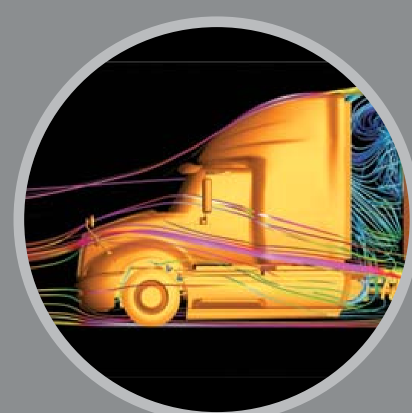
U.S. DEPARTMENT OF ENERGY

QTR

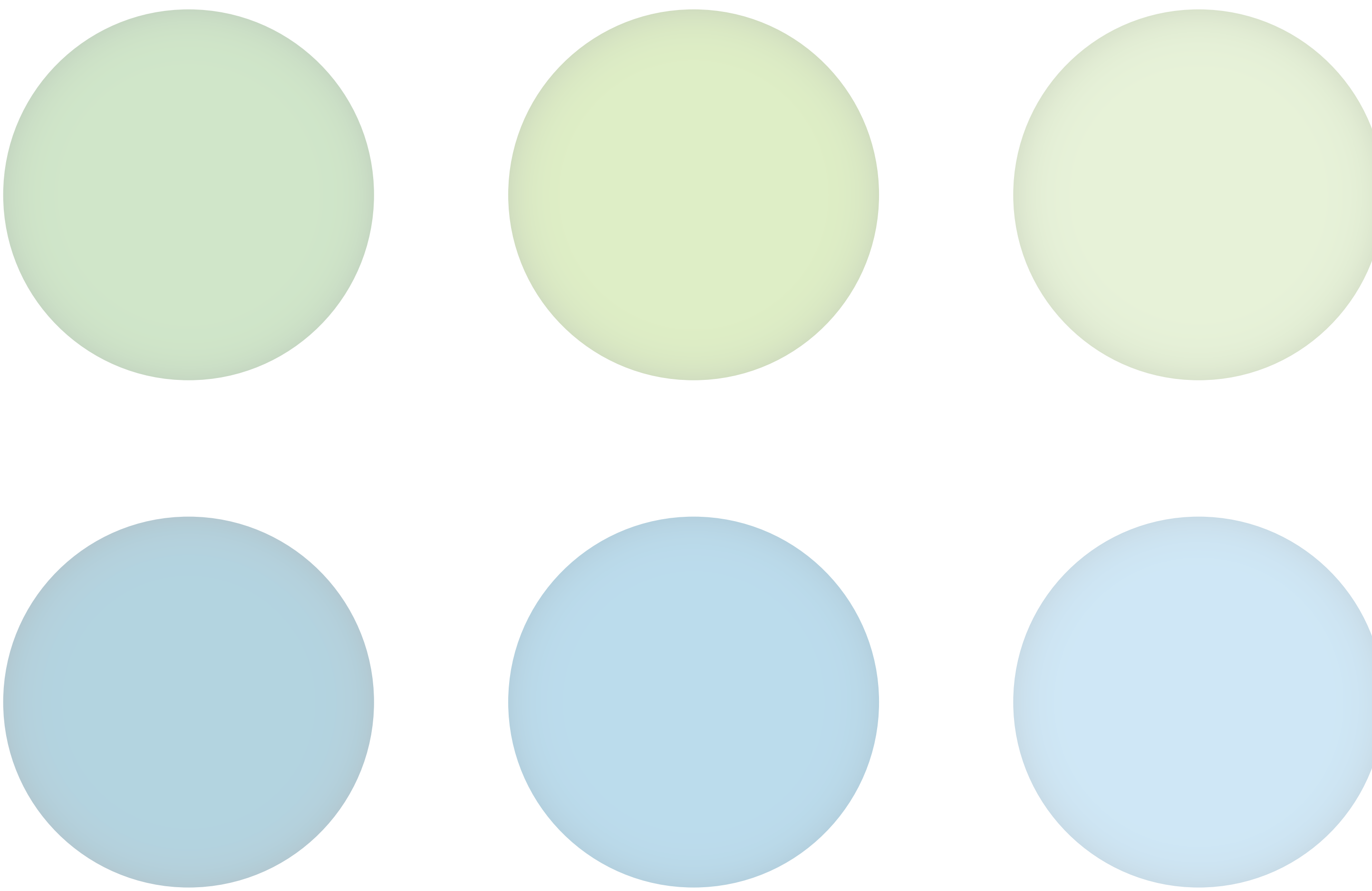
REPORT ON THE FIRST
QUADRENNIAL TECHNOLOGY REVIEW





September 2011



MESSAGE FROM THE SECRETARY OF ENERGY

Steven Chu, Secretary of the United States Department of Energy

Today, our nation is at a cross road. While we have the world's greatest innovation machine, countries around the world are moving aggressively to lead in the clean energy economy. We can either lead in the development of the clean energy economy or we can stand back and wait for others to move first toward a sustainable energy future. For the sake of our economic prosperity and our national security, we must lead. The Department of Energy (DOE) plays a central role in that effort by unleashing technological innovation, which can create new jobs and industries while building a cleaner, more efficient, and more competitive economy.

During this time of hard budget choices and fiscal challenge, we must ensure that our work is impactful and efficient. The question we face is: "How should the Department choose among the many technically viable activities it could pursue?" This first Quadrennial Technology Review (QTR), launched at the recommendation of the President's Council of Advisors on Science and Technology, lays out the principles I believe must guide these difficult choices.

Traditionally, the Department's energy strategy has been organized along individual program lines and based on annual budgets. With this QTR, we bind together multiple energy technologies, as well as multiple DOE energy technology programs, in the common purpose of solving our energy challenges. In addition, the QTR provides a multi-year framework for our planning. Energy investments are multi-year, multi-decade investments. Given this time horizon, we need to take a longer view.

We also recognize that the Department is not the sole agent of energy transformation. Our efforts must be well coordinated with other federal agencies, state and local governments, and with the private sector, who are the major owners, operators, and investors of the energy system.

This Report specifically places our efforts in a multi-agency policy framework. While the Department's QTR is not by itself an integrated federal energy policy, I believe it is the necessary first step of a multi-agency Quadrennial Energy Review that could dramatically improve the integration and effectiveness of the government's energy policy.

Finally, I would like to commend and thank Under Secretary for Science Steven Koonin for leading this inaugural review. He and his dedicated team sought advice from hundreds of energy stakeholders; engaged experts from academia, industry, and national laboratories; and consulted with our agency counterparts from across the government. As part of the Obama Administration's commitment to open government, the Review was conducted transparently and inclusively. It establishes a firm foundation upon which we can make significant progress in addressing our Nation's energy challenges.

The stakes are high for our country, and I am optimistic that we can still lead the world in technological innovation. The QTR will help ensure that we make thoughtful, wise investments to achieve our national energy goals and to strengthen our economic competitiveness in the 21st century.

Steven Chu
Secretary of Energy

MESSAGE FROM THE UNDER SECRETARY FOR SCIENCE

Steven Koonin, Under Secretary for Science of the United States Department of Energy

The most important goal for the Department of Energy's first Quadrennial Technology Review (QTR) is to establish a framework for thinking clearly about a necessary transformation of the Nation's energy system. We really have two energy challenges. In transportation, our challenge is energy security—we currently send $1 billion out of the country each day to pay for oil. In our residential, commercial, and industrial sectors, our challenge is to provide heat and power in environmentally responsible ways that strengthen U.S. competitiveness and protect the climate. This energy context drives a framework of six strategies:

- Increase vehicle efficiency,
- Electrify the vehicle fleet,
- Deploy alternative hydrocarbon fuels,
- Increase building and industrial efficiency,
- Modernize the grid, and
- Deploy clean electricity.

Our Review has been deeply informed by 17 assessments spanning the full range of energy technologies in which the Department is engaged. Prepared by teams of senior federal staff working with experts in our national laboratories, these assessments survey the history, status, and potential of relevant technologies. After undergoing peer review, the assessments will be published in a subsequent volume.

In carrying out the QTR, we have established portfolio principles that can guide the Department's investments over time with a disciplined and strategic approach to catalyzing innovation. We have benefited greatly in this exercise from extensive consultation with more than 600 of our stakeholders from industry, academia, civil-society organizations, research labs, and other government agencies. They have provided valuable insights into the economic, policy, and technical drivers of our energy challenges and in identifying where the Department delivers the greatest value for each of our six strategies. They have helped us better understand the Department's three core modes of action: harnessing research capability, pursuing targeted technology initiatives, and informing markets and policy with data and analysis.

The great challenge of this review has been to combine those three threads—context, technology assessment, and portfolio principles—to identify priority areas and to balance the portfolio both *within* and *across* strategies. By integrating these insights, the QTR establishes the framework for investment in energy-technology development paths against which we as a Department can be judged.

I would like to express my appreciation to colleagues in energy policy and technology development across the Administration for their incisive feedback, opening doors to improved coordination in areas of strategic interest. The level of interagency engagement signals strong potential for the federal policy integration envisioned by the President's Council of Advisors on Science and Technology.

Finally, it is important to acknowledge the thought-leadership and support offered by Secretary Chu and members of the Steering Committee, as well as the dedicated writing team that has stewarded every aspect of the QTR with extraordinary personal commitment. I am honored to have chaired this inaugural Review, and I believe its insights can serve the Department and the country well as we accelerate energy-technology innovation to meet the challenges of our time.

Steven E. Koonin
Under Secretary for Science

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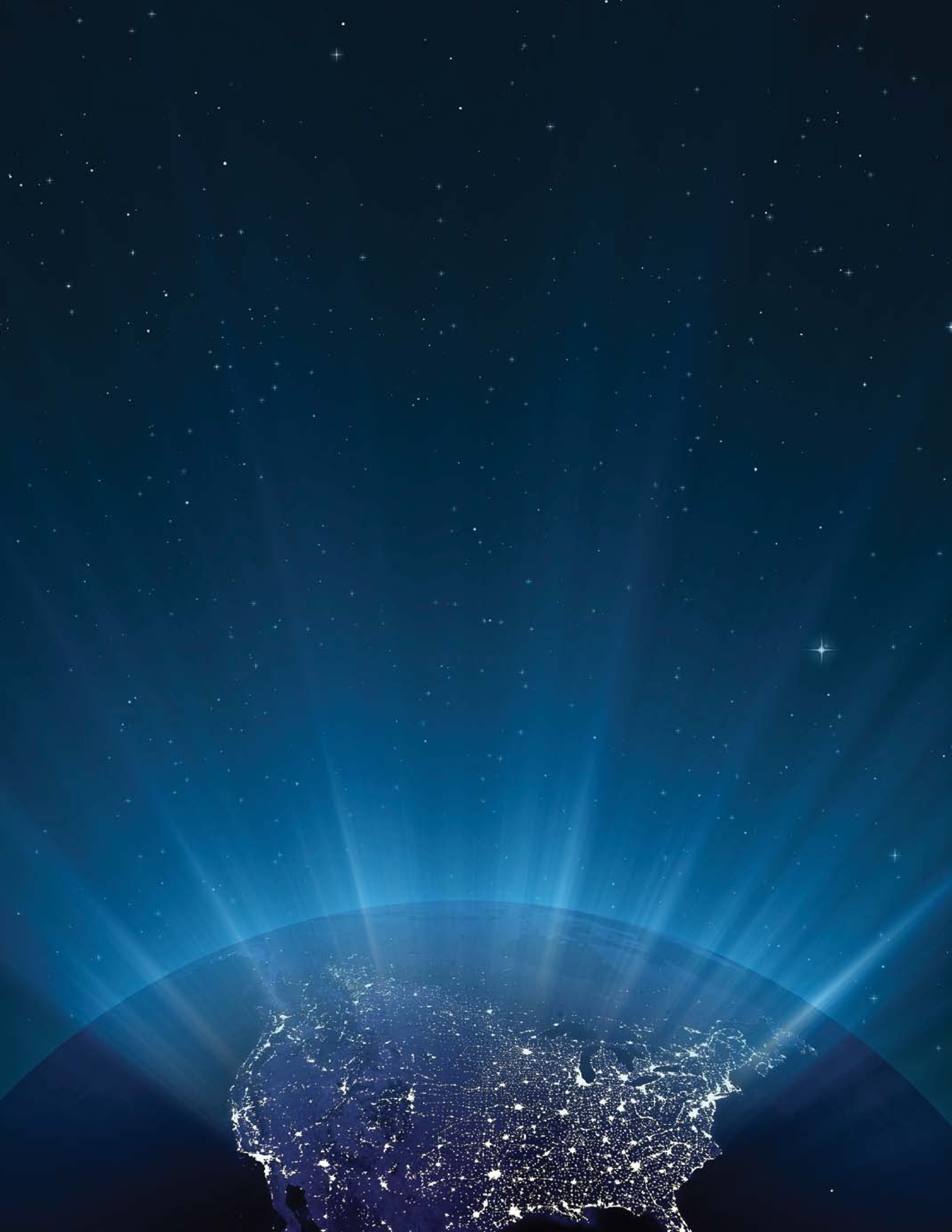

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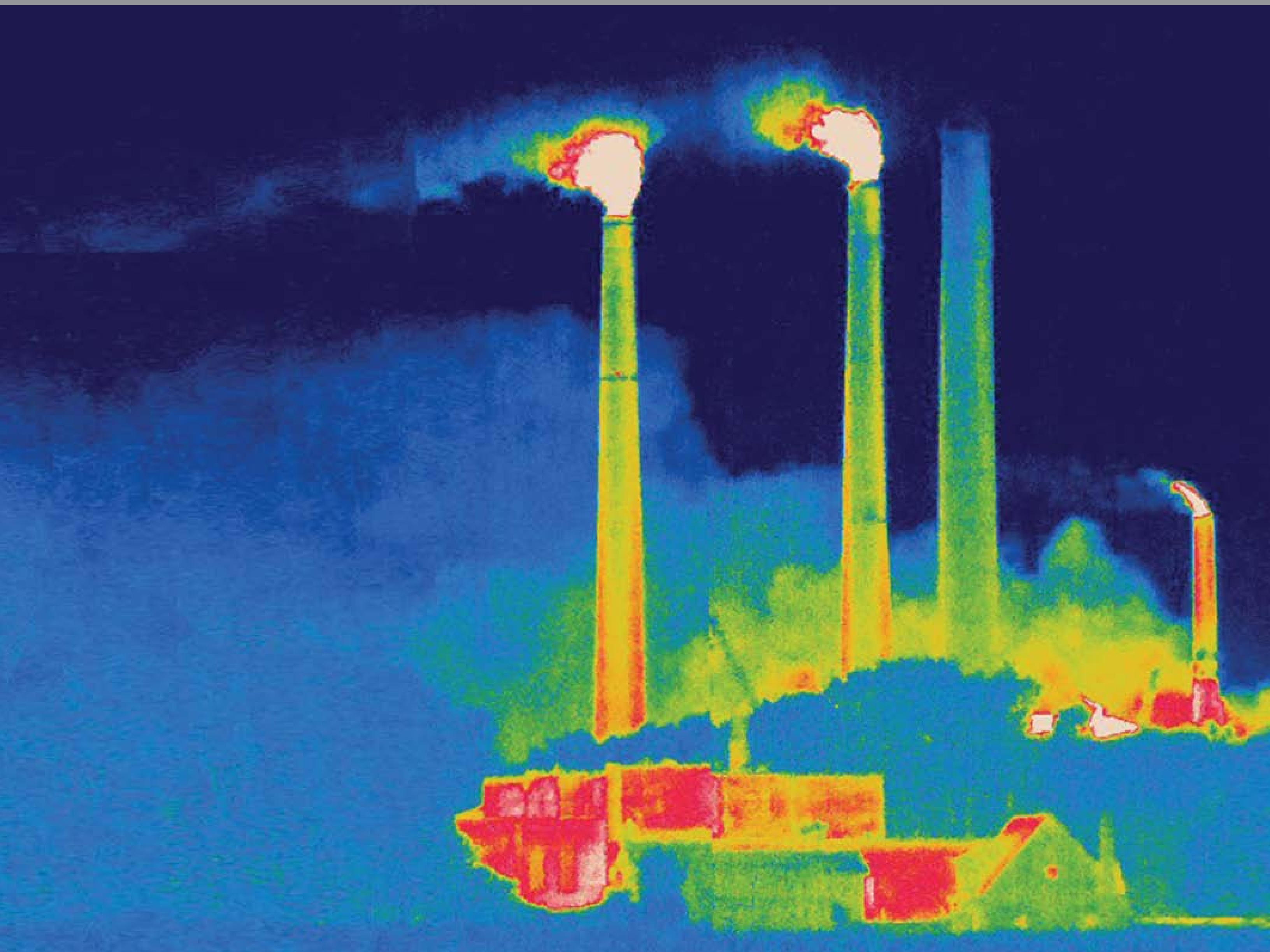
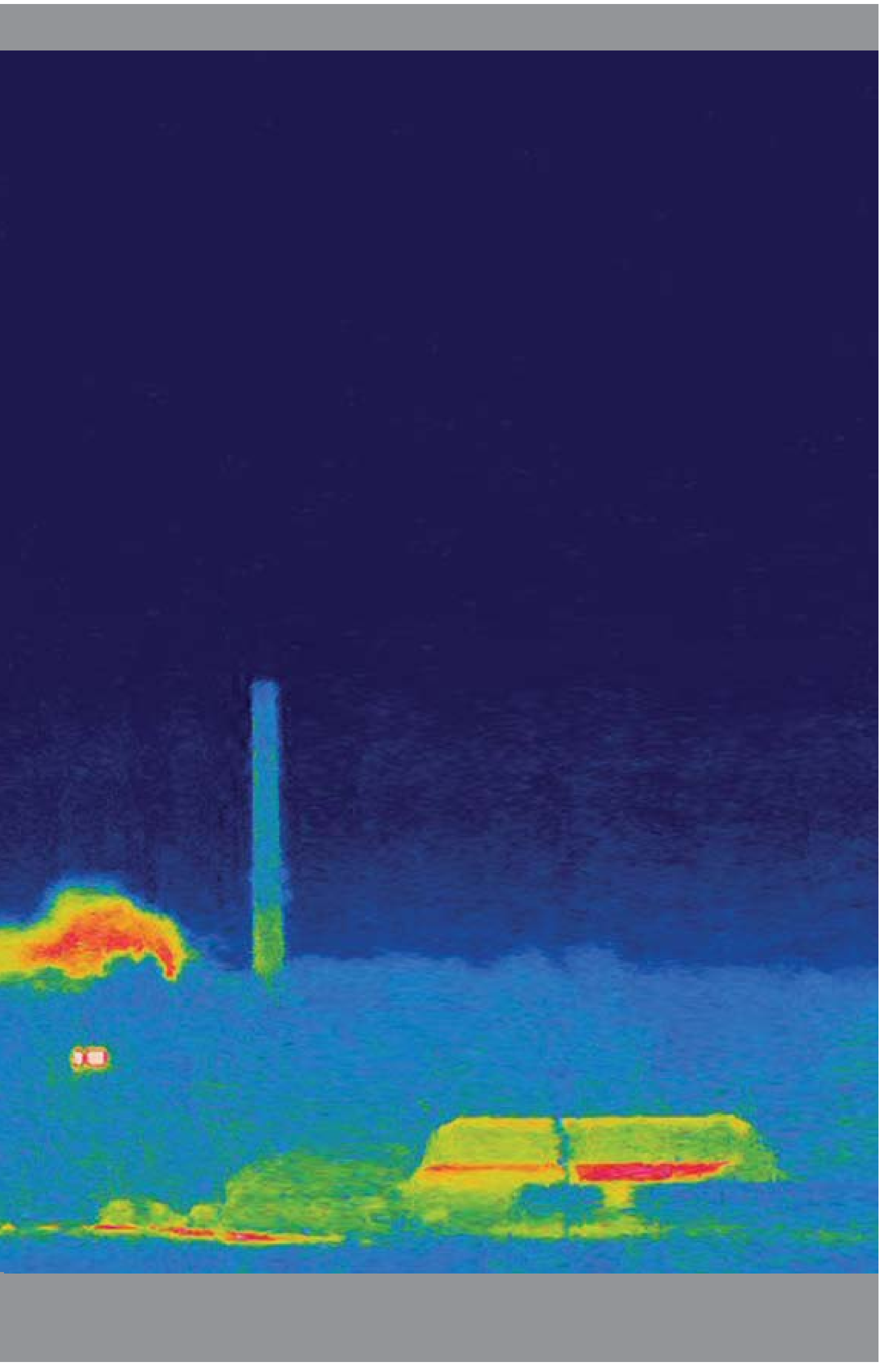
Thermal image of houses in front of a coal-fired power plant. White and red are hottest; blue and green coolest. For the average coal plant, only 32% of the energy is converted to electricity; the rest is lost as heat. The red shows the significant heat loss from the roofs of the houses.



EXECUTIVE SUMMARY



Source: Tyrone Turner

Access to clean, affordable, secure, and reliable energy has been a cornerstone of America's economic growth. The Nation's systems that produce, store, transmit, and use energy are falling short of U.S. needs. Maintaining energy security, bolstering U.S. competitiveness, and mitigating the environmental impacts of energy are long-standing challenges. Governments, consumers, and the private sector have worked for decades to address these challenges, yet they remain among the Nation's most pressing issues.

President Obama has articulated broad national energy goals for reducing U.S. dependence on oil, reducing pollution, and investing in research and development (R&D) for clean-energy technologies in the United States to create jobs. These include:[1]

- Reducing oil imports by one-third by 2025.
- Supporting the deployment of 1 million electric vehicles on the road by 2015.
- Making non-residential buildings 20% more energy efficient by 2020.
- Deriving 80% of America's electricity from clean-energy sources by 2035.
- Reducing greenhouse gas emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline.

In response to the *Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy* by the President's Council of Advisors on Science and Technology, the Department of Energy (DOE) has carried out its first Quadrennial Technology Review (QTR). The Review sought to define a simple framework for understanding and discussing the challenges the energy system presents; establish a shared sense of priorities among activities in the Department's energy-technology programs; and explain to the Department and its stakeholders the roles that DOE, the broader government, the private sector, the national laboratories, academia, and innovation itself play in energy transformation. This is a report on that Review.

One of the remarkable facts about energy technology is that there are often many different technical approaches to solving the same problem—and more are being proposed every day. While a testament to the power of human ingenuity, there is a basic, practical problem: because we have limited resources and urgent problems to solve, how do we choose which subset of these many approaches to pursue? Private venture capital and corporate R&D laboratories face this question every day—it is of equal importance for government-led technology development.

The QTR has been, at its core, about developing the principles that will guide difficult choices between different technically viable approaches that cannot all be pursued. Mere technical promise—that something could work—is an unjustifiably low bar for the commitment of DOE R&D funds. As every dollar matters, DOE's research portfolio will give priority to those technologies most likely to have significant impact on timescales commensurate with the urgency of national energy challenges.

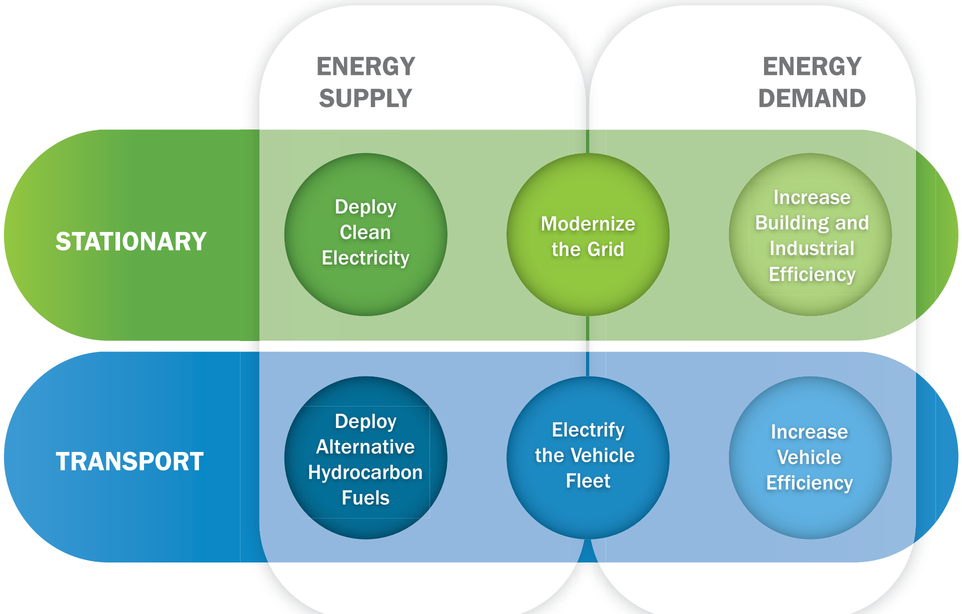
The Department will maintain a mix of analytic, assessment, and fundamental engineering research[2] capabilities in a broad set of energy-technology areas. Such activities should not imply DOE commitment to demonstration or deployment activities. The mix of analytic, assessment, and fundamental engineering research will vary according to the status and significance of the technology, which can be judged by maturity, materiality, and market potential:

Maturity	Technologies that have significant technical headroom, yet could be demonstrated at commercial scale within a decade.
Materiality	Technologies that could have a consequential impact on meeting national energy goals in two decades. We define "consequential" as roughly 1% per year of primary energy.
Market Potential	Technologies that could be expected to be adopted by the relevant markets, understanding that these markets are driven by economics but shaped by public policy.

Additionally, we will apply two themes to the development of the overall R&D portfolio. First, we will balance more assured activities against higher-risk transformational work to hedge against situations where reasonably assured paths become blocked by insurmountable challenges. Second, because the Department neither manufactures nor sells commercial-scale energy technologies, our work must be relevant to the private sector, which is the agent of deployment.

In the transportation sector, DOE will focus on technologies that significantly reduce oil consumption and diversify fuel sources for on-road transportation. DOE recognizes that technology developments can help make

Figure ES-1. The QTR has framed six strategies to address national energy challenges.



vehicles more efficient and alternative fuels more economic, but the deployment of any technologies it helps develop is largely determined by policies, such as Corporate Average Fuel Economy standards. Impartial DOE research can help inform these standards. In setting priorities for our R&D activities, DOE will support technologies that can integrate with existing energy infrastructure to ease market adoption. Furthermore, DOE will only support technologies that emit less carbon than incumbents—in keeping with our national energy goals. Recognizing the differences in the fleet, DOE will establish separate technology priorities for heavy-duty and light-duty vehicles.

There is significant headroom for DOE to work on increasing conventional vehicle efficiency by improving the internal combustion engine, by lightweighting, and by improving the aerodynamics of heavy-duty vehicles. Electrification is the next greatest opportunity to dramatically reduce or eliminate oil consumption in the light-duty vehicle fleet. DOE's most significant role in transport research is here. DOE's investment strategy does not preclude the market from selecting mild or strong hybrid, plug-in hybrid, battery-electric, or even fuel cell vehicles as the end point for electrification. Finally, DOE will support development of domestically produced, infrastructure-compatible biofuels to reduce carbon emissions from liquid transportation fuels where electrification is not viable (heavy-duty vehicles, marine, and air). Although biofuels have other economic or security advantages, DOE understands that any drop-in liquid fuel will not insulate consumers from the global oil price.

As a result of this Review, we find that DOE is underinvested in the transportation sector relative to the stationary sector (energy efficiency, grid, and electric power). Yet, reliance on oil is the greatest immediate threat to U.S. economic and national security, and also contributes to the long-term threat of climate change. Vehicle efficiency has the greatest short- to mid-term impact on oil consumption. Electrification will play a growing role in both efficiency and fuel diversification. DOE has particular capabilities in these areas. Within our transportation activities, we conclude that DOE should gradually increase its effort on vehicle efficiency and electrification relative to alternative fuels.

The Nation's greatest challenges in the stationary sector are economic competitiveness and the reliability and-sustainability of energy production and use. DOE's priority in energy efficiency will be to increase the energy productivity of the Nation's economy; efficiency measures that decrease household and business energy expenditures can help increase U.S. economic competitiveness. Improving data on real-world energy use will be a key enabler of efficiency. DOE will help improve building efficiency through coordinated R&D, standards development, and market-priming activities that ease non-technological barriers to increased energy productivity. DOE will help improve industrial efficiency by providing technical assistance for energy-intensive manufacturing and by developing new processes and materials. DOE's next greatest impact is to enable modernization of the grid. The Nation's energy aspirations—from clean electricity to energy efficiency to transport electrification—require more active control of the grid by power producers, grid operators, and energy consumers. Here, DOE will support data, communications, modeling, sensing, power electronics, and the storage technologies necessary to enable grid control and security. DOE will also use its convening power to foster coherence in a highly fragmented regulatory framework comprised of states, local governments, utilities, and grid operators. Finally, in clean electricity, DOE will focus on reducing the costs of low-carbon technologies for economic deployment as markets become ready. Policies, such as a federal clean energy standard, would shape those markets. DOE's clean electricity R&D fosters innovation that can position U.S. technologies for export to the growing international power-generation market.


Courtesy of National Renewable Energy Laboratory

Researchers are developing technology to produce biofuels from the fibrous material in the corn stalks and husks.

As a result of this Review, we find that DOE is underinvested in activities supporting modernization of the grid and increasing building and industrial efficiency relative to those supporting the development of clean electricity. DOE has a unique role as a systems integrator and convener, giving it particularly high leverage in these information-poor and fragmented sectors. DOE will focus on accelerating innovation in currently deployed technologies to maximize its impact on national energy goals.

There is a tension between supporting work that industry doesn't—which biases the Department's portfolio toward the long term—and the urgency of the Nation's energy challenges. The appropriate balance requires the Department to focus on accelerating innovation relevant to today's energy technologies, since such evolutionary advances are more likely to have near- to mid-term impact on the Nation's challenges. We found that too much effort in the Department is devoted to research on technologies that are multiple generations away from practical use at the expense of analyses, modeling and simulation, or other highly relevant fundamental engineering research activities that could influence the private sector in the nearer term. DOE also recognizes that new platforms—rather than the next generation of current technologies—could generate disruptive breakthroughs and will devote a fraction of its effort to their pursuit.

An important finding of this Review is that the Department impacts the energy sector and energy-technology innovation through activities other than targeted, technology-development initiatives. Public comments indicated that DOE's informational and convening roles are among its most highly valued activities. Information collected, analyzed, and disseminated by DOE shapes the policy and decisions made by other governmental and private-sector actors. That expertise in energy-technology assessment gives DOE the standing to convene participants from the public and private sectors to coordinate a collective effort. The Department's energy-technology assessments are founded upon its extensive R&D capabilities. By supporting pre-competitive R&D and fundamental engineering research, DOE builds technical capabilities within universities and its national laboratories and strengthens those capabilities in the private sector. Also heard clearly from external stakeholders was that DOE's technology-development activities are not adequately informed by how consumers interact with the energy system or how firms decide about technologies. As a result, DOE will integrate an improved understanding of applied social science into its technology programs to better inform and support the Department's investments.

Courtesy of Lawrence Berkeley National Laboratory

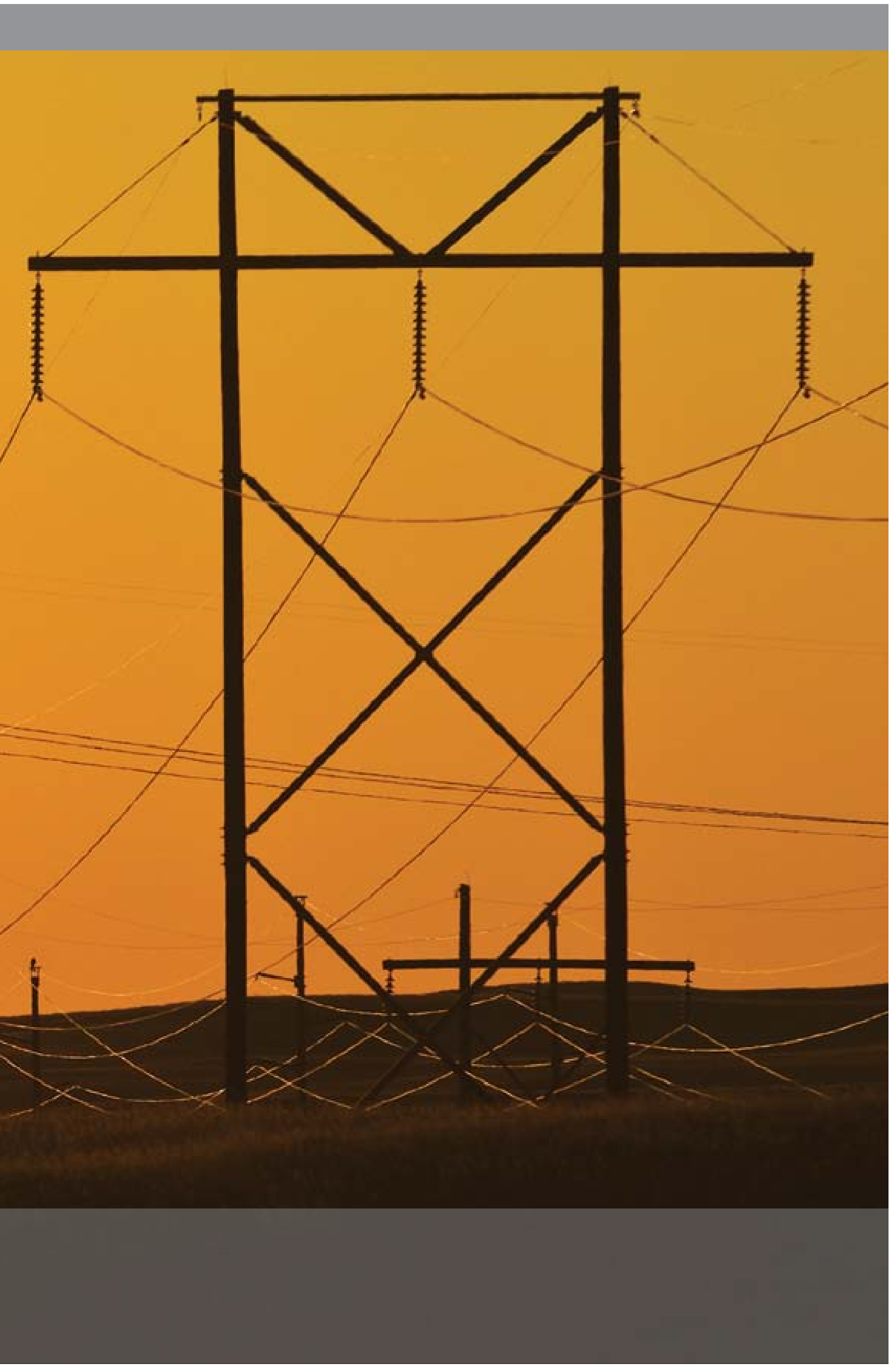
Energy-efficient windows are tested at a facility at Lawrence Berkeley National Laboratory.

Finally, the Department will seek to develop a strong internal capability in techno-economic and policy analysis to support its energy R&D strategy and to provide a sound basis for future Quadrennial Technology Reviews. The Department needs a professional group that can integrate the major functions of technology assessment and cost analysis, program planning and evaluation, economic-impact assessments, industry studies, and energy and technology policy analysis. Such a group would harmonize assumptions across technologies and make the analyses transparent.

The QTR is not a substitute for the annual budget process; it is intended to inform budgets over a five-year horizon. Further, the QTR is focused on energy technologies and is not a national energy strategy. The economic and policy tools necessary to progress toward national energy goals would properly be the subject of a future government-wide Quadrennial Energy Review, building upon the QTR.

Electric power is generated at power plants and then moved to substations by transmission lines—large, high-voltage power lines. In the United States, the network of nearly 160,000 miles of high-voltage transmission lines is a large part of what is known as "the grid."

INTRODUCTION



Courtesy of Duke Energy

A recent report by the President's Council of Advisors on Science and Technology (PCAST)[3] echoed and amplified numerous calls for better prioritization and planning of the federal government's energy-related activities.[4] PCAST recommended a government-wide Quadrennial Energy Review (QER). However, recognizing the scope and challenge of that task, PCAST also recommended beginning with a more limited review centered on Department of Energy (DOE) activities. Secretary Steven Chu initiated the Quadrennial Technology Review (QTR) in February 2011, tasking Under Secretary for Science Steven Koonin with responsibility for leading the process. This document is a report on that Review.

Goals of the QTR Process

- To define and promulgate a simple framework in which non-experts can understand and discuss the U.S. energy system and the challenges it presents. Scale, resources, economics, demand/supply, interoperability, policy, and technology are important issues that condition the range and effectiveness of various possible solutions to the Nation's energy problems.
- To explain to ourselves and our stakeholders the roles that the Department, the broader government, the private sector, the national laboratories, and academia play in energy innovation and transformation. Optimally leveraging the different strengths of the different players and ensuring coordination among them is important for progress toward solving energy challenges.
- To establish a robust conceptual framework for DOE's energy-technology programs and a shared sense of priorities among them. Techno-economic considerations with explicit principles and logic underpin the programmatic choices made in this document. The QTR is not a substitute for the annual budget process; it is intended to inform budgets over a five-year horizon.

Relation to DOE's Strategic Plan

DOE's recently released Strategic Plan[5] articulates a coherent framework for all of the Department's activities, including nuclear security, environmental management, applied energy, and basic research programs. The QTR focuses more deeply on the substance and process of DOE's applied energy programs and their impacts on accelerating progress toward national energy goals. The Department's nuclear security, environmental management, and basic science activities are addressed only to the extent that they relate to and inform the energy portfolio.

Balancing Evolutionary and Revolutionary Technology Advance

The Nation's energy challenges are simultaneously urgent and systemic. They are among the grand challenges of our time, demanding a mix of responses that balance low-risk, steady progress in today's technologies against the higher-risk possibility of developing breakthrough technologies. The dominant tone of this Report is goal-oriented and pragmatic, aiming primarily for material impact (Quads[6] of energy, billions of barrels of oil, billions of tons of carbon dioxide [CO_2] emissions) within the next two decades. Such an approach is important to underpin sound policy and regulation and to lay a credible foundation for a future government-wide QER. This Report also acknowledges that unforeseen breakthroughs could greatly accelerate progress.

Individual Technology Roadmaps

This Report includes summary roadmaps for advancing key energy technologies, systems, and sectors. These 17 technology assessments (which appear as Volume II of this report) discuss current status, historical pace of development and market diffusion, technology potential, factors affecting market prospects, and research, development, and demonstration milestones. They include enough detail to provide a firm analytical basis for the decisions made during the QTR, but are not detailed programmatic roadmaps. We expect that an important follow-on activity of this first QTR will be a deeper and more comprehensive analysis and comparison of energy technologies.

Volume II: Technology Assessments

Volume II of the Report on the first QTR includes technology assessments of 17 key energy technologies, systems, and sectors.

Vehicle Efficiency:

- Internal Combustion Engine
- Lightweighting and Aerodynamics

Vehicle Electrification:

- Vehicle Electrification

Alternative Hydrocarbon Fuels:

- Alternative Hydrocarbon Fuels

Stationary Efficiency:

- Building Efficiency
- Industrial Efficiency

Grid Modernization:

- Measuring, Modeling, and Control
- Infrastructure
- Storage

Clean Power:

- Carbon Capture and Storage
- Concentrating Solar Power
- Fuel Cells for Distributed Generation
- Geothermal Power
- Nuclear Power
- Solar Photovoltaic Power
- Water Power
- Wind Power

Establishing Prioritization Principles

The QTR establishes principles by which the Department can judge the priority of the full spectrum of our research efforts. Rather than an ordered prioritization of technologies or activities, these principles will be used to guide more detailed priority-setting during the annual budget process and to inform decisions about which technologies merit further investment. DOE will also use the QTR process of prioritization to determine whether demonstration projects are appropriate.

DOE's Analytic Capabilities

This Report describes the connections between energy-technology innovation and energy policy. While it focuses on activities within DOE's purview, those activities naturally impact the broader national energy-policy environment. Therefore, this document also identifies critical DOE analytical assets relevant both to the policy-making process across the government and to private-sector investment decisions.

Relation to Other Quadrennial Reviews

Coherent multi-year planning through reviews has been important to achieving success in other government missions. This QTR follows the purpose and spirit of other federal "QXRs," such as the well-known Quadrennial Defense Review, the Quadrennial Diplomacy and Development Review, and the Quadrennial Homeland Security Review.[7] However, the QTR is distinctive in that national defense, international diplomacy, and homeland security are almost entirely governmental functions whose implementation is determined directly by public spending decisions and policies. In contrast, the scale-up, manufacture, deployment, ownership, and operations of energy technologies are almost entirely non-governmental functions that are only partly shaped by government policies and investments. As a result, the influence of the Department's decisions and actions on the U.S. energy system is comparatively weak.[8] That circumstance, together with the many government agencies beyond DOE that have significant roles in establishing energy-relevant policies, required the QTR to have a broad and transparent extra-governmental and intra-governmental engagement throughout.

Uncertainties in Projections

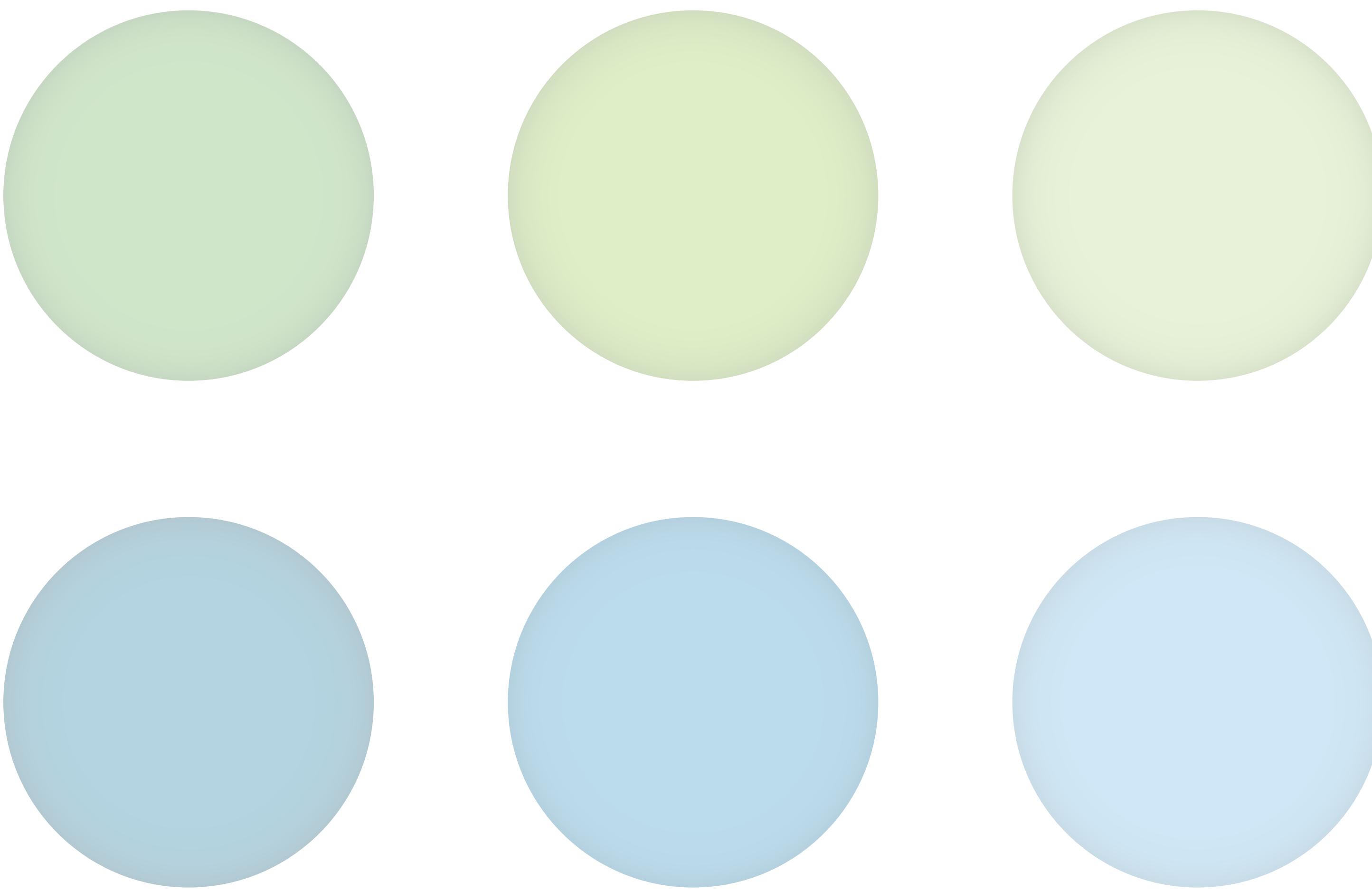
Any discussion of energy necessarily involves projections—projections of future policies, economics, behavior, and technologies. No one can predict with certainty the evolution of any one of these dimensions over a decade, much less over half a century. The intertwining of these dimensions makes energy forecasts particularly challenging. This Report strives for a balance between projections so general as to be useless and so specific as to be almost certainly wrong.

DOE Internal Coordination

Numerous programs within the Department are concerned with energy-technology development and the basic science that supports it. These programs have different reporting lines, budget lines, and management cultures. A major goal of DOE's current management is to integrate more effectively the Department's diverse talents and focus them on energy challenges. In that spirit, this document is written to be largely organizationally neutral, refering to "DOE's capabilities" or the "Department's accomplishments" to recognize the collective way in which the Department needs to act.

Organization of the Report

This Report is organized as follows: the second and third chapters introduce today's energy landscape and the energy security, economic, and environmental challenges it poses. The fourth chapter introduces six strategies to address those challenges, as well as a set of overarching portfolio principles. The next six chapters discuss each of the six strategies—the first three chapters are dedicated to transportation, the following three are focused on the stationary sector. Each of these chapters synthesizes the results of technology assessments with the energy context, challenges, and principles to determine the most effective and appropriate role for DOE in furthering each strategy. The following chapter addresses technology policy and includes structured descriptions of the kinds of activities the Department undertakes and guidance for making the most of DOE research and development (R&D) funding. Finally, the Report concludes with a discussion of balancing the Department's portfolio along a number of dimensions, including between strategies, and a number of particular findings to guide the Department going forward from this Review.



Drilling rigs and natural gas production pads at the Jonah Field and Pinedale Anticline in Wyoming. Improved shale gas extraction technologies have dramatically expanded the recoverable natural gas resource in the United States.

