QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

Chapter 1: Energy Challenges
September 2015

Energy is the Engine of the U.S. Economy

1 Energy Challenges

1.1 Introduction

The United States' energy system, vast in size and increasingly complex, is the engine of the economy. The national energy enterprise has served us well, driving unprecedented economic growth and prosperity and supporting our national security. The U.S. energy system is entering a period of unprecedented change; new technologies, new requirements, and new vulnerabilities are transforming the system. The challenge is to transition to energy systems and technologies that simultaneously address the nation's most fundamental needs—energy security, economic competitiveness, and environmental responsibility—while providing better energy services. Emerging advanced energy technologies can do much to address these challenges, but further improvements in cost and performance are important.[1] Carefully targeted research, development, demonstration, and deployment (RDD&D) are essential to achieving these improvements and enabling us to meet our nation's energy objectives.

This report, the 2015 Quadrennial Technology Review (QTR 2015), examines science and technology RDD&D opportunities across the entire U.S. energy system. It focuses primarily on technologies with commercialization potential in the mid-term and beyond. It frames various tradeoffs that all energy technologies must balance, across such dimensions as diversity and security of supply, cost, environmental impacts, reliability, land use, and materials use. Finally, it provides data and analysis on RDD&D pathways to assist decision makers as they set priorities, subject to budget constraints, to develop more secure, affordable, and sustainable energy services.

The energy science and technology RDD&D opportunities described in this report, if successfully conducted and commercialized at scale, would significantly impact the energy security, economic, and environmental challenges that face the United States and the world.

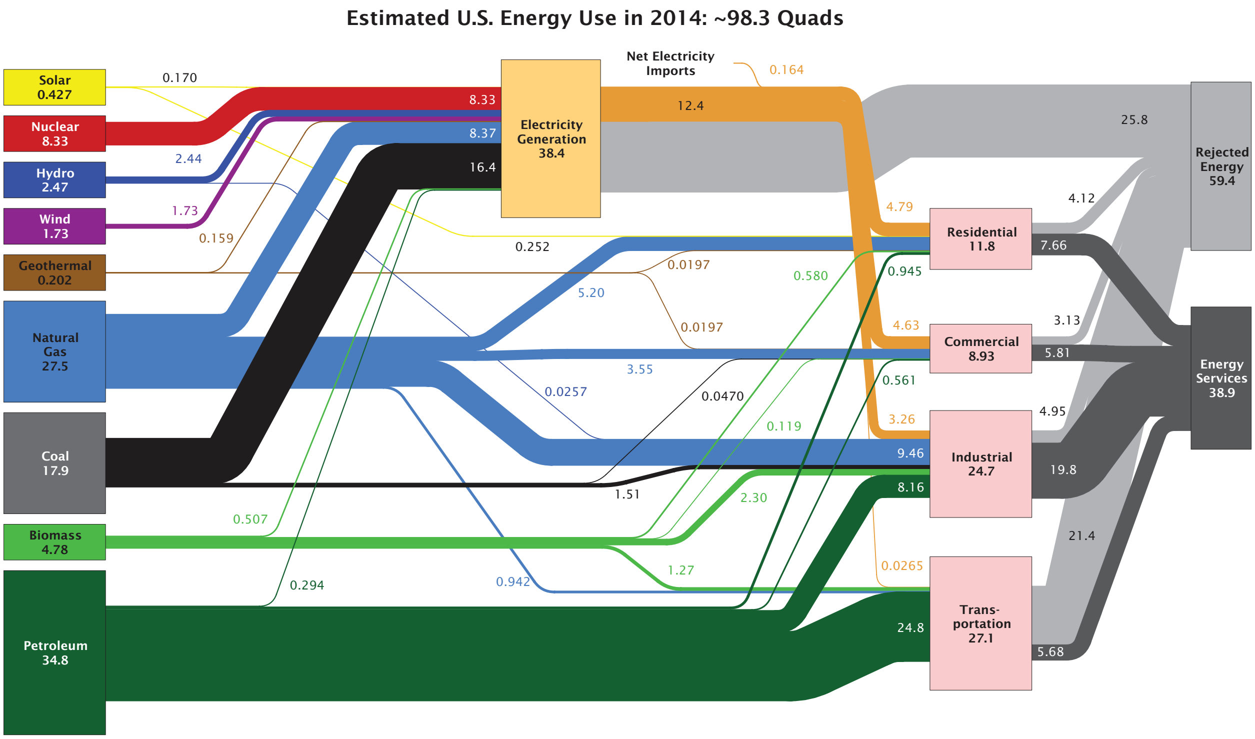
1.2 The U.S. Energy System

A vast and complex array of systems and associated technologies extract energy resources, convert them into usable forms of energy, and deliver them to end users to provide desired services such as manufactured goods, thermal comfort, lighting, and mobility.

