centralized energy generation, but will require substantially different deployment strategies. New technologies using conventional resources (e.g. CCS and nuclear) are often more expensive to build and operate than their legacy counterparts, with uncertain technical performance.

Beyond cost, the overall conservative and regulated nature of our utility sector places a very high burden on entry of new technologies. The variability of renewable resources, with fluctuations on timescales ranging from seconds to years, is in tension with the desire of system operators to control generator output. A properly designed power system incorporating distributed generation will be fundamentally more robust than the current system, thereby providing significant benefit and resilience to operators and consumers alike. Given the great projected rise in power demand in non-OECD nations, domestic development and deployment of alternative generation technologies can enhance the global competitiveness of the U.S. economy.

As you review these technologies, please keep in mind the cross-cutting questions described in Section 5. DOE is particularly interested in feedback on the resources and reports that are listed with each technology, as well as the technology roadmaps described in the *America's Energy Future* reports. Although DOE does continuously track new information emerging from the field, we welcome all data that updates these references on questions of cost, projections, integration into the grid, land and water use, and non-technical barriers to deployment.

6.2.3.1 Nuclear Energy

Nuclear power plants use the energy released by fission to produce heat, which then drives a turbine to generate electricity. Twenty percent of electricity produced in the United States comes from nuclear power. There are 104 operating reactors in the U.S. with a combined capacity of 101 GW. The NRC is in the process of reviewing 17 applications to build 26 new reactors with a combined capacity of 34 GW. Globally, 442 reactors are in operation with an additional 65 under construction, the majority of which are in Asia. Known uranium reserves would be more than sufficient to expand nuclear generation by a factor of ten over the course of decades.

Reactors are generally operated at constant output to maximize economic return on the high capital investment, and the capacity factor of nuclear energy (over 0.9) is the highest for any current generation technology. This rigid output prevents nuclear plants from providing dispatchable power.

The oldest nuclear power reactors still operating were built in 1969, and the last reactor built in the U.S. began operation in 1996. Pre-1980 reactors were smaller and had a lower cost per kW installed than those built after 1980. Improvements in operational performance have allowed reactor operators to extend their operational lifetime—sixty-one reactors have received 20-year license renewals from the NRC with an additional 21 currently under review and 17 more that have indicated their intent to apply for renewals.

U. S. utilities are currently proposing to construct Generation 3+ units, with the first expected to be completed by 2016. These are based upon the same light-water reactor technologies in use today, with improved safety and economic characteristics. They require large steel components that can be produced only in a few factories around the world, all of which are located abroad. Small modular reactors (SMRs) have the potential to lower the hurdle for construction financing while leveraging factory construction techniques to lower costs.

International nuclear development has diminished the importance of U.S. nuclear suppliers, and all major U.S. reactor vendors are either owned by or closely aligned with foreign companies. In addition, South Korea may begin exporting SMRs before U.S. suppliers. As more players emerge in the global nuclear power arena, the U.S. must lead engagement with international regulatory bodies to ensure safety and security throughout the nuclear fuel cycle.

DOE supports the continuing operation of existing plants through its Light Water Reactor Sustainability program and the Modeling and Simulation Hub. The DOE program to accelerate SMR development will provide financial support to reactor developers to reach commercialization while the DOE SMR R&D efforts will help to enable the NRC to establish the regulatory basis for SMR licensing. DOE is supporting development of Generation IV and Generation V reactor designs.

In developing roadmaps for nuclear technologies, we will draw upon the following sources:

- Congressional Budget Office, *Nuclear Power's Role in Generating Electricity*, 2008.
- Massachusetts Institute of Technology, *The Future of Nuclear Power: An Interdisciplinary MIT Study*, 2003, and the *2009 Update* to this report.
- Massachusetts Institute of Technology, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study*, 2010.
- University of Chicago, *The Economic Future of Nuclear Power*, 2004.

6.2.3.2 Wind

Wind turbines convert airflow directly to electricity. The capacity factor for wind power can be as much as 0.44 for new generation at good sites, but averages ~0.3 across the U.S. Wind power can be used as a distributed generation technology, but because of the size and area requirements it is more typically installed on the utility scale, and can be installed either on- or offshore. The U.S. wind resource is most dense in mountain areas (including the Rockies and Appalachians), in the Great Plains, and in some offshore locations.