TODAY'S ENERGY LANDSCAPE

Courtesy of Ecoflight

Today's energy landscape presents multiple and interlocking challenges in energy security, economic security, and environmental security. Addressing these challenges effectively, whether through technology or policy, requires that they be understood. This chapter provides a brief overview of the U.S. energy context, emphasizing those aspects most relevant to the challenges the Nation faces. A more detailed exposition can be found on the Energy Information Administration (EIA) website.[9]

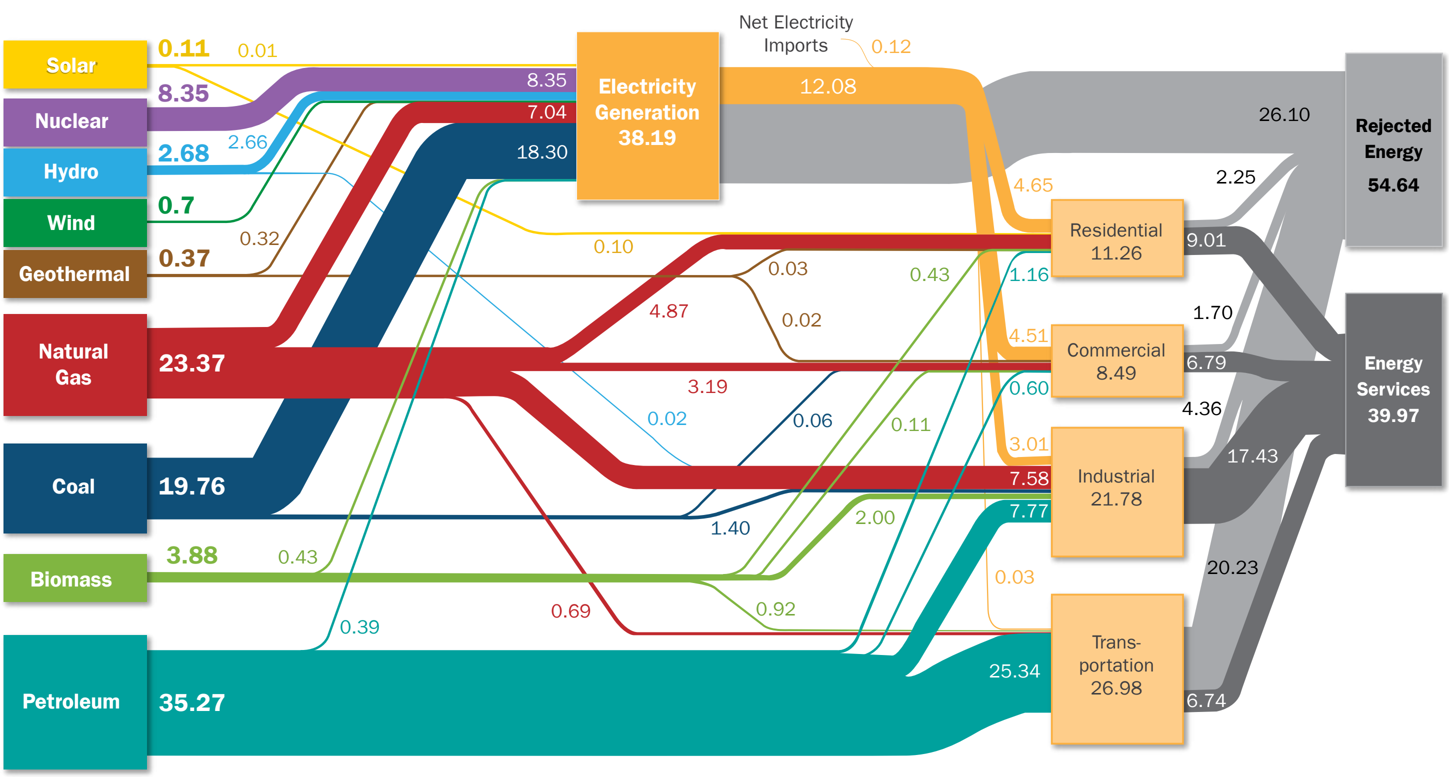
The energy sector is a large, complex system[10] that touches every aspect of modern life and comprises 9% of gross domestic product (GDP)[11] while enabling the rest of the economy. Figure 1 shows the flow of energy from supply to demand, scaled to show the relative amounts of energy produced from each energy source and consumed by each use. Several important points can be taken from Figure 1, as well as other data on the energy system.

Different Fuels for Different Uses

Fossil fuels currently provide 83% of U.S. primary energy, with almost all coal (93%[12]) used for power and most oil (72%[13]) used for transport. Natural gas (methane) is a flexible fossil fuel that is used for power and heat across multiple sectors of the economy (industrial, commercial, and residential), as well as for chemicals production. Petroleum-derived liquids (gasoline and diesel) are the near-exclusive fuel of transport, while many sources beyond fossil fuels are used to generate electricity, most significantly nuclear fission (20% of electricity) and hydropower (6% of electricity[14]). Today, other renewable sources supply less than 4% of U.S. electricity,[15] mainly wind (2%) and biomass (1%); however, wind generation in 2012 will be about 150% larger than it was in 2008.

Electricity and heat (produced on-site from natural gas) are the principal forms of energy used by the residential and commercial sectors, about 40%[16] of U.S. primary energy consumption. The industrial sector, supplied by diverse feedstocks, consumes another 30%[16] of the Nation's energy. New energy technologies to supply those stationary energy consumers must compete against an existing infrastructure that delivers energy reliably and at a low cost.

Figure 1. U.S. Energy Flows in 2009



Values are in quadrillion british thermal units. Total energy input is approximately 95 Quads. EIA data as portrayed by Lawrence Livermore National Laboratory.[17]

More than 90%[18] of transportation services are fueled by petroleum (see Figure 1). The high price[19] and price volatility[20] of current fuels provides motivation for making current technologies more efficient and for deploying alternative technologies. However, the hurdles are high. Alternative transport technologies must compete against the extraordinary energy density and low marginal production costs of petroleum-based fuels and adapt to, or compete with, the established fueling infrastructure.

Energy Efficiency

Primary energy (i.e., fuel) may power an energy service[21] directly, or it may be converted several times (for example, from fuel to electricity to light). Some 60% of primary energy is lost as waste heat (labeled "Rejected Energy" in Figure 1). Most of these losses occur when energy is converted from one form to another; physical laws place limits on the efficiency of these conversion processes, but theoretical limits are not achieved in practice. Implementing efficiency technologies available today could reduce U.S. energy consumption by 30 Quads by 2030.[22]

Energy efficiency can be improved through technological or modal changes.[23] For instance, improvements in engines or greater use of public transport can both increase the efficiency of moving people. In addition, lighting can be made more efficient by using a more efficient light bulb or by increasing the use of daylight. The exact 80% efficiency depicted in Figure 1 for each of the residential, commercial, and industrial energy uses is therefore misleading; those values are assigned rather than measured.[24]

Implementing efficiency measures to reduce ongoing energy costs generally incurs an up-front capital cost, although there are significant efficiency measures with little or no capital costs.[25] Market failures prevent the full implementation of efficiency measures. For example, consumers and professionals alike often lack the information necessary to choose the best product to meet their needs at the lowest life-cycle cost. There is ample evidence that first-cost considerations rather than life-cycle-cost analyses drive investment decisions, particularly for individual consumers.[26] Another notable market failure is the principal-agent problem.[27] Here, the interests of multiple parties to a transaction diverge, as commonly occurs in the following situation: landlords might not provide capital for efficiency upgrades because tenants are the ones benefiting from the lower operating costs and the difference is difficult for the landlord to include in rent. If principal and agent were one economic actor, both costs and benefits would go to the same party.

Private-Sector Dominance

By any measure, the U.S. energy system is in the hands of the private sector, which makes decisions based primarily on profit and cost. The private sector designs, constructs, and operates the overwhelming majority of energy-production and transmission facilities. On the supply side, the private sector owns all 150 U.S. refineries[28] and most of the electricity supply. Combined, the Power Marketing Administrations,[29] Tennessee Valley Authority, public utilities, and cooperative utilities account for less than 25% of national generating capacity and 20% of transmission. Further, even these entities generally function like private-sector organizations in striving to minimize costs while serving customer loads reliably.[30] On the demand side, while the federal government is the Nation's largest single user of energy, it still accounts for less than 2% of total demand, with the Department of Defense (DOD) accounting for almost 90% of federal energy use.[31]

Scale

Trillions of dollars of capital are embodied in the infrastructure to generate, distribute, and use energy, for example: ~$2.4 trillion in generating assets, ~$100 billion in high-voltage transmission, and ~$2.3 trillion for light-duty vehicles.[32] Great quantities of fuels are moved and consumed each year: 1 billion tons of coal,[33] 7 billion barrels of petroleum,[34] and 24 trillion cubic feet of natural gas[35] (which is 50% larger than the volume of Lake Erie)—fuels collectively valued at some $600 billion per year. Currently, there are nearly 10,000 square miles of residential and commercial buildings (about the size of the State of Vermont) that must be lighted, heated, and cooled. New energy technologies must be deployed at such scales if they are to have an impact on national energy challenges.

Supply Changes Slowly, Demand Rapidly

Throughout U.S. history, new energy resources have taken many decades to achieve scale, often 50 years or more.[36] Long-lived infrastructure slows supply change, and the continual growth in energy consumption has allowed new technologies to supplement rather than replace existing energy sources.[37] Still, the ages of current U.S. supply assets create opportunities for greater efficiency by upgrading existing technologies and introducing new technologies.

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

Energy-supply technologies produce commodities (e.g., gasoline or electricity) often with thin profit margins. In contrast, end-use technologies can provide differentiated services, and energy efficiency might only be one of many factors affecting consumer choice.

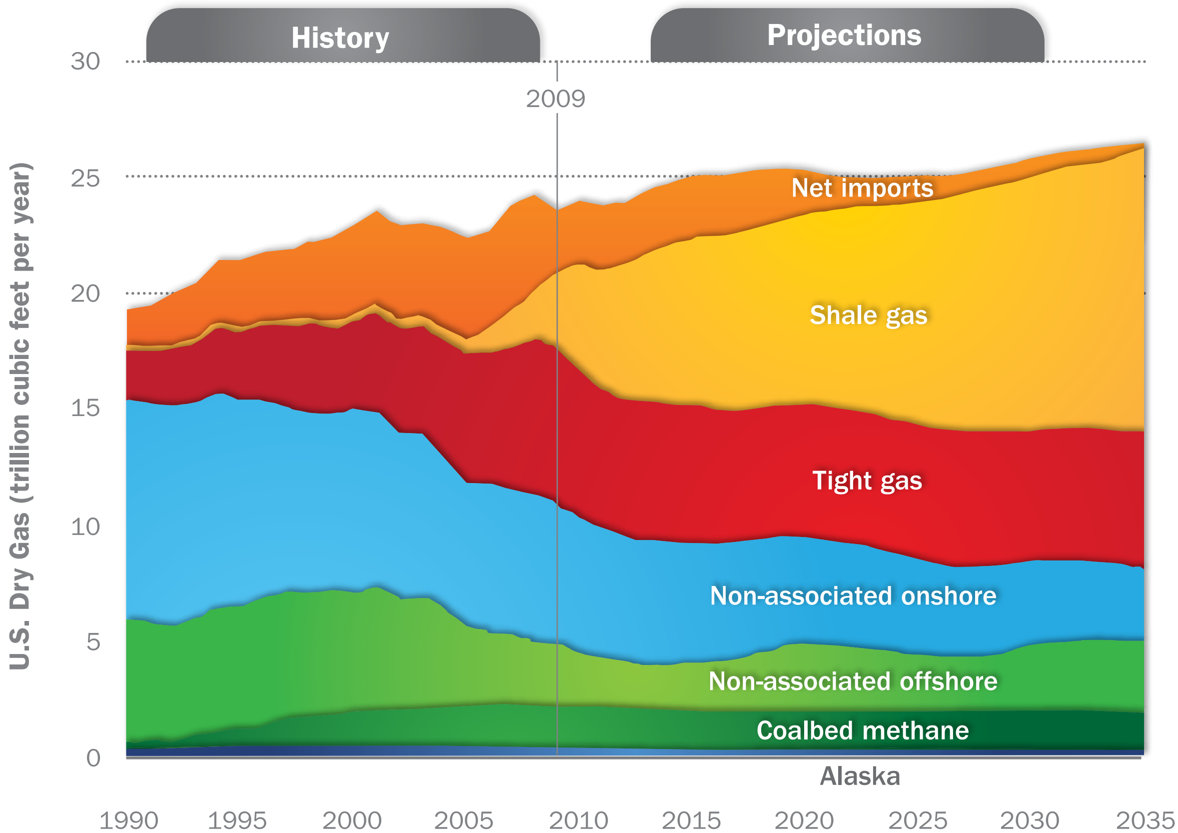
Supply and demand technologies face different risks. The transition from pilot to commercial scale presents some of the largest risks in developing new energy-supply technologies, while uncertainty regarding consumer preference and behavior presents the largest risks to the adoption and use of energy-consuming devices.

Market Forces

Private-sector decisions about technology deployment and infrastructure investment are based upon economic and regulatory considerations. Nowhere has this been more evident than with natural gas. Over the past decade, the combination of horizontal drilling and, more recently, hydraulic fracturing in shale formations has allowed access to large volumes of gas that were previously uneconomical to produce. EIA projects that shale gas supply will continue to grow (Figure 2).

Based on low capital costs and projected low and stable gas prices, gas-fired power is expected to dominate future deployment.[38] This current outlook for natural gas is one of the most significant shifts in the U.S. energy landscape over the past decade. Although natural gas has lower carbon emissions than coal,[39] the impacts of shale gas production and natural gas combustion need to be reduced, including air emissions, water quality, community disruption, and cumulative regional land use.[40] Such issues are associated with the development of any energy resource at scale.

Figure 2. U.S. Natural Gas Supply, 1990–2035



Shale gas is expected to grow in the next several decades, reducing net imports.[41]

Governmental Stakeholders

Incentives, standards, trade policies, and direct government investment are all factors that shape the markets for fuels, electricity, and demand technologies.[42] DOE only administers a handful of these factors. As authorized by Congress, more than a dozen federal agencies are charged with a wide array of responsibilities relevant to the energy sector. The Department of the Interior (DOI) regulates fossil fuel extraction and siting of energy projects on federal lands; the Department of Agriculture (USDA) leads the development of feedstocks for most biofuels; tax incentives are the purview of the Treasury; the Department of Transportation (DOT) sets Corporate Average Fuel Economy (CAFE) standards; the Department of Commerce (DOC) supports the development of standards for the SmartGrid; and the Environmental Protection Agency (EPA) is responsible for implementing the Nation's environmental laws.

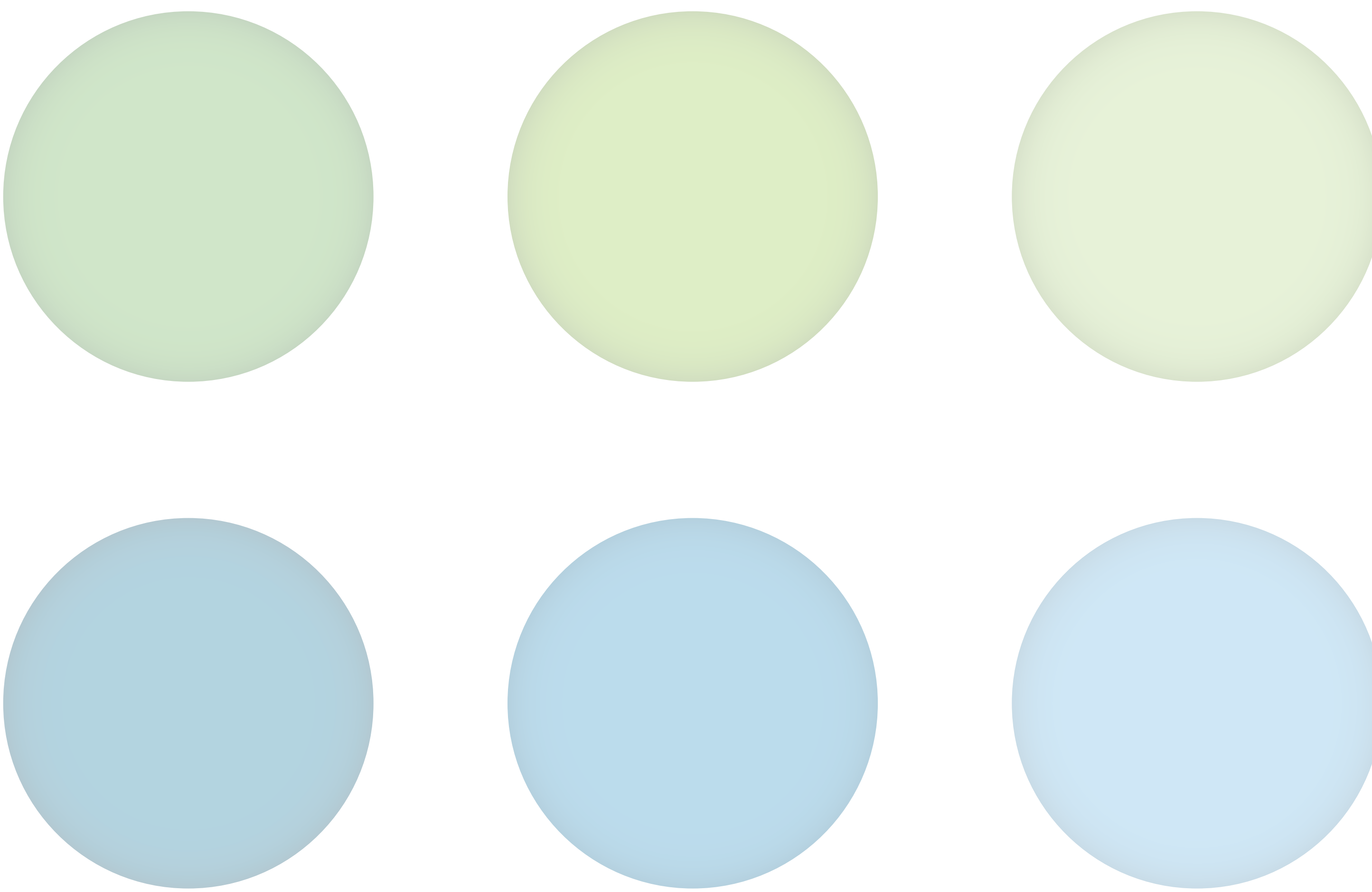
Beyond the cabinet agencies, independent commissions—such as the Federal Energy Regulatory Commission (FERC)—regulate interstate transmission and sale of electricity, natural gas, and oil. The Nuclear Regulatory Commission is responsible for oversight of the nuclear power industry. Independent financing institutions—such as the Export-Import Bank and the Overseas Private Investment Corporation—are actively engaged with the overseas energy sector through trade promotion of U.S.-made equipment and technologies. Federal agencies—such as the DOD, General Services Administration, Small Business Administration, and National Science Foundation (NSF)—also take actions that affect the pace of energy-technology innovation.

More than half of state governments have instituted portfolio standards and goals that require a certain fraction of the electricity sold to come from renewable and low-carbon sources.[43] Similarly, the Renewable Fuel Standard (RFS) [administered by EPA] creates demand for biofuels. Energy efficiency appliance standards (set by DOE) and building codes (set by states and localities) establish minimum performance standards across entire markets with the long-term goal of replacing the most wasteful products in specific end-uses.

Energy suppliers are also subject to consumer-protection and environmental regulation. A diverse set of stakeholders own[30] and regulate[44] the electricity industry.[45] This structure varies across states and regions, and many combinations of roles exist for different entities within the system. Public utility commissions within states control most of the retail electricity regulation and infrastructure siting. Natural gas for commercial and residential uses is generally subject to state regulation in a manner similar to electricity.

Environmental regulation of the atmosphere, land, and water affects both energy production and use. Since finding[46] that high levels of atmospheric CO_2 endanger public health and welfare, EPA established standards—in conjunction with DOT's CAFE standards—for greenhouse gas (GHG) 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[47] fuel economy[48] and emission[49] standards address the emission of CO_2 and other pollutants. There are federal regulations for the custody and disposition of fuel and waste from nuclear[50]and coal[51] power generation.

This diversity of energy-relevant policy instruments and authorities across any administration requires a level of coordination and integration beyond the reach of DOE alone. For that reason, DOE has worked closely with the Executive Office of the President, as well as with leaders in other agencies, to ensure that the QTR provides a useful platform for a broader QER.



Tanker unloading oil at the Port of Los Angeles in Long Beach, California. Oil imports contribute 70% of the United States' trade deficit.

TODAY'S ENERGY CHALLENGES

Credit: David Frazier/Corbis

Access to affordable, secure, and reliable energy has been a cornerstone of America's economic growth. However, the Nation's systems that produce, store, transmit, and use energy remain deficient in important dimensions. Energy security, U.S. competitiveness, and the environmental impacts of energy are long-standing challenges. Governments, consumers, and the private sector have worked for decades to address these challenges, yet they remain among the Nation's most pressing issues.

President Obama has articulated broad goals for reducing U.S. dependence on oil, expanding cleaner sources of energy, reducing pollution, and investing in R&D for clean-energy technologies in the United States. These include:[52]

- Reducing oil imports by one-third by 2025.
- Supporting the deployment of 1 million electric vehicles (EVs) on the road by 2015.
- Making non-residential buildings 20% more energy efficient by 2020.
- Deriving 80% of America's electricity from clean-energy sources by 2035.
- Reducing GHG emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline.

The Nation's energy challenges are also intimately linked to global challenges. Every nation faces the security and economic implications of access to affordable and sustainable energy, and global energy markets—particularly the global oil market—link them. Global development is increasing the quality of life and energy demands of billions of people around the world. These demands increase the risk of environmental damage from energy production, distribution, and consumption, with consequent impacts on human health and prosperity. Climate change links the impacts of energy-related emissions around the globe and over time.

An effective U.S. portfolio of technologies and policies to address these challenges must be based on three global realities. First, the great global build-out of long-lived infrastructure will continue for the next several decades as rapid global development progresses. As a consequence, the energy technologies deployed during this period of growth will largely determine global energy use through the end of this century. Economic, environmental, and security implications link America's future to the energy-technology choices made in other countries. Firms around the world are competing to supply and service the world's appetite for power, transportation, and built environments; nations that lead in technology will enjoy greater prosperity.

Second, CO_2—the dominant anthropogenic GHG—persists in the atmosphere for hundreds to thousands of years.[53] As a result, CO_2 emissions accumulate. Stabilizing concentrations of CO_2 at 450 parts per million will require an 80% reduction in global emissions by 2050 relative to a 2005 baseline.[54] Given the multi-decade lifetime of energy infrastructure, the energy technologies that will contribute to meeting this challenge must be consistently deployed at scale by 2030; fortunately, some of those technologies are being deployed at scale now and others are nearing maturity.

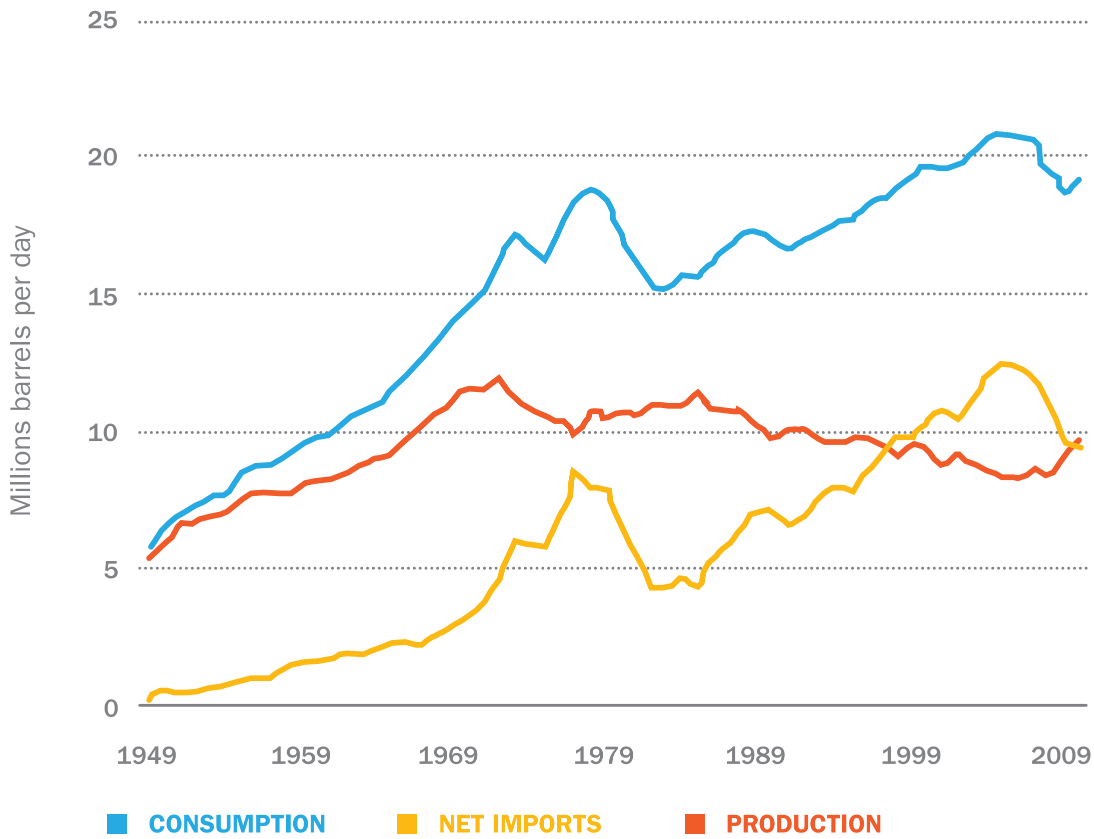
Third, while U.S. liquid-fuel consumption has changed little since 1990,[55] global petroleum consumption has risen by 30% over that period of time.[56] Demand in developing (non-Organisation for Economic Co-operation and Development [OECD]) countries is projected to increase global consumption by at least another 25% by 2035.[57] That growth, together with the increasing geographical concentration of "easy" crude oil resources, will place upward pressure on future crude prices and likely increase price volatility.[58]

Energy Security

The movement of goods and people is essential to our economy. Almost 95% of U.S. transport energy and 37% of primary energy comes from oil, nearly half of which is imported. The net import fraction of liquids has dropped from more than 60% in 2005 to 50% in 2010,[59] as shown in Figure 3, and is expected to drop even further to 42% in 2035.[60] This trend is due to a combination of greater vehicle fuel economy mandated by CAFE standards and increased domestic production of both crude oil and biofuels. In absolute terms, the volume of imports for the United States is projected to be effectively constant through 2035.[61]

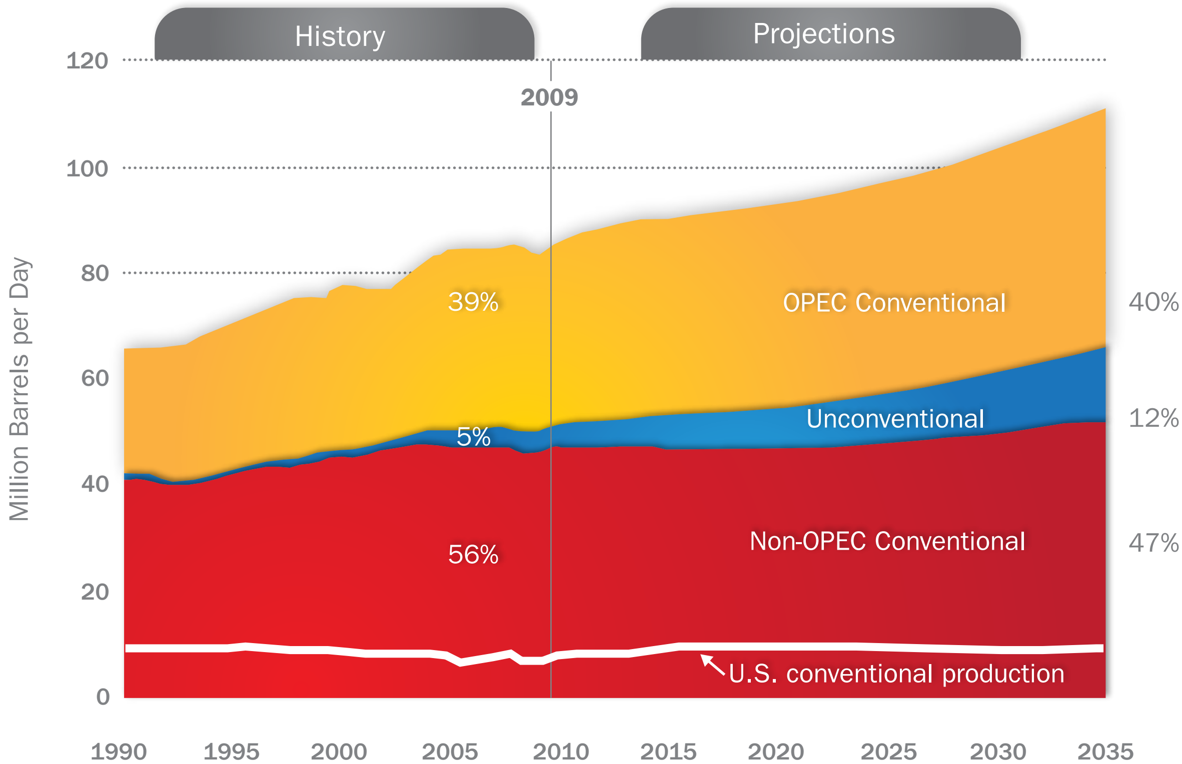
As shown in Figure 4, U.S. production of liquids (crude + natural gas liquids + biofuels) is a small and relatively constant part of a much larger global market. The world relies on Organization of Petroleum Exporting Countries (OPEC) countries for approximately 40% of supply, much of which is produced in regions and countries that are subject to disruptions and whose strategic interests can differ from those of the United States. This circumstance shapes U.S. foreign policy and engenders economic vulnerability. Further, there is effectively one global price for oil set in the long term by global supply and demand, modulated slightly by geography and quality differences in the crude. The increasing demand in developing economies creates upward pressure on the global price.[62]

Figure 3. Trends in U.S. Consumption, Production, and Net Imports of Petroleum and Other Liquid Fuels, 1949-2010[63]



Roughly half of the liquids used in the United States each day are imported, as shown in Figure 3. As a result, imports at current prices are responsible for 70% of the national trade deficit[64] (nearly $1 billion per day[65]). While that petroleum comes primarily from Canada, Mexico, and other sources in the Western Hemisphere (see Figure 5), the concentration of low-cost-of-production supply in a few OPEC countries gives Middle East producers significant influence over prices in the global market.

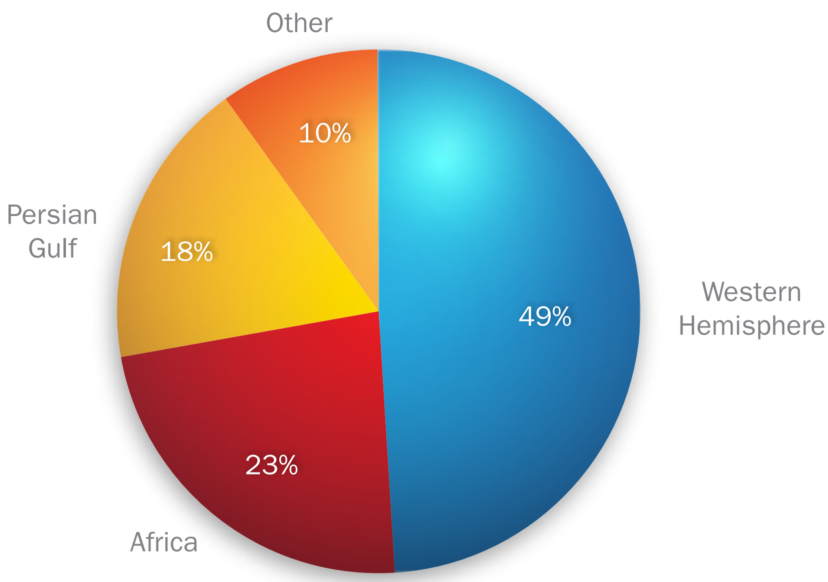
Figure 4. Global Liquids Production, 1990-2035



Total production includes crude oil, natural gas liquids, and biofuels. Constant U.S. conventional production is projected.[66] For reference, both Gulf of Mexico crude and corn ethanol productions increased by 0.8 million barrels per day over a decade.

Even if the United States was entirely self-sufficient in oil, domestic crude prices would remain coupled to the global market and be subject to the global dynamics of supply/demand, as well as international events. The United Kingdom (UK) fuel protests of 2000 are a sobering illustration of that simple point—even though the UK was entirely "energy independent" at the time. The almost doubling of global crude prices from early 1999 through the summer of 2000 drove a surge in domestic diesel prices, sparking unrest in a country that was a major crude exporter.[67]

Figure 5. Sources of U.S. Petroleum Imports, 2010



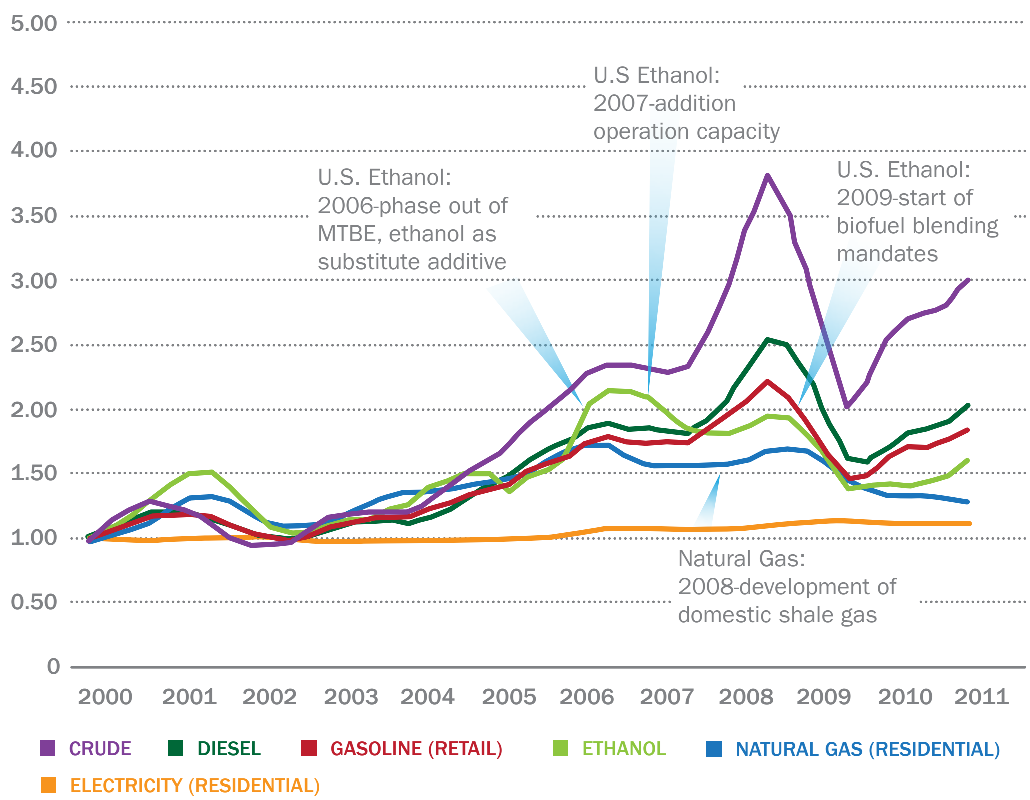
The United States gets close to 50% of its petroleum imports from the Western Hemisphere and less than 20% from the Persian Gulf.[68]

Fuel Diversity

Economy-wide impacts of oil price volatility can be mitigated by using less oil. This can be accomplished through vehicle efficiency or fuel diversification beyond drop-in hydrocarbons. Fuels fungible with gasoline and diesel will be similarly coupled to the global oil market and would not reduce the impacts of price or price volatility on the consumer (Figure 6).

Currently, the Nation is virtually energy independent in the stationary sector. Neither natural gas nor coal—the fossil fuels most important to stationary energy—are currently traded in an integrated global market that sets a global price. However, growing demand in developing economies, especially China, has spurred the export of U.S. coal. The recent expansion of domestic natural gas reserves has similarly raised the possibility of exports. Should U.S. coal and natural gas prices become coupled to global markets, the U.S. economy could become more vulnerable to price swings in those markets, as it is in oil.

Figure 6. Relation of Fuel Prices to Crude Oil Price, 2000–2011



Gasoline and diesel are most strongly coupled to crude. Ethanol prices started tracking more closely with crude oil prices a few years ago after blending mandates were instituted. U.S. natural gas prices have lowered in recent years and progressively decoupled from crude oil prices as a result of the nearly 50% increase in domestic reserves of shale gas. Residential electricity prices have been relatively constant and unaffected by crude oil prices. Four-quarter running average of prices in constant dollars.[69]

Other Energy-Security Concerns

Security concerns associated with the U.S. energy system extend beyond price volatility. Effective and credible international nuclear safeguards, export controls, and R&D are required for safe and secure nuclear power systems with appropriate mitigation of risks from terrorism and proliferation. While the burgeoning information overlay on the Nation's electric grid allows for improved monitoring and control, it also presents great cybersecurity challenges.

U.S. Competitiveness

America has a long history of excellence in industries that require innovation and a skilled workforce, most recently the information technology, aviation, and pharmaceutical sectors. Energy-intensive manufacturing, such as the steel and chemical industries, has also been a historical strength of the United States. Inexpensive energy—primarily electricity and natural gas—supports both quality of life and productivity across the economy and is critical to maintaining U.S. manufacturing facilities. The recent expansion of the Nation's domestic gas reserves and the associated drop in price is reviving the U.S. chemical industry.[70]

U.S. economic competitiveness is a growing challenge in a world made even more competitive by developing countries striving to create sustainable economic growth and establish themselves as technology leaders. Economic opportunities in the global clean-energy-technology market are driving deployment, innovation, and manufacturing worldwide. Clean-energy technologies are an opportunity for American leadership that can be a foundation for future economic growth. However, there are tensions.

Deployment

Modest increases in electricity consumption and the replacement of aging assets resulted in approximately 14 gigawatts (GW) of new generating capacity in 2010,[71] which corresponds to tens of billions of dollars in capital. This additional deployment was less than 2% of total U.S. capacity. In contrast, more than 100 GW of capacity was added each year in non-OECD countries from 2004–2008, a 6% annual growth rate.[72]

Courtesy of Joseph Kopp

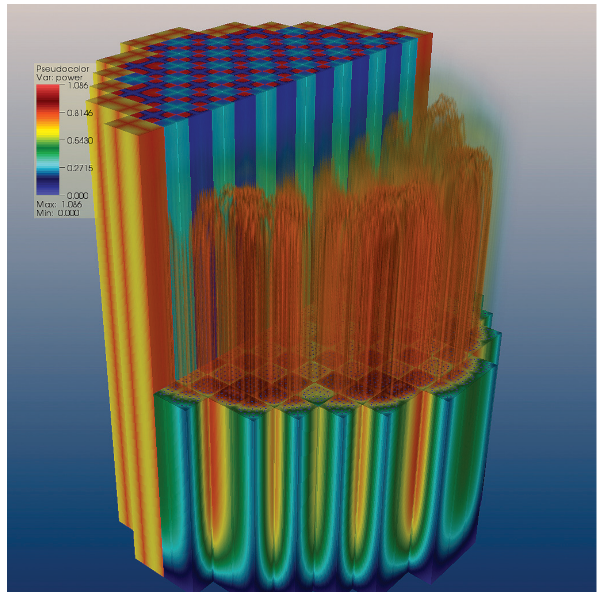
Workers testing the automatic stow-capability trackers for a concentrating solar photovoltaic module at the 30 MW Cogentrix solar power plant in Alamosa, Colorado.

Benefits of domestic deployment include those of the technology itself (e.g., decreased energy costs with efficiency technologies), lowered costs accrued by learning through deployment, and jobs that cannot be outsourced (including sales, installation, operation, and maintenance). Domestic deployment enhances economic competitiveness and establishes expertise that creates opportunities to access global markets.

While it is unlikely that the United States will lead the world in the absolute magnitude of clean-energy deployment over the long term, the market for clean-energy technologies is expected to grow as global economic development drives dramatic increases in energy demand and an increasing international focus is placed on environmental concerns. To lead the world in supplying the international market, the U.S. must have a robust energy-technology industry and well-developed supply chains.

Innovation

Historically, innovation has been the Nation's economic engine. The United States has led in innovation because of a culture of creativity and entrepreneurship coupled with government and private sector investment in basic and applied research. However, the United States is now out-spent in total R&D as a fraction of GDP by Japan,[73] and China's investments are rising steadily. In energy-related R&D, the U.S. is out-spent by its major trading partners as a fraction of GDP (including Japan, Korea, France, and China). Innovation is correlated with R&D funding.



Courtesy of the Consortium for Advanced Simulation of Light Water Reactors

The Consortium for Advanced Simulation of Light Water Reactors, one of the Department's first energy innovation hubs, supports supercomputer research such as this simulation of a Westinghouse PWR900 pressurized water reactor core.

Modest research investments by the energy industry reflect its conservatism; U.S. companies invested approximately $3 billion in energy R&D in 2010,[74] about 0.3% of total revenue. This is very small compared to non-commodity sectors, such as pharmaceuticals (18.7%) and computers and electronics (7.9%).[75] DOE's investment in energy R&D was $4.3 billion in 2010.[76]

Innovation has historically enabled U.S. leadership in manufacturing highly differentiated products, as close collaboration between researchers, engineers, and manufacturers is useful for rapidly deploying technologies. Beyond the invention of new and better products, innovation in manufacturing processes increases productivity and output and creates competitive advantage. However, once a product becomes a commodity in the broader market, manufacturing will shift to where it is economically optimal.

Manufacturing

Manufacturing facilities for mature technologies are generally built where the cost of manufacturing is lowest, while manufacturing facilities for innovative technologies are initially built near the site of invention. For example, while only 6% of solar photovoltaic modules were manufactured in the United States in 2008,[77] the Nation dominated production of innovative thin-film modules, which have been the recent focus of domestic R&D. Decisions regarding manufacturing capacity are also related to the cost of product transport. Consumer end-use technologies are manufactured worldwide with a vigorous global trade. Manufacturers in the developing world are becoming ever-more sophisticated; the

Credit: Waukesha Electric Systems Inc.

Employees of the Waukesha Electric Systems give Secretary Chu a tour of the transformer manufacturing plant in Waukesha, Wisconsin.

value added by Chinese high-tech manufacturing quadrupled from 1997–2007.[78] Private-sector decisions on the siting of manufacturing facilities are shaped by factors that include access to capital, tax incentives, regulatory hurdles, market access, modern and reliable infrastructure, and labor-force productivity.

Vigorous domestic manufacturing is necessary for U.S. economic competitiveness. While the United States has steadily shed manufacturing jobs since 2000,[79] manufacturing output[80] and wages[81] have increased over that same time period. Although increased manufacturing productivity can be a hazard to individual manufacturing jobs, it can provide a competitive advantage to U.S. companies and benefit the economy as a whole, spurring net job creation.

Environmental Impacts

Conventional energy production and consumption can have significant environmental impacts. Among these impacts are the emission of GHGs and other airborne pollutants, the production of solid wastes, the displacement of local wildlife, and the ecological impacts of the withdrawal and consumption of large quantities of water.[82]

Conventional combustion of fossil fuels is a major cause of CO_2 accumulation in the atmosphere, which is changing the climate. Global temperatures during the last 30 years have risen about 0.6°C,[83] which is consistent with expectations based on historical GHG emissions. Substantial climate change in the 21st century would have a serious impact on society.[84] Climate change could lead to global instabilities if water supplies or crop yields are threatened, or if a substantial rise in sea levels displaces populations.

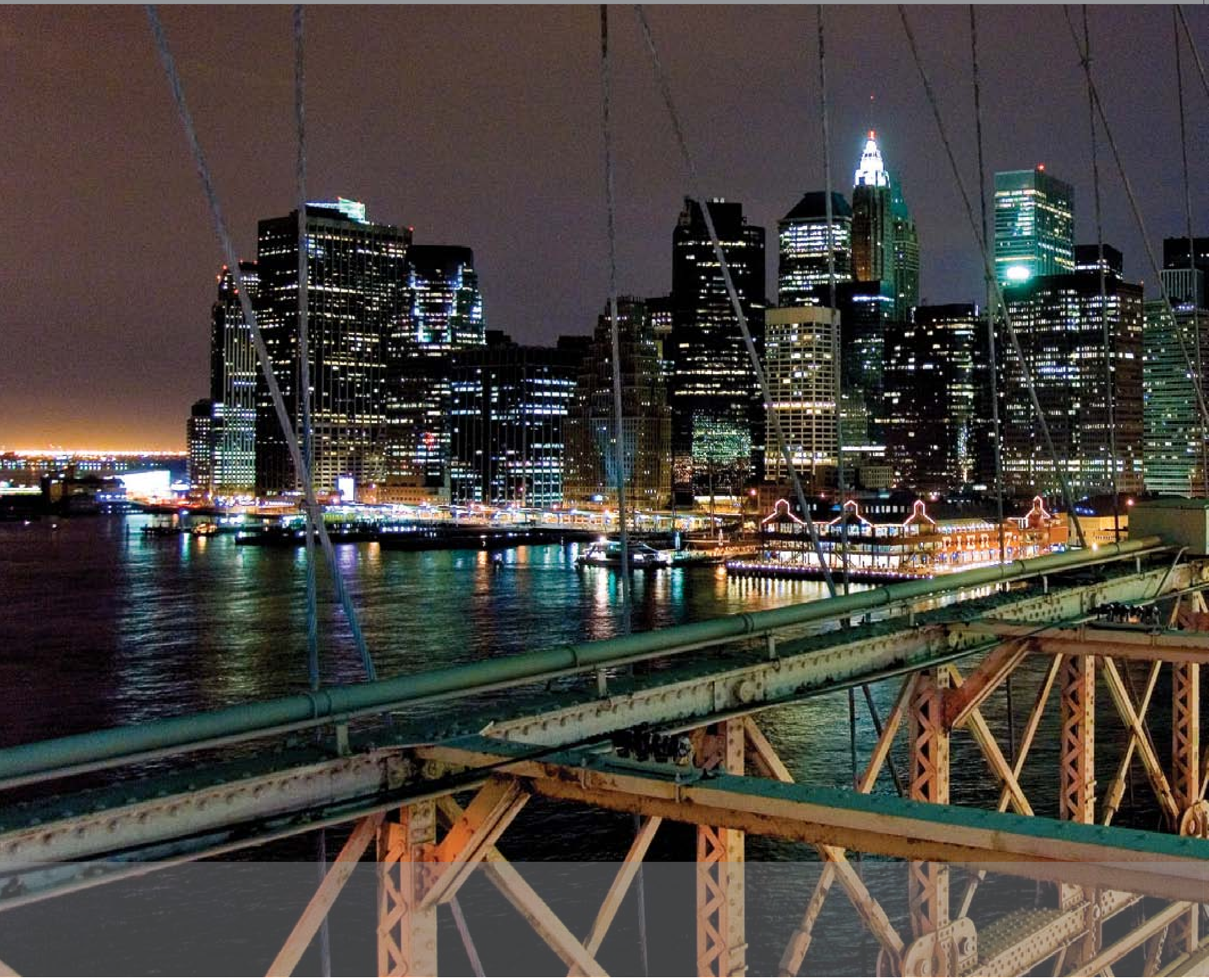
Energy and water are linked[85]—the production of energy requires large volumes of water, while the treatment and distribution of water depends upon readily available, low-cost energy. Climate changes might affect water availability in the United States and elsewhere.[86]

The burning of fossil fuels can also produce other types of solid[87] or airborne[88] waste that may contain sulfur oxides, nitrogen oxides and other ozone precursors, mercury, other heavy elements, and radioactive materials. In addition, fossil fuel extraction can have significant local and global environmental effects, including water quality concerns and emissions of methane, a potent GHG. Disposal of ash and wastes from the control of sulfur oxides also poses environmental risks.