The overall flow of energy through the U.S. energy system is illustrated in Figure 1.1.[2] It illustrates the initial energy resources, their conversions into fuels and electricity, and their use in the buildings, industry, and transportation sectors to provide the energy services that support our economy and our way of life. It also illustrates energy losses (rejected energy) that result from the fact that energy conversion processes are never 100% efficient.

Figure 1.1 The Sankey Diagram depicts the flow of energy resources (left) to end-use sectors (right).

Credit: Lawrence Livermore National Laboratory



1.2.1 U.S. Energy Supply and Use

Figures 1.2 and 1.3 provide more detail on the energy inputs and applications within the buildings, industrial, and transportation sectors.

Fossil fuels supply about 82% of the primary energy use in the United States. The challenges and opportunities associated with fossil fuels are explored in Chapters 4 (*Advancing Clean Electric Power Technologies*) and 7 (*Advancing Systems and Technologies to Produce Cleaner Fuels*), as well as elsewhere throughout the report.

There are many pathways to produce electricity, with the generation mix currently dominated by coal, natural gas, and nuclear resources. Options for improving the performance of the electricity grid are described in Chapter 3 (*Enabling Modernization of the Electric Power System*), while options for developing cleaner, more competitive, and more secure supplies are described in Chapter 4.

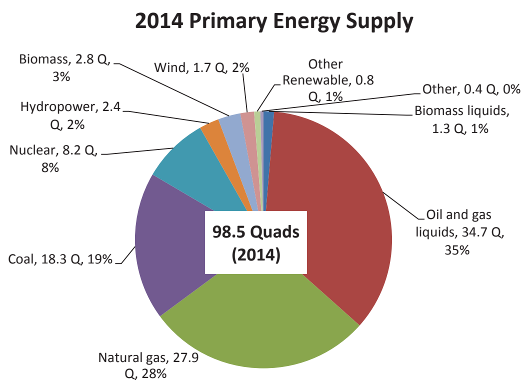
The buildings sector is the largest consumer of electricity, and electricity supplies the majority of primary energy that is consumed in buildings. Buildings sector energy technology opportunities, discussed in Chapter 5 (*Increasing Efficiency of Building Systems and Technologies*), are thus heavily weighted toward technologies powered by electricity.

The industrial sector is the most diverse consumer of energy, and also has the most diverse set of energy applications. This sector includes manufacturing (the focus here) as well as agriculture, construction, and mining. Opportunities to address energy challenges in the manufacturing sector, in particular, are likewise diverse, and are discussed in Chapter 6 (*Innovating Clean Energy Technologies in Advanced Manufacturing*).

The energy inputs for the transportation sector are almost completely dominated by petroleum-based fuels. Energy use in this sector is dominated by light-duty vehicles. Opportunities to displace and/or improve the use of petroleum fuels in light-duty vehicles are considered first, with other important opportunities discussed in somewhat less detail. Chapters 7 and 8 (*Advancing Clean Transportation and Vehicle Systems and Technologies*) cover the fuels and transportation space.

U.S. Energy: Supplies and Sectoral Uses[3]

Figure 1.2a U.S. Primary Energy (a) Supply and (b) Consumption in the End-Use Sectors in quads and as a percent of total U.S. primary energy, respectively. Note that fossil fuels supply about 82% of U.S. primary energy consumption.