Global wind power installations increased by 35.8 GW in 2010, bringing total installed wind capacity up to 194 GW, a 22.5% increase from the end of 2009. China currently has the most installed wind power capacity. In the U.S., just over 5 GW of new wind power capacity was added in 2010, bringing the total installed capacity to 40.2 GW. Wind power now provides over 2% of the nation's annual electricity generation. No offshore projects have yet been built in the U.S.

Over the past 25 years, wind turbine nameplate capacity has increased from about 50 kW to 1.5–3 megawatts (MW) for land-based wind turbines. Offshore wind turbines as large as 5 MW are being deployed, and even larger turbines are under consideration. Continued scaling of rotor size and tower height will increase energy capture, while advanced control and condition monitoring technology will lower installation costs and increase reliability. Installed costs could be further reduced through decreased component weight and simplified transportation logistics. Offshore wind requires further development of turbines, installation, and monitoring mechanisms designed for the marine environment.

The availability of fiberglass, carbon fiber, and permanent magnets (i.e., rare earth minerals) may present long-term barriers to continued scaling and deployment of wind energy. Non-technical barriers to wind deployment include transmission availability at remote locations, noise and viewshed concerns, danger to wildlife, and siting and permitting requirements.

DOE's goals are to facilitate wind deployment and decrease the cost of electricity for onshore and offshore wind systems to $0.036/kWh by 2012 and 0.07/kWh by 2014, respectively. The Recovery Act supported over 8 GW of wind capacity installation, more than 50 wind-related manufacturing projects, and development of innovative wind technologies and test facilities.

In developing roadmaps for wind technologies, we will draw upon the following sources:

- Musial, W. and Ram, B., *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers*, NREL/TP-500-40745, 2010
- DOE EERE, *2009 Wind Technologies Market Report*, DOE/GO-102010-3107, 2010
- DOE EERE, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, DOE/GO-102008-2567, 2008.

6.2.3.3 Concentrating Solar Power

Concentrating solar power (CSP) systems use mirrors to focus the sun's energy onto receivers in which a heat-transfer fluid is heated; that heat ultimately drives a turbine to generate power. CSP is suited for utility-scale generation, and could be base-load generation if long-term thermal storage is incorporated. The average capacity factor of new CSP generation is 0.3. Short-term storage (30 minutes to 1 hour) reduces the impact of thermal transients (such as clouds), while long-term storage (4–16 hours) can increase the system capacity factor (up to 0.7). The CSP solar resource in the U.S. is geographically concentrated in the desert southwest.

Between 1985 and 1991, 354 MW of solar trough technology were deployed in southern California. These plants are still in commercial operation and have demonstrated the longevity of CSP technology. In the U.S., 431 MW of CSP were in operation in 2009, generating about 0.03% of U.S. electricity, and there are more than 8 GW of CSP projects with signed power purchase agreements. Spain has 435 MW of commercial CSP generation and an additional 2 GW under development, and there are significant markets in the Middle East and North Africa.

CSP technology without thermal storage is relatively mature; integration of thermal storage is an area of active technical development. In addition, new technologies could reduce the use of water in CSP plants (as well as water use in other thermal power generation technologies). The DOE program aims for cost reductions to less than $0.10/kWh, which could make CSP competitive in the intermediate load market without subsidies by 2020.

In developing roadmaps for solar CSP technologies, we will draw upon the following sources:

- GTM Research, *Concentrating Solar Power 2011, Technology, Markets, and Trends*, 2009
- Mehos, M., D. Kabel, and P. Smithers, "Planting the Seed—Greening the Grid with Concentrating Solar Power." IEEE Power & Energy, 7 (3), 55-62, 2009
- SolarPACES/ESTELA/Greenpeace, *Concentrating Solar Power Global Outlook 2009 - Why Renewable Energy is Hot*, 2009.
- Turchi, C., M. Mehos, C.K. Ho, and G.J. Kolb, *Current and Future Costs for Parabolic Trough and Power Tower Systems in the U.S. Market*, NREL/CP-5500-49303, 2010.

6.2.3.4 Solar Photovoltaic

Solar photovoltaics (PV) use semiconductors (such as silicon or thin-film materials) to convert sunlight directly into electrical energy. They can be deployed at both utility (field) and distributed (rooftop) scales. The average capacity factor of new solar PV is ~0.2, with peak generation in daytime. The total solar resource exceeds U.S. energy consumption, although the intermittent nature of that resource requires new paradigms of energy management. The greatest resource density is in the desert southwest, although the resource is significant across the southern tier of the U.S. and the Great Plains.