Non-fossil generation technologies also have environmental impacts. The current fleet of nuclear plants produce toxic, highly radioactive spent fuel,[89] which presents a future problem of centennial-scale storage.[90]

In fact, the significant deployment of any energy technology will have an environmental impact simply because of the required scale. Environmental impacts of large wind or solar farms are site specific and range from noise to land use.[91] Biomass production can have both direct and indirect environmental impacts, ranging from residue removal to land-use change.[92] Seismicity and other environmental concerns are associated with the injection of liquids or gases into the earth, although the concerns vary whether the injections are for geothermal power production,[93] carbon storage,[94] or fossil fuel extraction.[95] The emission of hydrofluorcarbons from air-conditioning, refrigeration, and insulating foam adds highly potent GHGs to the atmosphere, which is projected to increase significantly.[96]

View from across the Brooklyn Bridge with the Manhattan skyline. The strategies and solutions for addressing the challenges in the stationary and transportation energy sectors are different.

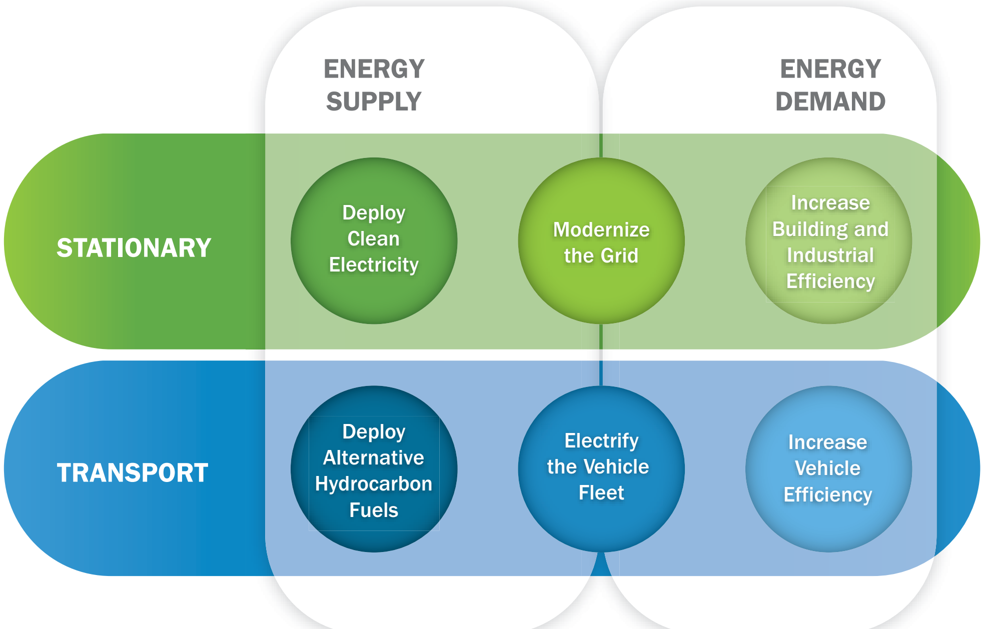


SIX STRATEGIES

Credit: Josh Bousel

Given the Nation's energy landscape and the challenges described in the previous chapter, one can define six evident strategies necessary to address the Administration's energy goals and enhance the Nation's energy, economic, and environmental security (Figure 7).

Figure 7. Six Strategies to Address the Nation's Energy Challenges



These strategies are displayed to align with the energy flow diagram in Figure 1.

In the transportation sector, these strategies are to:

- Increase vehicle efficiency,
- Electrify the light-duty vehicle fleet, and
- Deploy alternative hydrocarbon fuels.

Ordered in terms of cost-effectiveness and time-to-impact, these strategies will reduce oil consumption materially through the deployment of technologies compatible with the Nation's current infrastructures.

In the stationary sector, these strategies are to:

- Increase building and industrial efficiency,
- Modernize the electrical grid, and
- Deploy clean-electricity generation.

Also ordered in terms of cost-effectiveness and time-to-impact, these strategies have roughly equal weight in contributing to meeting stationary energy challenges.

This partitioning—stationary versus transport and supply versus demand—is apparent even in a simplistic view of the energy system (for example, the energy flow diagram shown in Figure 1). However, there are a number of subtler differences between energy for stationary and transport applications, as well as between supply and demand, that shape these sectors. (The differences between stationary and transport are summarized in the box below; the differences between supply and demand are discussed in **Today's Energy Landscape**.) These differences impact the speed of technology adoption and diffusion, as well as the interaction between the government and the private sector in driving technology innovation and deployment.

COMPARING THE TRANSPORT AND STATIONARY ENERGY SECTORS

1. Transport is dominated by a single energy source (oil), while stationary energy has numerous primary sources that compete to provide heat and power. New technologies that enter either sector must leverage, or compete against, existing infrastructure.
2. Oil for transport is priced on a world market, while domestic prices of the most common fuels for heat and power (coal and natural gas) are not. This leads to greater concerns about price volatility and supply disruptions in transport than in stationary energy.
3. Buildings last longer than vehicles. Turnover in the vehicle fleet occurs at a rate about three times that of buildings, thereby easing new technology penetration. Stationary assets that are installed now will be embedded for three or more decades compared to vehicle lifetimes of about 15 years.
4. Transport is nationally uniform and federally regulated, while stationary energy resources and end-use have large regional differences and are subject to federal, state, and local regulation. Transport has greater clarity from a national policy and regulatory framework, along with wider impact of individual technology advances, than the stationary sector.
5. Much of the energy used in transport provides on-road mobility, while energy in the stationary sector provides space conditioning, lighting, plug power, process heat, and other services. A smaller set of technologies is used in vehicles, while a broad set of energy-generation, transmission, and end-use technologies interact in the stationary sector. As a result, research and development program focus, target setting, and progress tracking are easier in road transport than in the stationary sector.
6. Retail consumers are arguably more aware of energy costs and performance levels in transport (gas prices, miles per gallon) than in the stationary sector (electricity and natural gas prices, a variety of efficiency metrics). This raises the profile and impact of advances in transport relative to the end-use of stationary energy.
7. Transport is responsible for about one-third of U.S. energy-related carbon dioxide emissions, while heat and power are responsible for the remaining two-thirds.

Strategies for the Transportation Sector

U.S. dependence on petroleum creates significant economic, security, and environmental challenges. Every president since Richard Nixon has known about the dangers of U.S. oil dependence and has talked about freeing the Nation from dependence on foreign oil. President Obama has set a goal of reducing oil imports by one-third by 2025. Reducing the demand for petroleum and diversifying transport energy sources are critical to meeting that goal. Road transport accounts for approximately 80% of U.S. transport fuel use[97] and is therefore the central focus of DOE's transportation activities—rather than rail, air, or marine.

Achieving success in the three strategies for reducing the petroleum-based fuel consumption of vehicles will require technology, policy, and time. None of them will singlehandedly eliminate the Nation's petroleum dependence, but combined, they will accelerate a smooth transition to a future decoupled from the global oil market. The QTR focuses on technology developments, particularly the scope and purpose of DOE activities relative to the private sector.

Oil consumption by road vehicles can also be reduced through changes in miles driven, population densification, urban planning, traffic management, expanded public transit, or telecommuting. There are also logistical efficiencies to be reaped in heavy-duty vehicles.[98] These strategies fall outside of DOE's purview, and are not addressed in the QTR, but clearly have technology components.

Vehicle Efficiency

Increasing vehicle efficiency is the most effective near- to mid-term strategy for reducing oil consumption in the transportation sector.[99] Vehicle fuel economy, largely unchanged over the past 30 years, can be improved rapidly and cost-effectively. Improving fuel economy will mitigate the impact of oil volatility on individual consumers and on the economy as a whole, while simultaneously reducing the transport sector's GHG emissions. Evolutionary changes that improve the efficiency of existing technologies are advantaged by a simple route to wide deployment.

There are multiple credible pathways to significantly improving today's engine and vehicle technologies, as discussed in **Vehicle Efficiency**. Those pathways provide benefits across the full spectrum of on-road vehicles, including light- and heavy-duty vehicles; conventional, hybrid, or EVs; and vehicles using alternative hydrocarbon fuels. However, because efficiency technologies can never eliminate oil consumption, other measures will be necessary for longer-term improvements.

Fleet Electrification

Electrifying the light-duty vehicle fleet is a strategy described in **Vehicle Electrification** for reducing oil consumption in the near- to mid-term, and for decoupling light-duty vehicles from oil in the long term. Partial powertrain electrification is also a rapid path to higher vehicle efficiencies that further mitigate the impact of gasoline prices on consumers. Full electrification would decouple fueling prices from the world oil market, but would likely require changes to infrastructure and driving habits. Electrification centralizes emissions from many individual mobile sources, potentially easing environmental impacts because pollution controls on a single power plant are more economical and effective than controls on individual cars. Growth in clean-electricity supply will then further diminish the environmental impacts of light-duty vehicles.

Alternative Hydrocarbon Fuels

Alternative hydrocarbon fuels could replace much of the remaining barrels of oil that cannot be eliminated by improved fuel economy or electrification. Developing these fuels, as described in **Alternative Hydrocarbon Fuels**, can lead to increased domestic production, with economic, security, and environmental benefits. However, as the price of infrastructure-compatible liquid fuels will remain tied to the global price of oil for many decades, alternative fuels are a longer-term approach to reducing the impact of gasoline price volatility on consumers and the economy. Some alternative fuels may require new infrastructure, or they may have environmental implications.

OUT OF THE BOX: TRANSPORT

This report gives priority to identifying reasonably assured research and development (R&D) pathways toward national energy goals. However, breakthroughs in high-risk technology development could accelerate progress on those paths or even create new ones. Therefore, DOE's R&D programs must include some potentially game-changing activities. Following are a few examples of breakthroughs that might be imagined for transport.

VEHICLE EFFICIENCY

Capturing waste heat in automobiles could increase fuel efficiency by up to 10%. For example, shape memory alloys, which are deformed by heat and returned to their original form upon cooling, can exploit heat differentials within the vehicle to generate useful energy.

Engines specifically designed to charge batteries onboard a hybrid could be dramatically more fuel efficient than current vehicle engines. These operating conditions open the door to completely new kinds of fuel-flexible engines, including those that don't use reciprocating pistons.

VEHICLE ELECTRIFICATION

New battery concepts and materials could dramatically lower the costs and increase the performance of batteries for use in electric vehicles (and potentially for grid storage applications as well). Nanomaterials, such as carbon nanofiber paper, could have properties that quadruple the density of energy storage.

Electric motors using magnetic materials that do not contain rare earths—either through novel magnetic materials or new designs—could reduce costs up to 75% with no loss in performance. Such materials could also find application in other clean-energy technologies, such as wind turbines.

ALTERNATIVE LIQUID FUELS

Farm-ready crops engineered to produce enzymes that break down their own cells after harvest would be easier to process into fuels and could dramatically lower production costs.

New catalysts could enable the inexpensive production of advanced fuels (including gasoline, diesel, or jet fuel) from biomass feedstock. Innovations might include the use of biological intermediates or long lifetime catalysts for pyrolysis pathways.

The relationships among fuels, engines, and vehicles are harmonized through standards, and any change in the system requires coordination across all relevant sectors, including vehicle manufacturers, fuel producers and distributors, government standards, and the consumer.

Success in reducing U.S. oil consumption and diversifying the energy mix in the vehicle fleet will have multiple benefits, including enhanced energy security, lowered costs for consumers, and reduced environmental impacts.[100] Further, the development and manufacture of alternative transportation technologies will create jobs and strengthen U.S. economic competitiveness in a dynamic global industry.

Strategies for the Stationary Sector

Energy generation, transmission, distribution, storage, and demand are interdependent. Supply on the grid must satisfy demand and losses in near-real time, as electricity is perishable in the absence of explicit storage capabilities. Any change in demand must be matched quickly by some combination of changes in generation and energy storage, which induces a change in power flows through transmission and distribution networks. A failure to balance the grid can damage equipment connected to it or lead to outages. This physical interdependence spans the full breadth of the electric system on timescales from seconds to seasons. It also helps explain why electricity suppliers and grid operators are conservative in adopting new technologies.

Fuels are used directly by energy consumers in the stationary sector (mostly natural gas and fuel oil for heat, plus petroleum as an industrial feedstock). The fuel supply and distribution system for these end-uses is much simpler than that for electricity, in both policy and technology.

Building and Industrial Efficiency

Efficiency is the most cost-effective and near-term strategy for increasing the U.S. economy's energy productivity, as described in **Energy Efficiency in Buildings and Industry**. Increased energy efficiency accelerates economic growth—both by freeing funds spent on energy for other investments and by creating installation jobs. Decreasing energy use for the same level of service also has environmental benefits.

Electrical Grid Modernization

Modernization will create a grid commensurate with the Nation's clean-energy aspirations, improve reliability, and drive down average energy costs. Strategies such as clean-electricity deployment, demand response, and vehicle electrification require greater control of electricity flow. **Grid Modernization** describes the new physical and informational capabilities required to observe and manage the system, as well as the analytical capability necessary to assess the grid's integrated dynamics. The growing information technology overlay on the physical system will better accommodate 21st century supply and demand technologies.

Clean Electricity Generation

Clean-electricity sources will reduce the environmental impacts of the power sector. Deploying clean-generation technologies as the Nation electrifies the light-duty vehicle fleet will further reduce the environmental impacts of transportation. As described in **Clean Electricity**, the Department's strategy will seek to improve the modularity, scalability, and infrastructure compatibility of clean-electricity-supply technologies while reducing water consumption.

A patchwork of regulations and actors shape the stationary sector. Federal, state, and local governments; utilities; and grid operators establish standards, goals, and regulations. Energy-technology markets are strongly influenced by these rules and are similarly complex. Federal energy policies, such as the existing appliance efficiency standards or a potential clean energy standard (CES), influence technology deployment.

OUT OF THE BOX: STATIONARY

This report gives priority to identifying reasonably assured research and development (R&D) pathways toward national energy goals. However, breakthroughs in high-risk technology development could accelerate progress on those paths or even create new ones. Therefore, DOE's R&D programs must include some potentially game-changing activities. Following are a few examples of breakthroughs that might be imagined for the stationary strategies.

BUILDING & INDUSTRY EFFICIENCY

Waste heat in U.S. facilities could be a large source of energy if it could be captured efficiently. Silicon nanotubes might allow flexible thermoelectric devices that convert waste heat to electricity without relying on rare materials like tellurium.

Bio-processing techniques that mimic the low-emission, low-temperature fabrication of living systems offer opportunities for the bio-products industry. Replacing traditional processing routes taken in areas such as chemical catalysis and polymer manufacturing can enable dramatically lower energy usage and greenhouse gas emissions.

Molecular sieve membranes may be effective at removing moisture from hot air, separating the process of latent and sensible cooling in building air conditioning and significantly increasing its efficiency.

GRID

Individuals are unlikely to guess which actions will make the biggest differences in their energy bills. Smart meters hold the promise that information will change energy use, but sensor information is complex and can be overwhelming. Personalized energy diagnostics that sit at the intersection of human behavior and technology can improve the interpretation of data to help optimize energy services.

CLEAN ELECTRICITY

Microbes can accelerate sequestered carbon captured from power plants into minerals. Engineered microbes may make it possible to tune mineralization rates and stabilize injected carbon.

Organic photovoltaic materials offer the promise of much lower costs for capturing solar energy than today's inorganic semiconductor materials. If organic materials could be developed with high efficiencies, as well as equivalent or better lifetimes, these flexible materials could see wide deployment.

CROSSCUTTING TECHNOLOGIES

Deploying advanced power electronics could reduce electricity demand by 25%–30% across all sectors. This requires fundamental advances in soft magnetics, high-voltage switches, and reliable, high-density charge storage.

Each stationary strategy is necessary to accomplish national energy goals, but insufficient by itself. Implementing each strategy will require coordinated policies and technology developments. While the QTR is focused on energy-technology development and the role of DOE activities relative to the private sector, the fragmented policy and economic context of technology in the stationary sector warrants a greater emphasis on DOE contributions beyond technology development. This Report highlights opportunities for the Department to reduce information barriers through the research it supports. The Department's role as a convener (of federal, state, and local government agencies and of government and the private sector) is also very powerful here.

Principles for the Department's Investments

DOE will give priority to those technologies most likely to have a significant impact on timescales commensurate with the urgency of national energy challenges. The Department will maintain a mix of analytic, assessment, and fundamental engineering research capabilities in a broad set of energy-technology areas without any expectation of DOE investment in demonstration or deployment activities. The mix will vary according to the status and significance of the technology, which can be judged by maturity, materiality, and market potential:

Maturity	Technologies that have significant technical headroom, yet could be demonstrated at commercial scale within a decade.
Materiality	Technologies that could have a consequential impact on meeting national energy goals in two decades.[101] We define "consequential" as roughly 1% per year of primary energy.
Market Potential	Technologies that could be expected to be adopted by the relevant markets, understanding that these markets are driven by economics but shaped by public policy.

Maturity is important in order to maintain the appropriate role of government investment and to ensure that large government investment isn't too far ahead of the technology. The urgency of our energy challenges sets a relentless clock on our actions. Meaningful progress on our energy challenges is underpinned by the adoption of new technologies by both consumers and industry. Because significant changes in energy supply can take 20 years or more, the Department will focus on technologies that can confidently be predicted to be material no later than 2030. Because the Department neither manufactures nor sells commercial-scale energy technologies, our work must be relevant to the private sector, which is the agent of deployment.

Credit: occupantproductions

Traders at work on the floor of the Chicago Mercantile Exchange. Material deployment of all energy technologies is dependent on their adoption in the market.

Established technologies, nascent technologies with large technical potential, and highly local technologies will have a lesser claim on DOE technology-development resources than those technologies that simultaneously satisfy the considerations of maturity, materiality, and market potential. "Established" technologies are technologies that are already in use, have significant market penetration, and thus have attracted robust private-sector investment. "Nascent technologies with large technical potential" are technologies that could have a large market but face sizeable technological and capital hurdles. "Highly local technologies" are technologies that might be significant in some regions but not nationally, regardless of their maturity. DOE will thoughtfully evaluate opportunities to demonstrate technologies that simultaneously satisfy the considerations of maturity, materiality, and market potential.

Principles for the Department's Activities in the Transportation Sector

DOE will focus on activities with the greatest potential to reduce oil consumption and promote the use of alternative sources for transportation energy. DOE recognizes that even if the United States was entirely self-sufficient in oil, domestic fuel prices would remain coupled to the global market and American consumers would still be subject to the global supply/demand balance, as well as international events. Reducing oil consumption will mitigate the impact of global oil price volatility on the Nation's economy. Alternative fuel technologies can further decouple U.S. transport from the global oil market.

DOE will preferentially support transportation technologies that can integrate smoothly with existing infrastructure. Technologies that can leverage existing infrastructures are more likely to enjoy wide deployment than those that require simultaneous deployment of fleet and fueling infrastructure.

DOE will only pursue transport technologies that also reduce environmental impacts. Technologies that have higher life-cycle carbon emissions than their petroleum-derived counterparts will not be supported. The Department will seek to reduce the environmental impacts of the technologies it supports.

Principles for the Department's Activities in the Stationary Sector

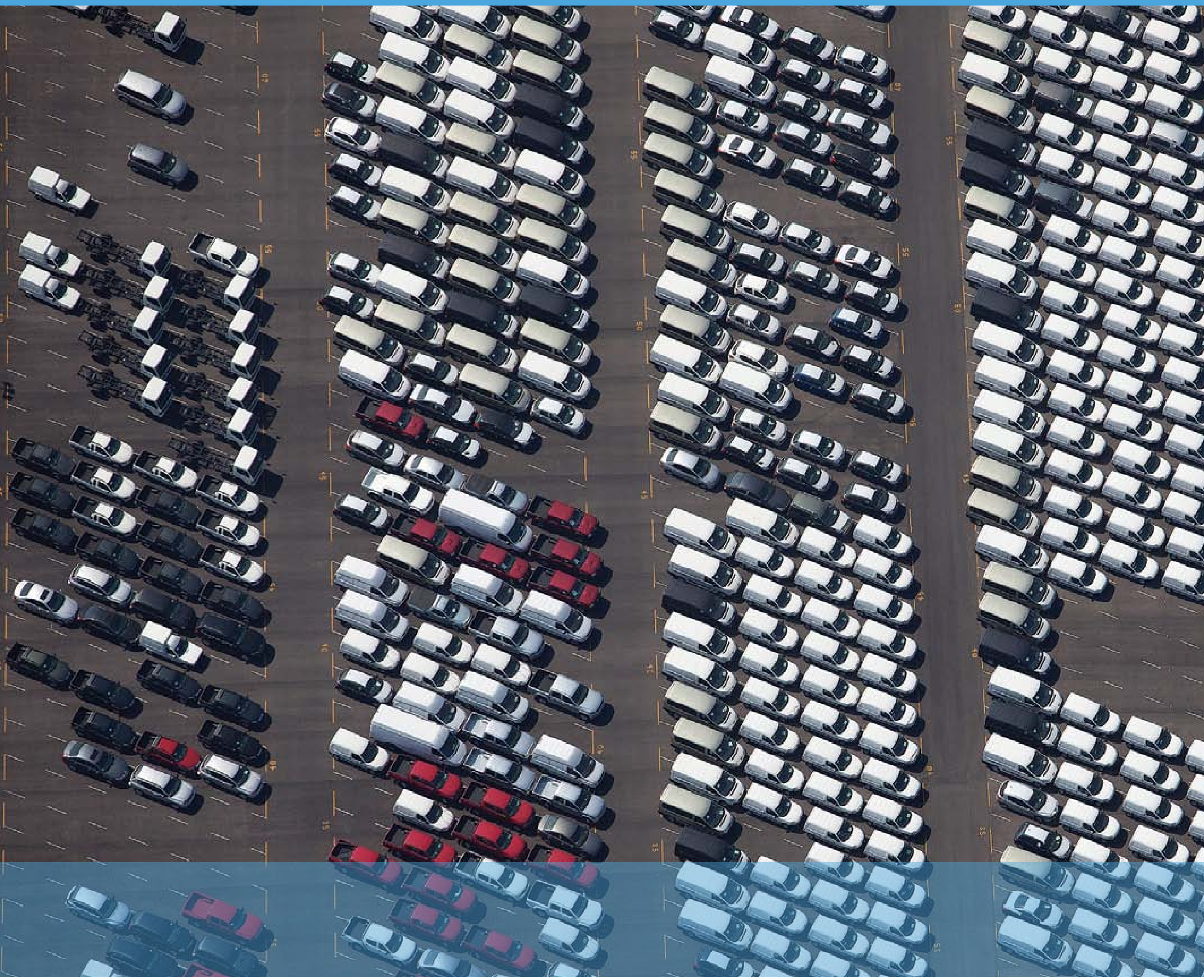
DOE will only pursue technologies that reduce environmental impacts. Electricity generation is the primary source of energy-related GHGs and many other significant air and water pollutants. DOE will support improved environmental quality by reducing costs and improving performance of energy efficiency technologies and clean-electricity generation.

DOE will preferentially support technologies that can enhance reliability and security. Disruptions in energy delivery can be avoided or mitigated through generation diversification, improved power management, and increased physical and cyber security of transmission and distribution.

DOE will give priority to technologies that enable electricity management. Integrating clean electricity, improving efficiency, and enabling transport electrification will require more active control of the grid by power producers, grid operators, and energy consumers. A key goal is to reduce the cost of energy services for the consumer.

DOE will strive to improve the quantity, quality, and accessibility of information related to stationary energy generation, delivery, and use. Lack of information frequently impedes the deployment and optimal use of technology, as well as the development of effective policies. DOE will remain a trusted source of high-quality data and analyses on the performance, economics, and use of energy technologies. DOE will also empower others to independently acquire and use data to make decisions.

Fifteen million new cars are sold in the United States every year, some 6% of the fleet. Improving the efficiency of new cars is the fastest and most economical technological route to reducing oil dependence.

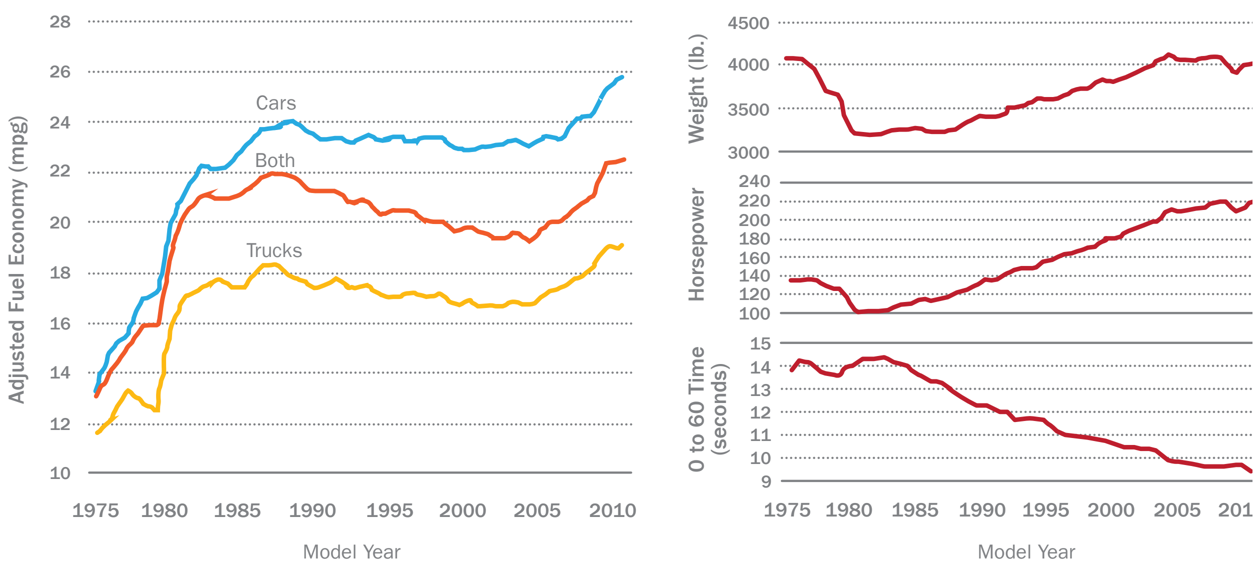


VEHICLE EFFICIENCY

Credit: roccomontoya

Improving vehicle efficiency is the most effective short-term route to reduce liquid fuel consumption. Today's technologies allow new vehicles to be twice as efficient as those they replace, while retaining the same consumer characteristics. Fully compatible with current fuels and infrastructures, efficiency improvements could save some 2 million barrels a day within a decade.[102] For comparison, multi-decadal efforts have built Gulf of Mexico offshore oil production to 1.6 milion barrels per day and U.S. corn ethanol production to 0.8 million barrels per day gasoline equivalent.

Figure 8. Light-Duty Vehicle Fuel Economy Trends: 1975–2010

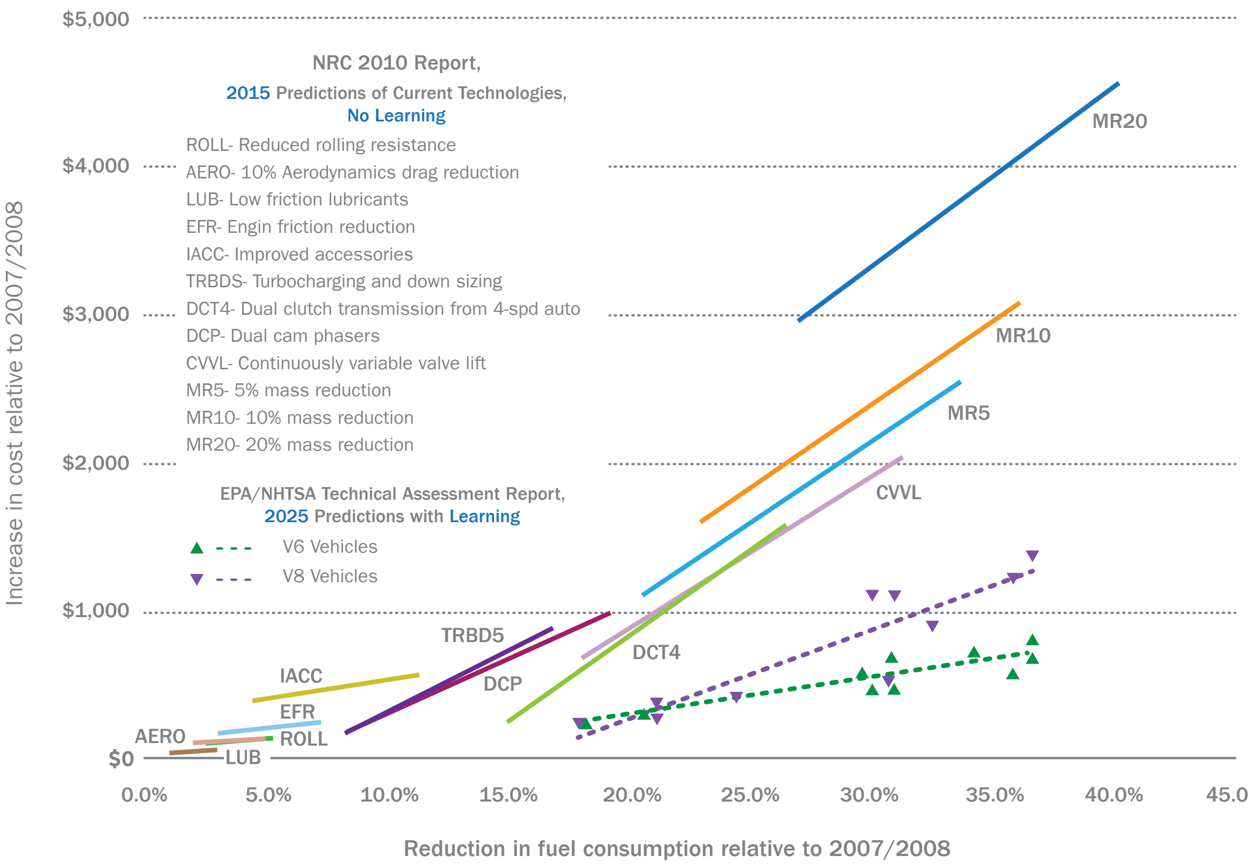


The performance of new vehicles has improved steadily over the last decades, even as fuel economy remained largely unchanged.[103]

Light-duty vehicle fuel economy remained largely unchanged between 1980 and 2005 (Figure 8). Improvements in engine efficiency during this time were dedicated to increasing vehicle size, features, and performance, as opposed to improving overall vehicle fuel economy.

The primary drivers of fuel economy are the CAFE and GHG tailpipe emissions regulations established by DOT and EPA. In May 2009, the Administration increased passenger car CAFE standards for the first time in 25 years. The standards are currently set through 2016, with further increases through 2025 announced.[104] For new passenger cars, the standards rise from 27.5 miles per gallon (mpg) in 2010 to 39 mpg in 2016; for light trucks, standards rise from 23.5 mpg in 2010 to 30 mpg in 2016.[105,106] The first standards of this kind for medium- and heavy-duty vehicles were published in August 2011.[107] While some portion of the increase in fuel economy will be met through hybrid technologies (primarily in the light-duty vehicle fleet), the increased efficiency of conventional vehicle components can also contribute substantially to improvements in fuel economy.

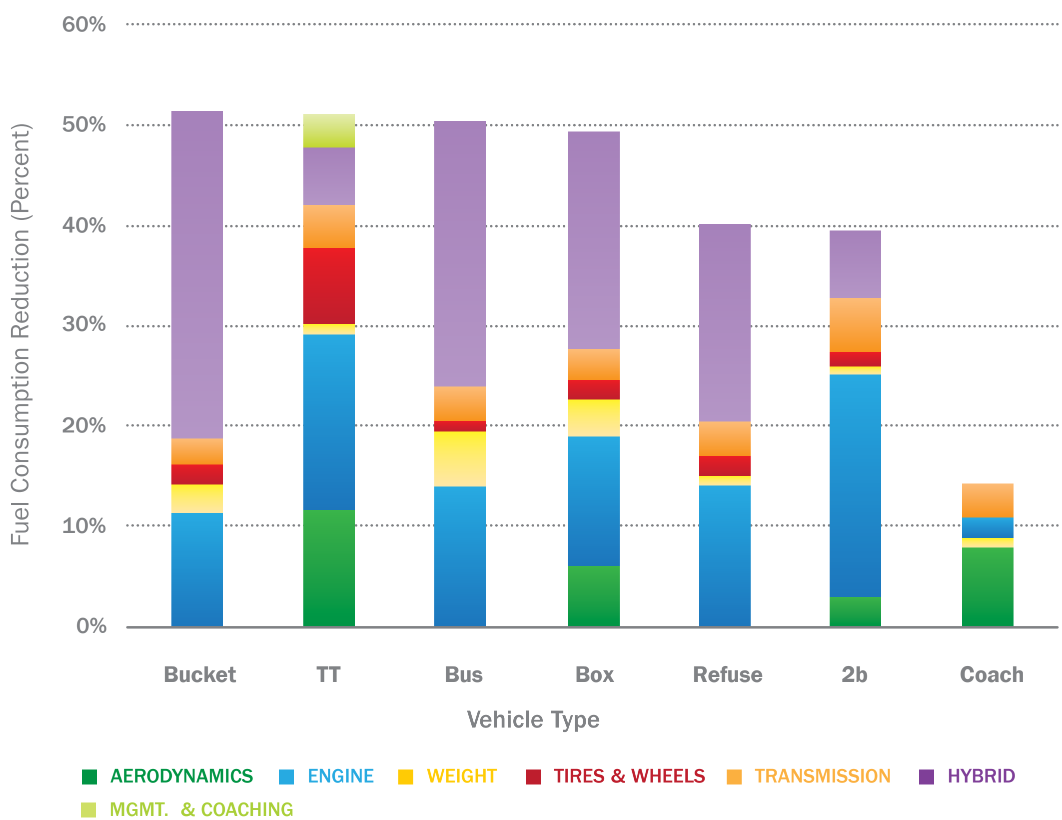
Figure 9. Projected Reductions in the Fuel Consumption of Large Cars and Small Trucks through Technology



The projected costs and impacts of various technologies are shown. Large cars and small trucks (including sport utility vehicles, pickups, and minivans) comprise nearly 60% of the light-duty fleet. The multicolored lines are National Research Council (NRC) data adapted by a National Petroleum Council study committee, while the triangles are from a joint study by the Environmental Protection Agency (EPA) and National Highway Transportation Safety Administration (NHTSA).[108]

Figure 9 shows that a variety of technologies can increase vehicle efficiency. These technologies can be combined in various ways to achieve cost-effective fuel efficiency improvements. They provide varying crosscutting benefits for a range of vehicle types, sizes, and fuels (see Figure 10 for opportunities in heavy-duty vehicles). Many technologies are commercially available now, but there are opportunities to further reduce costs through innovation, manufacturing experience, and process improvements—collectively referred to as "learning." The deployment of particular technologies will be determined by the market, which depends upon cost-efficiency tradeoffs and fuel economy, safety, and emission regulations. DOE can have the greatest impact in three efficiency technologies: greater efficiency of internal combustion engines (ICEs), reductions in vehicle weight (lightweighting), and improved aerodynamics.

Figure 10. Comparison of 2015–2020 New-Vehicle Potential Fuel-Saving Technologies for Seven Heavy-Duty Vehicle Types

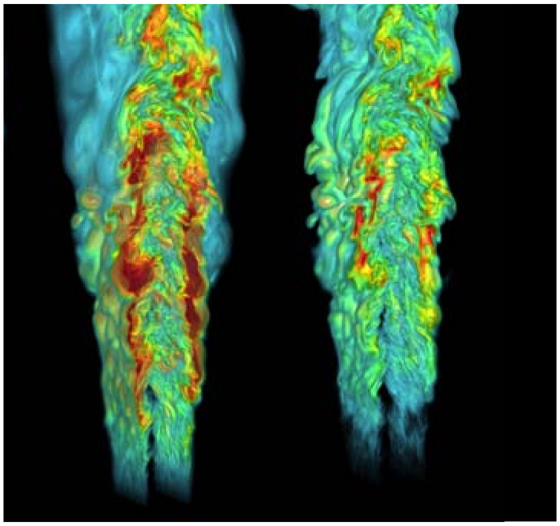


Engine improvements and hybridization are the dominant efficiency opportunities for service and urban vehicles. Aerodynamics is important for highway vehicles. Heavy-duty vehicle types: Class 3–6 bucket truck, tractor trailer (TT), transit bus, Class 3–6 box truck, Class 8 refuse truck, Class 2b pickup or van, and motor coach. Potential fuel reductions are not additive.[109]

Important differences between heavy-duty and light-duty vehicles shape the potential for deploying efficiency technologies. Heavy-duty and light-duty vehicles are subject to different standards and regulations. Heavy-duty vehicles are owned and operated by public and private organizations that have sensitivity to life-cycle costs and make efficiency an important market driver. In contrast, light-duty vehicles are purchased based on consumer preference, in which efficiency is only one factor, and are operated for personal convenience. Heavy-duty vehicles are more heavily used than light-duty vehicles, making operating expenses a larger fraction of the total cost of ownership. Diesel (primarily heavy-duty vehicles) and gasoline (primarily light-duty vehicles) engines also have different emissions profiles, and vehicle efficiency has been in tension with emissions reduction (particularly in diesels). Light-duty vehicles are generally more aerodynamic than heavy-duty vehicles, while heavy-duty vehicle engines are generally more efficient than light-duty vehicle engines. As a result, there is more headroom for aerodynamic improvements in the heavy-duty vehicle market and more room for engine improvements in the light-duty vehicle market. The ratio of payload to vehicle weight is dramatically different in heavy-duty and light-duty vehicles, so that lightweighting has greater potential in light-duty vehicles. The limited number of technical options for heavy-duty vehicles motivates an intense focus on conventional efficiency improvements and fuel substitution.

Internal Combustion Engine Improvements

The performance, low cost, and fuel flexibility of ICEs makes it likely that they will continue to dominate the vehicle fleet for at least the next several decades. ICE improvements can also be applied to both hybrid electric vehicles (HEVs) and vehicles that use alternative hydrocarbon fuels. Historically, engine technologies have taken more than 20 years after first introduced to diffuse throughout the vehicle marketplace. This rate is faster for heavy-duty vehicles where fuel economy provides a business advantage to the vehicle's owner. New flexible manufacturing techniques will likely accelerate technology diffusion in light-duty vehicles; government regulations can accelerate the rate of technology diffusion for all vehicles.



Simulations of ethylene-air jet flame. Hydroperoxyradical (left) and formaldehyde (right) are good markers of autoignitionupstream of the lifted flame base. The Department of Energy has unique capabilities in modeling combustion, which can accelerate improvements in the efficiency of internal combustion engines.

Increased efficiency and reduced emissions of ICEs can be realized through technologies that improve engine design and better integrate systems, potentially doubling the fuel economy of light-duty vehicles and increasing heavy-duty vehicle fuel economy by 60%.[110] In addition, the application of high-performance computing (HPC) and simulations to engine design can reduce the time and cost of integrating new technologies. As ICE technologies are proven and refined, the primary barriers to their adoption include cost, consumer acceptance, resource constraints, capital requirements, and turnover rates.

Lightweighting

The weight of a mid-size passenger car is typically evenly distributed among the powertrain, body, chassis/suspension, and remaining non-structural components. The maximum weight-reduction potential of the mid-size passenger car has been estimated to be 50% by 2050.[111] The choice of materials for specific components is based on their material properties (i.e., strength, stiffness, elasticity, heat tolerance, and corrosion resistance), ease of manufacturing and cost.

For vehicles using conventional ICEs, a 10% reduction in vehicle weight can improve fuel economy by 6%–8%, while the same lightweighting of a battery-electric vehicle increases its range by up to 10%. Weight can be reduced through decreasing vehicle size, innovative chassis design, or by introducing light-weight (but structurally-appropriate) materials; consumer expectations make the latter two approaches more likely in the short term.

Cost is a significant barrier to vehicle weight reduction; there are also safety concerns about some measures. There are also tradeoffs with the embedded energy in advanced materials. The growing number of materials likely to be used in a single vehicle raises issues of advanced joining techniques and complexity in recycling, which adds manufacturing and capital costs.

Aerodynamics

As a vehicle's frontal area increases and average speeds exceed 45 miles per hour, aerodynamic drag tends to dominate vehicle efficiency. Aerodynamics therefore has a large impact on vehicles with a large frontal area and highway-dominated driving patterns in large-vehicle classes, such as tractor trailers, pickups, sport utility vehicles, and passenger vans.

Better aerodynamics could improve on-road truck fuel economy by more than 10%; they require a combination of modeling and real-world validation. The headroom for passenger cars is much smaller due to the smaller frontal area, a drive cycle not dominated by highway driving, and current light-duty vehicle designs that are already quite aerodynamic.

DOE Activities

Increases in fuel economy, and therefore vehicle efficiency, are primarily driven by regulations established by agencies other than DOE. DOE provides technical support to EPA and DOT in setting CAFE and GHG standards,[112] as well as providing information to consumers and the vehicle industry.[113]

DOE works closely with industry to help develop next-generation technologies to further improve vehicle efficiency. DOE's laboratories are home to unique capabilities for engine R&D. For example, DOE provides facilities for combustion science and technology, and DOE's HPC facilities are used for ICE and aerodynamics research.

DOE supports pre-competitive vehicle efficiency R&D at its laboratories, universities, and through public-private partnerships. The structure of the vehicle industry, with a few large original equipment manufacturers and a large number of competing and specialized suppliers, is conducive to working with consortia.

DOE will strive to balance its vehicle efficiency R&D efforts between technical issues faced by light-duty and heavy-duty vehicles. While light-duty vehicles are responsible for a larger fraction of national fuel consumption, they are more easily electrified than heavy-duty vehicles. The more limited technical options for heavy-duty vehicles motivates an intense focus on conventional efficiency. Within the vehicle efficiency portfolio, ICE improvements will receive the greatest emphasis. This is both because it contributes to light-duty and heavy-duty vehicle sectors and because DOE's capabilities are well-aligned with the field's technical needs.

Smart Truck

Long-haul trucks play a major role in keeping the Nation's economy moving, carrying 75% of all U.S. freight and supplying 80% of all U.S. communities with all of their consumables. However, these trucks average 6 miles per gallon and emit some 423 million tonnes of carbon dioxide per year.

BMI Corporation, an engineering firm in Greenville, South Carolina, teamed up with the Department of Energy's Oak Ridge National Laboratory to tackle long-haul truck's efficiency and environmental challenges. Utilizing Oak Ridge's Jaguar supercomputer, they developed a new "SmartTruck" that has higher fuel efficiency.

Among the technologies simulated on Jaguar is BMI's Trailer UnderTray System. The system included a variety of fuel-saving components, such as aerodynamic wheel fairings, a special sled that attaches to the axels to direct airflow under the suspension, and a rear diffuser to optimize air flow and boost fuel efficiency. Through simulation, BMI showed that retrofitting existing trucks with advanced components like the Trailer UnderTray will improve current fuel efficiencies by nearly 12%, with the potential of making future advanced trucks up to 50% more efficient.