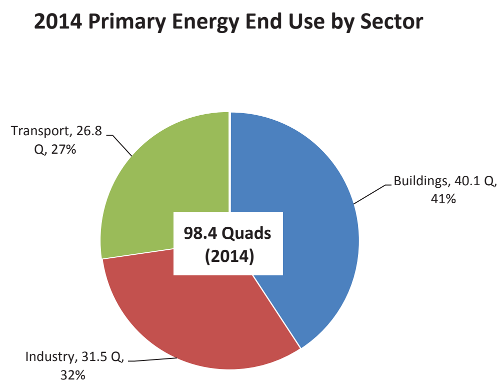
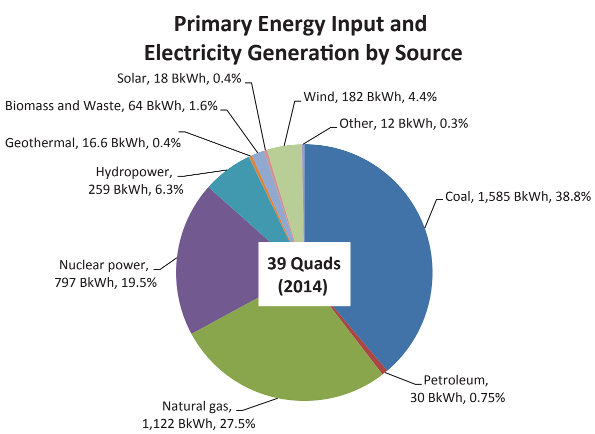
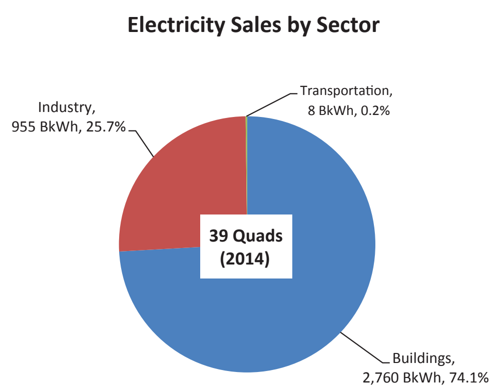


Figure 1.2b U.S. Electric Power by (a) Total Primary Input (quads) and Electricity Generation by Source (kWh and %); and (b) Electricity End Use by Sector in kWh and as a percentage of total U.S. electricity generation. Note that coal is the largest source of energy and the buildings sector accounts for 74% of electricity consumption.





Use Sectors: Supplies and End Uses[4,5,6,7]

Figure 1.3a Building Sector Energy by (a) Primary Energy Supply and (b) Energy End Uses in quads and as a percent of total U.S. building energy supply and use. Note that the building sector directly uses large amounts of natural gas.

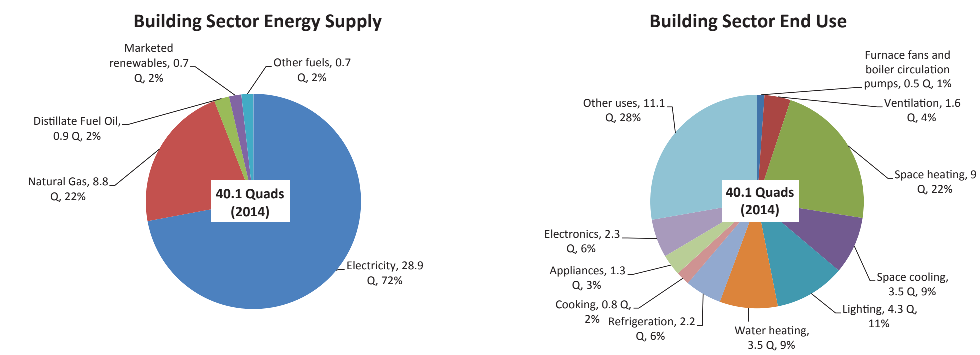


Figure 1.3b Industry Sector Energy by (a) Primary Energy Supply and (b) Energy End Uses in quads and as a percent of total U.S. industry energy supply and use. Note that natural gas and petroleum dominate energy use in the industry sector. Much of the energy is used for energy-intensive commodity materials processing.