Global solar PV installations reached nearly 37 GW at the end of 2010, growing at an annual rate of almost 40% over the past decade. U.S. PV capacity grew at similar rates to approximately 2.0 GW in 2010, but nearly 70% of the world's solar capacity is in Europe. Even with this growth, PV currently supplies less than 0.1% of US electricity.

The U.S. solar industry has grown into a $6 billion market, the majority of which is solar PV. However, the U.S. share of global PV manufacturing has fallen from nearly 46% in 1995 to 6% in 2008. China, the world leader, manufactured nearly 9 GW of solar PV in 2010, compared to roughly 900 MW produced in the U.S.

Cost is currently the major barrier to greater solar PV deployment. Improvements in cell efficiency, along with advances in manufacturing and the balance of the PV system, can drive down deployment costs. DOE's PV program aims to facilitate cost reduction to $1/W for utility-scale installations by 2020 through activities on three key components: the module, the power electronics, and the balance of system. At that cost, widespread deployment is expected. The Recovery Act supported the construction of PV manufacturing facilities and the deployment of 322 MW of PV capacity.

In developing roadmaps for solar PV technologies, we will draw upon the following sources:

- International Energy Agency, *Technology Roadmap: Solar photovoltaic energy*, 2010

6.2.3.5 Carbon Capture and Storage

Carbon capture technology removes CO_2 from fossil fuel combustion product stream for potential geologic storage, thereby reducing GHG emissions. Fossil fuels supply 80% of the world's energy, and coal accounts for 25% of world energy supply and 40% of global carbon emissions. The U.S. possesses 1/4 of the known coal resource, and the U.S., Russia, China and India together account for 2/3 of world reserves. The existing and predicted coal-burning energy infrastructure in these countries implies substantial continued coal use in the next few decades.

Currently available CCS technologies are neither cost-effective nor demonstrated with electric generation. The highest-cost CCS step is CO_2 capture, due to the added capital cost and energy required to release the CO_2 from the chemicals that extract it from the combustion flue gas and the subsequent compression. A new generation of capture technologies is under development with DOE support, and DOE expects them to be ready for demonstration by 2015. If these are successful, CCS could be an economically viable GHG reduction option by 2020. Assigning a monetary value to the reduction in CO_2

emissions would provide a market incentive to further improve and deploy CCS technologies. Multiple technology paths are being pursued in an effort to maximize the likelihood of commercial success.

Another challenge to CCS deployment is demonstrating CO_2 storage. This will require comprehensive characterization and monitoring of geologic CO_2 storage sites and the ability to predict underground behavior, migration, and trapping of CO_2 as well as a legal regime that addresses allocation of long term potential liabilities associated with storage. Injection of CO_2 has long been used to enhance oil recovery.

DOE supports the development of 5–10 commercial-scale CCS demonstration projects in the U.S. by 2016 for both retrofit and new-plant applications; these projects have been funded in part by the Recovery Act. DOE's RD&D aims to reduce costs by improving overall power plant efficiency and reducing cost for CCS systems. DOE is also supporting research in CO_2 storage that will lead to the reduction and quantification of risks. DOE participates in several international collaborations to develop and demonstrate CCS technologies.

In developing roadmaps for CCS technologies, we will draw upon the following sources:

- *Report of the Interagency Task Force on Carbon Capture and Storage*, 2010.
- Massachusetts Institute of Technology, *The Future of Coal: Options for a Carbon-Constrained World*, 2007.

6.2.3.6 Other Clean Electricity Supply Technologies

DOE expects that each of clean electricity supply technologies described above could contribute significantly to meeting the Nation's energy goals, and DOE RD&D support has the potential to materially improve these technologies. Other clean electricity supply technologies could also contribute to varying degrees; these include hydroelectric, marine, and geothermal power technologies. Increasing the deployment of hydroelectric power is expected to consist largely of deploying evolutionary technologies, where DOE RD&D would not play a significant role. Geothermal and marine power technologies face uncertainties that exceed those of the previously discussed clean power technologies, including uncertainty in the materiality of their impact.