Courtesy: Oak Ridge National Laboratory

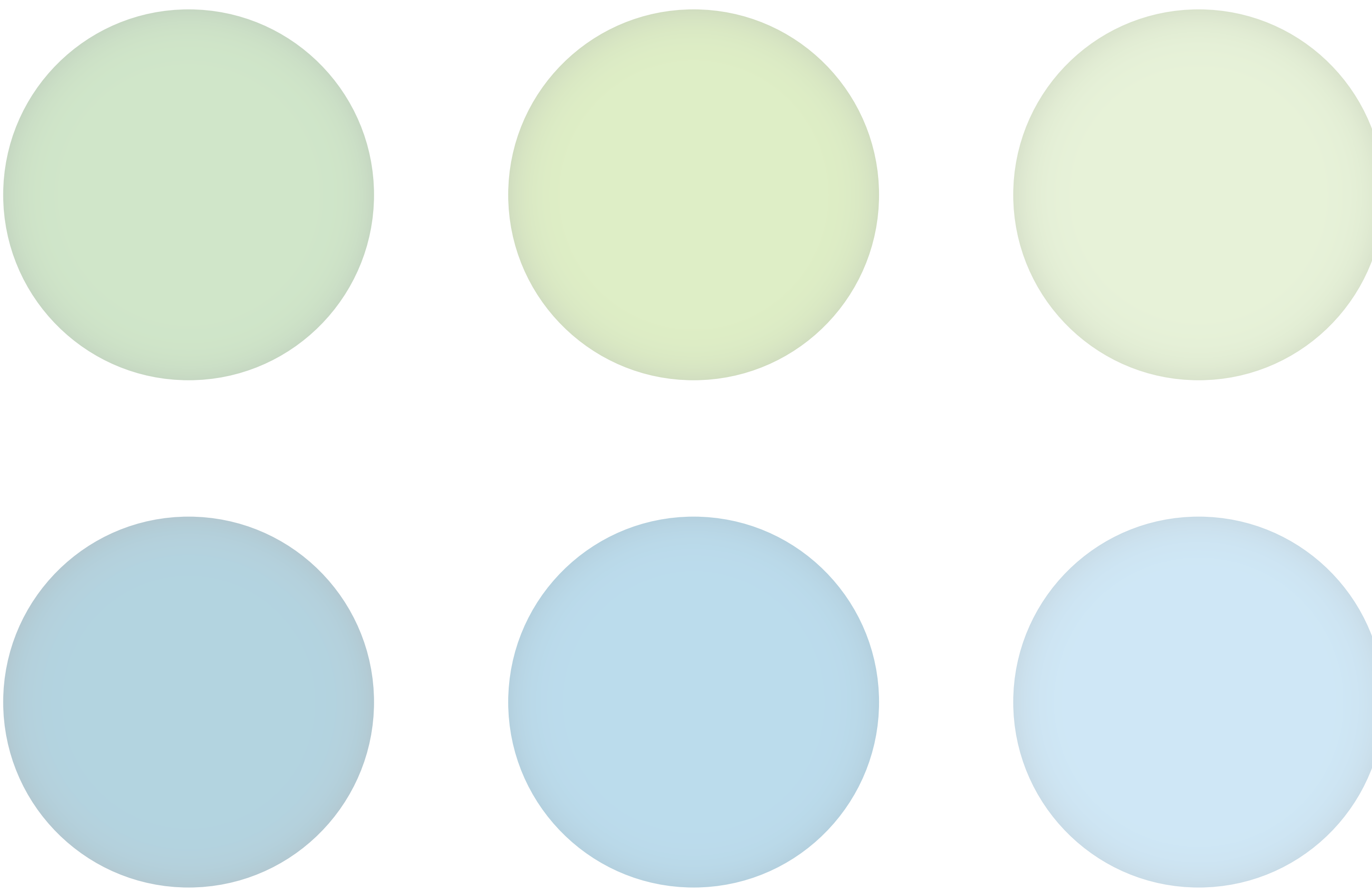
Simulated air flow around a heavy-duty vehicle. The turbulent flow between the tractor and the trailer and the vortex underneath the tractor increase drag and therefore fuel consumption.

Interagency Coordination

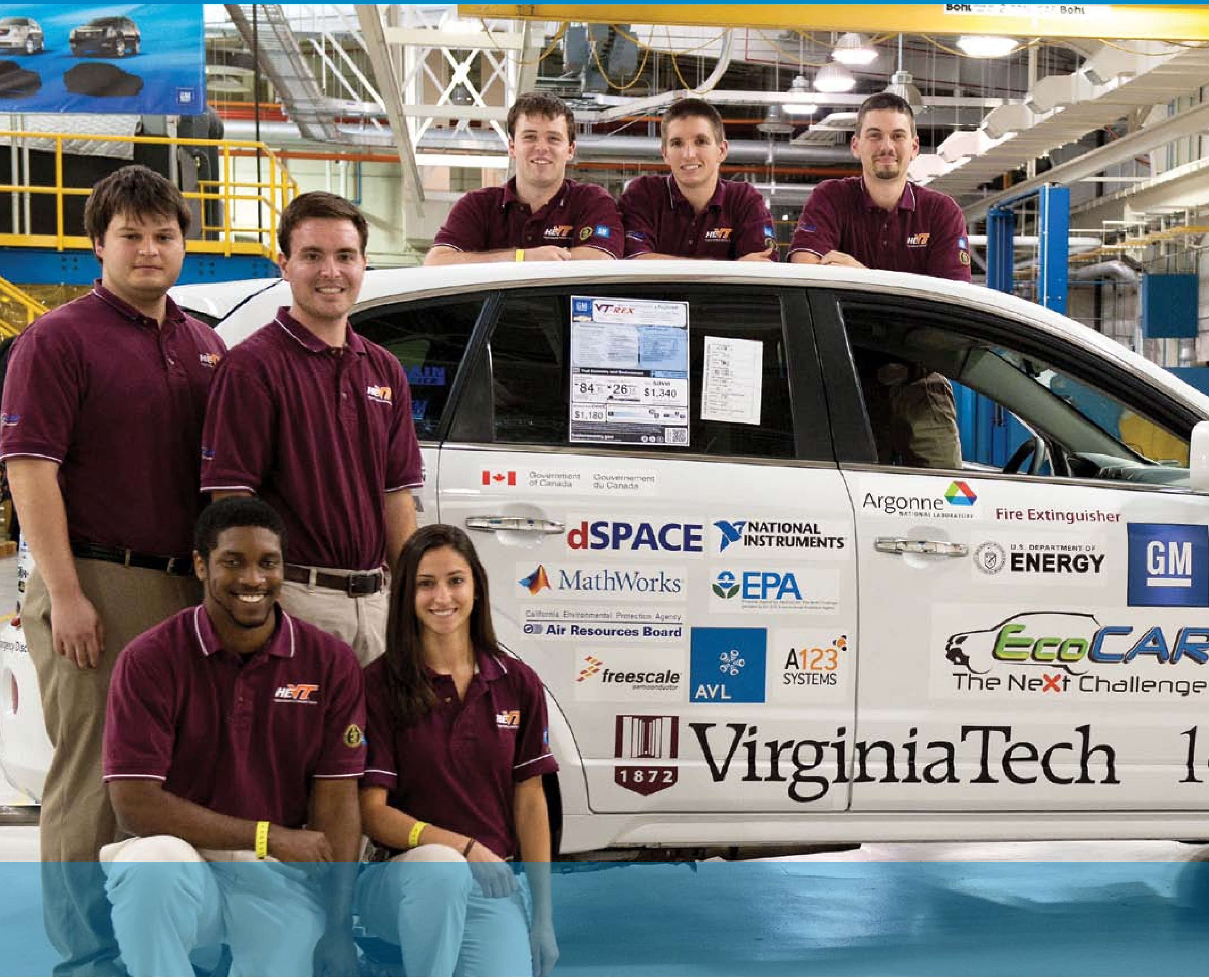
To accelerate the adoption and diffusion of innovative vehicle technologies, DOE works closely with DOT and EPA, agencies responsible for setting federal fuel economy standards. As a complement to making vehicles more efficient, both agencies also encourage improvements to urban planning and traffic management that can increase the efficiency of vehicle operations. The National Institute of Standards and Technology (NIST), as part of DOC, encourages interoperability among innovations in the automotive sector through work on standards. Multiple federal agencies also share responsibility for a variety of safety and environmental issues unique to the transportation sector, and intergovernmental engagement with state and local governments is vital to implementation. Table 1 illustrates the diversity of federal agency engagements to support innovation in vehicle technology, ranging from crash-testing ratings to vehicle procurement.

Table 1. Summary of Non-DOE Federal Agency Activities in Vehicle Efficiency with Examples

Department/ Agency	R&D	Regulation	Finance	Information
Commerce	NIST Transportation Programs			
Defense	Tank Automotive Research, Development, & Engineering Center (TARDEC)		Procurement	
Environmental Protection Agency	Clean Automotive Technology Program	Corporate Average Fuel Economy (CAFE) Standards		Fuel Economy Labeling
Transportation	Federal Highway Administration (FHWA) Exploratory Advanced Research Program	National Highway Transportation Safety Administration (NHTSA)		Transportation & Climate Change Clearinghouse
Treasury			Tax Credits for Electric & Alternative Fuel Vehicles	
General Services Administration			Procurement	



The 2011 EcoCar Challenge champions, Virginia Tech. College teams explored a variety of electric vehicle solutions, including hybrid, plug-in hybrid, all-electric, and fuel cell technologies. Teams incorporated lightweight materials into their vehicles, improved aerodynamics, and utilized alternative fuels.



VEHICLE ELECTRIFICATION

Courtesy of Advanced Technology Vehicle Competition

Technologies that increase conventional vehicle efficiency impact both light-duty and heavy-duty vehicles. However, electrification (whether partial or full) is more viable for light-duty than heavy-duty vehicles. The Department's electrification technology strategy is therefore focused on light-duty vehicles, with ancillary benefits for some heavy-duty vehicle applications where partial or full electrification can be effective.

Hybridization of the light-duty vehicle fleet can reduce oil consumption at the pump in the near- and mid-term; full electrification would decouple light-duty vehicles from the volatile global oil market. Degrees of electrification for electric drive vehicles (EVs, see Table 2) range from mild and strong HEVs, through plug-in hybrid electric vehicles (PHEVs), to pure electric vehicles powered by batteries (all-electric vehicles, or AEVs) or fuel cells (FCEVs). HEVs and PHEVs offer increased fuel economy but still require some liquid hydrocarbons, while AEVs and FCEVs do not require liquid hydrocarbons and thus decouple transport from oil.

Table 2. Current Electric Vehicle Types

Vehicle Type	Capabilities	Key Attributes	Electric Range‡	Battery Capacity¥	Fueling Options
Mild Hybrid† (HEV)	Allows vehicle engine stop/start, may allow electric assist of engine during propulsion	ICE required for all propulsion	0	small	Gasoline, does not plug in
Strong Hybrid† (HEV)	Engine and electric drive used in combination to meet propulsion demands, batteries charged through regenerative braking, engine.	Can be driven on electric power over very short distances	<1 mi	<1 kWh	Gasoline, does not plug in
Plug-in Hybrid (PHEV)	Uses electric propulsion alone for all electric range, then switches to HEV power management.¶	Charges via the electrical grid	15–40 mi	5–15 kWh	Gasoline, 120V wall outlet (3–10 h), or 240V home charging station (1–4 h)
Fuel Cell Electric Vehicle (FCEV)	Always electric propulsion, no ICE. Energy is stored in the form of hydrogen, which is converted to electricity via a fuel cell.	Requires a hydrogen fueling source	>250 mi	N/A	Hydrogen fueling station (5 min)
All-Electric Vehicle (AEV)	Always electric propulsion, no ICE. Energy is stored in batteries.	Requires high power charging for daily use.	80–250 mi	35–55 kWh	120V wall outlet (20 h), 240V home charging station (10 h), or DC fast-charging (30 min)

† Both mild and strong hybrids are referred to as hybrid vehicles.

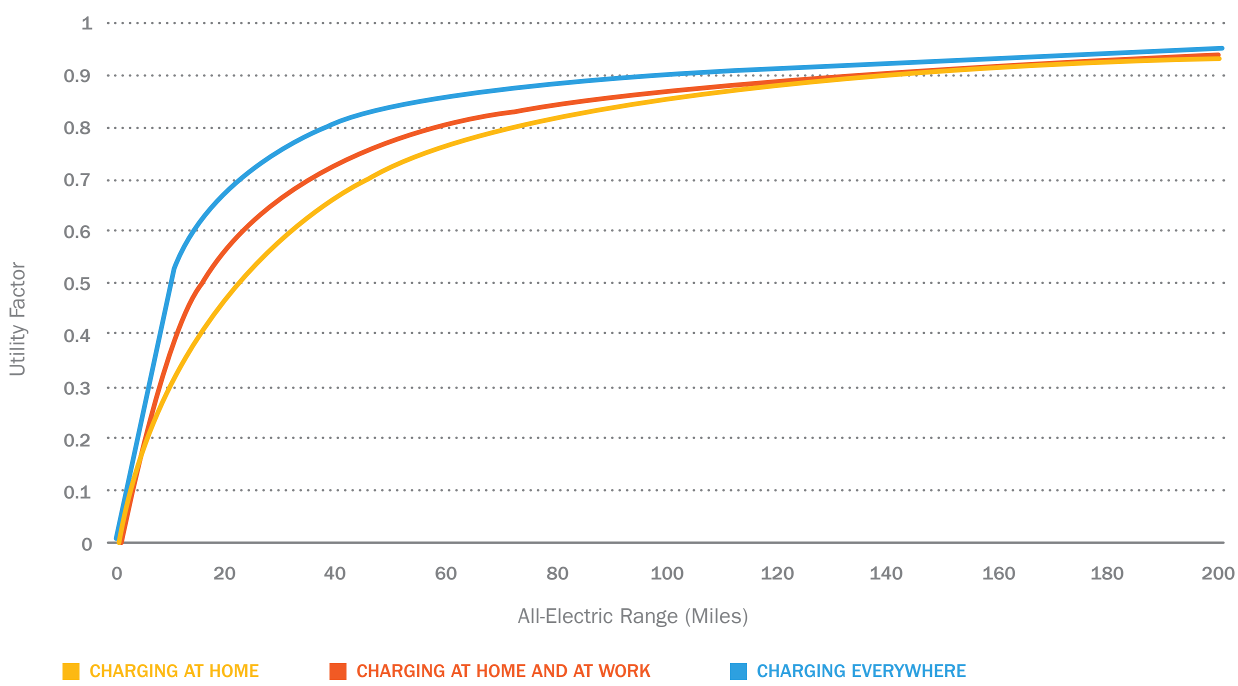
‡ Electric range is typical of today's vehicles, but could increase for PHEV and AEV as batteries improve. FCEV "electric range" is on a full tank of hydrogen.

¥ Utilized battery capacities.

¶ Some PHEVs use the engine to recharge the battery without driving the wheels directly; these vehicles can be referred to as "extended range electric vehicles."

The vehicle industry is more than a decade into the commercial deployment of electric powertrains in HEVs and is generating expertise in integrating conventional and electric powertrains. Although HEVs currently represent only 3% of new light-duty vehicle sales, market penetration is increasing. As both General Motors and Nissan recently began mass production of plug-in vehicles, expertise in next-generation EV powertrains is growing.

Figure 11. Impacts of Plug-In Hybrid Electric Range and Charging Infrastructure



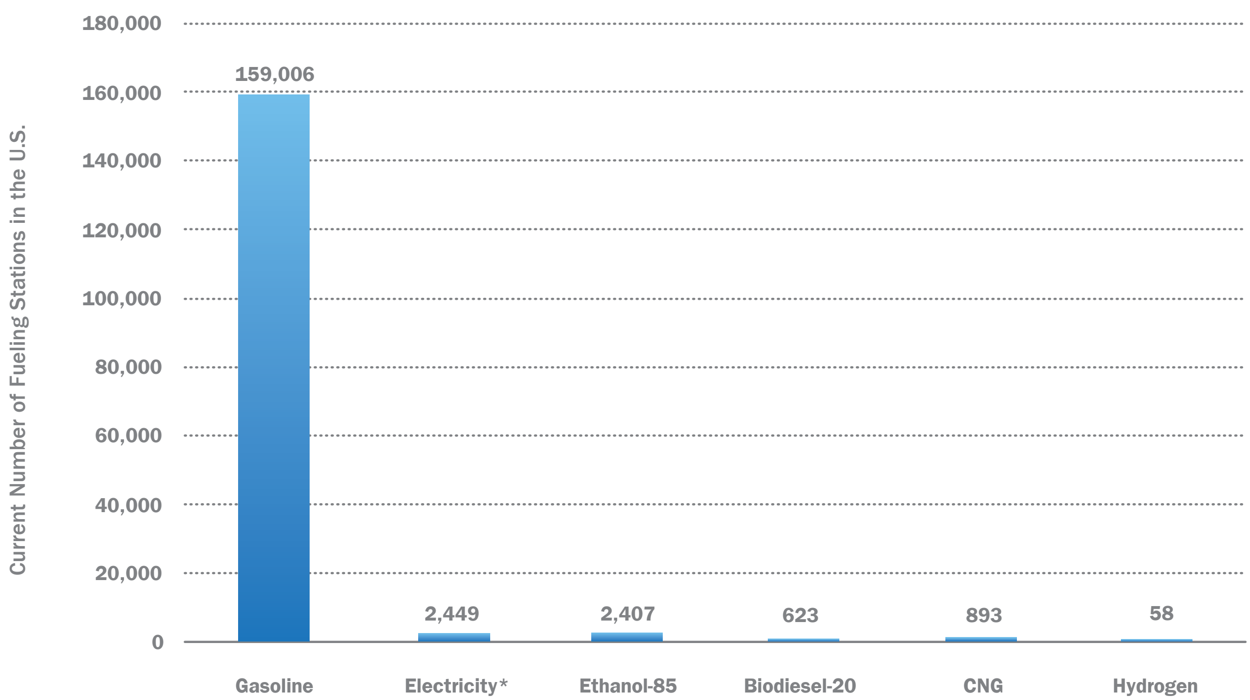
Utility factor is the fraction of vehicle miles that would be driven on electric power without recharging. Different charging scenarios are shown. The benefit of ubiquitous charging becomes smaller as the all-electric range increases; for most applications, home charging is sufficient.[114]

PHEVs and HEVs are more energy efficient than conventional vehicles because electric motors are four times more efficient than today's ICEs, because hybridization of the powertrain allows for the use of more efficient ICEs than conventional powertrains, and because regenerative braking allows energy to be recovered and re-used. PHEVs further reduce oil consumption by replacing liquid fuels with electricity. As shown in Figure 11, a PHEV with a 40-mile all-electric range would replace at least two-thirds of gasoline consumption with electricity.

Infrastructure Matters

New technologies will be deployed rapidly and seamlessly if they can integrate with the existing energy infrastructure. The fueling patterns of on-road transport require extensive infrastructure (Figure 12). The United States has 55,000 miles of crude oil pipeline feeding 150 refineries and another 95,000 miles of refined product pipelines[115] supplying 160,000 gas stations.[116]

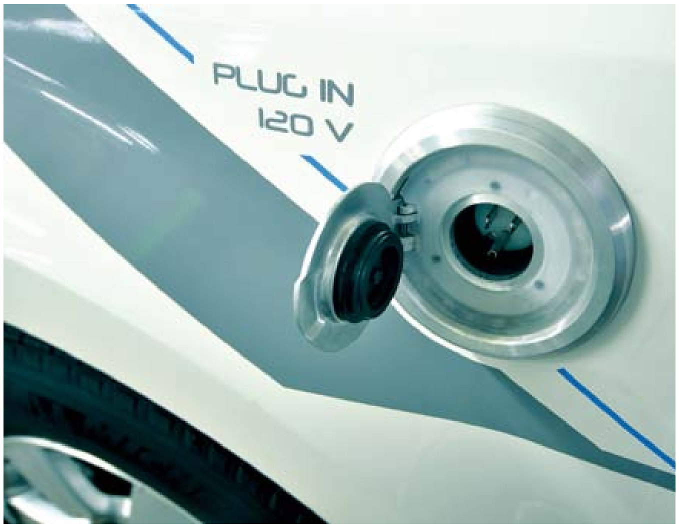
Figure 12. Current Fueling Stations in the United States



There are many more fueling stations for gasoline than for other fuels. *Electricity stations are the publicly available stations only. Not shown are the millions of existing locations for home charging. Source: DOE EERE[117] (for alternative fueling stations) and EIA[116] (for gasoline stations).

There is an existing infrastructure that can accomodate the significant and immediate deployment of HEVs and PHEVs, and could eventually support full electrification of the light-duty vehicle fleet with some upgrades and modifications. There are 11 million miles of electrical distribution circuits that can, today, accommodate virtually unconstrained residential 120-volt (V) wall outlet charging of PHEVs (Level 1, ~2 kilowatts [kW], equivalent to a hair dryer). Ubiquitous charging does not significantly increase the utility factor of a PHEV with an electric range greater than 40 miles (Figure 11). HEVs and PHEVs will therefore see the fastest deployment and have the greatest near-term impact on oil consumption.

Charging time is a potential barrier to further electrification; 10 hours are required to fully charge a PHEV with a 40 mile electric range from a 120V charger. Vehicles with longer electric ranges will require faster charging, which would eventually require grid upgrades. While the household circuits necessary for 240V Level 2 chargers (>3 kW) are commonly used for appliances, obtaining vehicle access to those circuits may require specialized wiring and could affect grid distribution circuits if deployed in clusters. Fewer than 2% of U.S. fueling stations currently offer 240V charging for EVs (Figure 12). Direct current (DC) "fast" charging (Level 3, 480V DC, 50kW) would stress today's grid and require special infrastructure and power management for widespread deployment.



Credit Avi Gopstein

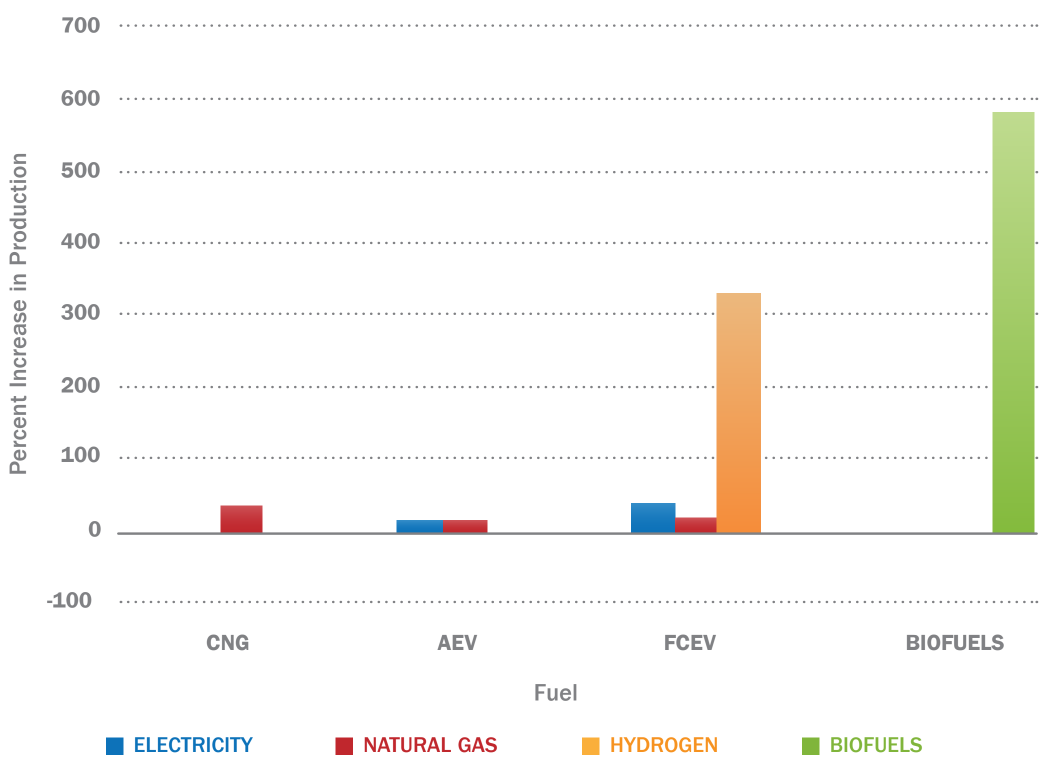
Close up of recharging socket on a plug-in hybrid electric car.

As the market progresses from HEVs to PHEVs of various ranges to AEVs, the demands on the electric charging infrastructure will gradually increase. These increases can be accommodated as they occur, allowing for a smooth path toward greater electrification.

The U.S. hydrogen fueling infrastructure is extremely limited. Fewer than 0.05% of U.S. fueling stations supply hydrogen.[117] Hydrogen can be centrally generated and distributed in the United States by truck or through the 1,200 miles of pipelines, mostly in Illinois, California, and along the Gulf Coast.[118] Mass-market FCEVs would therefore require vastly expanded hydrogen generation, distribution, and fueling infrastructure, which will hinder, if not limit, their impact in the transport sector.

Infrastructure requirements vary across application. Vehicle fleets with their own fueling infrastructure could benefit from specialized fuels. Examples include overhead electrification for designated public transportation routes and hydrogen or compressed natural gas (CNG) fueling at fleet depots. However, these are specialized applications, and technology pathways that leverage existing infrastructure are more likely to succeed in mass markets. Because of their infrastructure requirements, AEVs and FCEVs are most easily introduced into vehicle fleets with a captive fueling infrastructure. AEVs are not viable for the majority of the heavy-duty vehicle market.

Figure 13. Estimated Impacts of Meeting 50% of Today's Light-Duty Vehicle Demand by Various Alternative Fuels



Values are expressed as a change relative to today's supply.[119] Required increases in natural gas and electricity are relatively modest, while hydrogen and biofuels production would need to increase severalfold to meet light-duty vehicle fuel demands. CNG = Compressed Natural Gas; AEV = All-Electric Vehicle; FCEV = Fuel Cell Electric Vehicle. For AEV, the natural gas increase shown is that required to generate all of the required electricity; for FCEV, the electricity or natural gas required to produce the hydrogen are shown. Of course, there are many incremental sources of electricity beyond natural gas.

Infrastructure challenges extend beyond fueling. The energy requirements of the transportation sector are big. Therefore, the marginal expansion of current infrastructure systems is more likely than the build-out of a new infrastructure or major expansion of an existing infrastructure. Fuels and carriers currently used in the stationary system (electricity, natural gas) would require only fractional increases in scale to accommodate significant portions of the transportation system (Figure 13).

In Sum

CAFE and other emissions standards[120] will drive the continued deployment of EV technologies, as ICEs alone cannot accommodate the strictest transportation emissions standards.[121] As with the vehicle efficiency strategy, one of DOE's roles will be to serve as a source of technical knowledge. In addition, DOE can convene and coordinate relevant stakeholders in the electric grid and vehicle industries to smooth the integration of EVs with the electrical infrastructure.

DOE will focus on partial electrification because HEVs and PHEVs can access existing infrastructure. The relative priority in the DOE portfolio of full electrification compared to partial electrification can be reevaluated as batteries and charging infrastructure advance, and once penetration of EVs into the light-duty vehicle fleet is significant. The structure of the vehicle industry is particularly conducive to consortia, such as the U.S. Advanced Battery Consortium.

Battery Technology

Batteries present the greatest technical challenge in vehicle electrification. High-cost (currently about $650/kilowatt-hour [kWh] of usable energy[122]) and low-energy density are the primary drawbacks of today's lithium-ion batteries; significant advances in energy density, performance, and cost are required for the cost-effective deployment of EVs. Those technical barriers contribute to the primary market barriers for EVs: vehicle cost and range anxiety (the latter only for AEVs). Further, there are physical limits to the storage capacity that can be used; the required, but unusable, capacity dictates a heavier and more costly battery.

DOE-funded research has helped to develop the batteries used in many EVs currently on the market, including those produced by GM, Toyota, BMW, Mercedes, and Fisker. Recognizing the opportunity to stimulate domestic manufacturing of the next generation of batteries for EVs, the American Recovery and Reinvestment Act funded 20 DOE-initiated projects to establish domestic battery manufacturing facilities covering the supply chain—from battery materials and components to cell and pack assembly through battery recycling.

DOE's goal is to reduce battery costs through a combination of better materials, optimized battery designs, and improved manufacturing. Such near-term improvements will likely be the result of better lithium-ion batteries. More dramatic advances in energy density, weight, cycle life, and power rates can be achieved through novel chemistries, such as metal polymer and lithium-sulfur batteries. While next-generation batteries have shown promise in the laboratory, they require significant R&D before they can become commercial products.

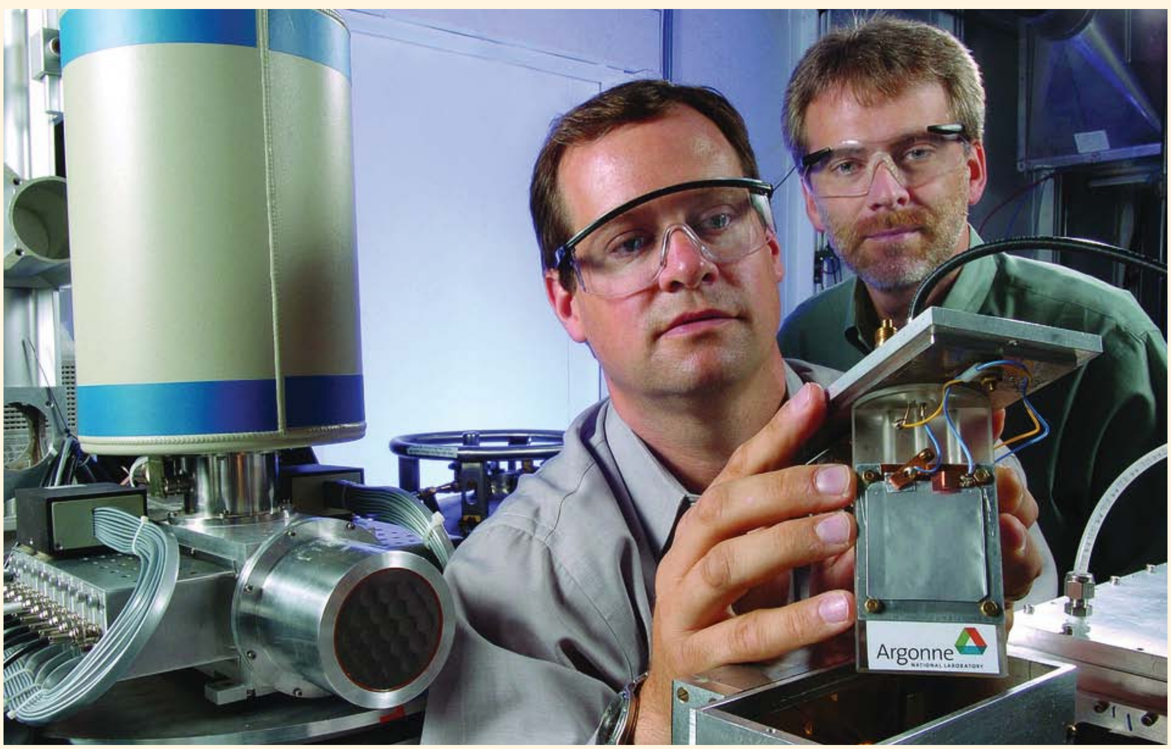
DOE will develop capabilities in advanced battery technologies through scientific research in materials and chemistries, innovation of material architectures, and analytic work on cell design and performance. DOE will engage industry consortia to increase the capabilities of vehicle and battery manufacturers in materials science, electrolyte chemistries, cell manufacturing techniques, and technology performance.

Argonne Technology in the Volt

In December 2010, GM released the first mass-produced plug-in hybrid electric car—the Chevy Volt—with battery technology developed at Argonne National Laboratory. That technology helped the Volt's battery—a lithium-ion system similar to those in cell phones or laptops—last longer, run more safely, and perform better than other batteries currently on the market.

Focusing on improving the cathode, Argonne scientists used intense X-rays from Argonne's Advanced Photon Source to watch chemical reactions while they were occurring in the battery. These observations allowed Argonne to modify and optimize the cathode materials to be remarkably more stable than those in existing designs. This new material made the batteries safer and less likely to overheat.

The materials research performed at Argonne allowed industry to deploy a better product. Ongoing research in new materials will allow the next generation of batteries to last twice as long as current models.



Courtesy of Argonne National Laboratory

Argonne chemist Christopher Johnson (foreground) and physicist Jeremy Kropf load a lithium-ion battery pouch into an X-ray beamline at the Advanced Photon Source to evaluate the stability of the electrode material structure during charging and discharging.

Fuel Cells

DOE's support of fuel cell research has led to significant progress in recent years, helping reduce the cost of fuel cells by a factor of five and improve on-vehicle hydrogen storage to acceptable ranges for a light-duty vehicle. However, significant further improvements in key technologies remain to be demonstrated to meet program goals. If those program goals are met, the cost of driving (vehicle plus fuel) for FCEVs will likely be comparable to other alternative technologies (including vehicle efficiency improvements, electrification from HEVs to PHEVs to AEVs, and biofuels). However, those other alternative technologies are currently economically superior and will continue to improve rapidly.

Infrastructure deployment is a major hurdle for FCEVs. Other alternative technologies that integrate smoothly with the existing infrastructure are being deployed now and will accelerate progress toward national energy goals. DOE will therefore maintain a limited program of fundamental R&D in fuel cells for transportation and in hydrogen production and storage.

Electric Motors and Power Electronics

Inverters and electric motors convert electricity into physical power that moves the EV. These components add significant cost to electric drive vehicles, though costs have decreased by 35% over the past five years. Current technologies rely on both induction and permanent magnet motors, depending upon the drive design criteria. Permanent magnet motors, which use rare earth elements to achieve their high-power density, high power-to-weight ratio, and efficiency, are particularly suitable for building compact electric drive systems. The supply and cost of rare earths are therefore potential barriers to the wide deployment of EVs. Reducing costs by using smaller motors (thereby reducing the rare earth material used) is in tension with requirements for thermal management and performance. Yet, there are technical opportunities to reduce both cost and rare earth content.[123]

DOE will develop technical capability in power electronics and electric motors via research in high-temperature capacitors, low-loss soft magnetics, wide-bandgap semiconductor materials, and their integration into low-cost power conversion devices and systems operated at high temperatures. This can reduce the size or even eliminate the need for advanced thermal systems. Research in novel magnetic materials, rare earth recycling, power electronics, and magnetic materials is important to many DOE interests. This research will be coordinated across DOE in activities ranging from materials discovery science through device prototyping.

Future Infrastructure

As market penetration of PHEVs and AEVs increases, multi-family dwelling charging infrastructure and fast charging needs will have to be addressed. Approximately 40% of the current U.S. population lives in multi-family dwellings[124] that require a different model for vehicle charging than in single-family residences. Furthermore, extensive Level 3 charging would severely stress the current grid.

The Department will not emphasize the deployment of fueling infrastructure. There are still many unknowns regarding the integration of the transport and electric sectors. DOE will support technical research to understand control and interoperability issues. The Department will also support research to better understand technology adoption and driving/charge-cycle patterns for PHEVs. Reevaluation of that posture may be required if market conditions change.

Interagency Coordination

Electrification is a strategy that ultimately displaces demand on an existing fueling infrastructure by moving that function to the grid. As those market dynamics evolve over decades, several federal agencies that serve specific functions for the current fuels distribution infrastructure will continue to be instrumental in national energy policy. For example, the Departments of Interior, State, and Transportation each play prominent roles in permitting decisions for certain types of pipelines. Table 3 illustrates the diverse set of agencies involved in both research and technical assistance for both today's petroleum-based fuels and for alternative fuels, including electricity and energy-storage technologies for vehicles.

Table 3. Summary of Non-DOE Federal Agency Activities in Fuels Distribution with Examples

Department/ Agency	R&D	Regulation	Finance	Information
Agriculture			Rural Energy for America Program (REAP)	Agricultural Marketing Service: Rail Tariff Publications
Commerce	NIST Pipeline Safety Testing			
Environmental Protection Agency		Clean Air Act: National Emissions Standards for Hazardous Air Pollutants (NESHAP)		
Homeland Security	Infrastructure Protection & Disaster Management Division			National Infrastructure Protection Planning
Interior		Right of Way Permitting		
State		Presidential Permits		
Transportation	Pipeline & Hazardous Materials Safety Admin. (PHMSA) R&D	PHMSA		Research & Innovative Technology Administration
Treasury			Renewable Fueling Infrastructure Tax Credits	
Federal Energy Regulatory Commission		Office of Energy Market Regulation		
Commodity Futures Trading Commission		Energy Commodity Market Regulation		
Export Credit Agencies			OPIC Investment Funds	

Alternative hydrocarbon fuels will be needed to replace barrels of oil that cannot be eliminated by improved fuel economy and electrification. Heavy-duty vehicles will rely upon liquid fuels.

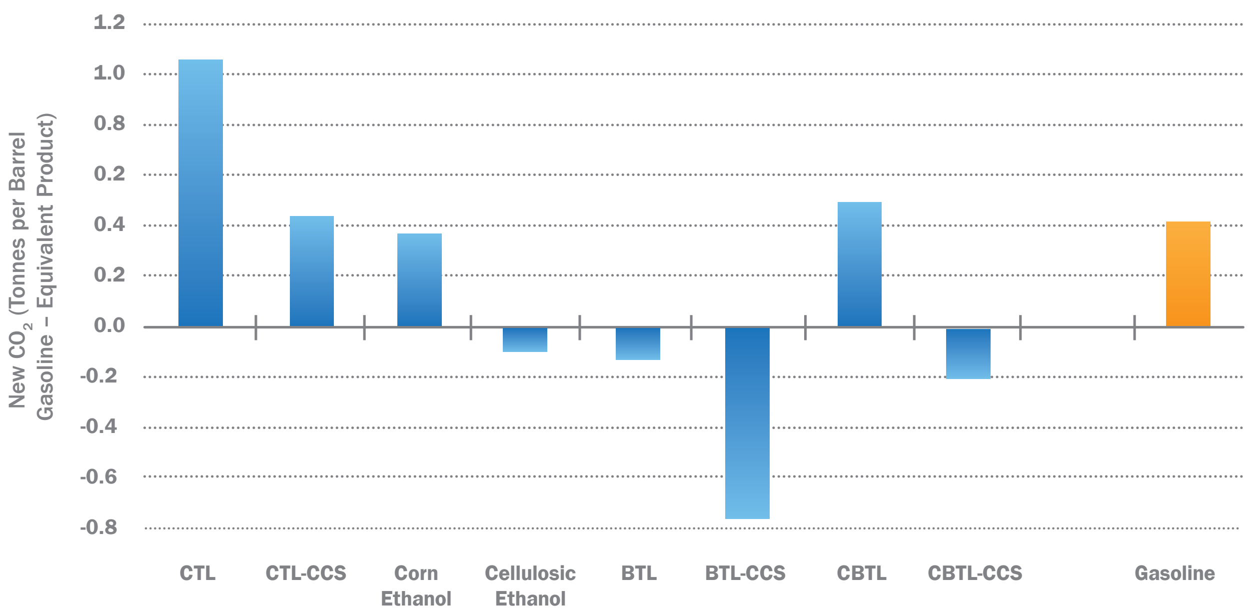
ALTERNATIVE HYDROCARBON FUELS

Credit: Tom Grill/Corbis

Liquid hydrocarbon fuels will remain important to the transportation sector for the foreseeable future. Even if light-duty vehicle demand for gasoline is reduced by improved efficiency and electrification, liquid fuels will be necessary for heavy-duty vehicles, as well as air, marine, rail, and niche markets. Despite dominance of crude-derived hydrocarbon fuels in the United States, there are successful alternative fuel implementations that demonstrate the possibilities for meaningful market penetration of alternative fuels (including ethanol in Brazil and the United States, synfuels in South Africa and China, and CNG in the Pacific region).

The Nation's transportation fuels are currently dominated by gasoline, diesel, and specialty fuels derived from crude oil. Each alternative fuel provides different benefits when compared with conventional crude-derived fuels. Many alternatives can be produced domestically, providing economic and security-of-supply advantages. Increasing the production of any alternative hydrocarbon fuel to meaningfully displace petroleum-derived fuels would require dramatic increases in feedstock production (Figure 13).

Figure 14. Life-Cycle Carbon Emissions for Various Transportation Fuels



The greenhouse gas emissions from some alternative fuels are less than those from conventional fuels, while others are higher. The production and extraction of feedstocks also have environmental impacts. CTL = coal to liquids, CCS = carbon capture and storage, BTL = biomass to liquids, and CBTL = coal and biomass to liquids.[125]

Corn-derived ethanol makes up about 10% of gasoline by volume[126] (7% by energy content), and CNG is a viable alternative for vehicle fleets, although it currently accounts for only about 0.1%[127] of primary transportation energy. The United States has 150 crude oil refineries with an average refinery capacity of about 120,000 barrels per day.[128] Ethanol is produced at more than 200 refineries with an average capacity of about 4,500 barrels per day,[129] the vast majority of which use corn as a feedstock, consuming about 40% of the U.S. corn crop.[130]

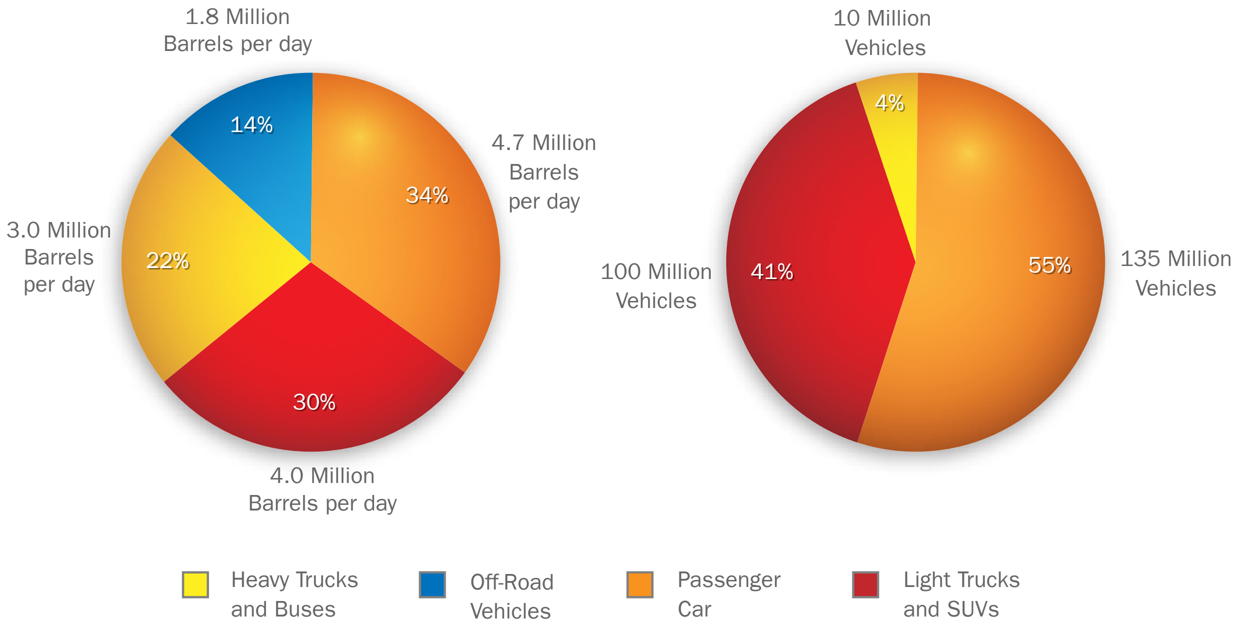
Novel liquid fuels that are chemically similar to those refined from petroleum ("drop-in" fuels) can be derived from a variety of biological and fossil feedstocks. Drop-in fuels can easily enter the market through the existing pipeline and retail infrastructure. Other liquid fuels, such as alcohols (e.g., ethanol, methanol, and butanol) and propane, are less energy dense and/or more corrosive than conventional fuels. Therefore, they must be blended or modifications are required to both the fueling infrastructure and vehicles. For example, 90% of E85[131] is currently transported via truck or rail, though dedicated ethanol pipelines have been proposed.[132] Fewer than 2% of fueling stations offer E85 (two-thirds of these are in the Midwest),[117] raising significant supply chain and distribution infrastructure issues.

Drop-in fuels are fungible with current liquid fuels thereby easing their introduction into the market, although they provide no meaningful benefit in fuel price at the pump. Alternative hydrocarbon fuels also vary in their environmental impacts. For example, the GHG emissions from some fuels are less than those from conventional fuels, while others are higher (see Figure 14).[133] Notably, alternative fuels made solely from fossil feedstocks have life-cycle emissions equal to or greater than gasoline. The production and extraction of feedstocks (both petroleum and alternatives) have additional environmental impacts. The current and future policy contexts for these fuels differ as described in each section below.

Light-Duty and Heavy-Duty Vehicles Are Different

The three transportation strategies for addressing oil dependence have different implications in the light-duty and heavy-duty transportation sectors. It is therefore important to distinguish technology options for light-duty vehicles (e.g., cars, minivans, and sport utility vehicles) and heavy-duty vehicles (e.g., trucks and buses). While both currently rely almost entirely on ICEs fueled by crude oil-derived liquids (gasoline for light-duty vehicles and diesel for heavy-duty vehicles), the services, operation, and requirements of these two sectors are fundamentally different. Individual heavy-duty vehicles travel much further each year than light-duty vehicles, although the sheer number of light-duty vehicles makes the annual on-road consumption of gasoline three times that of diesel (Figure 15). Heavy-duty vehicles can operate with a captive fueling infrastructure (depot for returning fleets, dedicated filling stations along defined long-haul routes), while light-duty vehicles operate with near-ubiquitous fueling that is interoperable across diverse vehicles and fuel suppliers.

Figure 15. Total Vehicle Fuel Use and Total U.S. Road Vehicles in 2009



Off-road vehicles include planes, trains, and boats. Note that although heavy-duty vehicles account for less than 5% of the fleet, they use 22% of the fuel.[134]

Diesel-powered heavy-duty vehicles will continue to use significant quantities of liquid fuel, making the development and deployment of alternative fuels for that sector a high priority. DOE will preferentially focus fuels research on the heavy-duty vehicle market, where electrification is not as effective. In alternative hydrocarbon fuels, the Department will give priority to fuels that are compatible with current infrastructure and that have the potential to be cost-competitive with petroleum-based fuels, as they are most likely to be deployed in the mass market. DOE recognizes that this approach does not solve the problems of high or volatile fuel prices. However, there are other benefits. Diversification of energy supply via domestic production of alternative drop-in fuels as a substitute for petroleum will positively impact national energy security, domestic employment, balance of trade, and other public benefits.

Biofuels

Federal policies encourage the domestic production of biofuels. The RFS administered by EPA sets minimum amounts of biofuels that must be blended into vehicle fuels. The Energy Policy Act of 2005 established RFS1, which sets a minimum amount of ethanol (7.5 billion gallons) that must be blended into gasoline by 2012. The Energy Independence and Security Act of 2007 established RFS2, broadened the RFS to include second- and third-generation biofuels, set a new target (36 billion gallons in 2022), established separate volume requirements for new categories of fuel based on feedstock and vehicle compatibility, and required EPA to apply life-cycle GHG standards. Biofuels blenders also receive tax credits ranging from $0.45–$1.01 per gallon, but the extent to which such credits serve to incentivize the use of biofuels beyond the levels mandated by RFS2 is not clear. Smaller federal subsidies are available for both the production and construction of new plants. In addition, ethanol imports (from all but Caribbean countries) are subject to a $0.54 per gallon import tax.[135]

Biofeedstocks can be divided into several categories: (1) conventional crop-based carbohydrates or lipids (e.g., corn and other starches, sugarcane, or vegetable oils), (2) cellulosic feedstocks (e.g., switchgrass, crop and wood byproducts), and (3) non-land based organisms (algae and other concepts). Each feedstock can be converted into a range of fuels through various pathways.

Resource requirements (e.g., water and land intensity) and interactions with food and feed markets complicate the deployment of crop-based biofuels at material scales, driving research into alternative feedstocks. At the same time, increasing productivity of the corn crop will produce large amounts of starch. Furthermore, the easy conversion of starch to ethanol makes it likely that corn ethanol will continue to contribute to the domestic fuel supply.