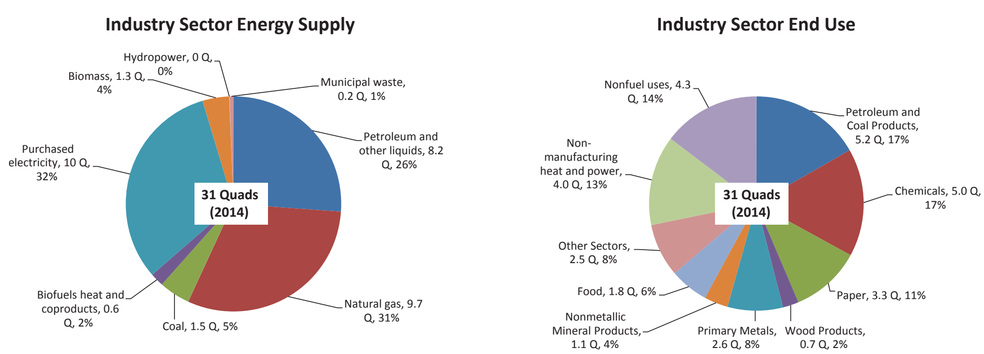
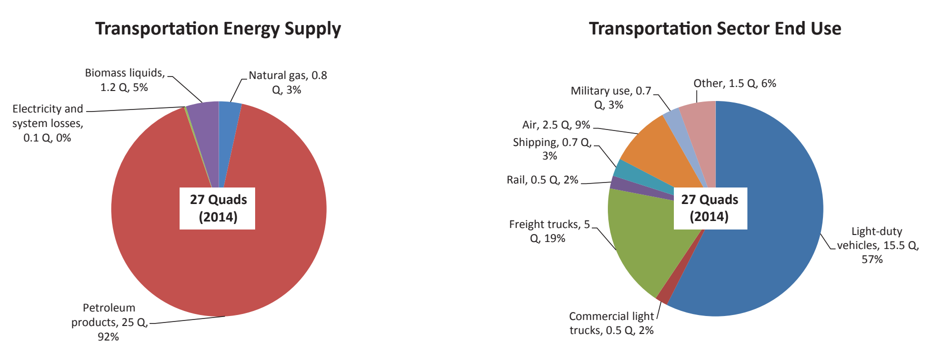


Figure 1.3c Transportation Sector Energy by (a) Primary Energy Supply and (b) Energy End Uses in quads and as a percent of total U.S. transportation energy supply and use. As can be seen, the transportation sector is almost entirely dependent on petroleum.



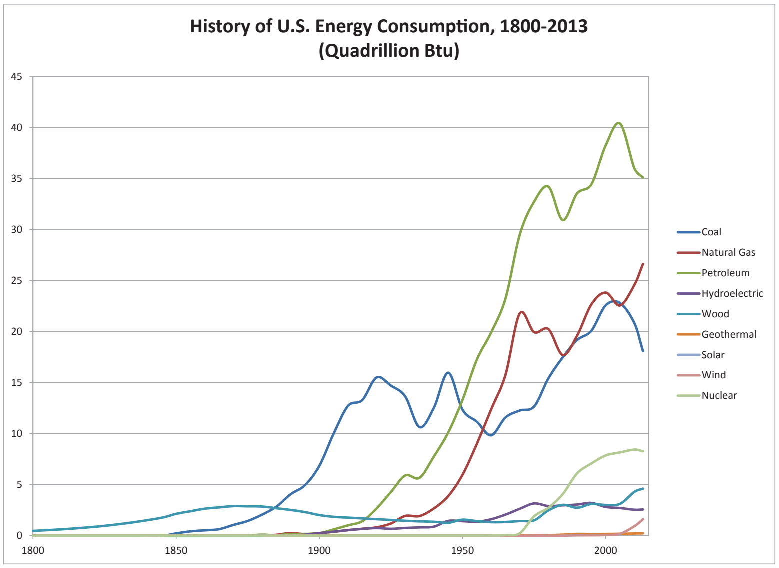
1.2.2 Changes in U.S. Energy Supply and Demand

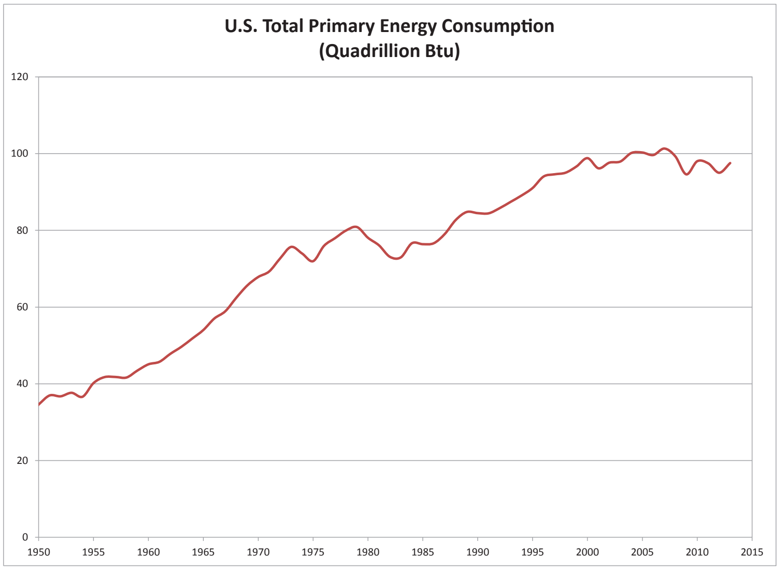
Over the past 200 years, the predominant source of energy supply in the United States has changed several times, with typical transition times of fifty to one hundred years. Figure 1.4 illustrates these shifts from wood to coal to oil and now toward natural gas and renewables. Much of this report is aimed at accelerating beneficial shifts in shorter time frames in the future.