Cellulosic feedstocks are likely to be of growing importance, driven by RFS2 and the potential for minimizing impacts on food and feed markets. While the lignin in cellulosic feedstocks makes their conversion inherently more difficult than sugar or starch, there are many promising technical pathways to lower the cost of conversion of low-value feedstocks at scale.

High-value coproducts (i.e., chemicals for the pharmaceutical, cosmetic, and food-science markets) can augment the economics of early-stage biofuel penetration. However, the coproduct market will saturate as fuel production is taken to scale.

DOE Activities

Since advanced biofuels do not yet have cost parity with petroleum products, their short-term economic viability will continue to depend upon government policies. One of DOE's roles in this field is to provide technical knowledge and analyses, available to both the fuels and vehicles industries, as well as other government agencies. Analyses—such as the so-called Billion-Ton Study and its recent update,[136] which evaluate the availability of biomass resources—bring technical rigor to policy development. We heard clearly from stakeholders that DOE's evaluations of life-cycle impacts, food-fuel interactions, land-use requirements, and techno-economic forecasts are highly valued by industry stakeholders, academia, and government agencies alike.

The private sector (with support from USDA) is incentivized to increase crop yield, although most research in this area is focused on crops currently grown at scale. Similarly, private investment in conversion technology primarily supports incremental advances in starch ethanol production. RFS2 and other government actions have spurred some private investment in advanced biofuels, such as cellulosic ethanol and algae fuels.

Standards for molecular composition, infrastructure compatibility, and combustion characteristics allow future engines to be optimized around new chemistries. Diversity in feedstocks must be overcome to provide the common fuel molecules and attributes necessary for such products. Technical analyses of biofuels are informed in part by DOE-funded precompetitive research at the national laboratories, in academia, and in the private sector.

The Department collaborates with USDA, the primary federal supporter of agricultural research, to develop new feedstocks. DOE focuses on the chemistry, biology, and engineering of feedstock digestion and conversion, while USDA investigates crop and soil science for energy crops. The Department also supports the development of technologies to gather and transport feedstocks to processing plants, including compression (to reduce bulk) and treatment (to reduce fouling). To maintain leadership in technologies that could have a long-term impact, DOE will support research in advanced biofuels for the heavy-duty vehicle market (mainly diesel). Because ethanol is neither a total drop-in fuel nor ideal for the heavy-duty vehicle market, and because it already has substantial investment from the private sector, DOE will not give high priority to R&D activities in conversion pathways to produce ethanol.

Petrochemicals account for 2% of petroleum consumption.[137] Therefore, bioproducts are not likely to make a material impact on the primary objective of DOE activities in the transportation sector: reduced oil consumption. Accordingly, DOE will not support the development of bioproducts in the absence of fuels production.

Alternative Fossil Fuels

Liquid transportation fuels that are very similar to existing petroleum-derived fuels can be produced from coal, natural gas, or mixtures of coal and biomass. These fuels are compatible with the existing fueling infrastructure and vehicles. The primary barriers to deploying these conversion processes are scale, capital intensity, and environmental impact. Scaling coal to liquids (CTL), coal and biomass to liquids (CBTL), or gas to liquids (GTL) to replace petroleum-derived transport fuels would require a large increase in domestic coal or gas production.

In 2008, 150,000 of the Nation's 250 million road vehicles (less than 0.1%, mostly buses and corporate-fleet vehicles) were powered by CNG. Natural gas must be compressed to meet the volume requirements of mobile applications, but even CNG takes considerable space in vehicles. Advantages of CNG as a substitute for petroleum include engine efficiencies greater than those for gasoline, a GHG reduction of up to 10% compared to gasoline, and the existing natural gas distribution infrastructure.

SynFuels

Two primary thrusts were: (1) an aggressive Department of Energy (DOE) research and development program in the early 1980's to build large-scale synthetic fuels demonstration plants, and (2) the establishment of the Synthetic Fuels Corporation (SFC) in 1980.

DOE efforts included two projects, known as SRC-I and SRC-II, that used advanced technology to produce both liquids and clean solid fuel products from coal. However, a continued downtrend in oil prices led to the cancellation of planned demonstration plants in 1981.

DOE also partnered with a consortium of gas utility companies known as the Great Plain Gasification Associates (or GPGA) and provided a loan guarantee that led to the opening of the $2.1 billion Great Plains Synfuels Plant in 1984 in Beulah, ND. Two years later, GPGA backed away from the project. DOE sold the Great Plains Synfuels Plant to the Basin Electric Power Cooperative in 1988 at a substantial discount, although the majority of DOE's investment has now been recovered through revenue sharing. Basin Electric currently sells synthetic natural gas, carbon dioxide for enhanced oil recovery, and a variety of byproducts.

Credit: Basin Electric Power Cooperative.

Great Plains Synfuels Plant in Beulah, North Dakota.

While there are many reasons that these synfuel demonstrations failed, market conditions and industry's involvement, or lack thereof, played large roles. Although some projects met predicted levels of technical performance, because the cost of production was so far above the prevailing market prices for gasoline, the projects were ultimately market failures. Recognizing synfuels' cost constraints, industry quickly became skeptical of the economic viability of these projects. Without industry interest, deployment of this technology became very difficult; with declining oil prices, synfuels were abandoned.

The U.S. has more than 210 natural gas pipeline systems that total more than 300,000 miles of transmission pipelines and 1.9 million miles of distribution lines.[138] However, this infrastructure is optimized to supply power plants and commercial and residential end users. CNG for transportation requires a compressor to fuel a vehicle from the distribution pipeline. Fewer than 1% of U.S. fueling stations supply CNG.[117]

The higher energy density of liquid natural gas makes it a potential fuel for heavy-duty vehicles, although significant investment in infrastructure would be required.

DOE Activities

The Department will not support R&D on fuel pathways that have greater life cycle carbon emissions than conventional fuels. The GHG emissions of GTL, CTL, and CBTL without carbon capture outweigh the potential benefits for petroleum displacement.

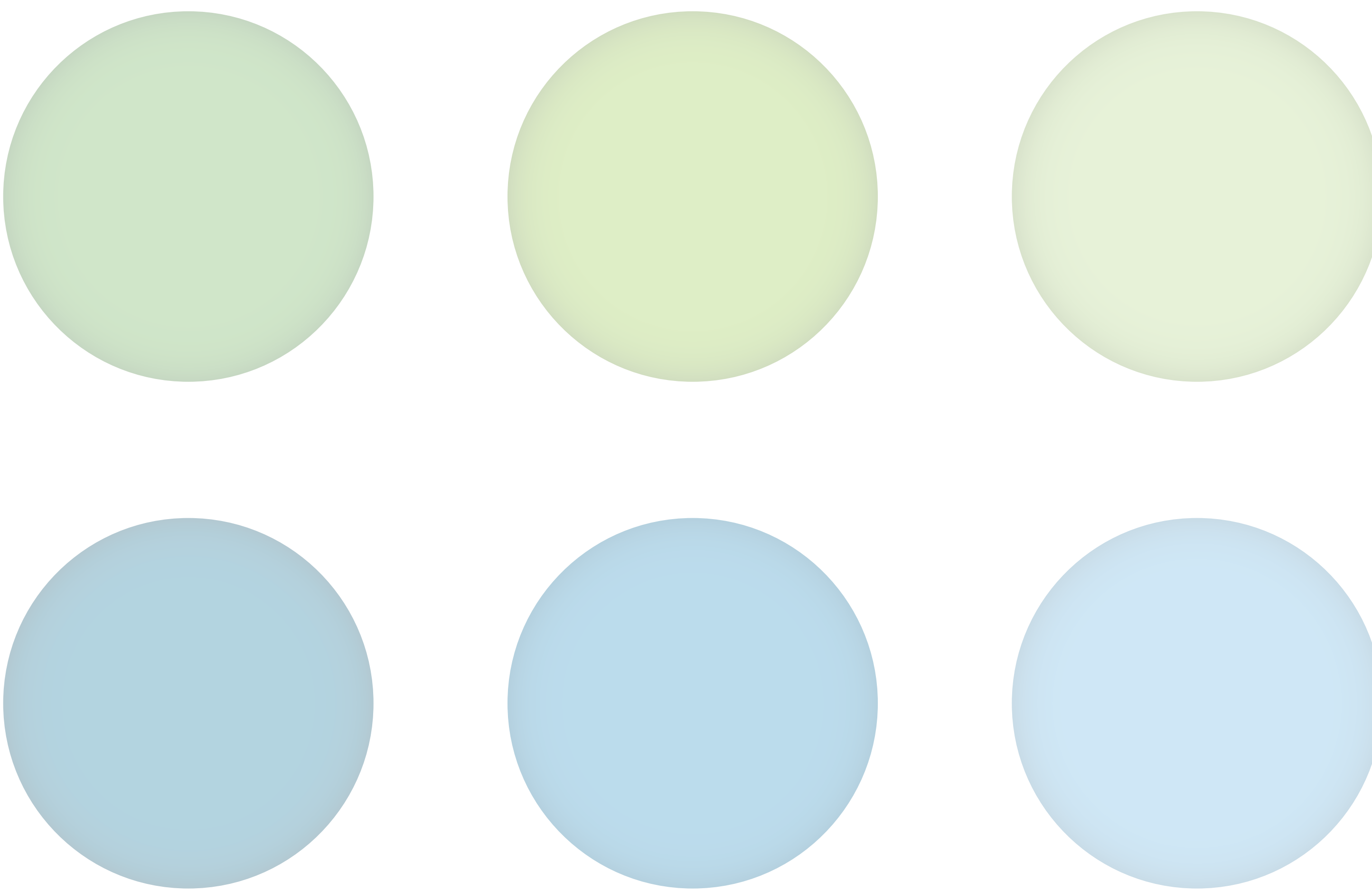
The abundance, low cost, and domestic supply of natural gas makes it an increasingly attractive candidate for captive fueling applications (i.e., fleets). DOE will support the development of new technologies that may make natural gas more applicable for transport. However, there are challenges for natural gas use in transport: infrastructure and competing demand from electrical, heat, and chemical uses.

Interagency Coordination

There are many agencies with authorities relevant to the production of transportation fuels, as illustrated in Table 4. For example, agencies associated with the management of public land play a vital role in both the development of the fuel products used today, as well as the feedstocks that can be used in the future. USDA is particularly active on this front, co-chairing the Federal Biomass Research & Development Board with DOE to enhance coordination. Federal research objectives, financial incentives, and technical-assistance programs related to fuels production are informed by the needs of stakeholders striving to attain specific policy objectives, such as the RFS.

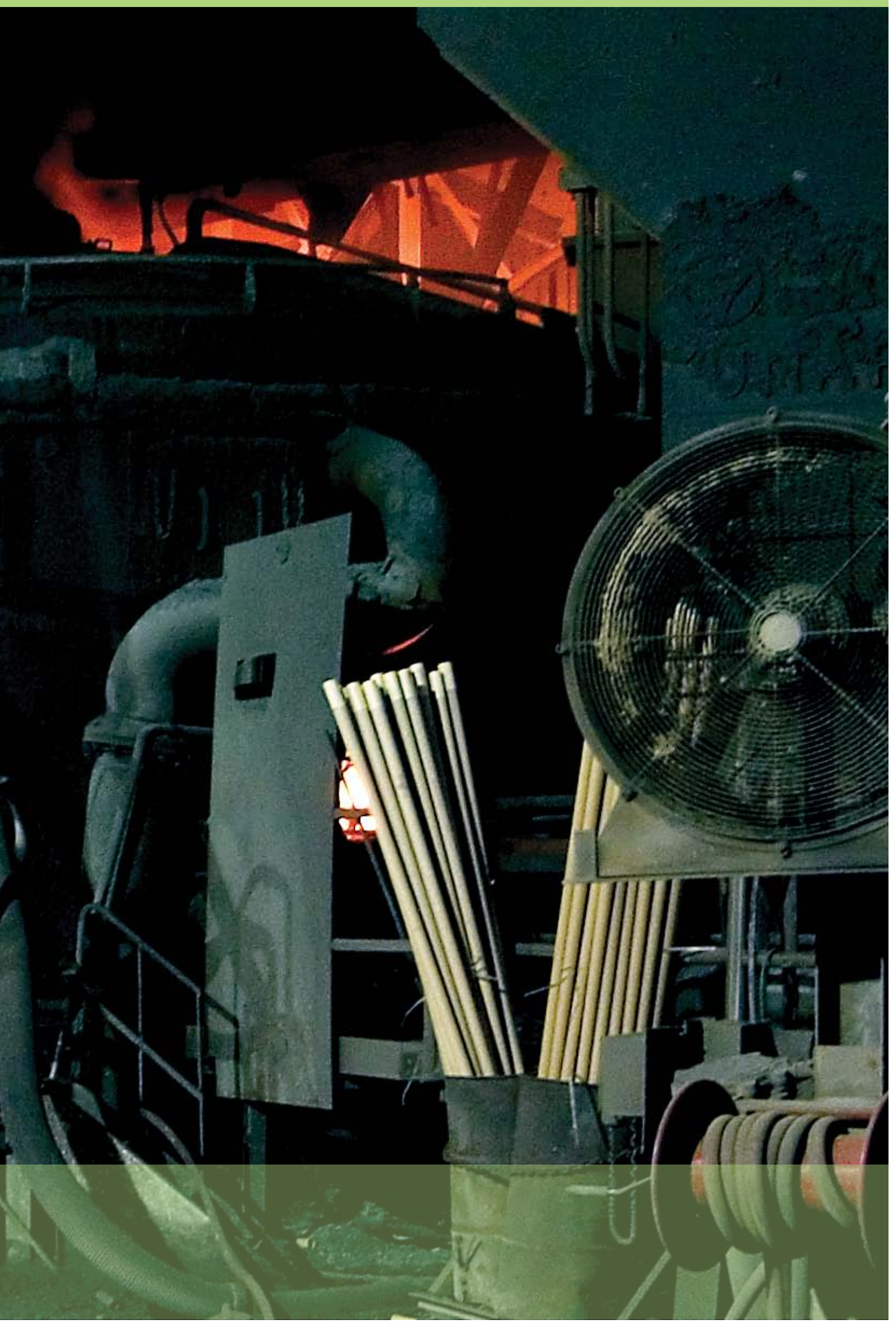
Table 4. Summary of Non-DOE Federal Agency Activities in Alternative Hydrocarbon Fuels with Examples

Department/ Agency	R&D	Regulation	Finance	Information
Agriculture	Biomass R&D Initiative		Biofuel Loan Guarantee Program	Econ. Research Service (ERS) Bioenergy Market Analysis
Commerce	NIST Biofuels Standards Program			
Defense	Defense Advanced Research Projects Agency (DARPA)		Defense Production Act	
Environmental Protection Agency	National Vehicle & Fuel Emissions Laboratory	Renewable Fuels Standard 2		Clearinghouse for Inventories & Emissions Factors (CHIEF)
Interior		BLM and BOEMRE Leasing		U.S. Geological Service
Transportation	Research & Innovative Technology Administration (RITA)			Research & Innovative Technology Administration (RITA)
Treasury			Tax Incentives for Biofuel Production	
General Services Administration			Procurement	
Commodity Futures Trading Commission		Energy Commodity Market Regulation		
Export Credit Agencies			OPIC Investment Funds	Foreign Market Analysis



Electric-arc furnace for steel plate production at Nucor Hertford Mill in North Carolina. U.S. industry uses 22 Quads of energy per year; steel production uses approximately 1 Quad of energy.

ENERGY EFFICIENCY IN BUILDINGS AND INDUSTRY

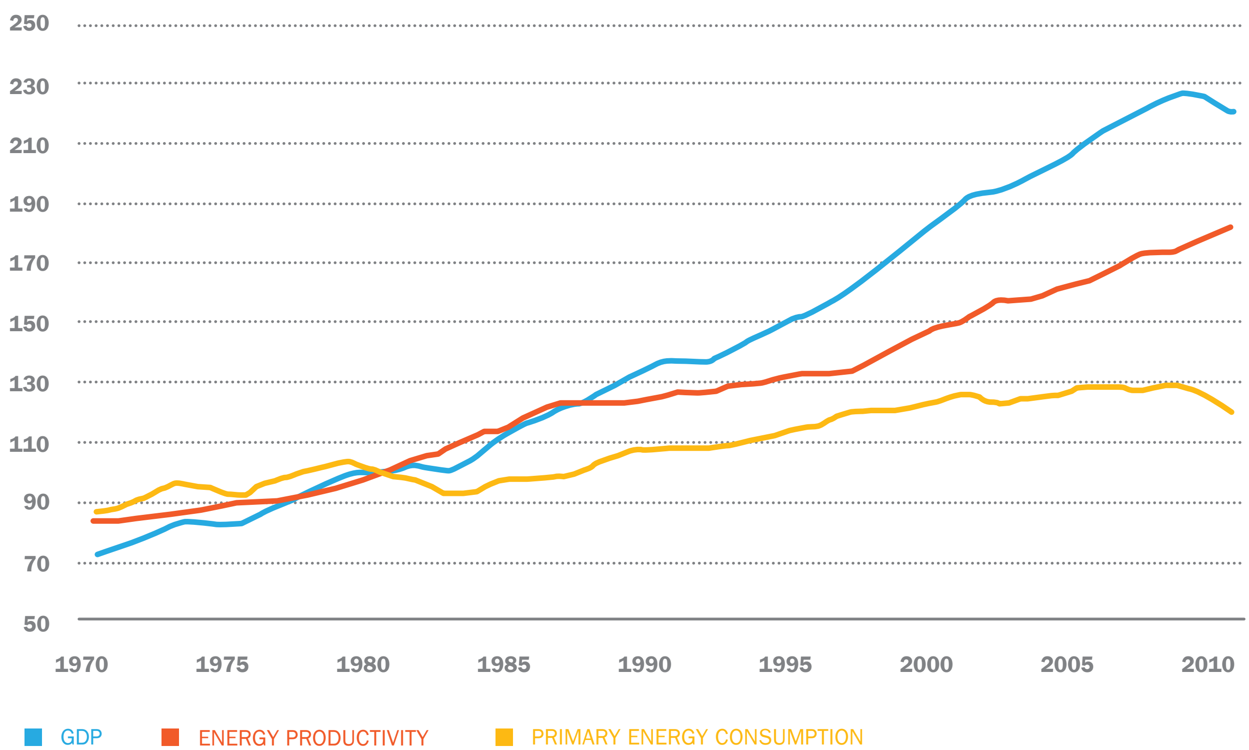


Credit: Brian Hayes

The energy productivity of the United States has increased by more than 85% during the last three decades,[139] as shown in Figure 16. Roughly one-quarter of this change can be attributed to increased efficiency in the delivery of energy services;[140] structural changes in the economy have also played an important role. Further improvements in stationary energy efficiency will enhance U.S. economic competitiveness while reducing environmental impacts. The Administration has therefore set a goal of making commercial buildings 20% more efficient within a decade, which could reduce business owners' energy bills by about $40 billion per year.

Increasing energy efficiency provides a net economic advantage by decreasing energy expenditures for the same level of service. Consumers can direct those financial resources toward other goods and services while reducing their exposure to energy price volatility. This strategy also reduces environmental impacts by reducing or restraining the growth of energy consumption.

Figure 16. Trends in Energy Productivity of the U.S. Economy, 1970–2009



Energy productivity, gross domestic product (GDP) divided by primary energy consumption, has increased 85% since 1980.[141]

This Report separates the stationary energy efficiency strategy into residential and commercial buildings (about 40% of primary energy consumption) and industry (about 30% of primary energy consumption). Efficient use of energy in buildings and industry guarantees reduced upstream energy input and losses; this is particularly significant for electricity.

Many of the cost-effective energy efficiency measures available *today* for buildings and industry are not implemented. Non-technological barriers slow the deployment of these measures. There is also a tension between increasing the efficiency of individual components and their function within the larger system (including individual and institutional behaviors). Understanding these barriers can help the Department direct its efforts most effectively to increasing energy productivity.

DOE Principles for Energy Efficiency

DOE will give priority to those activities having the greatest impact on the Nation's energy productivity. Energy consumers are more likely to adopt efficiency measures that have greater financial benefits. Therefore, DOE will focus on increasing cost-effectiveness. Because there is an overwhelming number of technologies the Department could work on, DOE will also focus its efforts toward uses that consume the largest amounts of energy or are projected to do so in the near future.

DOE will pursue activities that increase users' knowledge and control of energy use. Lack of credible information is a significant barrier to the adoption of cost-effective end-use technologies. Improved knowledge of energy flows within buildings and in industrial processes will also enable new technology development and business models.

DOE will preferentially support technologies compatible with current infrastructure. Approximately 60% of the commercial floor space and 75% of the homes that will be occupied in 2030 have already been built.[142] These structures commit the Nation to significant future energy consumption and must be addressed if we are to meaningfully impact national goals. DOE will therefore emphasize technologies that can integrate seamlessly with both current and newly-built infrastructure over technologies limited to new builds.

Building Efficiency

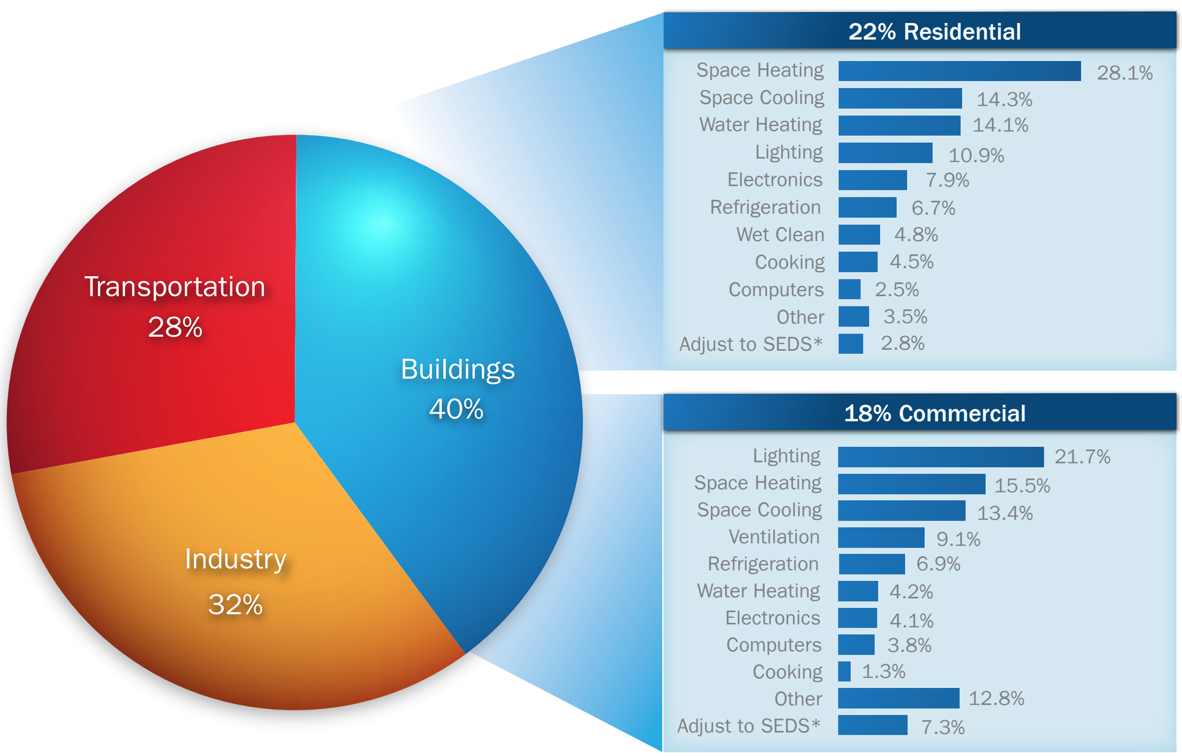
After losses in generating and delivering electricity, about 11 Quads of fossil fuels and 9 Quads of electricity were consumed in buildings in 2009. That energy was principally used for heating, ventilation, and cooling (HVAC); lighting; water heating; and electronics (Figure 17). Electricity accounts for 40% and 53% of site energy use in residential and commercial buildings, respectively; fuels for heating and cooking comprise the balance. Commercial buildings use 75% more energy per square foot than residential buildings.[143] On average, American households spend $2,200 per year on energy at home.[144]

The Department undertakes three types of activities related to building efficiency: codes and standards, R&D, and market priming (listed in order of decreasing impact and leverage). Codes, standards, and market-priming activities are primarily directed at reducing non-technological barriers to increased energy productivity, while R&D addresses technological challenges. These activities reinforce each other. R&D advances new technologies, while market priming helps to establish more advanced technologies in the market. As new technologies become more established, the Department can upgrade standards to achieve their level of performance. Regular updates to codes and standards spur market participants (and DOE) to explore new technologies, closing the cycle.

Non-Technological Barriers to Greater Efficiency

Market failures and other factors[146] present non-technological barriers to building efficiency and influence the adoption of efficient technologies. Split incentives are common in both residential and commercial buildings. To give but one example, building owners who do not pay for energy consumption have no incentive to invest in efficiency measures, while tenants are unlikely to improve efficiency when the payback time exceeds their tenancy. DOE's building R&D will include research to improve understanding of both the prevalence and form of such market failures and the impact of human and institutional behaviors on building energy use.

Figure 17. U.S. Energy Use in Residential and Commercial Buildings in 2008



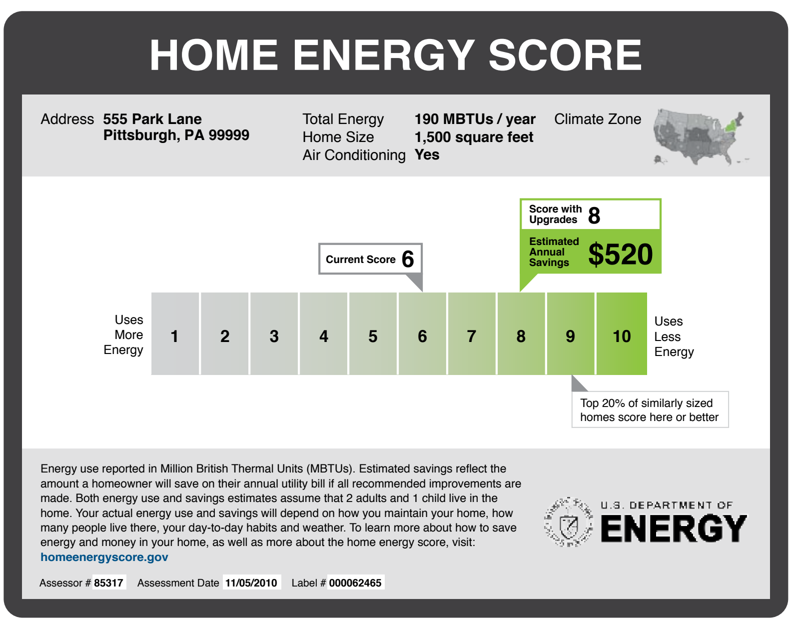
* Energy adjustment EIA uses to relieve discrepencies between data sources. Energy attributes to the commercial buildings sector, but not directly to specific end-users.

Buildings consume 40% of primary energy. Of that, 22% is consumed in residential buildings (dominated by space heating) and 18% in commercial buildings (dominated by lighting).[145]

Another challenge is the availability and awareness of actionable information about energy use and opportunities for efficiency. Informational market failures can be addressed through labels, as well as through codes and standards for buildings and their components. The Department is responsible for setting minimum energy efficiency standards for some appliances and commercial equipment. These standards, set to reduce life-cycle costs for most consumers, remove the least efficient products from the market and compensate for consumers' lack of information. Each standard must be both technologically feasible and economically justified. DOE will continue to broaden the coverage of appliance and equipment standards to capture cost-effective energy savings in large and/or rapidly growing end-uses. The ENERGY STAR® program, run jointly with EPA, and the Federal Energy Management Program provide credible information to private- and public-sector consumers about which products and buildings are most efficient. The programs also help establish markets for more efficient technologies.

Building codes, generally the purview of state and local governments, rarely require the measurement and verification of building performance; code compliance remains inadequate.[147] DOE assists in the development of credible model building codes that can be adopted by state and local governments. Non-governmental, voluntary standards (such as those set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, a professional society) guide the design and construction of building systems.

Often, actual building performance does not correlate with design intent. This can happen because of the fragmented nature of the buildings industry—with disconnects between design, construction, and operation—and because of a lack of real-world verification of performance. Many day-to-day actions in buildings can cause operations to differ from design intent. Additionally, a lack of information about performance hampers the real estate market's ability to value efficiency and raises a barrier to lending for efficiency improvements. Residential energy consumers face particular challenges in financing significant up-front costs. Once residential consumers obtain financing, they can face an additional hurdle of finding tradespeople who are trained to identify and implement efficiency measures. DOE's Weatherization Assistance Program addresses non-technical barriers to residential retrofits through workforce and curriculum development. Financing and a trained workforce are more readily available for commercial building owners, particularly through energy service companies (colloquially referred to as ESCOs). However, the ESCO market is still small and consumers may lack the information needed to take full advantage of these opportunities.



The Department of Energy's Home Energy Score allows a homeowner to compare her or his home's energy consumption to that of other homes, similar to a vehicle's mile-per-gallon rating.

Energy consumers also face tradeoffs between investments in energy efficiency and other investments that better address household needs or offer firms greater rates of return. Synergies between energy efficiency investments and other building renovations that improve comfort, environmental quality, or appearance can lower barriers.

Technical Pathways

Improved technologies can increase the cost-effectiveness of energy efficiency measures and ease their implementation. Some of these improvements will be in component efficiency—deploying the current leading technologies or technologies available through low-risk R&D over the next three decades could reduce building-related energy consumption by 25%[148] to 45%.[149] Others are improvements in dealing with buildings as systems. An integrated approach to building design and operation can cost-effectively yield energy savings exceeding 50% in new builds.[150] More than 40% savings have been demonstrated in retrofits in a variety of climates,[151] including more than 20% savings over the current minimum requirements.[152] Key enablers include calibrated data through distributed sensors, validated modeling, and real-time control of a building's components and their interactions with the electrical grid.

Improving Component Efficiency

HVAC, lighting, water heating, and electronics account for about three-fourths of primary energy demand for buildings. Current technologies or known R&D pathways have the potential to reduce energy demand for these uses. Miscellaneous electric loads are the fastest-growing set of end-uses. There is also significant potential to reduce energy demand from additional well-characterized building end-uses, such as refrigeration, laundry, cooking, and dishwashing.

Nearly all residential building appliances use common classes of components, such as motors, heat exchangers, direct-current electronics, and insulation. Improvements in these crosscutting components will have broad impacts on residential energy efficiency.

Significant energy savings might be possible in the long term by using physical processes different from those used in the incumbents they replace. Such innovations could increase efficiency in the same revolutionary way that solid-state lighting did (solid-state devices generate light by photoemission from semiconductors instead of the thermal emission from a hot metal filament used by incandescent bulbs).

DOE will focus its component R&D on large and/or fast-growing end-uses with significant technical headroom, particularly HVAC, water heating, building envelopes, miscellaneous electrical loads, and crosscutting R&D. For technologies with shrinking technical headroom and more industry involvement, such as solid-state lighting, DOE can transition away from R&D to market-facing activities, such as testing and certification.

Solid-State Lighting

An astounding 22% of U.S. electricity is used to provide light, costing more than $50 billion annually. Traditional incandescent lighting generates considerable heat, wasting 90% of the power used. Solid-state lighting, including light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs), has the potential to deliver unparalleled energy savings with longer lifetime and better light quality.

While several companies had already demonstrated first-generation LED technology, the Department of Energy's (DOE's) initial partnerships with industry to develop white LED and OLED technology focused on fundamental technical hurdles. Today, LED light sources are more than four times as efficient as they were in 2002, and almost eight times as efficient as incandescent bulbs.

DOE's focus has evolved with the developing industry. Since commercial white LED products are becoming widely available for general illumination, DOE now supports manufacturing innovations to drive down costs, addressing a range of challenges in developing products that could compete directly with incandescent lighting.

DOE emphasizes third-party performance verification for solid-state lighting to help consumers, businesses, and government agencies identify good products and applications. The CALiPER testing program is one way DOE provides this unbiased product performance information.

Developing a Systems View

Viewing whole buildings as systems, as opposed to treating them as collections of components, opens the door for additional energy efficiency opportunities. A systems-integrated building efficiency approach has three primary strategies: reduce internal loads through system integration; improve the building envelope; and design for, and maintain, efficient building performance. Understanding buildings as integrated entities through validated modeling and data collection enables greater control over building operations and energy use. A multi-building view of neighborhood or district energy use can reveal further opportunities for optimization, particularly of heat flows. The Department's whole-building R&D portfolio will focus on gaining a better understanding of how buildings operate as a system, including the development of sensors, controls, and validated building energy models. This will guide R&D in component and envelope technologies, as well as the development of the next generation of model codes and building labels.

System integration can reduce loads by integrating building design (such as size, siting, and daylighting) with intelligently coordinated components and controls. Today's design and construction practices, which treat a building as a collection of components, are not conducive to an integrated view. Holistic consideration of the building envelope (the walls, roof, and windows) can reduce load while improving indoor environmental quality, task lighting, and management of energy flows through the building. A variety of approaches are required for different climates, as well as for new and existing buildings. Integrated design would leverage modeling advances to improve decision-making throughout design, construction, commissioning, and operations.

Designing for and maintaining efficient building performance requires an understanding of how energy flows throughout the building. Wireless sensors and controls, linked with software, can help optimize energy use, lower maintenance costs, and improve thermal comfort and air quality. Sensor-generated data can both validate building models and provide actionable information for energy users, allowing continuous real-time tuning of the building HVAC and lighting to increase comfort while decreasing energy costs. Building retro-commissioning, which relies on measurements of building performance, can save energy by optimizing operations.[153] Acquiring "real world" energy-use data is a critical aspect of the Department's R&D activity on both the component and systems levels. Such data will allow DOE to identify common inefficiencies, best practices, and opportunities for retrofits. Understanding the use patterns of appliances and equipment, how they interact, and how real buildings operate is critical to: (1) characterizing energy use for regulation and code development, (2) developing R&D programs that address real-world energy challenges, and (3) validating building energy models.

Peak power generation is expensive, inefficient, and polluting. Buildings could help electric utilities meet peak load requirements by reducing loads as needed. Dynamic information exchange between the grid and buildings, combined with building controls, enables such demand response. Standardization[154] and demonstrations are underway to enable these tools.

Industrial Efficiency

In 2009, U.S. manufacturing accounted for 11% of GDP, directly employed 12 million people,[155] supplied 57% of U.S. exports,[156] and produced nearly 20% of the world's manufacturing output.[157] About two-thirds of industrial energy use is in energy-intensive industries such as chemicals, refining, pulp and paper, iron and steel, glass, aluminum, metal casting, and cement.[158] There is also a variety of manufacturing operations that convert raw materials into finished products. Nearly 3% of the value of industrial output is spent on energy.[159] However, energy-intensive sectors significantly exceed that average;[160] energy efficiency can be a significant competitive advantage in those industries.

Industry is the most diverse end-use sector—both in the types of energy services required and in the mix of energy sources providing those services. Approximately two-thirds of primary energy used in industry comes directly from fuels (predominantly petroleum and natural gas), with the remaining one-third coming from electricity.

Between 1980 and 2009, the Nation's industrial energy productivity rose 90% as the structure of U.S. industry changed, new technologies were deployed, and firms improved the efficiency of their operations. Some industries have taken advantage of new technologies; for example, new furnace and casting technologies in the steel industry have decreased the energy use per dollar of value produced by more than 40% between 1998 and 2006.[161]

As with buildings, non-technological barriers to greater energy efficiency in industrial processes include poor information about both the energy used throughout an industrial process and the potential of any specific efficiency measure (or the systems impacts of a set of measures). This creates uncertainty and risk in efficiency investments: an efficiency measure might be cost-effective, but its return relative to the perceived risk might be insufficient to elevate that investment over other opportunities. The unique nature of each production process and facility further challenge the development of best practices and model systems, elevating transaction costs.

Industrial facilities can operate profitably even when their technologies and processes are much less efficient than the state-of-the-art. Some energy productivity improvements require the development and integration of new processes. Manufacturers are more likely to include these improvements in new builds rather than retrofits. Supporting energy systems can also be improved during scheduled maintenance. Facilities can also be made more efficient by adopting best practices in energy management, often through operational changes, with little or no capital investment.

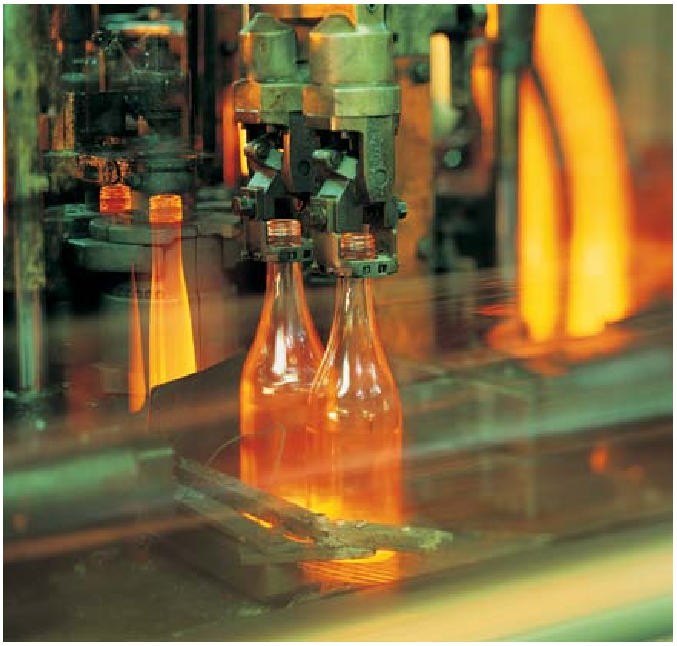
DOE will address non-technological barriers to industrial efficiency by maintaining its high-leverage analytic and technical-assistance expertise, together with activities that support efficiency improvements in traditional processes. The Department is an effective collector, analyzer, and disseminator of energy-use and energy-management data related to energy-intensive industrial processes. For example, DOE will collect and analyze data in a variety of common unit operations and support the development of tools and best practices to measure, model, and manage industrial energy use to inform outside organizations that develop standards.[162] As application of these tools and practices requires an effective workforce, DOE will also support the education and training of energy-management engineers.

Technical Pathways

Industrial energy efficiency can be increased by improving the efficiency of common processes used to produce energy-intensive products and by developing next-generation products and processes that use less energy to provide the same or better service over the life cycle.

Heating materials for manufacturing (process heating) is the largest industrial use of energy, accounting for more than 6% of U.S. primary energy consumption.[163] Opportunities to reduce the energy demand for process heat include more efficient heat generation, system design to reduce losses prior to heat use, and alternative manufacturing processes that require less heat to produce the same material.

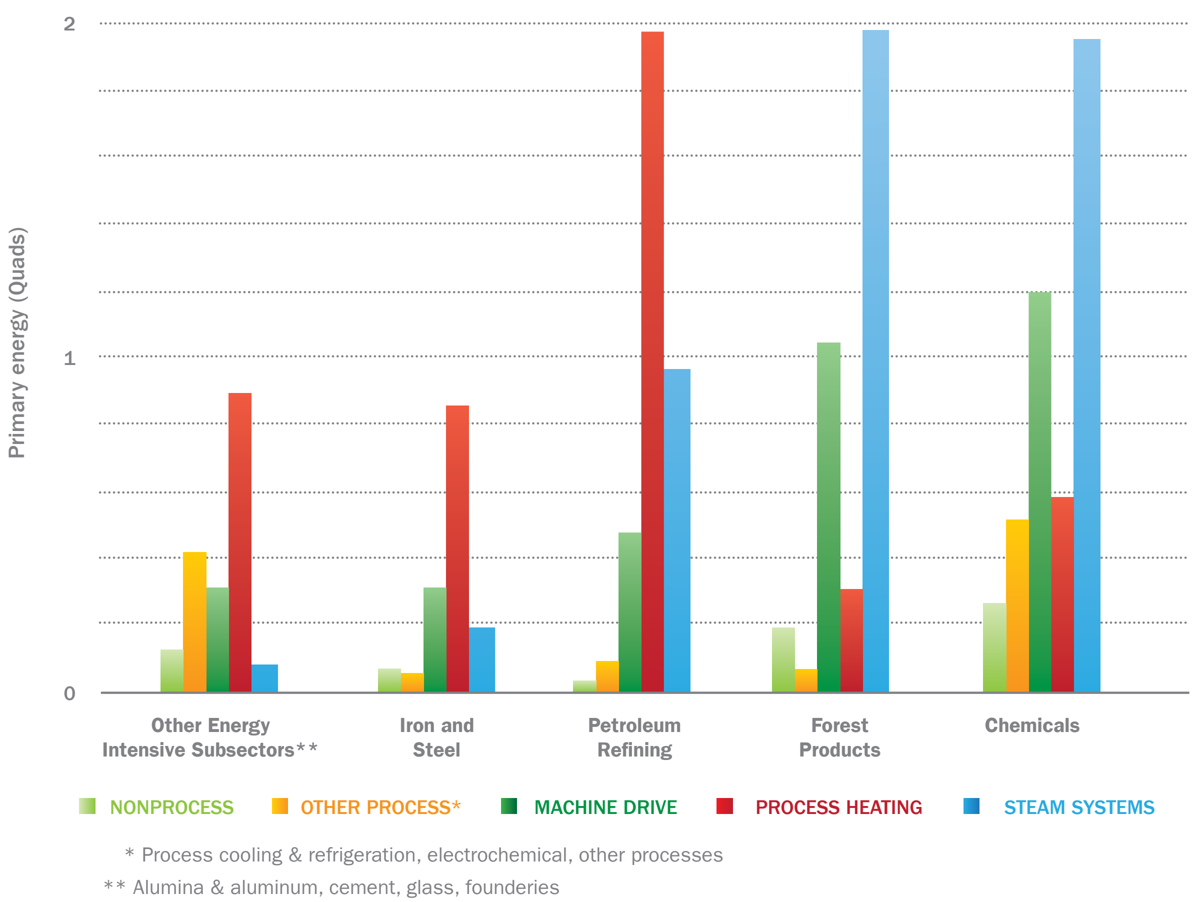
Improved boilers are the primary targets for steam system improvements; these systems can also be integrated with electricity generation for combined heat and power (CHP).



Credit: Ocean/Corbis

Individual selection machine making glass bottles. Process heat accounts for 6% of the Nation's primary energy consumption.

Figure 18. Annual Industrial Energy Use in Energy-Intensive Manufacturing by Technology and Subsector



Steam systems for chemicals and forest products and process heating for petroleum refining are the largest energy consumers.[164]

Machine-driven equipment currently account for more than 5 Quads of primary energy use.[163] In many cases, machine-driven processes can be made more efficient by upgrading the motor or by integrating a variable speed drive.

CHP is appropriate for co-located electrical and thermal demand. Overall efficiencies of more than 70% can be achieved and CHP also eliminates transmission and distribution losses. CHP is already an important resource for the United States–the 85 GW of CHP generating capacity supplies more than 12% of total U.S. electricity and could grow significantly.[165] Integrating cost-effective thermal storage with CHP may enhance the market potential for this technology by bridging the sometimes different usage patterns for heat and electricity.

To address technical barriers to increased energy productivity, DOE will focus its industrial R&D efforts on pre-competitive technologies, targeting mid- to long-term impacts. Near-term impacts most likely arise from evolutionary improvements to processes; R&D enabling those evolutionary improvements is appropriately the role of industry.

While efficiency improvements of existing processes are important, new manufacturing concepts can enable improvements in energy efficiency in either the industrial process itself or the resulting product's application. Innovative processes to produce current or future advanced materials will enhance the Nation's economic competitiveness while transforming energy demand.

Titanium, the Next Aluminum?

Before the Hall-Héroult process was developed in 1886, aluminum was exceedingly difficult to extract from ores, making it as expensive as silver. The 100-ounce piece of aluminum installed as the capstone of the Washington Monument in 1884 was, at the time, the largest single piece of aluminum ever cast. The electrolytic Hall-Héroult process was discovered independently and almost simultaneously by the American chemist Charles Hall, who went on to found the Aluminum Company of America (Alcoa), and Frenchman Paul Héroult. That process changed the economics of metallic aluminum, making it cheaper to produce and therefore more widely usable in transportation, building construction, packaging, and other applications where its lighter weight, electrical conductivity, and ductility are tremendous advantages.

Titanium is produced today by the Kroll process, the analog of the pre-1886 aluminum reduction process. Since 2000, research initiated by the Defense Advanced Research Projects Agency has resulted in a number of innovative electrolytic-reduction processes that yield high-quality titanium powder and promise to drastically reduce the cost of producing titanium; the new processes can use as little as one-ninth of the energy of the Kroll process. These and other manufacturing breakthroughs promise substantial reductions in the cost of shaped titanium components, enabling broad applications of this strong, light-weight metal.