Over the last four years since QTR 2011 was published, dramatic changes in U.S. energy supply and demand have taken place (see textbox: *Major Changes in the Energy Landscape*). The recent "shale revolution" in oil and gas has garnered the most attention of late, but transformations are occurring in a number of energy sectors (Table 1.1). Over the same period, U.S. energy consumption has increased by only about 1%, even as the population grew 3.1% and the economy grew 8.2%, reflecting extraordinary gains in energy productivity.

As rapid as the changes have been to the U.S. energy system over the past four years, future growth in the global energy system is anticipated to dwarf these changes. The developing world requires large increases in the services that energy provides to continue its economic development. Bringing modern energy services to the more than five billion people with little or no service today is a monumental challenge. For the foreseeable future, the bulk of new market growth for energy technologies will be in the emerging markets of Asia, Latin America, Africa, and other areas outside the Organisation for Economic Cooperation and Development (OECD). The U.S. Energy Information Administration (EIA) projects that total annual primary energy use by OECD countries will increase from today's 240 quads to about 280 quads in 2040, while primary energy use by the rest of the world will increase from

Figure 1.4 U.S. Primary Energy Use over time in Quads: (a) from 1800 to the present by source,[8] and (b) total primary energy use from 1950 to the present.[9] Note how the largest primary energy resource has changed several times over history.





Major Changes in the Energy Landscape

The period from 2010 through 2014 was one of dramatic change in the U.S. energy landscape. These four years have seen the culmination of decades-long RDD&D investments beginning to transform the market. This transformation is occurring across supply and distribution of fuels and electricity, and across end uses—buildings, industry, and transportation. The U.S. energy enterprise is engaging the challenges of energy security, economic competitiveness, climate change, and other environmental issues, driven by a variety of factors ranging across technology readiness, market demand, and public policy.

Increased domestic oil and gas production

Over the past decade, adoption of technology to recover oil and gas from "unconventional" resources, such as shale and tight geological formations, has significantly increased proved reserves and production of oil and gas. From the beginning of 2010 through the beginning of 2014, proved oil and lease condensate reserves in the United States increased by more than 60%, from 22 to 36 billion barrels.[24] Similarly, oil production increased by 40%, from 11 to 16 quadrillion British thermal units (quads) per year.[25] Over the same period, proved reserves of wet natural gas increased by 25%, from 280 to 350 trillion cubic feet,[26] while annual production increased by 18%, from 21 to 25 quads.[27] Beyond increased economic activity in the energy sector, the benefits of improved oil and gas accessibility in the United States include vastly reduced oil imports, an improved investment outlook for energy-intensive industries, and lower direct greenhouse gas (GHG) emissions due to gas replacing coal in the electricity generation sector.

Decreasing growth of gasoline consumption

After twenty-five years of virtually uninterrupted growth, gasoline consumption began to decline in 2008 and has been relatively flat since 2011. Multiple factors have driven this trend as described below:

- Per-capita vehicle miles traveled peaked in 2004[28] and have been declining ever since.
- Shifting consumer preferences toward smaller and more fuel-efficient vehicles, combined with higher fuel economy standards,[29,30] have increased new light-duty fuel economy to a record high in 2014.[31]
- Blending of ethanol into the gasoline supply, which ramped up in 2005, has displaced approximately 10% of the petroleum content of gasoline.[32] Continued growth in ethanol use will depend on either growth of gasoline consumption or market uptake of higher-level blends such as E15 and E85.

Between the decrease in demand for fuel and the increase in domestic supply, net imports of oil and petroleum products have decreased by 35% since 2011 and 50% since their peak in 2005.[33] Global oil prices also fell by almost 50% during the latter half of 2014,[34] driven by a combination of increased supply in the United States, reduced economic growth forecasts in the developing world, and a dynamic geopolitical environment.