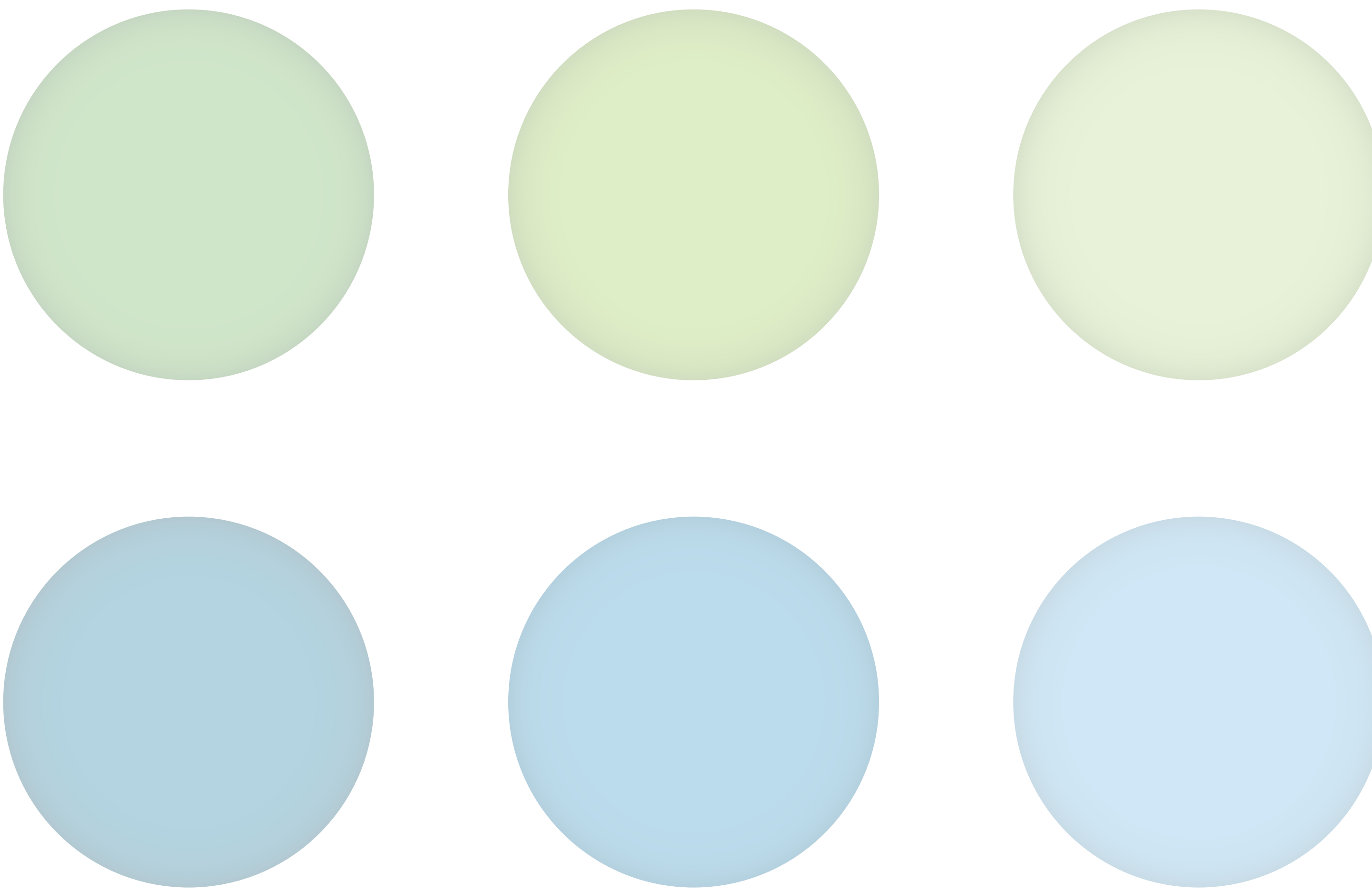
DOE's next-generation manufacturing R&D will focus on developing and demonstrating new energy-efficient processes and materials technologies, where risks are higher than industry will accept and the economy-wide benefits of innovation are unlikely to be captured by the innovator. One particularly promising crosscutting area is the low-cost manufacture of lightweight materials, such as low-cost carbon fiber, which could impact vehicles, wind turbines, and other energy technologies. Another includes low-cost chemical and physical ways to store heat to enable greater use of CHP.

Interagency Coordination

DOE works with multiple federal agencies (Table 5) to accelerate innovation, adoption, and diffusion of highly efficient technologies and systems for buildings and industry. For example, EPA and DOE each support the successful ENERGY STAR program, which establishes top-tier standards that complement the minimum appliance and building performance standards developed by DOE. The DOD and General Services Administration pursue aggressive energy-performance goals for large-built infrastructure and collaborate with DOE to accelerate the commercialization of highly efficient building technologies. The Department of Housing and Urban Development (HUD) is the only federal agency with the authority to enforce a minimum building energy efficiency code, and with a utility bill that exceeds $5 billion per year for low-income housing, it has a particular interest in efficiency measures that can reduce energy costs. Because state or local governments establish many of the policies that influence market conditions for end-use technologies, intergovernmental engagement is an important part of national strategies to accelerate energy innovation.

Table 5. Summary of Non-DOE Federal Agency Activities in Stationary End-Use with Examples

Department/ Agency	R&D	Regulation	Finance	Information
Agriculture			Rural Energy for America Program (REAP)	
Commerce	NIST Intelligent Manufacturing Standards Program			Renewable Energy & Energy Efficiency Export Initiative
Defense	Defense Research & Engineering		Procurement	
Environmental Protection Agency				ENERGY STAR®
Housing and Urban Development	Sustainable Communities Program	Building Code Standards	PowerSavers Program	Sustainable Communities Database
Labor				Green Career Program
Treasury			Energy Efficiency Tax Credits	
General Services Administration			Procurement	
Federal Housing Financing Authority			Federal Underwriting Standards	
Small Business Administration			Green 504 Program	



A regional control center of PJM Interconnection, which governs electrical transmission over 13 states. The wealth of data now available to grid operators allows for better energy management and reliability, but increases the need for improved cybersecurity.

GRID MODERNIZATION

Courtesy of PJM Interconnection

The "grid" is the system that manages and delivers electrical power from the power plant to the consumer. A high-voltage bulk power system is used for electricity generation and transmission, while a lower voltage distribution system delivers electricity to the user. The grid is tightly coupled from the power plant to the plug so that all connected devices affect system performance. Technologies and devices that directly consume or generate electricity are discussed in **Energy Efficiency in Buildings and Industry** and **Clean Electricity**, respectively, while integrated coordination and control of those devices is addressed here.

The Nation needs an electrical grid commensurate with its aspirations. One that is adaptable, secure, reliable, resilient, and can accommodate changing loads, generation technologies, and operating business models. The QTR focused on the subset of technical issues most relevant to the Department's R&D capabilities and strategy, not on larger grid modernization policies and barriers.

Northeast Blackout

The electrical grid is a large, complex system that touches most aspects of modern society, from communication to clean drinking water. The 2003 Northeast Blackout was the largest blackout in North American history, and wiped out essential services for 55 million people across the United States and Canada. Caused by a cascading series of failures across the Midwest and Northeast, the blackout led to eleven deaths and cost an estimated $7–10 billion.

Two hours before the system collapsed, poor control of power flows allowed the shut down of a single generator to overload a transmission line, causing it to sag into a tree branch and fail. Although generator and transmission line failures are relatively common, a missed warning signal and limited capability to monitor the grid in real-time led to unstable operations. Ultimately, the grid was taken down by simple errors in power management combined with limited system awareness—problems that can be addressed using new technologies.

Modernizing the grid requires advances on many fronts ranging from policy to information and security to physical infrastructure.[166] Conventionally referred to as the "smart grid," improvements such as customer access to data, cyber security protections, and power flow control will bring new capabilities to utilities and their customers. This will facilitate clean energy technology integration into the grid, while enabling more reliable and efficient grid operation.

In part, grid modernization requires new physical and informational capabilities to observe and manage the system, as well as the analytical capability to assess the grid's integrated dynamics. The grid integrates the electrical generation and consumption sectors, and increasingly, the transportation sector. Evolution in each of these sectors will alter the dynamics and demands on the grid, requiring new technology and operational strategies.

The Changing Grid

The electrical grid evolved during the last century in a largely regulated context, tightly integrating generation, transmission, and distribution to provide reliable and cost-effective electricity to the Nation. However, current operational and business models are still adapting to the more segmented, less regulated conditions that exist today and are expected for the future. The mix of old and new technologies creates stress within the system that adversely affects reliability and power quality. Three important aspects of the evolving grid are the generation mix, the changing loads, and the integration of information technology.

Generation Mix

The grid matured under a generation mix dominated by steam cycles and hydropower. However, the generating technologies deployed over the past 20 years are more varied and have shifted to smaller scales, ranging from combustion turbines and combined cycle plants to generation from intermittent resources like wind and solar; even more diverse generation technologies are likely to be deployed in the coming decades. Each of these technologies has unique physical and operational characteristics that affect grid reliability, economics, and power quality.[167] The changing generation mix is discussed more fully in **Clean Electricity**.

Changing Loads

Today's load mix is dramatically different than that of the past century, requiring more energy, better power quality, and at different times of the day. Electricity demand is projected to grow at 1% per year over the coming decades.[168] Analog loads (e.g., incandescent bulbs, motors) can tolerate poorer power quality than modern technologies (e.g., electronic ballast for lighting, computers). That transformation will accelerate with the continued digitization of end-use equipment. The electrification of the transport sector will further change consumption patterns. The grid needs new approaches to address changing requirements for energy management, system operation, and power quality.

Information Technology

The grid of the 20th century was operated in ways that are increasingly inadequate. Distribution circuits had simple characteristics, and issues ranging from power outages to system topology (circuit configuration) were verified by physical inspection. The changing generation and load mixes are increasing the uncertainty of grid dynamics, which requires better monitoring and control of power across the system. Introducing information technology for data awareness and communication will transform business models through new mechanisms of system diagnosis and operations, but raises potential cybersecurity concerns. Two-way communication and ubiquitous high-quality data from a range of devices (e.g., smart meters and phasor measurement units [PMUs]) will induce unprecedented software-based innovation in the system, including integrated management of both loads and generation.

These changing fundamentals alone require modernization of the grid, but the task is made more urgent by growing demand and aging infrastructure. For example, distribution transformers are nearing an average age of 40 years and have a life expectancy of no more than 50 years.[169] While the need to replace aging components creates opportunities for modernization, maintaining system reliability is a challenge to rapid deployment of new technologies with uncertain performance characteristics and higher capital costs.

Measuring Grid Performance

The grid spans many temporal and spatial scales, from millisecond variations in power quality on a single distribution circuit to seasonal energy-use patterns across entire regions of the country. Metrics for grid or component performance and value are therefore difficult to identify. As a result, priorities for technology R&D programs tend to be justified by ad hoc value assessments.

Historically, grid performance has been interpreted by regulators to mean reliability and power quality. Reliability, the most conventional measure, describes the ability of the grid to adequately serve the load. The duration and extent of blackouts (and lesser reliability events) are the primary reliability indicators. Power quality describes the frequency and voltage stability of delivered electricity and may vary even in the absence of a blackout. A significant future challenge to power quality is the rapidly growing number of devices plugged into any distribution circuit and the introduction of more distributed generation and demand response that could introduce unanticipated voltage swings without proper management.

These traditional benchmarks of system performance do not fully capture the benefits of new technologies. New characteristics and services, including flexibility, grid awareness, and distribution control, provide value to the Nation. Flexibility is the ability to accommodate and compensate for local variability, while maintaining system-wide function and service quality. Grid awareness is the ability of grid performance and topology to be monitored in real-time.[170] Distribution control is the ability to dynamically control power flow to provide high-quality energy services to the consumer, while accommodating new technologies from distributed generation to dynamic load response.

DOE Principles for Grid Modernization Technologies

DOE will focus on activities that enable monitoring and control of the transmission, storage, and distribution of electricity by power producers, grid operators, and users. Control over energy and power flow will allow more reliable and efficient operation of the system, better integration of renewable and other clean generation technologies, and the provision of energy services through new business models and approaches.

DOE will prioritize technologies that enable system control under high voltages. Higher operating voltages increase power capacity and reduce energy loss while diminishing infrastructure requirements.

DOE will identify potential cybersecurity issues and pursue only those grid technologies for which cybersecurity risks can be mitigated. The burgeoning information overlay on the grid allows for improved monitoring and control, but can also create vulnerability.

Strategies

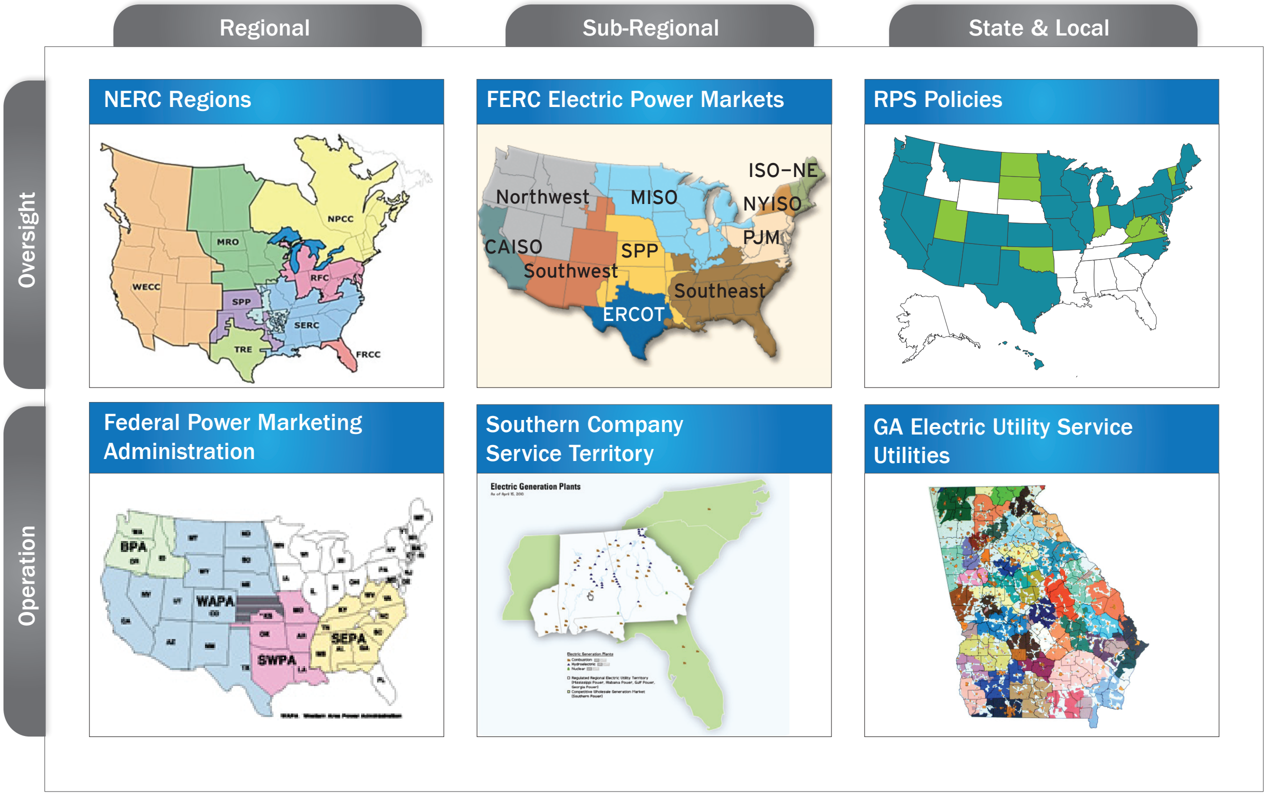
The uncertain dynamics of the evolving grid require improvements in the ability to observe and control energy across the system. Technological change will be a particular challenge for the risk-averse utility sector. There are three high-impact technical strategies:

- Improve how the system is observed, understood, and operated
- Improve control of power flow and energy, and
- Deploy power management strategies such as storage to enable temporal flexibility.

While technology advances will enable grid modernization, significant non-technical barriers will affect its pace. Entities from local communities through the federal government oversee and regulate the grid, with thousands more responsible for operating the system (see Figure 19). Their motivations are not always aligned, slowing infrastructure deployment. This is most evident in transmission, where siting and construction are technologically simple, but politically constrained.

This diversity of grid organizations complicates an integrated perspective, critical to cost-effectively addressing the infrastructure, environmental, and reliability challenges. The Department is uniquely situated to serve as a resource for energy and technology data, information, and analysis that can enhance understanding, operation, and planning across all organizations—a cornerstone of our grid modernization strategy.

Figure 19. Illustration of the Grid's Complex Interactions Between Governance and Operations



From left to right, top to bottom: North America Electric Reliability Council (NERC) regions,[171] Federal Energy Regulatory Commission (FERC) regions,[172] map of renewable portfolio standard (RPS) policies in individual states.[173] DOE's Federal Power Marketing Administrations,[174] service territory of Southern Company,[175] and map of electric utility service territories in Georgia.[176]

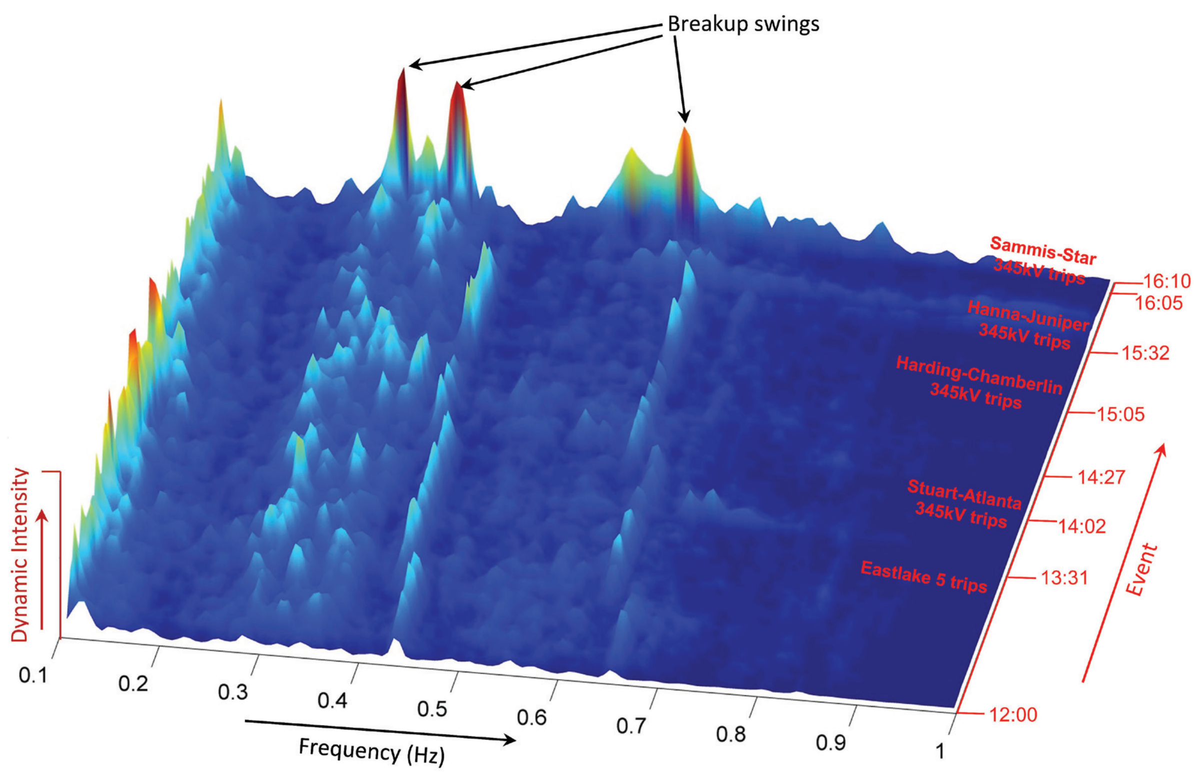
Improve How the Grid is Observed, Understood, and Operated

Dynamic control of the entire system will revolutionize the grid. The forthcoming information technologies and digital contols will entail swift—if unpredictable—introduction of new technologies, services, and business models. Data, modeling, and simulation will be key to dynamic control.

Sensors and Data

Improving grid awareness requires advances in data coverage, resolution, fidelity, and access. Such improvements will allow operators to observe and track dynamic events that are invisible to current monitoring technology,[177] allowing for early response to sub-critical system failures and thereby preventing the cascading failures that lead to major disruptions (Figure 20).

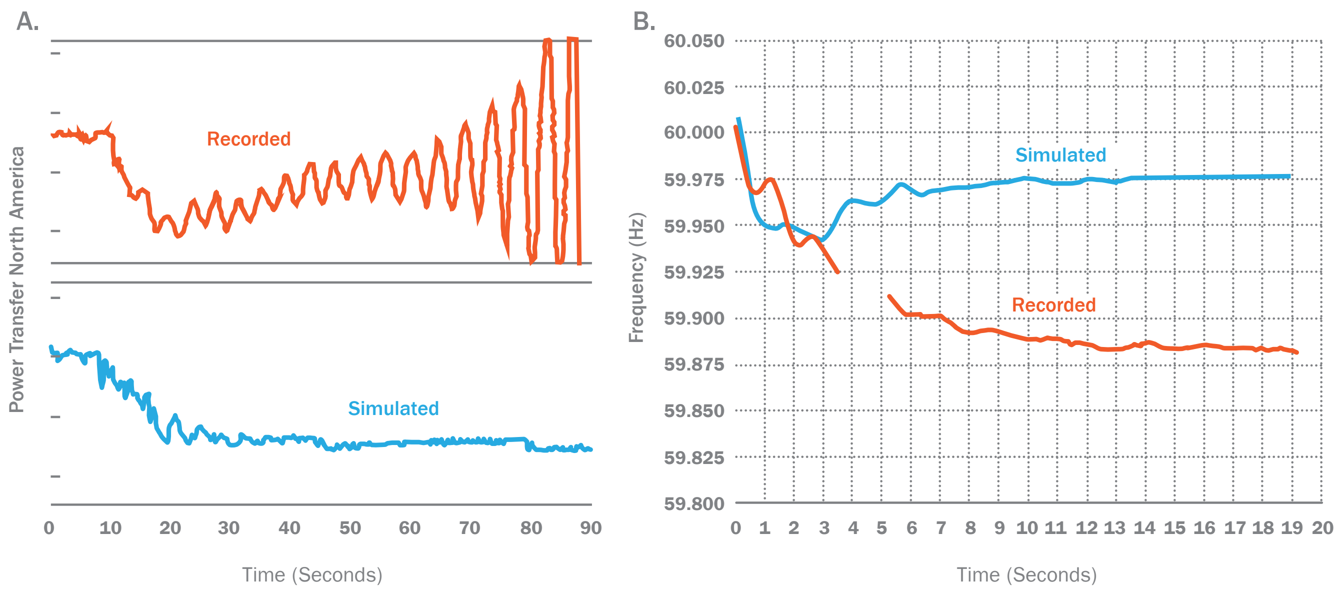
Figure 20. High Quality Data Recorded Prior to 2003 Blackout[178]



Failures began occurring at 1:31 PM, more than two hours before the blackout at 4:10 PM. These failures ("trips"), seen as changes in dynamic intensity, are indicated on the event axis. Because early failure signatures lasted only a few seconds (i.e., at frequencies higher than 0.25 Hz), these incidents were invisible to conventional monitoring technologies that only measure data every several seconds.[179] One of the earliest PMUs deployed captured this data, which was not available to operators at the time of the blackout.

Technology will improve data quality and availability across the grid, not just in the transmission system. Sparse measurements of energy consumption (e.g., monthly meter readings) will transition to real-time data on voltage, power flow, phase angle, and other physical parameters at all scales. Using and protecting this data requires new data management capabilities, from communications and cybersecurity through data processing and visualization.

Figure 21. Observed Dynamics and Simulated Results



These simulations, performed after-the-fact, were unable to reproduce the measured grid responses to major failure events.[180] (A.) shows an inability to simulate the unstable grid dynamics that led to the 1996 western blackout affecting 7.5 million customers. The slower than expected recovery of the Eastern Interconnect following a generator failure shown in (B.) indicates the system is more susceptible to cascading failures than models predict.

Modeling and Simulation

To optimize operation and planning, stakeholders must have a comprehensive understanding of how the grid responds to stress and how it would operate under different technology scenarios. Lacking this understanding, stakeholders are less able to predict which situations will lead to failures, and so must operate the grid more conservatively; they are also less willing to adopt new technologies. Although it is impossible to simultaneously account for all aspects of the grid,[181] validated computer models would help reduce uncertainty. However, current tools are inadequate. Figure 21 shows two examples where computer models fail to reproduce observations, even qualitatively.

The ability to accurately model and describe grid dynamics and predict system responses across multiple spatial and temporal scales will improve functions from real-time operation to multi-decadal planning. Current models and toolsets cannot scale to the physical and temporal resolution necessary to confidently assess and predict grid operation under stress. Updated software design and improved models of the physical system are required to better represent dynamics. Comprehensive and high-quality data will permit validation, refinement, or rejection of models.

Modeling and analysis of the electric system considers both physical and behavioral processes. The response of electricity consumers to dynamic prices or dispatch signals will have a significant impact on future system capacity, reliability, and flexibility. For distribution utilities, the historic models of energy demand and distribution circuits alike must be reinvented to reflect new capabilities being deployed across the grid. Today, there is no validated behavioral model to assess the impacts of these technological capabilities.

DOE Activities

DOE launched the large-scale national deployment of PMUs, smart meters, and other high-quality data acquisition devices with several programs under the American Recovery and Reinvestment Act. Nearly 1,000 PMUs and 26 million smart meters will be deployed by 2013, providing unprecedented data about the power system. This will improve real-time observation of system dynamics and model validation. The Department will catalogue, validate, and widely disseminate this data, respecting security and privacy limitations.

Data use in real-time operation requires new operator capabilities. DOE will coordinate with industry to support activities to develop and demonstrate new sensors critical to improving reliability while adopting clean energy technologies.

The Department has unique capability to analyze complex systems—including developing and validating models—supported by world-leading HPC facilities. DOE will apply that capability to improving grid models for more effective grid operation and planning. We will convene the power industry and the HPC community to share knowledge and resources, advancing the industry's understanding of the technical opportunities for the next generation of analytic toolsets.

The Eastern and Western Interconnection planning efforts funded through the American Recovery and Reinvestment Act have augmented regional planning. We will continue to strengthen DOE's approach to transmission planning to become more proactive in supporting stakeholders in their broad set of regional planning activities. The Department will focus on the modeling and analytics that stakeholders need to develop long-term regional policies and plans and will identify system requirements to improve reliability while transitioning to clean electricity generation. Progress in these areas is essential to enable, and to accelerate, decisions about new transmission facilities.

To address the need for validated behavioral models, the Department will create an interdisciplinary research community of social science, power systems, and electricity market experts.

Improve Control of Energy and Power Flow

Distributed generation, demand response, and two-way power flow—all of which rely upon new data collection and communication mechanisms—will integrate the bulk and distribution power systems as never before. Doing so reliably requires knowledge of distribution circuits and their connected technologies, which will be provided by advanced metering infrastructure (AMI).

Continual monitoring of grid information at the home will allow for dynamic control of load along distribution circuits. This will improve power quality, enable proactive system optimization, reduce infrastructure costs, and enable new services and business models that benefit utilities and consumers alike.

All of this must be done while protecting the cyber and physical security of the grid itself. Absent the proper cybersecurity safeguards, ubiquitous communication could mean near-ubiquitous vulnerability.

Communications and Load Control

Dynamic response to grid conditions is among the most significant aspects of grid modernization. Properly controlled and integrated into the system, small variations aggregated across many individual loads can mitigate issues ranging from infrastructure capacity constraints to uncertain renewables generation. Conversely, poorly-controlled dynamic response could reduce power quality and even system stability.

While AMI's technical capabilities to communicate data are well understood, the real-world potential for demand response to improve grid services is not.[182] Better understanding of how consumers respond to user interfaces and economic signals is needed, requiring integration of social science research with grid operation and planning.

Power Flow Control

Power electronics underpin the converters, controllers, and switches that regulate power flows on the grid. Advanced power electronics will ease renewable energy integration while improving stability as they can accommodate—and even counteract—voltage swings along circuits and dynamically reroute power in response to varying generation and system conditions. Transitioning to semiconductors with high operating temperatures (such as wide band-gap semiconductors) will allow for improved alternating current–direct current conversion, higher voltage operation, and improved efficiency. The cost and manufacturability of semiconductor materials tolerant of high voltage and temperature is a key challenge.

DOE Activities

The Department will apply all capabilities in materials discovery and design to high-voltage and high-temperature control of electricity, including wide bandgap semiconductors. We have largely completed our applied R&D work on high-temperature superconductors and expect the private sector to deploy those technologies according to market conditions.

The Department will provide integrated testbeds to enable confident predictions of in situ technology performance and operation.

The Department will leverage its information technology skills developed for protecting national security information to support grid cybersecurity. In addition, we will leverage our knowledge of the grid and the stakeholder communities to support standardization efforts at DOC (NIST) and within industry (for example, those set by the professional society, the Institute of Electrical and Electronics Engineers, or IEEE).

Energy Storage

Energy storage will better match the temporal characteristics of generation, load, and infrastructure. It provides services on timescales from a few milliseconds to a few days, through a broad set of physical processes.

Not limited by the size and weight constraints of vehicle applications, stationary energy-storage technologies can be optimized for particular aspects of performance. For example, power and responsiveness can be maximized at the expense of total stored energy (e.g., flywheels), or vice versa (e.g., compressed air energy storage, flow batteries). Some deployment barriers arise because storage can simultaneously provide a variety of services spanning regulatory classifications and business models.[183]

Markets for grid energy storage require managing either power or energy, but rarely both. Grid energy storage will be most valuable initially for dispatchable power and load, such as the short-term, high power/low energy requirements for regulation services. Other storage services, such as bulk energy management for diurnal balancing and infrastructure upgrade deferral, will become more economic as storage costs decline.

Grid Services

Ancillary service markets (e.g., frequency regulation) require rapid but short-term response to transient power quality issues. These services require continual balance and provision of power, but not energy. High power/low energy technologies such as flywheels, supercapacitors, and batteries[184] are most useful for ancillary services, and technology costs depend on power (i.e., $/megawatt [MW]).

Energy Management and Load Shifting

Managing energy, as opposed to power, will become increasingly important as more non-dispatchable, generating technologies deploy. Storing energy between the time of generation and the time of use accommodates resource diversity, and can improve infrastructure utilization. Energy-management economics depend on the cost of energy stored (i.e., $/megawatt-hour [MWh]), rather than power.

Separation of power and energy capacities is useful for energy-management storage technologies, allowing for independent scaling of energy capacity without affecting the cost of delivered power. Historically, this has been accomplished through pumped water, and to a lesser extent, compressed air; however, these processes are geographically limited. Self-contained storage technologies with separate power and energy capacities, such as flow batteries, are technically immature today, but could become significant in the future.

DOE Activities

The deployment of storage technologies faces barriers that include deficient market structures, limited understanding of system value, and limited large-scale demonstrations. Quantifying the benefits of storage under various operating conditions will be a priority so that industry and regulators alike can fully assess the value of deployed storage capacity. The Department will measure, validate, and disseminate performance information for grid-integrated storage technologies, and develop the analytic tools necessary to assess and predict value and service as a function of operation and location.

Current DOE large-scale storage demonstration projects, funded through the American Recovery and Reinvestment Act and scheduled for completion in the next two years, will provide the foundation for these efforts. The Department will develop testing protocols for large-scale energy storage and standards for technology validation. The Department will develop research roadmaps based on the R&D needs identified in the demonstrations to ensure that support is directed toward refining the most promising storage technologies.

The Department recognizes that battery technologies developed to meet the constraints of the transportation sector may not be optimized for the grid. DOE will therefore continue to support select precommercial R&D on materials and components for stationary-specific batteries, although these efforts will be limited in scope.

Interagency Coordination

The federal agencies with authorities relevant to the U.S. grid are shown in Table 6. In the area of technology development, DOD is collaborating with DOE on major investments in the design and development of micro-grids and related controls technology. With regard to policy and finance, FERC has the most sweeping regulatory authorities, while the Rural Utility Service of the USDA and the Treasury Department offer specific financial incentives for transmission deployment. Because the grid is organized and operated as a collection of regional systems, many issues that affect the deployment of innovative grid technologies are under the purview of the state agencies and regional transmission organizations.

Table 6. Summary of Non-DOE Federal Agency Activities in the Grid with Examples

Department/ Agency	R&D	Regulation	Finance	Information
Agriculture			Rural Utility Service	
Commerce	NIST Energy Storage & Power Delivery	NIST Smart Grid Interoperability Standards		
Defense	Defense Research & Engineering			
Homeland Security	Resilient Electric Grid Project			National Infrastructure Simulation & Analysis
Interior	Reclamation HydroPower Design and Maintenance	Transmission Siting & Permitting on Federal Lands		
Treasury			Transmission Restructuring Preferential Tax Treatment	
Federal Energy Regulatory Commission		Office of Electric Reliability		State of Market Reports
Tennessee Valley Authority		Power Systems Operations	Borrowing Authority	
Commodity Futures Trading Commission		Energy Commodity Markets Regulation		

The 250 MW Smoky Hills Wind Farm west of Topeka, Kansas, came on-line in February 2008 and consists of 56 1.8 MW wind turbines and 99 1.5 MW wind turbines.

CLEAN ELECTRICITY

Credit: Drenaline

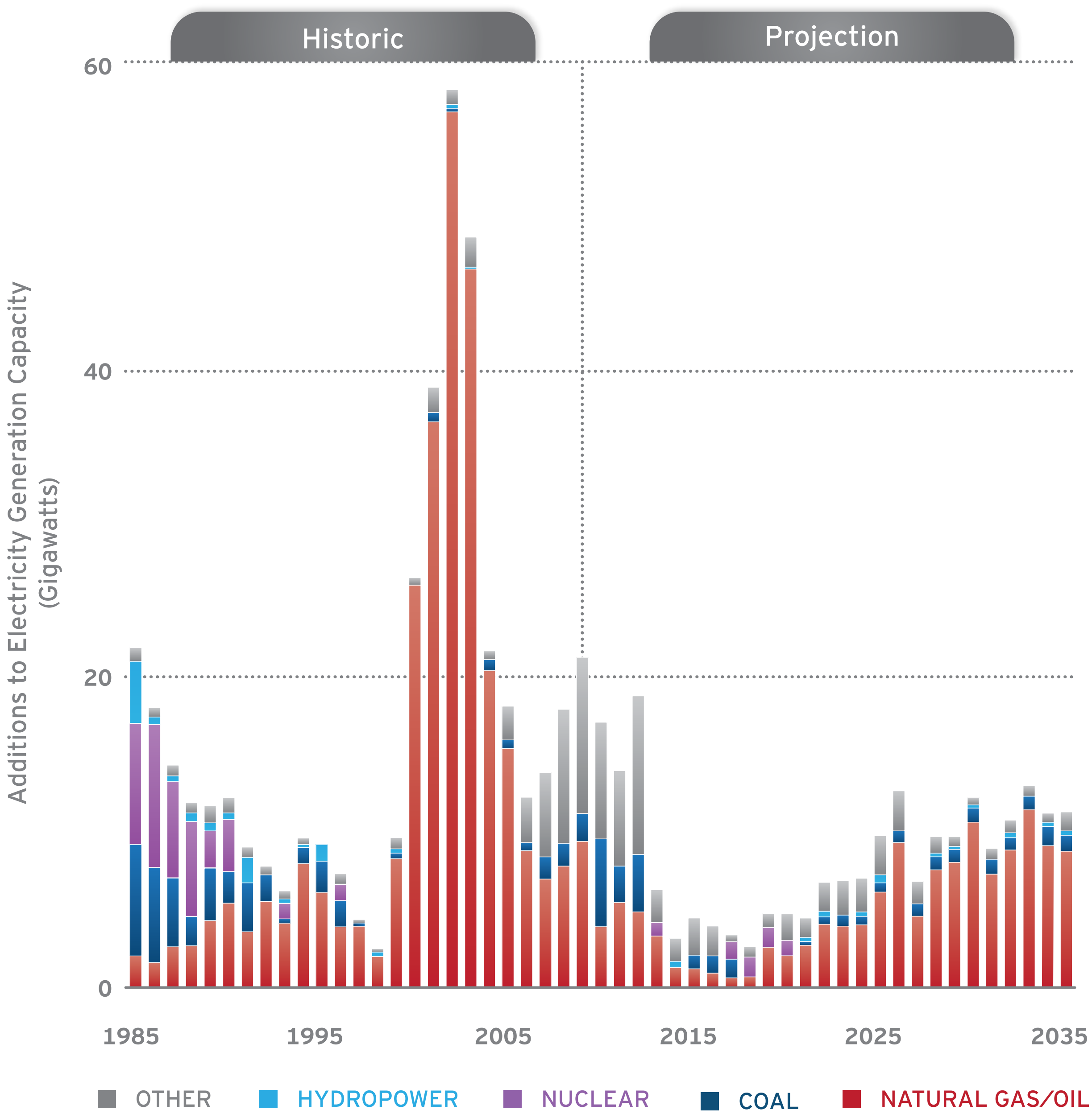
The Nation depends on reliable, affordable electricity. Smaller electricity expenditures, whether through higher efficiency or lower cost, enhance U.S. competitiveness in a global market.

The Nation's electricity generation accounts for some 40% of energy-related GHG emissions (largely CO_2) and also emits 6 million tons of sulfur dioxide and 2.4 million tons of nitrogen oxides each year.[185] Deployment of clean electricity will reduce those emissions which lead to smog, cause acid rain and haze, impact human health, and increase the risks of climate change. Clean electricity will also become more important as the light-duty vehicle fleet electrifies and increases electricity demand,[186] making transportation cleaner and more secure.[187] Developing and manufacturing clean electricity technologies will create jobs and strengthen U.S. economic competitiveness. President Obama has set a goal of producing 80% of the Nation's electricity from clean energy sources by 2035.

Factors Affecting the Generation Fleet

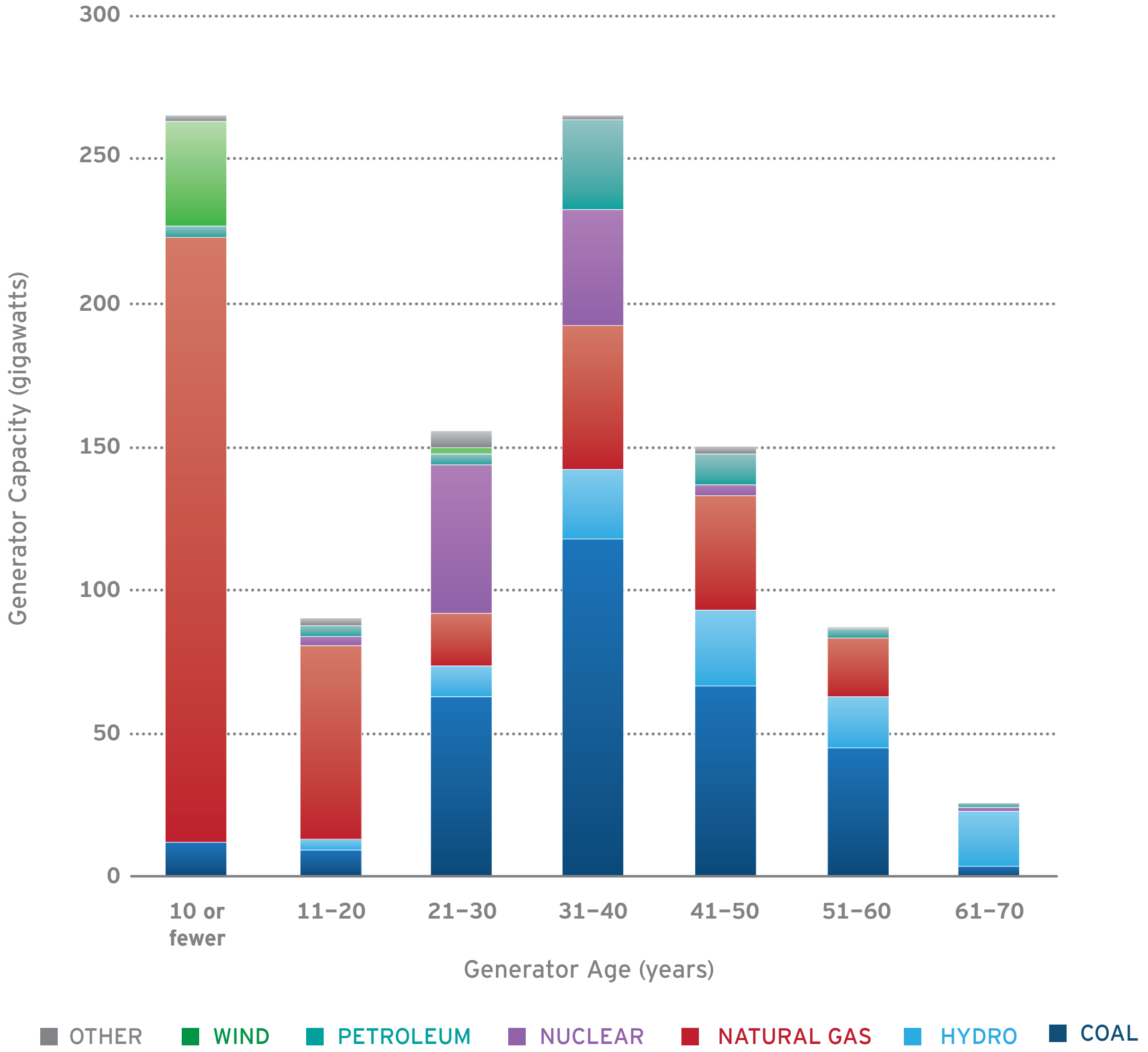
The United States currently has excess generating capacity, driven in part by deployments over the past decade and in part by the 2008 recession. The EIA has predicted that the Nation will add, on average, only 7 GW of capacity each year from 2012 to 2025 (0.7% of the total U.S. capacity of approximately 1 TW, Figure 22).

Figure 22. Additions to U.S. Electricity Generation Capacity, 1985–2035



The United States is predicted to add less than 10 GW of generating capacity (~1% of total) per year, over the next 25 years, most of which will be natural gas.

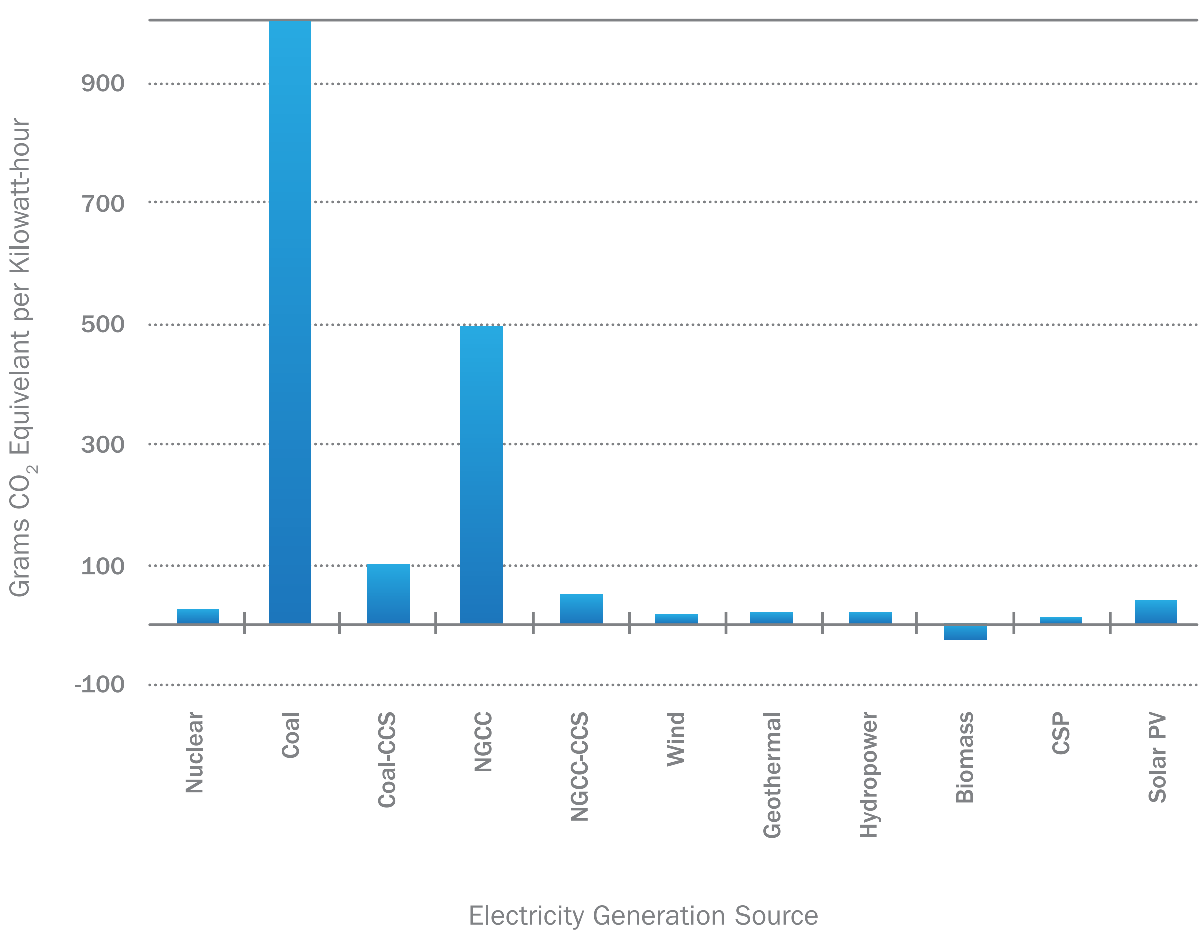
Figure 23. Age and Capacity of Generators by Fuel Type



Additional natural gas generators are coming online while coal generators are reaching their rated lifetimes.[188]

Today's asset turnover is similarly slow—only 7 GW of generating capacity was retired in 2009.[189] That slow pace means that the United States will most likely continue to rely on substantially the same generating infrastructure over the next two decades absent significant changes in policy, such as a CES, comprehensive climate policy, or new environmental regulations. However, generating assets are aging,[190] and virtually all assets could be replaced or refurbished before 2050 (see Figure 23).

Figure 24. Estimated Greenhouse Gas Emissions From Generation



CCS = Carbon Capture and Storage; CSP = Concentrating Solar Power; NGCC = Natural Gas Combined Cycle; PV = Photovoltaic. [191]

Today's modest capacity additions and the looming larger turnover create opportunities to deploy new generating technologies. Clean electricity technologies, like other generation technologies, are deployed by the private sector. Federal, state, and local policies that incentivize or require low-carbon power are the most effective mechanisms to encourage development and deployment. Innovation might drive clean electricity costs down to parity with natural gas (levelized cost of electricity, or LCOE, less than $0.10/kWh). However, the lower operating expenses of non-fossil technologies may not overcome their higher up-front capital expense.[192] Therefore, the low capital expense, technical maturity, and dispatchability of natural gas generation are likely to dominate investment decisions under current policies and projected prices.[193]

Typical Valuations of Clean Electricity

Discussions of clean electricity technologies are often framed in terms of cost (usually LCOE) and emissions. Cost is a fundamental concern of both operators seeking profit and regulators seeking to keep prices low. Generating costs include the capital cost of construction, the costs of fuel, plant operations and maintenance, and financing (whose cost and availability depend, in part, on the project's perceived risk). Each of these components can change through technological innovation, economies of scale, or public policy. DOE can work toward reducing costs by addressing both technical and non-technical factors and, in fact, most of the technologies considered by DOE have the potential to be cost-competitive without subsidy. However, current or projected LCOE is not the only metric useful for shaping DOE's R&D portfolio.

GHG emissions are a critical component in the definition of clean electricity. While all of the clean electricity technologies have *some* environmental impacts, they all have much lower GHG emissions than current fossil fuel generators (see Figure 24). As a result, differences in GHG emissions intensities among the technologies in the DOE portfolio are not significant enough for portfolio prioritization.