A newly dynamic nuclear power landscape

Since 2012, five nuclear reactors have been retired in California, Wisconsin, Florida, and Vermont. In 2019, one additional reactor is scheduled for retirement in New Jersey. During this same time, construction continued on a reactor in Tennessee and started on four new Generation III+ reactors in Georgia and South Carolina.[35] These new reactors have advanced passive safety features that are predicted to make them the safest in the fleet.

Increased deployment of wind and solar energy

Between 2011 and 2015, the installed capacity of wind energy increased by 65%, from 40 gigawatts (GW) to 66 GW.[36] During that same period, the capacity of installed solar photovoltaic generation increased from about two GW to

18 GW.[37] Today, enough wind energy has been deployed that it is a significant contributor to the nation's electricity supply (more than 4%).[38]

Increased deployment of smart grid technologies

More than 1,300 digitally connected phasor measurement units and millions of smart meters were connected to the electrical grid between 2010 and 2014.[39] These devices and advanced communication networks are allowing unprecedented visibility of the operation of what many call "the largest machine on earth."[40] The volume, variety, and speed of the newly available data streams are at the early stages of improving grid management.

Slowing growth of electricity consumption

Growth in U.S. electricity demand is at its lowest level in decades.[41] In the residential and commercial sectors, which now account for approximately 74% of electricity consumption, adoption of significantly more energy efficient devices has played a major role in this decline. Policies that promote energy efficiency are partly responsible for this adoption, while technology shifts to more appealing and effective devices that are more energy efficient (e.g., mobile computing, flat panel monitors) are also a factor.

Increasing opportunities for U.S. manufacturing

The availability of lower-cost natural gas and natural gas liquids has created an advantage for U.S. manufacturers that use these resources for heat, power, or as chemical feedstocks. This has contributed to some expansions and additions to the U.S. petrochemical manufacturing sector.[42] The industrial sector as a whole can similarly benefit from low-cost natural gas.

Growing market for electric vehicles

Over the past four years, electric vehicles have successfully carved out a niche market. Plug-in electric vehicle (PEV) sales went from virtually zero in 2010 to approximately 100,000 per year by 2014.[43] These sales include premium vehicles, such as Tesla Model S, and mass-market vehicles, such as the Nissan Leaf and Chevrolet Volt. At current levels of market share, these vehicles do not materially change the overall energy demand or emissions profile of our national energy economy. However, because adoption tends to be regionalized, use of PEVs is changing electricity consumption patterns at the local level, and the vehicles are prevalent enough to require thoughtful planning for public charging infrastructures.

Regionally constrained water availability

At the time of publication of this report, California was experiencing its fourth year of an historic drought. Hydroelectric production in California was 60% lower in 2014 than it was in the most recent wet year (2010).[44] Additionally, the state is expending more energy than usual for water delivery due to the pumping of groundwater by the agriculture industry to keep its fields and orchards productive during current drought conditions. California is an example of what can happen when water availability is altered. In regions that rely on river flow for power plant cooling, a drought could threaten the operability of those power plants.

Reductions in carbon dioxide (CO_2) emissions

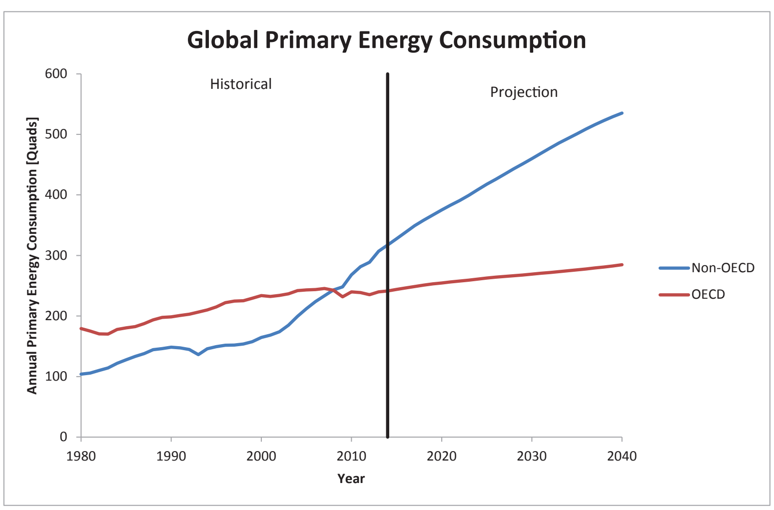
U.S. CO_2 emissions from fossil fuels have declined by 10% since 2005, and were virtually unchanged between 2010 and 2014, despite significant economic growth during that time.[45] Key factors contributing to this trend include reductions in demand growth for gasoline and electricity, fuel switching from coal to lower-carbon natural gas in the electricity sector, and growth in electricity generation from wind and solar. Globally, the rate of growth of emissions has slowed as well. In 2014, global CO_2 emissions were unchanged from 2013.[46]