Beyond the givens of low cost and low emissions, other structural factors and trends are important in imagining the future of electricity generation. Four factors to consider are listed below.

The Power Sector Is a System

Supply, transmission, distribution, and demand are all interdependent. Because generated electricity that isn't used immediately is wasted, utilities highly value dispatchable generation. Some renewable generation depends upon resource availability (i.e., the sun must be shining, or the wind must be blowing), while hydroelectric, geothermal, coal, natural gas, and nuclear generation have various degrees of dispatchability depending on physical, economic, and environmental constraints. This interdependence also requires that power producers either locate generation near the load or establish transmission infrastructure. It can be difficult to site some generation technologies near population centers, and similar barriers inhibit construction of transmission lines. Transmission lines often have the added complexity of crossing state lines, making them subject to many jurisdictions.

Regional Variability

There are significant regional variations in renewable resource across the United States. Wind resources are concentrated in the Midwest and offshore;[194] solar resources in the Southwest;[195] geothermal in the West;[196] and biomass in the Midwest and Southeast.[197] Additionally, the water resources critical for thermoelectric generation are unevenly distributed across the Nation.

Electricity Is a Commodity

Generation assets with high capital costs have payback times over decades. Two uncertainties—the price of natural gas and future carbon regulations—create risk in those investments. The price of natural gas, highly volatile over the past decade and a half, has stabilized since 2008 due to growing low-cost production of large domestic natural gas reserves (see Figure 25). If natural gas prices remain low, the relatively low capital and operating expenses of natural gas generation will advantage it over other generating technologies. While forecasts predict that gas reserves can supply U.S. needs for the next century,[198] many uncertainties remain. The policy and market risks make it easier to finance assets with low capital and uncertain operating expenses (e.g., natural gas generators) than those with high capital and low operating expenses (e.g., renewable and nuclear power plants).

Figure 25. U.S. Natural Gas Wellhead Price

The price of natural gas, highly volatile over the past decade and a half, has stabilized since 2008 due to low-cost production of expansive domestic natural gas reserves. Monthly data presented in constant/FY11 dollars per thousand cubic feet.[199]

Federal, State, and Local Regulations Impact the Electricity Mix

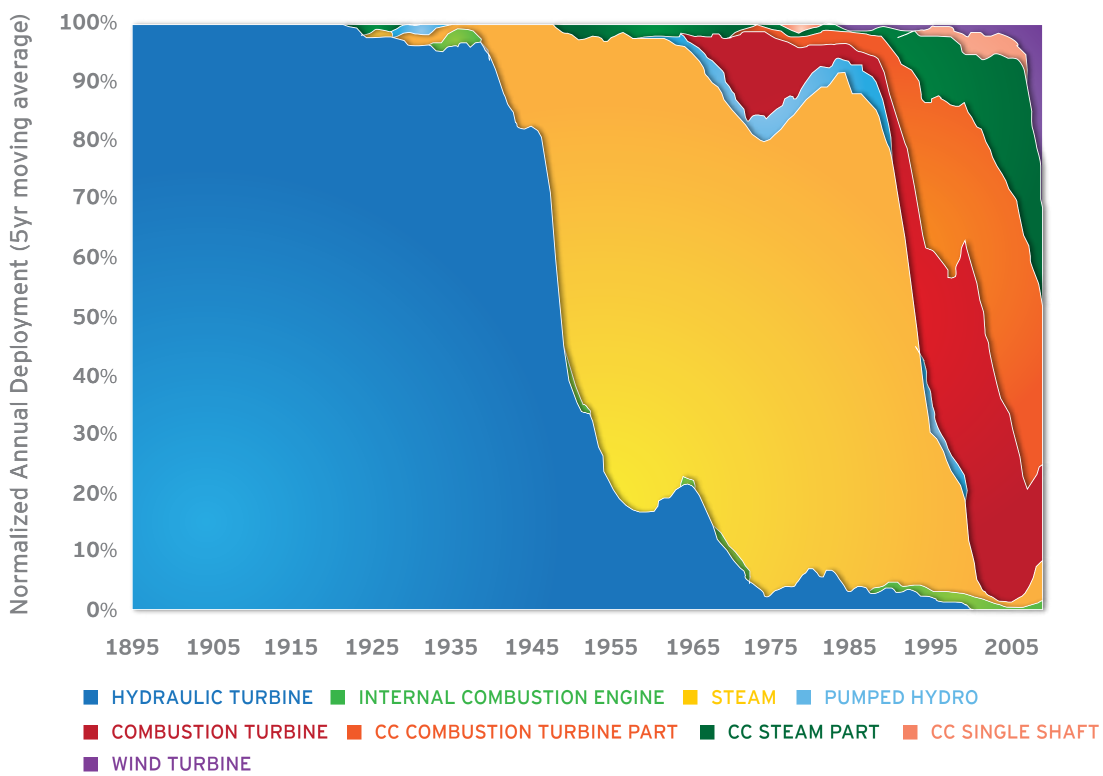
More than half of U.S. states have Renewable Portfolio Standards that, in combination with grants, tax credits, and loan guarantees, drive investment in wind, solar, biomass, and geothermal electricity generation.[200] President Obama has proposed a Federal Clean Energy Standard[201] that would include nuclear generation and would give natural gas and coal with carbon capture and storage (CCS) partial credit based on carbon emissions.

Generation Diversification

Generation technologies have diversified dramatically over the past two decades (See Figure 26). New grid-connected capacity has been shifting away from conventional steam technology toward alternative fuels, to the extent that coal-fired U.S. generation is decreasing for the first time.[202]

Recent power generation deployment trends show that economics, technology, incentives, and regulation are already driving the Nation to new and more diverse generating technologies, and there is every indication that, even absent new energy or emissions policies, the next decades' deployed generation will be very different from the incumbents. R&D will be most productive if it is conducted in a manner cognizant of these trends.

Figure 26. Annual Grid-Connected Generation Deployment



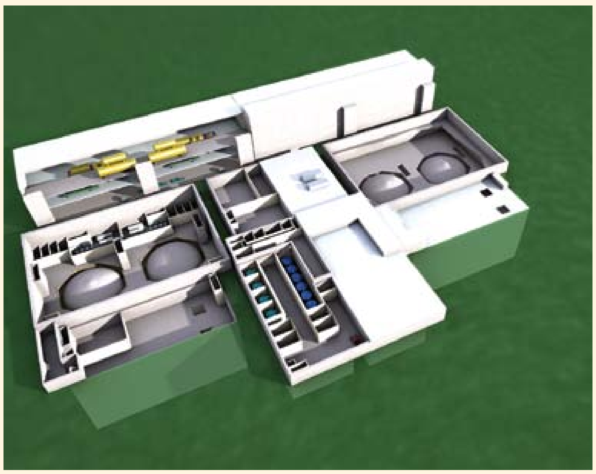
Illustrated by conversion technology, not energy resource. CAES = compressed air energy storage. C.C. = combined cycle. The Steam category includes coal, nuclear, oil, solar thermal, and some natural gas. Combustion Turbine, Combustion Turbine Part of Combined Cycle, and Steam Part of Combined Cycle are all fueled by natural gas.[203]

Creating the DOE Portfolio

Considerations beyond emissions, the relative cost of electricity, and structural factors should shape the DOE clean electricity research portfolio. These include modularity and scalability; water use; infrastructure compatibility; global context; and materiality, markets, and maturity.

Small Modular Reactors

Small Modular Reactors (SMRs) are nuclear power plants that are smaller (300 MWe or less) than current plants (1–2 GWe). These compact designs would be factory-fabricated reactors that could be transported by truck or rail to the site. SMRs would be designed to require limited on-site preparation.



Babcock & Wilcox Company

Concept for a four-module small modular reactor by mPower. Large capital requirements have proven to be a significant barrier for conventional nuclear power. Small modular reactors have lower capital costs and may allow for step-wise deployments.

The modularity of SMRs allows for enhanced safety features, the economics and quality afforded by factory production, and more flexibility (financing, siting, sizing, and end-use applications) compared to larger nuclear power plants.

Although SMR concepts expected to be available in the near term are based on proven reactor technologies, they have not yet been designed or licensed for commercial deployment. The Department of Energy believes that these SMRs can be commercially deployed within the next decade and will focus on engineering support for for light water reactor-based SMR licensing to promote this timeline for commercialization and deployment.

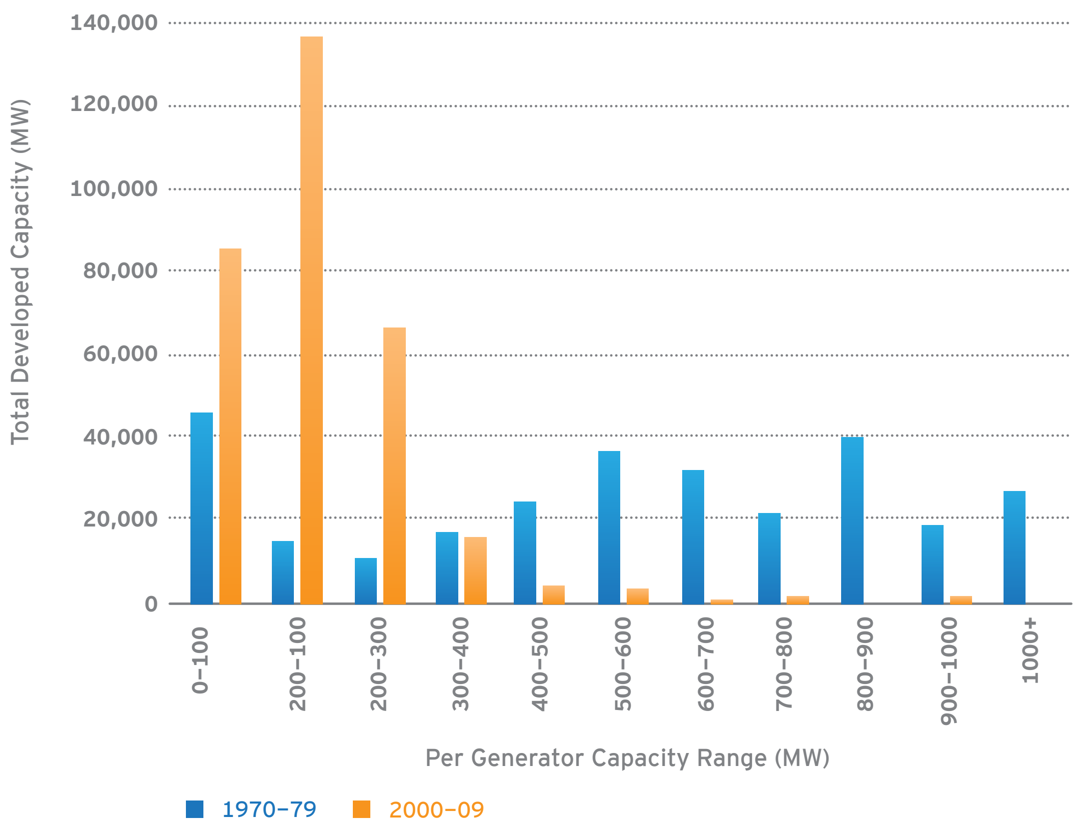
Modularity and Scalability

New generation deployments have been shrinking in scale and dispersing geographically, driven by changes in policy, business models, and technologies. The Public Utility Regulatory Policies Act of 1978 (PURPA), along with subsequent deregulation and other market shifts, allowed independent power producers to thrive. These shifts also changed the finance structure for deploying new generation, limiting tolerance for technologies with large capital costs. Figure 27 shows the smaller scale of recent deployments relative to those of the late 1970s, before PURPA and other policies initiated changes to the market structure.

Smaller-scale and modular generation technologies have multiple advantages over GW-scale facilities. Combinations of smaller generation cycles (e.g. natural gas combined cycled and CHP) use fossil fuel energy more efficiently than older technologies and allow for modular deployment. Because planning, regulatory, physical, security, and capital risks increase with scale, investors and policy makers have preferred modular deployment of new technologies at the scale of a few hundred megawatts, a market trend highlighted in Figure 26. Smaller-scale technologies also enable consumer deployment of generating technologies—a trend in the residential, commercial, and industrial sectors. Generators closer to the load also provide more reliable service and lower transmission costs, although there can be local resistance to new deployment. Generating capacity distributed over many locations can also increase reliability and energy security.

Recognizing the market preference for generation technologies deployed at capacities smaller than 300 MW_e,[204] DOE will give priority to new clean electricity technologies that conform to this trend. For technologies with unit size larger than 300 MW_e, DOE will focus on efforts to collect and analyze information and conduct fundamental engineering research relevant to the existing infrastructure base (e.g., the Consortium for Advanced Simulation of Light Water Reactors Hub). Subsequent QTRs should be informed by possible shifts in market scale preference.[205]

Figure 27. Additions to Generation Capacity, 1970–1979 vs. 2000–2009



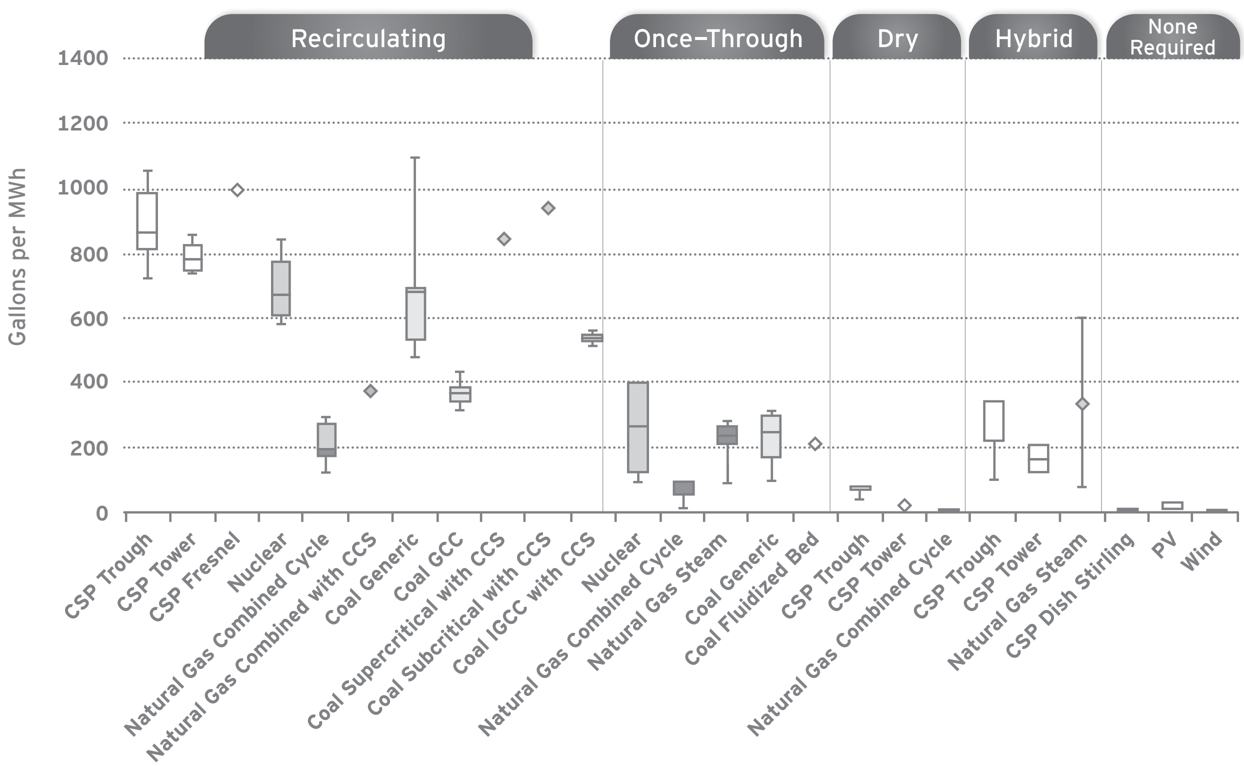
The unit size of deployed generation technologies has shrunk considerably in the past 30 years.[206]

Generation and Water Are Linked

Thermoelectric power generation accounts for nearly half of U.S. water withdrawals,[207] largely through the wet-cooling cycles common at thermal power plants[208] (Figure 28). Although alternative dry cooling technology exists, wet cooling has been preferred due to lower capital cost and better thermodynamic efficiency.[209] Once-through wet cooling is used more often than any other cooling cycle.[210] Though once-through cooling consumes less water than recirculating cooling, it withdraws significantly more water and has greater environmental impact. Therefore, new deployments of once-through cooling have fallen significantly over recent decades. Efficiency, and even operation, of once-through cooled power plants can be adversely affected by environmental conditions such as water availability and water intake and effluent temperatures.[211]

The ongoing migration of U.S. population to arid regions of the country (see Figure 29) will burden already scarce water supplies; deploying wet-cooled thermoelectric generating technologies to meet projected demand growth will exacerbate the problem.

Figure 28. Water Consumption for Various Power Generation Technologies



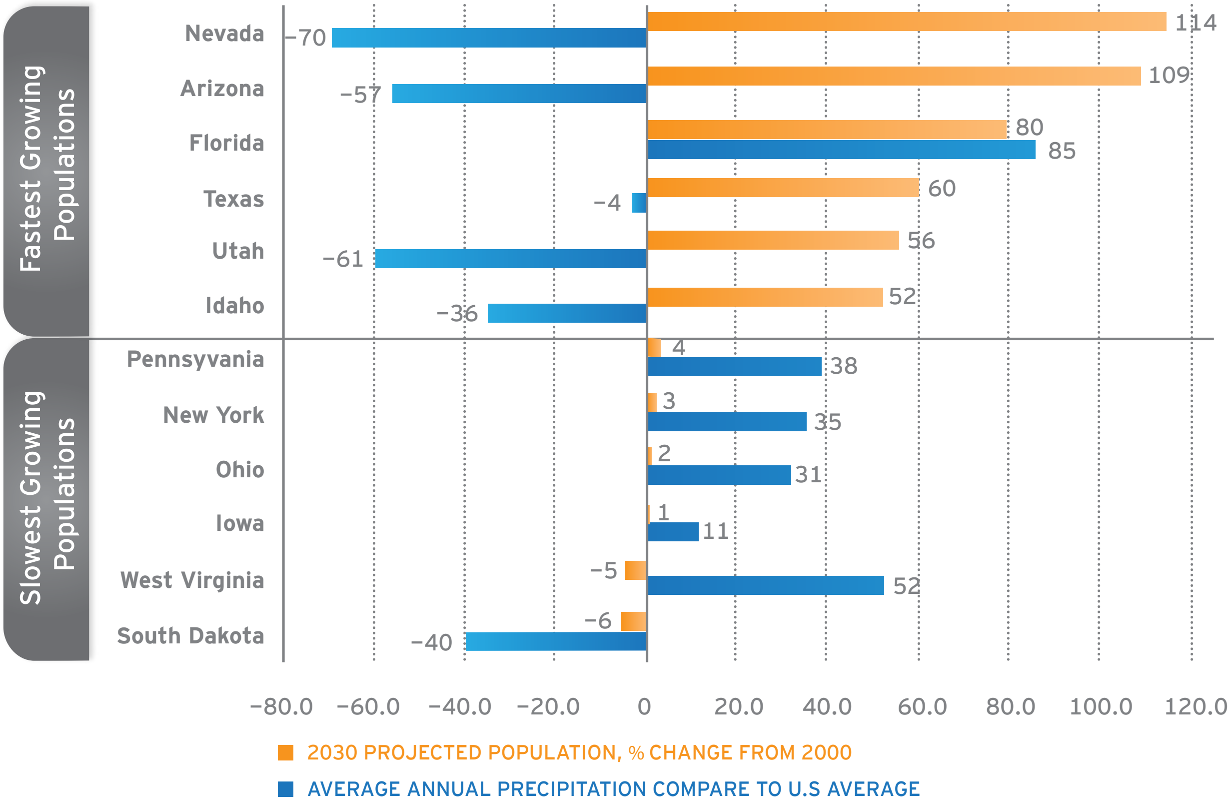
Divisions represent cooling technologies. CSP = concentrating solar power; CCS = carbon capture and storage; PV = solar photovoltaic. Water use in PV is for washing panels, not cooling.[212]

The Department will give priority to research on technologies that can be operated economically with low water consumption, including solar photovoltaic and wind. For thermoelectric power generation technologies (e.g., fossil, nuclear, solar thermal, biopower, geothermal) the Department will pursue a crosscutting research effort to advance the state of dry-cooling technologies common to each of these platforms. The Department will preferentially support research for technologies that will consume less water than the average of operating generators (500 gallons per MWh[213]). Additionally, the Department will assess economics and reliability of thermoelectric generating technologies under realistic water availability and cooling assumptions, rather than the most optimistic.

Credit: Brian Hayes

Cascade at the base of a cooling tower at the Arkansas Nuclear One Power Plant. Water use for power generation accounts for 49% of total water withdrawals and 53% of fresh surface water withdrawals.

Figure 29. Projected 2030 Population Growth and Corresponding State Rainfall



Data for 12 states projected to have the fastest and slowest growing populations.[214]

Infrastructure Compatibility

Electricity generation technologies that integrate well with existing infrastructure and business models are more likely to be deployed than those that do not. Despite recent trends towards modularity and scalability, existing infrastructure is dominated by large, central facilities, powered by coal, natural gas, nuclear fission, or hydropower. These facilities have well-established fuel infrastructure, transmission connectivity, and operational characteristics. The existing fuel infrastructure includes fuel extraction (e.g., mining or drilling), transportation (e.g., by pipeline or train), and waste storage and management. There are also infrastructure needs related to storing spent fuels or waste, most significantly for nuclear and coal technologies.

As other technologies mature and attempt to enter the electricity market, easy integration into the established system is a competitive advantage. Generators that run on fuel can be sited more flexibly than those that directly capture a diffuse, renewable resource. In particular, they can be located near load centers and existing transmission infrastructure, lowering barriers to deployment. Some renewable generation technologies can be deployed under a distributed model (such as rooftop solar photovoltaic), which can minimize these barriers.

Grid operators depend on the dispatchability of generators—the ability to increase a generator's output to meet an increase in demand or shortfall in other sources of supply. Generation technologies that can dispatch power are more flexible and provide greater reliability for grid operators. This flexibility is intimately related to interoperability: generators that can substitute for one another have a deployment advantage. The most dispatchable electricity technologies are natural gas, conventional coal, and conventional hydropower. Renewable power technologies that rely on intermittent resources such as sunlight and wind must be coupled with other generation or storage technologies to provide dispatchability. This integration will be improved by better prediction of intermittent resources and understanding non-dispatchable generation.

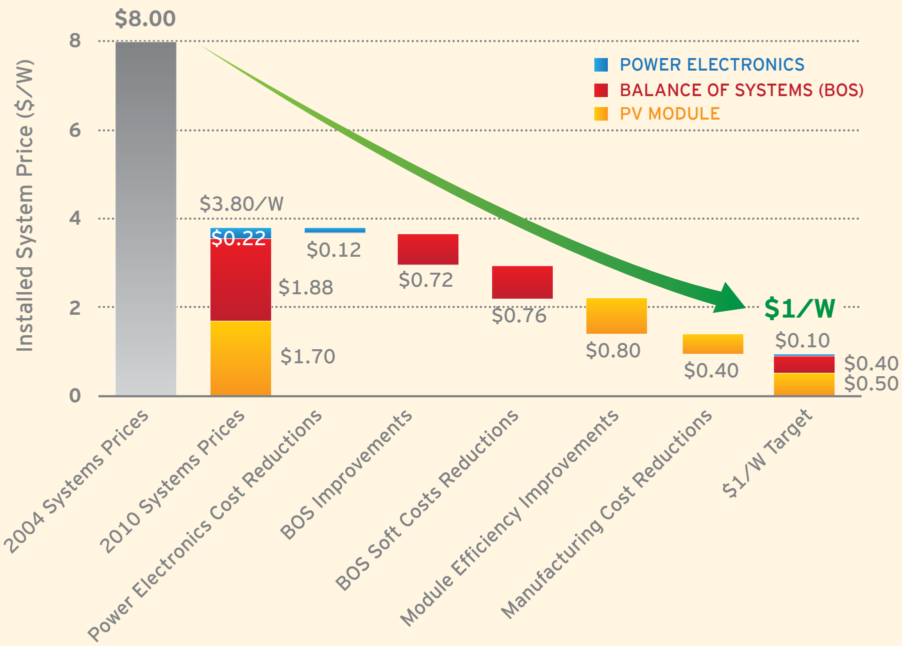
DOE will consider implications of infrastructure compatibility in defining clean electricity R&D programs. In particular, DOE will pursue CCS technologies because they can directly use today's fossil fuel and transmission infrastructure. While retrofits of fossil fuel generation facilities would carry this infrastructure advantage all the way to the generator itself, they are not technically feasible at all existing power plants. The current economics of CCS retrofits favor less than half of existing coal generation capacity[215] and are generally disadvantaged relative to new generators incorporating CCS.[216]

Credit: Bloom Energy

Bloom Energy Servers, solid oxide fuel cells that convert natural gas to electricity, installed outside a corporate headquarters building in California. Distributed power generation increases reliability of service.

SunShot

Solar energy is an important part of the Department of Energy's (DOE) technology research and development due to its modularity, low water use, and ideal position in materiality, maturity, and market considerations. In February of 2011, DOE announced its SunShot Initiative. SunShot's goal is to make solar energy technologies cost-competitive with other forms of energy by reducing the cost of solar energy systems by about 75% before 2020 to reach roughly 6 cents per kilowatt hour without subsidies. SunShot's approach considers the photovoltaic system as a whole, from manufacturing needs, to non-technical barriers, to installing and integrating solar energy into the grid.



SunShot will make solar electricity cost-competitive with other power sources, enabling rapid, large-scale adoption of solar electricity across the United States, re-establishment of American technological leadership, and strengthening U.S. economic competitiveness in the global clean energy race.

Global Context

The security, environmental, and economic impacts of energy technologies are global in scale and so shape DOE's portfolio, particularly in nuclear power and CCS.

The United States has traditionally taken a leading position in crafting the international civilian nuclear technology "rules-of-the-road" and has helped develop a sound technology base to implement and enforce those rules. With a current global deployment of 442 civilian nuclear power reactors and an additional 65 reactors currently in some stage of construction, civilian nuclear energy sits at the nexus of energy, climate, and security. Nuclear power requires that we address issues related to nonproliferation, management of the nuclear fuel cycle, nuclear counter-terrorism, nuclear and radiological emergency response, and arms control. The mid- and long-term impacts of the crisis at Japan's Fukushima Daiichi nuclear complex on the global expansion of nuclear power are not yet clear. Maintaining U.S. expertise and capabilities in civilian nuclear energy are important for national strategic security.

President Obama has called for the development of a new framework for international nuclear energy cooperation to develop economically viable options for managing the nuclear fuel-cycle. That new framework may include features, such as international fuel banks, multilateral fuel service assurances, storage facilities, or repositories for used fuel and nuclear waste. The Department will conduct R&D in search of fuel-cycle technologies that improve resource utilization while reducing the risk of proliferation.

While the United States has relatively stable generation infrastructure, rapidly developing nations such as India and China rapidly deploying new generation. Clean electricity innovations developed in the United States can provide economic advantage to U.S. firms and also mitigate global GHG emissions. DOE will consider the international market potential and needs for clean electricity technologies when building its portfolio.

Materiality, Markets, and Maturity

The Department will support a mix of analytic, assessment, and fundamental engineering research capabilities in a broad set of energy technology areas. DOE will maintain moderate levels of R&D to facilitate breakthroughs that could fundamentally change the techno-economics of clean electricity generation.

There are some clean electricity technologies that have great potential to make rapid, material impact on our energy goals. Because all clean electricity technologies provide the same service (generating electricity), considerations of materiality and markets identified in **Six Strategies** can be evaluated with greater specificity.[217] Here, the benchmark for materiality is roughly 100 TWh in 2030, which is about 2% of the Nation's current annual electricity needs. Expectations for market potential are a LCOE in 2020 of no more than about 1.2 times that of natural gas combined cycle, keeping in mind that adoption of power generation technologies is subject to many other considerations, including capital size and dispatchability. Our expectation for maturity remains that technologies have significant headroom and can be demonstrated at commercial scale by 2020. For technologies that simultaneously satisfy these considerations, DOE will develop an ambitious goal and thoughtfully coordinate R&D activities along the supply chain, including evaluating opportunities for demonstration and for addressing market barriers.

Table 7. Evaluation of Clean Electricity Technologies for DOE Investment*

Technology		Status
Biopower		**Materiality:** Will likely be material in 2030.[218] **Market:** An economic use for waste from mandated production of biofuels. **Maturity:** Mature technology with little technical headroom.
Carbon Capture and Storage (CCS)		**Materiality:** Can take advantage of vast domestic and international hydrocarbon fuel infrastructure. **Market:** Returns on investments in CCS primarily depend on policies that establish value for CO_2 abatement. CO_2 itself has value in a limited market for Enhanced Oil Recovery (60 Mt of CO_2 from natural sources, equivalent to 1% of U.S. emissions, used in 2009). **Maturity:** Technical headroom in capture; questions remain in scale, integrity, and operation of storage. CCS could be demonstrated at commercial scale by 2020.
Concentrating Solar Power		**Materiality:** Could be material. Large resource, but highly regional. **Market:** Private interest in large-scale deployment already demonstrated, driven by policy. **Maturity:** Innovation in thermal storage required to improve value as a baseload resource.
Distributed Fuel Cells		**Materiality:** Uncertain. **Market:** Limited interest expressed, primarily in applications with high energy assurance requirements. **Maturity:** Technical headroom exists. Demonstrated manufacture of several technologies. Innovations in materials science could accelerate commercialization.
Geothermal	Conventional	**Materiality:** Highly localized and limited resource. **Market:** Well developed industry, yet front-end exploration costs and risks are high. **Maturity:** Mature technology, some technical headroom exists in resource exploration.
	Enhanced Geothermal Systems	**Materiality:** Exploitation of potentially large resource is uncertain. **Market:** Costs uncertain, resistance due to seismicity concerns. **Maturity:** Unvalidated reservoir management models.

Technology		Status
Hydropower	Conventional	**Materiality:** Already material at 7% of generation. **Market:** Well-developed industry, potentially competitive costs. **Maturity:** Mature technology with little technical headroom.
	Marine & Hydrokinetic	**Materiality:** Uncertain resource. Highly localized conditions complicate deployment. **Market:** Costs uncertain, competing resource uses challenge adoption. **Maturity:** Many technologies with varying levels of maturity.
Natural Gas Combustion		**Materiality:** Already material at 23% of generation and expected to grow. **Market:** Current cost leader. **Maturity:** Mature technology with little technical headroom.
Nuclear	Gen II	**Materiality:** Already 20% of U.S. generation. **Market:** Continued operation is cost-competitive. **Maturity:** Technical headroom in improving safety and life extension.
	Gen III+, SMR	**Materiality:** High potential for materiality. **Market:** Smaller scale (SMR) plays to U.S. market trends and could become cost-competitive; U.S. expertise and leadership important for national security. **Maturity:** SMR depends on Nuclear Regulatory Commission licensing, Gen III+ under construction.
	Gen IV	**Materiality:** Not material by 2030. **Market:** Costs uncertain. No current demand. **Maturity:** Pilot scale exists, but unlikely to be demonstrated at commercial scale by 2020.
Solar Photovoltaic		**Materiality:** Material by 2030 at current growth rate. **Market:** Current high costs falling rapidly; cost competitive by 2020. **Maturity:** Significant technical headroom remains.
Wind	Land-based	**Materiality:** Already material at 2% of generation. **Market:** Currently cost competitive at good sites. **Maturity:** Deployment growing; technical headroom exists in grid integration and gearbox durability.
	Offshore	**Materiality:** Large resource; could be material by 2030. **Market:** Currently expensive, costs could fall. Resistance due to viewshed impacts. **Maturity:** Diverse levels of maturity among technologies for different conditions, primarily characterized by ocean depth.

* Greater detail on these status evaluations will be included in the technology assessments in Volume II.

As the cost and performance of components are optimized, economic, policy, and systems issues become dominant factors in deployment. Going forward, DOE will take a more active stance in addressing these non-technical barriers. For example, DOE will perform rigorous economic and regulatory analyses to predict and support deployment. We will leverage our technical expertise to inform certification of technologies for regulators and utilities. DOE will continue to partner with other agencies such as DOI and the National Oceanic and Atmospheric Administration to evaluate resource potential for renewable energy technologies. And to ease their integration with the power grid, DOE will support prediction of intermittent resources.

In Sum

Our discussion of "clean electricity" is not as crisp as that of other strategies. Multiple generating technologies with diverse characteristics at diverse stages of maturity make it difficult to definitively stratify the clean electricity research portfolio against the full set of prioritization principles. Certainly the Materiality/Markets/Maturity criteria must be paramount, but weighting of the various other dimensions we have described depends on policy considerations beyond the scope of the QTR.

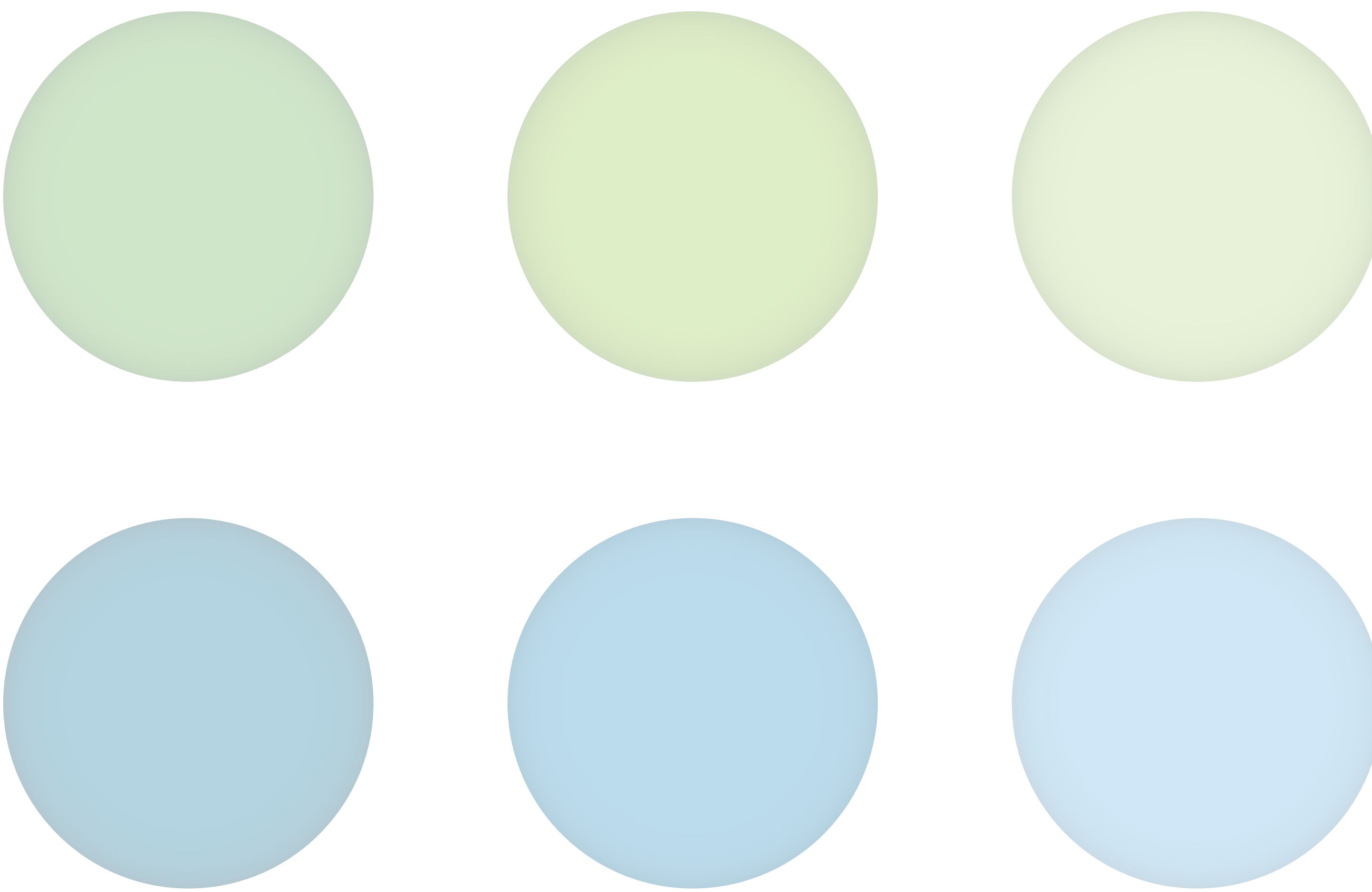
Interagency Coordination

While private sector ownership dominates the electric power sector, regulatory and oversight agencies at both the state and federal level shape the market conditions in which those firms compete. In addition to state public utility commissions, agencies such as the Nuclear Regulatory Commission and FERC have key oversight roles in their respective areas of authority. The pace at which new technologies are adopted and diffused through the marketplace is influenced by both regulatory decisions and policies enacted through legislative bodies. In support of that work, DOE provides information and technical assistance to state and federal agencies on a wide range of issues from resource extraction[219] to siting to operational safety. Table 8 illustrates the diversity of departments and agencies engaged in four major types of activity. By coordinating and integrating complementary activities, other federal agencies are able to leverage DOE's investments in innovation, just as DOE is able to leverage the capabilities and authorities uniquely available through those agencies.

Table 8. Summary of Non-DOE Federal Agency Activities in Clean Electricity Generation with Examples

Department/ Agency	R&D	Regulation	Finance	Information
Agriculture	Ag. Research Service (ARS) Bioenergy Program		Rural Energy for America Program (REAP)	Sustainable Bioenergy Challenge
Commerce	NIST Power Device & Thermal Metrology Project			Renewable Energy & Energy Efficiency Export Initiative

Department/ Agency	R&D	Regulation	Finance	Information
Defense	Environmental Security Technology Certification Program (ESTCP)	Army Corps of Engineers Licensing	Procurement	
Environmental Protection Agency	Air, Climate & Energy Research Program	Clean Air Act		ENERGY STAR Portfolio Manager
Interior	Bureau of Reclamation Science & Tech. Program	BLM, BOEMRE, BuRec Permitting/ Licensing	Reclamation Fund	U.S. Geological Survey
Labor		Mine Health & Safety Administration		
Treasury			Production & Investment Tax Credits	
Federal Energy Regulatory Commission		Office of Energy Market Regulation		State of the Market Reports
Nuclear Regulatory Commission		Nuclear Reactor Licensing		
Small Business Administration			Green 504 Loan Program	
Federal Housing Financing Authority			Federal Underwriting Standards	
General Services Administration			Procurement	
Tennessee Valley Authority		Power Systems Operations	TVA Borrowing Authority	
Export Credit Agencies			Export-Import Bank: Env. Exports Program	Foreign Market Analysis



At the Arlington Agricultural Research Station in Wisconsin, the Department of Energy's Great Lakes Bioenergy Research Center is conducting field trials to evaluate how crops like corn stover, switchgrass, miscanthus, poplar, or native prairie would stack up as potential bioenergy cropping systems. The Energy Innovation Hubs build on the model established by the Bioenergy Research Centers.

TECHNOLOGY POLICY

Courtesy of the Great Lakes Bioenergy Research Center. Credit: Gregg Sanford

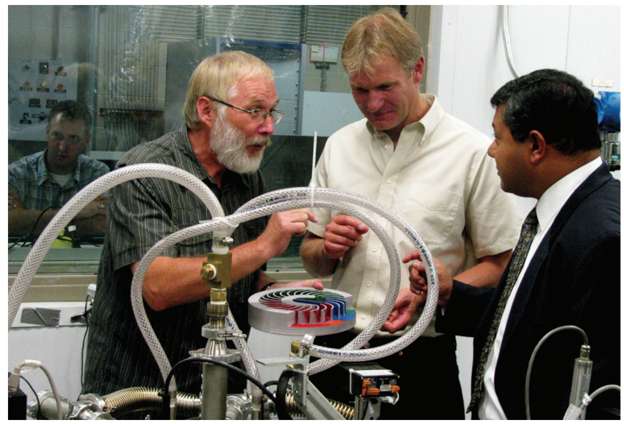
This chapter of the Report focuses on the research policies that shape DOE's energy technology R&D. A full consideration of the best economic and policy tools in service of national energy goals would be properly within the scope of a QER rather than the QTR.

DOE's programs have the greatest impact when public-sector scientific research and fundamental engineering research catalyze private investment. But mere technical possibility that something could work is an unjustifiably low bar for the commitment of public funds; every research dollar must matter. DOE is therefore most effective when its R&D efforts are first coordinated with national priorities and then aligned with the private-sector context in which technologies are deployed. A central purpose of this QTR is to lay out a set of principles for prioritizing the Department's energy activities.

The Department of Energy's Programs

The Department's R&D programs include the Offices of Energy Efficiency and Renewable Energy, Electricity Delivery and Energy Reliability, Nuclear Energy, Fossil Energy, and Science, and the Advanced Research Projects Agency–Energy (ARPA-E). The National Nuclear Security Administration also touches on energy matters. The Office of Science is the single largest funder of basic research in the physical sciences in the country. ARPA-E funds the development of high-risk, high-payoff, clean energy technologies.

As a whole, the Department's programs are an engine of U.S. innovation, supporting mission-related research in academia, the DOE complex of national laboratories and user facilities, non-profit institutions, state and local governments, 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 combination of applied research, test beds, and simulation decreases risks associated with new technologies, accelerates technological progress, and can catalyze private-sector investment for the wide deployment of clean energy technologies.



Advanced Research Projects Agency–Energy (ARPA-E) Director Arun Majumdar (right) visiting ARPA-E funded researchers at Michigan State University (MSU) who are developing a novel wave disk engine. MSU predicts that its technology will enable hybrid vehicles to be 30% lighter and 30% less expensive.

The Department's core strength is its science and technology efforts, which have led to technology improvements and breakthroughs, and these efforts are the focus of this QTR Report. However, these are not the Department's only responsibilities. 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.

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 (independent DOE agencies) offer experience in power generation and transmission and can demonstrate and deploy new technologies and capabilities into the grid.

The Department works with dozens of foreign governments and international organizations to promote best practice policies and programs 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.

Throughout the QTR process, we heard strong messages from DOE's diverse stakeholders about the value of two particular classes of DOE activities:

- The importance of supporting basic research as a core federal responsibility.
- DOE as the transparent, objective arbiter of information and analysis about the energy sector.

Underpinning the Nation's high-tech economy, both basic scientific and fundamental engineering research increase knowledge of nature and integrate that knowledge in ways directly useful for practical engineering applications. In the course of their work, researchers develop new tools and techniques to discover and measure previously inaccessible physical phenomena. Those tools then form the basis of new technologies or solutions to overcoming long-standing technical barriers. Scientific understanding is at its most practical when it solves problems that arise in the design, manufacture, or operation of complex technologies. DOE investments in materials science, simulation, and non-medical biology are particularly important to energy technology. The goal of fundamental engineering research is to make better predictions about the behavior of human-made systems and components, which will broadly improve our ability to design, build, and maintain engineered products and services for particular purposes.

Modes of DOE Operation

There are three categories of DOE activities in energy technology:

- Pre-competitive R&D and fundamental engineering research creates a depth of knowledge about new and incumbent energy technologies, harnessing the capability of the national laboratories and universities and strengthening those capabilities in our private sector partners.
- Information collected, analyzed, and disseminated by DOE shapes policies and decisions made by other governmental and private sector actors.
- Targeted initiatives bring goal-driven, coordinated efforts to bear throughout the research, development and demonstration process to help prove technologies for adoption by the private sector.

Operating in any of these modes, DOE has a unique ability to convene energy sector participants from the public and private sectors and coordinate their efforts. We also have opportunities to leverage the globalization of innovation, capital, and markets by engaging international partners in energy technology development and deployment.

In May 2010, Secretary Chu conferring with scientific experts and BP officials in Houston on plans for stopping the Deepwater Horizon oil spill.

There are different measures of success for each of these modes. Capability activities seek to fully explore the range of possible technologies while cultivating the knowledge base relevant to the energy sector. Informational activities aim for maximal dissemination of high-quality information needed by decision makers in the public and private sectors, while targeted initiatives seek to catalyze deployment of a particular technology. Pursuing activities without clarity about the mode of operation reduces DOE's effectiveness.

Capability

In what is arguably its most broadly beneficial mode of operation, DOE supports a scientific and technical community with expertise in an expansive set of energy technologies, including those currently deployed at scale, those expected to contribute in the next decade, and those further from implementation (and even some unlikely to ever see deployment). That expertise serves to both explore the full spectrum of energy technologies for potential breakthroughs and to develop the technical workforce capable of addressing energy challenges. Construction and operation of scientific and engineering facilities, as discussed later in the Report, is a core component of a strong national research capability. As a practical matter, DOE's energy R&D portfolio has some investment in a broad range of options.

A well-constructed capability portfolio is focused on solving practical problems, both pushing the boundaries of current industrial practice, and maintaining momentum in the development of longer-term energy options. Technical interest is a prime selection criterion, which serves to attract top research talent and to explore the energy R&D space. A weakly constrained capability portfolio runs the risk of supporting research as an intrinsic good, one where every technical opportunity has equal claim. DOE and its predecessor agencies have sometimes followed that path to bewildering ends.[220]

DOE seeks to maintain at least some research and technology competence across the broad spectrum of technologies as budgets rise and fall. That breadth allows it to take a long-term view and bring attention to technical challenges before they become choke-points. A budget spread thinly over the broadest spectrum of technologies, however, is unlikely to influence the energy sector quickly or meaningfully.

Research capability has several corollary benefits. It can respond flexibly to changes in the energy system and to disasters where in-house knowledge and a trained workforce can be readily deployed. In two recent energy catastrophes—the Deepwater Horizon oil spill and the Fukushima nuclear situation—DOE stood out as an authoritative technical voice, marshalling a broad set of independent experts to support government's response. A capability-mode portfolio also provides the Nation the ability to understand and rapidly exploit advances occurring anywhere in the world, reducing the probability that another country out-innovates the United States. It is difficult to measure how well the Department is performing in a capability mode; a National Academies report[221] provides one approach.

Informational

DOE gathers, analyzes, and disseminates information about energy technologies. It will emphasize an informational role that spans fields important to policy makers and regulators, or to those technologies that can reasonably be predicted to be commercially important in the next decade.

For commercial technologies that are currently deployed at scale, DOE will focus on understanding developments that mitigate environmental, health, and safety (EHS) impacts and increase operational efficiency. For less mature technologies and for those not yet widely deployed, DOE's analyses will center on the techno-economic potential, EHS impacts, and on understanding the role a technology would play in the energy system. This latter includes potential market, barriers to deployment, and the full range of risks (technical, market, capital, policy, operations, etc.) that firms face. Examples where DOE has done this to great effect include the "20% Wind Energy by 2030"[222] report (which identified the economic and operational potential of U.S. land-based wind), and the "The Potential Impacts of a Competitive Wholesale Market in the Midwest"[223] (which helped members of a new Midwest Independent System Operator understand the benefits of centralized dispatch in a bigger balancing authority).

Critical to realistic technical analyses is an appreciation of energy as a technical, financial, and regulatory system. DOE will enhance its systems-level analytical capabilities to complement current technological expertise.

Gathering data related to energy technologies can require DOE to support work along the full spectrum of research, development, testing, and evaluation. Technical potential is a function of underlying basic and applied science, and DOE's role may require characterization of performance of devices at a variety of scales and operating conditions, from bench-top to large experimental facilities. Underground carbon storage field tests are one example of a large-scale experimental program. Such programs must produce actionable information that is worth the investment and is widely disseminated. Information regarding technical failure is often as valuable as that describing success, so DOE will ensure that complete and accurate information is available regardless of project outcome.

Targeted Initiatives

Targeted technology initiatives are the most visible of the Department's energy programs. Here DOE R&D attempts to reduce technical and financial risks through a progression of activities from basic research to demonstration-scale and from demonstration- to commercial-scale. Such initiatives are frequently organized around a visionary goal ("technology push"), though historically such goals have proven unrealistically ambitious. Regulatory compliance targets have also been strong organizing principles for DOE R&D programs, providing clear incentives for technology adoption ("technology pull"). Successful examples here are control technologies developed to meet SO_x and NO_x emissions limits established under the Clean Air Act. As noted by the National Academies retrospective analysis,[224] environmental benefits of NO_x control are on the order of $60 billion, enabled by DOE investment of $67 million (1999$) to develop and demonstrate control technologies.

Technology push initiatives are easy to explain, can provide a clear organizing principle for program activities, and often capture the imagination. They also often presuppose that meeting a particular cost or performance metric for a product, process, or service (for example, LCOE) will induce market adoption, but policy and alternate business strategies are often more significant drivers of adoption.

Technology push initiatives also imply that DOE will coordinate expertise on key aspects of the supply chain (for example, in biofuels this includes feedstock supply, product design, manufacturing, consumer acceptance, and regulations). Thus, any technology push requires a concrete plan and commitment from industry partners for further deployment and diffusion beyond DOE-supported initiatives. Relying on intimate collaboration with the private sector prompts debate about the legitimate role of government beyond proof-of-concept experimentation. Such concerns can be alleviated through industrial consortia, for example the United States Advanced Battery Consortium (USABC), which allow for collaborative pre-competitive R&D activities but leave product development to individual firms.

Many technology push initiatives imply, or create the expectation of, a government commitment of substantial financial resources for large-scale demonstrations, commercialization support, and deployment activities. Realistically, it is difficult to cost the full program of work at the outset, and budget realities often interfere. Also, as initiatives often last a decade or more, they are susceptible to termination before they achieve their goals especially if costs were poorly estimated at the project's inception. Over its history, the Department has been criticized frequently for failing to deliver on the promises made in ambitious technology push initiatives. The Department will not invest in demonstration and deployment in one technology simply because it invested in another. Attempting to commit the Department's limited resources to significant pushes in all possible technologies will dilute resources to ineffectiveness. Initiatives should therefore be rare, carefully planned, and have clear technical off-ramps.

Funding Mechanisms

The QTR process made evident that different programs label comparable activities differently; for example, a "testbed" in one program is a "demonstration" in another. Common terms such as "demonstration" are used in significantly different ways even within a single program—for example, defined by budgetary thresholds, or by throughput, or by a fraction of commercial scale. Such confusion about the character of research and funding mechanisms impedes DOE's ability to explain itself and its activities.

Several shorthand concepts further confuse discussion. All research funded by the Office of Science is termed "basic," and all research supported by the four technology programs is termed "applied"—irrespective of whether those characterizations are consistent with the OMB definitions (Circular A-11). In truth, all support some fundamental scientific research and some fundamental engineering science. All programs are engaged in "technology development" of the tools, instruments, and facilities necessary to progress their research. All programs support efforts that integrate information produced from individual research projects into increasingly capable "products," whether that is a computational simulation, a more powerful theory, or a new material.

Standard, higher-resolution descriptions of activities across DOE could further understanding of how research is integrated across DOE programs. The 27 institutes and centers of the National Institutes of Health (NIH) might offer a model. NIH uses a standard set of detailed activity codes covering the spectrum of research programs, research projects, training, and cooperative agreements.[225] For each activity code, NIH defines a particular intended use. Differing distribution of funds by activity provides insight into how each NIH component is managing its portfolio. There is no comparable set of activity codes within DOE, since statistical summaries[226] of the Department's funding distributions primarily describe the path those funds take from program to performer rather than the nature of the activity they support.

As a result of this QTR, the Department will undertake an analysis of individual projects and establish consistent Department-appropriate definitions and activity descriptors.

Technology User Facilities

The Department has a core competency in the design, development, construction, and operation of unique world-class user facilities that benefit the entire U.S. research community. Among the most familiar facilities are the accelerators, colliders, light sources, lasers, neutron sources, materials fabrication and characterization facilities, gene sequencing facilities, and powerful scientific computers built and operated primarily by the Office of Science. This suite of facilities is used annually by more than 26,000 users from academia, industry, national laboratories, and other government agencies.

Less well known are the facilities supported by the energy technology R&D programs at many of the national laboratories. Those facilities offer a broad range of prototype fabrication, measurement, characterization, testing, and analysis capabilities to industrial and academic researchers engaged in energy technology development. DOE technology facilities provide resources that are too large, costly, or specialized for individual researchers and most firms to afford on their own (for example, wind turbine blade testing facilities). Collectively, they are one of the Department's most important tools for accelerating energy technologies.

The support models for technology facilities are much more varied than those for scientific user facilities. Virtually all of the Office of Science's facilities operate under a model of cooperative stewardship[227] with other federal agencies, such as NSF, NIH, and DOD. The four DOE technology offices will undertake a review of their policies, with input from the relevant academic and industrial research communities, for facility access, operations, and budgeting with a goal of maximizing their benefit to energy technology development.

Technology Transfer

While the innovation and uptake of technologies from federally-funded research is increasingly the subject of study and inquiry, there is little disagreement that more and better outcomes can be derived from the federal investment in scientific and engineering research. One of the most effective mechanisms for technology transfer is early engagement with industry in the development of research plans. DOE's Energy Innovation Hubs place such engagement as a cornerstone of their design.

Courtesy of National Renewable Energy Laboratory

Integrated Biorefinery Research Facility at the National Renewable Energy Laboratory provides high-bay laboratory space for pilot-scale biomass processing equipment and additional space for feedstock milling and storage.

To promote commercialization and other uses of technological results from DOE research at the laboratories and facilities, DOE has set out four goals for its technology transfer program: (1) to reduce barriers to effective technology transfer; (2) to catalyze interactions with the private sector along the entire technology innovation chain; (3) to facilitate the exchange of information on technological outcomes of research; and (4) to improve understanding of the impact of technology transfer and commercialization activities.

To reduce barriers to working with the laboratories and facilities, the Department's technology transfer program is considering options for modifying the existing mechanisms of technology transfer. Informed by responses to a November 2008 Request for Information, as well as reviews conducted across the DOE complex since that time, we are modifying terms and conditions related to the issues of highest concern. These include advance payment requirements, retained government rights, U.S. manufacturing requirement, indemnification, and liability consistent with a goal of streamlining access. Additionally, there are gaps in the types of R&D relationships supported easily by existing mechanisms, such as consortia. To further catalyze interactions with the private sector, DOE is exploring additional uses and constructs within the framework of existing legal authorities, with a view toward lowering transaction costs for those willing to develop and deploy early-stage innovations arising in the laboratories.

The latter two longer-term goals for technology transfer will be achieved through a comprehensive information infrastructure to collect and facilitate access to DOE inventions. Additional information related to ongoing and past DOE-funded research activities would include identification of the laboratory and scientists conducting the research, a single point for finding out about facilities available to users, and technical assistance programs at the laboratories. This readily available information will lower transaction costs and accelerate relationships with the private sector.

The Department is making progress on providing a single point of entry to a set of DOE-funded energy technology patents and licensing opportunities.[228] This is part of the 2011 Options Program launched as part of the Startup America Initiative, which facilitates private industry access to energy technologies available for licensing from the DOE laboratories.

The public tours the 2009 Department of Energy Solar Decathlon on the National Mall in Washington, D.C. The biennial competition features energy-efficient, solar-powered houses built by 20 university teams from North American and Europe.

CONCLUSIONS AND NEXT STEPS

Courtesy of the Solar Decathlon

The national energy priorities underpinning this Report are energy security, U.S. economic competitiveness, and reducing the environmental impacts of energy. The DOE has deep knowledge and technical capabilities that can be leveraged to address these urgent energy challenges and there are many useful contributions the Department could make across the energy sector. Limited resources demand thoughtful and consistent program choices to maximize impact. Alignment with national energy priorities is also a self-evident criterion.

Balancing the Portfolio

The national energy priorities underpinning this Report are energy security, U.S. economic competitiveness, and reducing the environmental impacts of energy. The DOE has deep knowledge and technical capabilities that can be leveraged to address these urgent energy challenges and there are many useful contributions the Department could make across the energy sector. Limited resources demand thoughtful and consistent program choices to maximize impact. Alignment with national energy priorities is also a self-evident criterion.

Balancing Timescales

Even the most optimistic budget leaves government funding for energy technologies a small fraction of private sector expenditures. The Department will seek to maximize the impact of its programs. Deployment activities have lower leverage than earlier-stage R&D or informational activities.

There is a tension between supporting work that industry won't, which biases toward the long-term, and supporting work that will have impact on timescales commensurate with the urgency of the Nation's energy challenges. The appropriate balance requires the Department to emphasize accelerating innovation relevant to today's energy technologies, because such evolutionary advances are more likely to have near- to mid-term impact on the Nation's challenges. Information for private- or public-sector decision making has both high leverage and relatively near-term impact, so DOE will maintain or build information-gathering, analytical, and dissemination capabilities across the spectrum of energy technologies.

To accelerate transformation of the energy system toward national energy goals, DOE will be mindful of the appropriate role for government in research, development, demonstration, and deployment. The Department drives innovation to mitigate market failures and create net public benefits by taking greater technical risks than the private sector is likely to sustain; beyond the technology itself, there is also the spillover effect, which is the risk that the benefits of innovation will not be captured by the innovator. DOE will therefore de-emphasize activities that are also undertaken by the private sector—though the absence of private sector funding should not be taken as evidence of the need for public funding. Maturity, materiality, and market potential are always relevant considerations for public support.

Fundamental R&D and emerging technologies must remain a part of DOE's portfolio, if only because they are rarer in the private sector; such research generates breakthroughs, although unpredictably. DOE will reserve up to 20% of the Department's energy technology R&D funding for "out of the box" activities. ARPA-E is one program designed to search for new technologies, rather than to further scientific understanding or incrementally improve existing technologies. Each of the four traditional energy technology programs also has some "out of the box" activities to hedge the risk that reasonably assured paths become blocked by insurmountable challenges. There is also scientific research in the Office of Science and NNSA that bears upon the missions of the applied energy technology programs.

DOE R&D portfolios will consider risk, timeframes for impact, and the character of the work supported, balancing more assured activities against higher-risk transformational work. We will also balance work developing technologies against highly relevant fundamental engineering research. DOE programs are expected to characterize their portfolios with impacts on near-term (0–5 years), mid-term (5–15 years), and long-term (>15 years) timescales, as well as timeless fundamental scientific and engineering research. Activities with near-term impact include ongoing projects that will hit externally relevant milestones within five years or shorter projects that can start and complete in that same timeframe. World events or unexpected technological progress should be expected to affect changes to a program's near-term portfolio.

The definition of impact will vary according to the R&D activity, technology, and timescale. Near-term impacts might be through informing decisions made by policy makers or the private sector. R&D might target market entry of a new technology in the near-, mid- or long-term, or advance fundamental engineering research. Fundamental engineering research is relevant across all timeframes and typically does not target a particular date for impact. DOE neither can, nor should, set private sector deployment as the only desirable outcome of all R&D.

The optimal balance of each of these portfolio dimensions will vary for individual technologies according to their scale, rates of deployment, and the current barriers to deployment (e.g., near-term technical assistance for nuclear fission vs. mid-term demonstration of CCS). Currently, DOE focuses too much effort on researching technologies that are multiple generations away from practical use at the expense of analyses, modeling and simulation, or other fundamental engineering research that could influence private-sector engineering practice in the nearer term.

Balancing Energy Challenges

Any given technology will address the energy security and environmental challenges in different proportions, while the competitiveness challenge is less technology-specific. A DOE portfolio that addresses all three challenges is more likely to remain coherent long enough to be relevant to energy system transformation. Energy security is most closely tied to oil dependence, and therefore transportation. Environmental impacts, such as GHG emissions, are more closely associated with the stationary heat and power sector.[229] World events and politics change faster than DOE's portfolio can.

To accelerate economic growth and associated job creation, DOE will give priority to technological innovation and other activities that best lower deployment barriers. Energy technology innovation that leads to the adoption of new energy technologies has the greatest impact on competitiveness when it reduces costs for energy consumers, stimulates domestic manufacturing, or establishes the expertise that creates opportunities to access global markets.

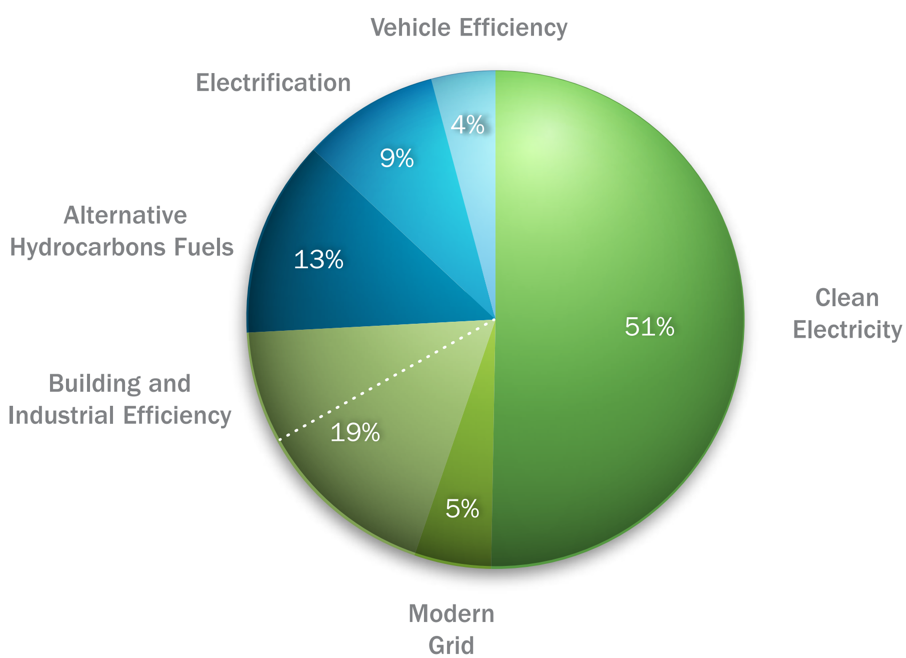
In developing its portfolio, DOE will be mindful of both the domestic and global context and markets for energy technologies. While the Department's focus will remain on technologies that can directly move the U.S. energy system toward domestic energy goals, competitiveness and energy's global environmental impacts inspire R&D in technologies with the potential for global deployment. The national security implications of energy technologies will also shape DOE's portfolio.

Balancing Among Strategies

Diverse sources fund energy technology R&D. Beyond the DOE, there are other federal agencies, international sources, and the private sector. All of these work together in various proportions to advance energy technologies. Of particular interest to the QTR is DOE's budget balance. Figure 30 shows the Department's Fiscal Year 2011 energy technology R&D budget (approximately $3 billion), categorized by the Six Strategies defined in this Report. Half of DOE's energy technology funding supports clean electricity generation, 19% funds building and industrial efficiency, and 5% supports the electrical grid. The remaining 26% supports transport—9% for vehicle electrification, 13% for alternative fuels, and 4% for vehicle efficiency.

Informed by the QTR process, DOE will give greater emphasis to the transport sector, where innovation can impact all three energy challenges. Because new technologies can diffuse through the transportation sector faster than in heat and power, innovation will have more immediate impact. Among the transport strategies, DOE will devote its greatest effort to electrification of the light-duty fleet, a sweet spot for pre-competitive R&D in areas of DOE strength. Conventional vehicle efficiency can have large and near-term impacts on national energy goals, but the vehicle industry is generally well-equipped to undertake this development; DOE will contribute where it brings its fundamental engineering research capabilities, most notably in advanced materials and simulation. Alternative hydrocarbon fuels address only a portion of the energy security challenge, but are essential for the environmental challenge—especially carbon emissions from the residual fuel demand after partial or full electrification of the light-duty fleet.

Figure 31. The Department's Fiscal Year 2011 Energy Technology Budget, Categorized by Strategy



The total funding captured in the chart is $3 billion. Included is a majority of funds of the four applied energy technology programs (Nuclear Energy, Fossil Energy, Electricity Delivery & Energy Reliability, and Energy Efficiency & Renewable Energy) as well as an additional $338 million in the Office of Science that is highly coordinated with the energy technology programs. The dotted line in the Buildings & Industrial Efficiency wedge indicates the $231 million dedicated to non-R&D weatherization activities. Not included in this chart are ARPA-E ($180M), the Loan Guarantee Program ($180M), or EIA ($95M). Also excluded are the type of funds in the four technology programs that are commonly excluded from R&D crosscuts, such as program direction, conventional national laboratory infrastructure or safeguard & security expenditures ($788M).

Within the stationary heat and power sector, DOE will increase emphasis on efficiency and understanding the grid. These sectors each have thousands of independent stakeholders and points of authority (and millions of energy consumers). DOE can leverage its role as a systems integrator and convener, particularly with the growing importance of information. While technology R&D is a foundation for DOE's work in both efficiency and the grid, DOE will direct additional effort toward high-impact but relatively inexpensive activities that reduce non-technological barriers and increase coordination. Balancing within DOE's portfolio of clean electricity technologies is discussed in **Clean Electricity**.

Findings

Integrated Techno-economic and Policy Analysis. Fundamental to improving Departmental strategy, to implementing the outcomes from this process, and to future QTRs will be the development of strong internal capability in integrated technical, economic, and policy analysis. The Department needs an enduring group to provide an integrated understanding of technology, markets, business, and policy for the planning and operation of technology programs. This professional group should have the following major functions: energy and technology policy analysis; industry studies, program evaluation, and economic impact assessments of R&D; and technology assessment and cost analysis. A team of senior career staff with strong technical, economics, private sector, and policy backgrounds to inform Departmental strategy would provide the consistency of knowledge, perspective, and logic required.

Previous attempts to establish such capability within the Department have resided within support offices, rather than at the leadership level—an approach that has had limited impact. Other federal agencies have established long-term analytic and advisory capabilities, such as the 50-year history of Cost Assessment and Program Evaluation capabilities within the Office of the Secretary of Defense.

Social Science

The aggregated actions of individuals and organizations determine many aspects of the energy system, with demands on the system and the balance of supply and demand affected as much by individual choice, preference, and behavior, as by technical performance. Domestic[230] and international[231] organizations alike have recognized the importance of social barriers in deploying technologies, but much remains unknown.

To fully assess potential impact of technology R&D, the Department must be versed in all the issues that affect market adoption of new technologies and capabilities. DOE will integrate applied social science into its technology programs in order to better understand how technologies diffuse through a sector and are used in the real-world.

Measuring Program Impacts

Rather than simply asserting the net benefits of our R&D investments or offering anecdotes, DOE must be more consistent, systematic, and rigorous in analyzing how its programs create public value. Congress and the President are demanding greater transparency and accountability in our spending of taxpayers' money. The Department will develop the tools for a data-driven analysis of research investments and their benefits in cooperation with other agencies, such as NIH, NSF, and the Office of Science and Technology Policy. The STAR METRICS program is an example of an early effort to develop those tools.

Next Steps

Implementation of the QTR. The Department has been formulating its Fiscal Year 2013 budget request in parallel with the QTR. That budget has been shaped and informed by the Department's recent Strategic Plan,[232] in addition to the results of the QTR. Future budget planning cycles will benefit more completely from this QTR, particularly through the continuing development of program plans that integrate the decision criteria and priorities expressed here.

One tool to assist the implementation of the QTR would be to subsume several of the existing advisory committees into an Under Secretary's Advisory Council, a Federal Agency Committee Act (FACA) committee structure that would span the Department's four energy technology programs to promote an integrated view of solving energy challenges (rather than advocacy for any particular technology) and advise on implementation of the QTR.

Improvements for a Future QTR

As the name of the QTR implies, the Department intends to return to this process approximately every four years, although continuous evaluation and adjustments in programs plans will be required by evolving technology and changes in policy. The next QTR will benefit from the framework developed as part of this process, and will be able to use the Department's growing analytical capabilities to produce a more detailed and comprehensive report.

The next QTR will benefit from an honest assessment of the impact of this QTR and the performance of DOE against the decision criteria and priorities it established. One of the first questions the next QTR will face is whether the framing and construction of this process was useful. A modified, or wholly new, framing might better suit contemporary conditions, and future QTRs will benefit from revisiting this QTR's decision criteria and priorities.

The technology assessments and roadmaps prepared for this iteration of the QTR (see Volume II) focused on synthesizing existing information, developed within a variety of existing frameworks. Further external assessments would provide a foundation for the next QTR, as the *America's Energy Future* report of the National Academies did for this process. Technology assessments and roadmaps in the next QTR process will also benefit from the common framework developed through this QTR. For example, the decision criteria and metrics developed through this QTR and the subsequent Departmental processes should result in more robust technology roadmaps. Improved understanding of R&D conducted by other players, including the private sector and internationally, should be developed over the intervening period and would provide a better context for the DOE role.

Toward a QER

When PCAST recommended the DOE QTR, the most important recommendation was the development of a multi-agency QER led by the Executive Office of the President. That QER would forge a more coordinated and robust federal energy policy, engaging many agencies and departments across the Executive Branch (see Table 9).

As envisioned by PCAST, a QER would provide a multiyear roadmap that lays out an integrated view of technology-neutral energy objectives and would put forward anticipated Executive actions, coordinated across multiple agencies. The emphasis of the QER would be on establishing government-wide goals, and identifying the non-budgetary resources needed for the invention, translation, adoption, and diffusion of energy technologies.

Because responsibility for setting these goals goes well beyond the reach of the DOE, the QER would serve as a mechanism for managing this crosscutting challenge. In both its development and implementation, the QER would provide an effective tool for Administration-wide coherence. Recognizing the scale of the task, PCAST recommended that the QER be implemented in a staged process led by the Executive Office of the President that would provide some elements of a QER during each of the next four years drawing on the support of an Executive Secretariat, provided by the Secretary of Energy.

Table 9. Summary of Federal Agencies with Roles in U.S. Energy Policy

	ENERGY FOR STATIONARY SERVICES			ENERGY FOR TRANSPORTATION		
Department / Agency	**Power & Heat**	**Grid**	**End-Use**	**Fuels Produc-tion**	**Fuels Distribu-tion**	**Vehicles**
Agriculture	■	■	■	■	■	
Commerce	■	■	■	■	■	■
Defense	■	■	■	■	■	■
Energy	■	■	■	■	■	■
Environmental Protection Agency	■		■	■	■	■
Homeland Security		■			■	
Housing & Urban Development			■			
Interior	■			■	■	
Labor	■		■			
State					■	
Transportation				■	■	■
Treasury	■	■	■	■	■	■
Federal Energy Regulatory Commission	■		■			
Tennessee Valley Authority	■	■	■			

	ENERGY FOR STATIONARY SERVICES			ENERGY FOR TRANSPORTATION		
Department / Agency	**Power & Heat**	**Grid**	**End-Use**	**Fuels Produc-tion**	**Fuels Distribu-tion**	**Vehicles**
General Services Administration						
Small Business Administration						
Export Credit Agencies						

APPENDICES

Process

Upon issuance of the PCAST report, Secretary Chu asked Under Secretary for Science Koonin in December 2010 to propose a process for assessing the Department's energy technology portfolio in this inaugural DOE QTR. Dr. Koonin responded with a structured project plan involving clearly defined scope, schedule, organization, processes and resources, with the goal of delivering a draft report for White House concurrence by the middle of summer 2011. That plan, approved by the Departmental leadership in January 2011, was the baseline against which the QTR project was executed and tracked.

The QTR team first developed a framing document that described the nation's energy landscape and challenges, identified R&D policy choices to be made, and asked for input on the best way the Department can make those choices. That document, created with DOE program and leadership input, was a principal vehicle for stakeholder engagement.

The framing document, announced March 15, 2011, in the *Federal Register*, began the public engagement process of the QTR. Over the course of the public comment period ending April 15, 2011, more than 60 individuals and organizations submitted their comments on the QTR framing document. Those comments highlighted topics missing or underemphasized in the framing document, directly addressed the questions posed in the request for information (RFI), and provided input on the structure and expectations for the final Report; they were an essential foundation for the rest of the public engagement process.

The subsequent process had four major elements:

Technology Assessments

The QTR team chartered 14 technology assessment teams to evaluate the current state and future potential of 17 technologies or sets of technologies. The Under Secretary solicited input from the Department leadership and National Laboratory Directors to form teams that integrated expertise from the applied energy programs, the Office of Science, ARPA-E, and the DOE national laboratories. The QTR staff met with the 14 teams to first define and document the scope of each team and then guide the drafting of 17 technology assessments.

Focus Groups

Nine focus groups with Departmental thought leaders were convened. Structured discussions moderated by Dr. Koonin focused on key energy challenges and goals, broad strategies to achieve those goals, and decision rules to prioritize DOE investments in service of those strategies. Technical experts from national laboratories participated in the Departmental focus groups, and discussions were held separately with Laboratory Directors and Chief Research Officers. Two further focus groups were convened with representatives from other federal agencies to solicit QTR engagement and gather diverse energy technology perspectives. Dr. Koonin met with energy R&D and policy leaders in a number of other agencies, including the EPA, DOT, HUD, USDA, DOI, and DOD.

Technical Workshops

Five sector-specific workshops were convened to gather external input on the portfolio principles and technology assessments. Those meetings brought together the expertise of the private sector, academia, nongovernmental organizations, the Department, and the national laboratories. The themes of these workshops shadowed the six QTR strategies:

- Alternative Fuels; Chicago, IL; April 26
- Vehicle Efficiency and Electrification; Knoxville, TN; May 4
- Building and Industrial Efficiency; Pittsburgh, PA; May 17
- Grid Modernization; Scottsdale, AZ; May 23
- Clean Electricity; Boulder, CO; June 7

Within the scope of each workshop, participants were asked to consider the questions raised in the framing document in panel and break-out discussions. Presentations by the technology assessment teams provided context for technology-specific breakout sessions. While these workshops were invitation-only meetings, DOE attempted to ensure participation by a diversity of stakeholders with a diversity of perspectives; a total of 260 people attended the five workshops.

Capstone Workshop

On July 13, 2011, in Washington, D.C., Dr. Koonin hosted a capstone workshop that was open to the public and had over 300 participants from all aspects of the energy sector. Four panel discussions paralleled the major issues addressed by this document: the transportation sector, the stationary sector, technology policy, and balancing the portfolio.

Following each of the six workshops, a small focus group was convened to review what had transpired at the larger workshop and to provide an opportunity to discuss issues that had not been covered in the larger group. These smaller groups helped the QTR team consolidate the key takeaways from each workshop.

In the synthesis phase of the QTR, all of the stakeholder input, departmental and core team thinking were integrated into successive drafts of the Report. Throughout, the core team maintained a schedule of circulating drafts and meetings to solicit comments and feedback from various governmental stakeholders, the Steering Committee, staff from the Executive Office of the President, Secretary of Energy Advisory Board, Energy Program Assistant Secretaries, National Laboratory Directors, agency counterparts, and the PCAST study co-chairs.

Throughout the QTR process, Dr. Koonin gave dozens of public talks highlighting the Department's efforts to establish a framework to assess its energy technology R&D. Those talks covered the purpose, scope, and timeline of the Review and encouraged public comment. Discussions among the audiences, who ranged from academia to industry to laboratory staff, were further input into the QTR process.

In keeping with the Administration's commitment to open government, the entire QTR process was designed to be inclusive and transparent. The names, materials discussed, and subject matter (including transcripts or detailed notes where appropriate), for all QTR-related meetings between QTR team members and the public have been posted on the QTR website, http://energy.gov/qtr/.

The guiding body for the study was a Steering Committee formed from the Departmental leadership:

Steven Chu, Secretary of the Department of Energy (chair)

Daniel Poneman, Deputy Secretary

Steven Koonin, Under Secretary for Science

Thomas D'Agostino, Under Secretary for Nuclear Security and Administrator of the National Nuclear Security Administration

Arun Majumdar, Director of the Advanced Research Projects Agency - Energy

William Brinkman, Director of the Office of Science

David Sandalow, Assistant Secretary for Policy and International Affairs

Jeffrey Lane, Assistant Secretary for Congressional and Intergovernmental Affairs

Sean Lev, Acting General Counsel

Howard Gruenspecht, Acting Administrator of the Energy Information Administration

Dan Leistikow, Director of Public Affairs

Brandon Hurlbut, Chief of Staff

The Steering Committee convened face-to-face at key milestones early in the project and met nearly weekly during the final two months. It provided high-level governance and concurrence and also served as a sounding board in developing the Report's form and content. As sections of the document developed, this group provided feedback on numerous versions, ultimately strengthening and refining it to the integrated text delivered to the Office of Management and Budget.

Project execution was in the hands of a core QTR core team responsible for connectivity within the department, engaging stakeholders, maintaining transparency, managing and analyzing public outreach, and finally drafting the Report. That project team included:

Shouvik Banerjee

Robert Fee

Avi Gopstein

Mike Holland

Asa Hopkins

Holmes Hummel

Laurel Miner

Additional input throughout the process came from Megan Chambers, Cynthia Lin, Colin McCormick, Tom Reynolds and Peter Weeks.

This Report on the QTR also benefited from the comments, insight, and assistance of Jeff Navin and Owen Barwell, and our former colleagues Scott Harris, Steven Isakowitz, Richard Newell, Rod O'Connor, Missy Owens, and Cathy Zoi during their tenure at the Department.

The Report was edited and designed by Morgan Evans, Taryn McKinnon, Borys Mar, and Jared Largen of BCS, Incorporated.

Glossary

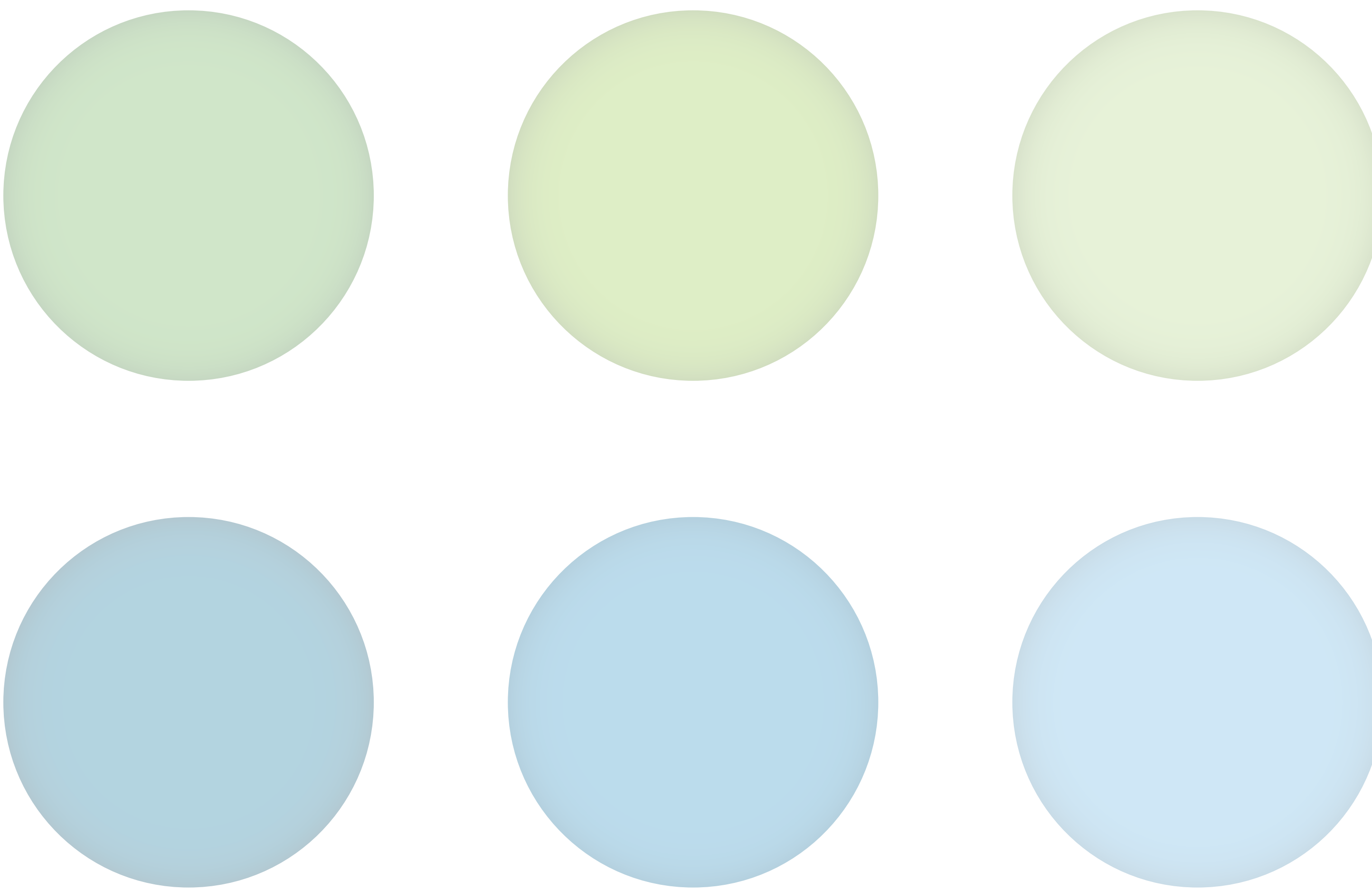
AEV	All-Electric Vehicle
AMI	Advanced Metering Infrastructure is a system of communications networks and database systems that enable two-way communications with "smart" meters and other energy management devices.
ARPA-E	Advanced Research Programs Agency - Energy. An agency established within the DOE.
BLM	Bureau of Land Management. An agency within DOI.
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement. An agency within DOI.
BTL	Biomass To Liquids
BTU	British thermal unit, a unit of energy equal to the heat required to raise the temperature of 1 pound of water by 1 °F. 1 British Thermal Unit equals 1055 Joules.
Bulk power system	The high voltage (>10kV) portion of the grid consisting of centralized generation facilities and transmission infrastructure
BuRec	Bureau of Reclamation. An agency within DOI.
CAES	Compressed air energy storage
CAFE	Corporate Average Fuel Economy (CAFE) standards are regulations first enacted by Congress in 1975 intended to improve the average fuel economy of cars and light trucks (trucks, vans and sport utility vehicles) sold in the US.
CBTL	Coal and Biomass To Liquids
CCS	Carbon Capture and Storage
CES	Clean Energy Standard
CHP	Combined Heat and Power (cogeneration) is the simultaneous generation of both electricity and useful heat.
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
CSP	Concentrated Solar Power systems use mirrors or lenses to concentrate a large area of sunlight onto a small area. Most often used for thermoelectric generation, the concentrated light is converted to heat to produce electricity (usually through a steam turbine).
CTL	Coal To Liquids
CTL-CCS	Coal To Liquids using Carbon Capture and Storage

DARPA	Defense Advanced Research Projects Agency. An agency within DOD.
Distributed generation	Small scale power generation (<10MW) close to the load from which electricity is fed into distribution circuits or directly to the consumer.
Distribution circuit	Low voltage (<10kV) grid electrical circuits that are used to deliver power to the consumer.
DOC	Department of Commerce
DOD	Department of Defense
DOI	Department of the Interior
DOT	Department of Transportation
Drive cycle	Pattern of vehicle use (includes the number and length of trips)
Dynamic response	Varying electrical load in response to grid conditions
E85	Ethanol fuel blend up to 85% of ethanol and gasoline
EERE	Office of Energy Efficiency and Renewable Energy. An applied energy program office in the DOE.
Effluent temperature	The temperature of water leaving a power plant.
EHS	Environmental Health and Safety
EIA	Energy Information Administration
Energy	The ability to do useful work. Can be measured in units of Joules (J), British thermal units (BTU), kilowatt-hours (kWh), Quads. 1 BTU = 1055 Joules 1 kWh = 3.6 million Joules 1 Quad = 1 quintillion (10^{18}) Joules
Energy efficiency	The ratio of the amount of energy service provided to the amount of energy consumed.
Energy productivity	The ratio of GDP to primary energy consumed
ENERGY STAR	An energy efficiency certification program on products, buildings, and plants. Jointly sponsored by EPA and DOE.
Enhanced oil recovery	A process to increase the oil produced from a reservoir.
EPA	Environmental Protection Agency
EPACT	Energy Policy Act of 2005 (EPAct 2005) established a number of energy management goals for Federal facilities and fleets. It also amended portions of the National Energy Conservation Policy Act (NECPA).

EV	Electric Vehicle; includes HEV, PHEV, FCEV, and AEV
FACA	Federal Advisory Committee Act
FCEV	Fuel Cell Electric Vehicle
FERC	Federal Energy Regulatory Commission
Fleet vehicles	A collection of vehicles used by a single enterprise, managed, serviced, and potentially fueled through a central process
Flow batteries	A rechargeable battery in which a liquid electrolyte flows through a chemical cell that converts chemical energy directly into electricity and vice versa.
Flywheel	A device that stores energy by in a high-speed rotor. That energy can be converted to electricity by using a motor/generator.
GHG	Greenhouse gases
Grid reliability	The ability of the electric grid to adequately serve the load without blackouts
GW	Gigawatt, a unit of power. 1 gigawatt equals 1 billion (10^9) Watts
HEV	Hybrid electric vehicle
HPC	High performance computing
HUD	Department of Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning
ICE	Internal combustion engine
IEEE	Institute of Electrical and Electronics Engineers
Joules	Unit of energy.
kW	Kilowatt, a unit of energy. 1 kilowatt equals 1000 (10^3) Watts
kWh	Kilowatt-hour, a unit of energy. 1 kilowatt-hour equals 3.6 million Joules
LCOE	Levelized Cost of Electricity, which smoothes capital depreciation over the asset lifetime
Level 1/2/3 chargers	Classifications of outlet types for plug-in hybrid and battery electric vehicles. Level 1 is a common wall outlet (120V AC), Level 2 is a higher voltage outlet similar to those used for home appliances (240V AC), and Level 3 is an even higher voltage direct current charging station (480V DC).
LNG	Liquid Natural Gas
Load mix	The diversity of loads served by the electric grid.
MEP	Manufacturing Extension Partnership. Sponsored by NIST.
Miscellaneous electric loads	Electronic devices used in buildings, such as computers and displays, televisions, VCRs, digital video recorders, printers, and small kitchen appliances

Mpg	Miles Per Gallon
MW	Megawatt, a unit of energy. 1 megawatt equals 1 million (10^6) Watts
MWh	Megawatt-hour, a unit of energy. 1 megawatt-hour equals 3.6 billion Joules
NESHAP	National Emissions Standards for Hazardous Air Pollutants. Emission standards set by EPA.
NGCC	Natural Gas Combined Cycle
NHTSA	National Highway Transportation Safety Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OECD	Organisation for Economic Co-Operation and Development
OPEC	Organization of Petroleum Exporting Countries. Member countries: Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, Venezuela
OPIC	U.S. Overseas Private Investment Corporation
PCAST	President's Council of Advisors on Science and Technology
PHEV	Plug-in Hybrid Electric Vehicle. The accompanying number (ex: PHEV40) is the number of miles that vehicle can be driven on an electric charge before switching to chemical fuel.
PHMSA	Pipeline and Hazardous Materials Safety Administration. An agency within DOT.
PMA	Power Marketing Authorities
PMU	Phasor Measurement Unit. A device that precisely measures electric waveform characteristics (amplitude and phase) in the bulk power system.
Power	Power is the measure of how quickly energy is delivered. Can be measured in Watts (W) or horsepower (hp). 1 W = 1 J/s 1 hp = 745.7 W
Power electronics	Solid state electronics used to control electric power.
Power quality	The frequency and voltage stability of delivered electricity
Primary energy	Energy found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels.
PURPA	Public Utility Regulatory Policies Act
PV	Photovoltaic

QER	Quadrennial Energy Review
QTR	Quadrennial Technology Review
Quad	Unit of energy. 1 Quad equals 10^{15} (1 quadrillion) British thermal units (BTUs)
QXR	Quadrennial X Review (when compared to Quadrennial Defense Review (Department of Defense), Quadrennial Diplomacy and Development Review (Department of State), and Quadrennial Homeland Security Review (Department of Homeland Security)
R&D	Research and Development
REAP	Rural Energy for America Program. Sponsored by USDA.
RFS1	Original Renewable Fuel Standard enacted in the Energy Policy Act of 2005. RFS1 established minimum levels of domestic corn-ethanol production that increased with time.
RFS2	Update to RFS1 that was enacted in the Energy Independence and Security Act of 2007. RFS2 expands domestic biofuels production requirements and includes new categories of cellulosic ethanol and advanced biofuels.
RPS	Renewable Portfolio Standard. State regulations requiring utilities to procure at least some fraction of their delivered electricity from renewable sources.
SMR	Small Modular (nuclear) Reactors, a nuclear fission technology
TARDEC	Tank Automotive Research, Development and Engineering Center. An organization within the U.S. Army.
TVA	Tennessee Valley Authority
UK	United Kingdom
USDA	U.S. Department of Agriculture
V	Volt
Watt	Unit of power. 1 Watt equals 1 Joule/second.
W_e	Watt electrical. The amount of electric power produced. In contrast to watt thermal, which is the amount of thermal power produced.



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2 Fundamental engineering research is research intended to understand the sensitivity of man-made systems or components to specific laws of nature. The goal of fundamental engineering research is to make better predictions about the behavior of those systems, which will broadly improve our ability to design, build, and maintain engineered products and services for particular purposes. Fundamental engineering research is an essential precursor to technology development.

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5 Department of Energy. (2011). *DOE Strategic Plan*, Washington, DC. Accessed at: http://energy.gov/sites/prod/files/edg/news/documents/DOE_StrategicPlan.pdf

6 Throughout this report we use the "Quad" to measure national-scale energies. One Quad is 10 British thermal units (Btu). The United States uses almost 100 Quads of energy per year.

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8 Another important organizational difference between defense and energy is that the Department of Defense has specialized workforces (the Armed Services, professional Acquisition and Logistics corps, etc.), enduring organizations spanning the Department (Office of the Secretary of Defense, Joint Chiefs of Staff, etc.), and a multiyear planning horizon to ensure coordinated and predictable mission execution. Those intra-Departmental structures are bolstered by a dedicated Executive Office of the President organization (National Security Council) and special Congressional committees. In contrast, there are no enduring coordinating bodies for energy policy or even just for energy technology. The highest ranking career staff in energy technologies are the Deputy Assistant Secretaries in the technology-specific DOE program offices.

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[19] Energy Information Administration. *Weekly Retail Gasoline and Diesel Prices*," Washington, DC. Accessed September 16, 2011 at: http://www.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm

[20] Energy Information Administration. (2011). "Market Prices and Uncertainty Report," *Short-Term Energy Outlook*, Washington, DC. Accessed September 16, 2011 at: http://www.eia.gov/emeu/steo/pub/uncertainty.html

[21] Energy does not directly provide a service. Instead, appliances, lights, or equipment use energy (usually in the form of electricity or heat) to perform services, such as providing comfortable and lit living spaces or processing an industrial material.

[22] National Academy of Sciences, National Academy of Engineering, National Research Council. (2009). Real Prospects for Energy Efficiency in the United States. Washington, DC.

[23] Energy efficiency is the ratio of service provided to energy consumed. Energy conservation reduces energy consumption by reducing the amount of service provided.

[24] The minimum energy required to provide many energy services cannot be measured, or may be zero (e.g., lighting service can be provided by a window using no energy). The relative efficiency of two processes can be judged by comparing the energy used to provide the same service.

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[33] Energy Information Administration. (2011). "Table 6.1—Coal Overview," *July 2011 Monthly Energy Review*, Washington, DC. Accessed at: http://www.eia.gov/totalenergy/data/monthly/pdf/sec6_3.pdf

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[39] Compared to coal, natural gas produces half as much CO_2, one-third as much NOx, and 1% as much SO_2 per MWh of electricity generated.

[40] Secretary Chu has asked a panel of experts to recommend improvements to the safety and environmental performance of hydraulic fracturing for natural gas extraction. Department of Energy. (2011). "Secretary Chu Tasks Environmental, Industry and State Leaders to Recommend Best Practices for Safe, Responsible Development of America's Onshore Natural Gas Resources," Washington, DC.

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[99] While our focus here is on road transport, there are strong drivers for, and steady improvements in, rail, air, and marine efficiencies.

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[101] This is about 1% of U.S. energy use. In the transport sector, it is equivalent to 500,000 bbl/day of oil or 4% of current consumption. For the power sector, assuming an average 30% thermal-to-power efficiency, it is equivalent to 80 TWh or about 2% of current generation.

[102] The annual light-duty vehicle fleet turnover is some 6%. If those oldest vehicles were to be replaced by new vehicles with twice the fuel economy, fuel consumption would decrease by 3% per year, with no change in infrastructure or consumer behavior required. Over a decade, light-duty vehicle fuel consumption would drop 30% or some 2.7 M bbl/day.

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[106] The first increases in miles per gallon (mpg) are the most important. For example, taking a vehicle from 30 mpg to 50 mpg will save as much fuel as going from 50 mpg to 150 mpg. More explicitly, a 30-mpg car uses 10 gallons to drive 300 miles, while a 50-mpg car uses only 6 gallons (saving 4 gallons). To save a further four gallons over 300 miles, a car would have to get 150 mpg.

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