Table 1.1 Changes in Energy Supply and End-Use Demand from 2010 through 2014

Sector	2010	2014
Domestic oil and liquids production[10]	7.56 MMB/d (million barrels/day)	11.7 MMB/d
Oil demand[11]	19.2 MMB/d	19.0 MMB/d
Net oil imports[12]	9.44 MMB/d	5.04 MMB/d
Coal consumption[13]	1,050 Mt (million short tons)	917 Mt
Unconventional natural gas production[14]	5.8 TCF (trillion cubic feet)	11.9 TCF (2013)
Natural gas generating capacity[15,16]	407 GW (gigawatts)	432 GW
Nuclear power	One reactor under construction	Five reactors under construction
Wind generating capacity, cumulative[17]	40.3 GW	65.9 GW
Photovoltaic generating capacity, cumulative[18,19]	2.02 GW	18.3 GW
Electricity end use[20]	3,887 Billion kWh (BkWh)	3,862 BkWh
Total energy demand[21]	**97.5 quads**	**98.4 quads**
Total population[22]	**309 million people**	**319 million people**
Total economy (gross domestic product)[23]	**$14.8 trillion (chained-2009-$)**	**$16.0 trillion**

today's 330 quads to roughly 530 quads in 2040 (see Figure 1.5). This burgeoning growth is a substantial market opportunity but will also increase the pressure on global energy supplies, with corresponding security and market volatility risks.

Figure 1.5 EIA Projections for Growth of Energy Demand (in quads) in OECD and non-OECD Markets to 2040. The growth in the emerging economies is projected be five times faster than that of the OECD nations over the next twenty-five years. (Source: EIA International Energy Outlook, 2013, Figure 14)



1.3 National Energy System Strategic Objectives

As in the past, the future energy system will be influenced by many factors, some of which are technology developments, others which are not. An appropriate RDD&D agenda endeavors to anticipate and incorporate all potential factors, including those that are still emerging and evolving. In the face of the inevitable uncertainties, three definitive and enduring goals are foundational to the nation's energy RDD&D agenda.

U.S. Energy Objectives

Secure and resilient: Energy systems should be secure from and resilient to natural disruptions as well as man-made attacks. Security must be addressed along the entire energy service value chain from supply (including energy resources, materials, and technologies) to operations (including distribution, storage, and end use of fuels and electricity).

Economically competitive: Energy systems should provide energy services that are abundant, sustainable, and affordable, taking into account the full market impacts and life cycle costs of the energy service value chain.

Environmentally responsible: Clean energy systems should minimize air, water, and land pollutant emissions; GHG emissions; biota impacts; and disruption of water and land resources.

Fully successful energy systems will be secure and resilient, economically competitive, and environmentally responsible. Such systems will include a portfolio of technologies whose inherent strengths are complementary and weaknesses are mitigated. Future uncertainties make it prudent to explore multiple technologies and approaches. A diversified portfolio of technology options is essential to mitigating risk.

1.3.1 Energy Security and System Resiliency

Energy-related risks to national security can broadly be categorized into physical, cyber, economic, and conflict-related, though significant overlaps among these categories exist. Energy technologies must be robust and resistant to these vulnerabilities.

Physical security risks are related to damage to energy supply, storage, and delivery infrastructures. These infrastructures include the electrical grid, pipeline networks, and rail and marine systems.[47] Hurricane Sandy[48] and the attack on the Metcalf substation[49] are recent examples that highlight the physical vulnerabilities of energy systems to natural and man-made threats. The increase in extreme weather with climate change raises these risks.[50]

Cybersecurity vulnerabilities generally are related to the compromise of computer-based systems in their various activities of data inputs and analysis and, more specific to energy systems, the operation and coordination of energy supply, delivery, and end-use systems. The challenges of maintaining the integrity of these systems correspond with the number of access points to these systems, the need to validate and manage data inputs, the need to monitor the systems for intrusion, and the need to address other vulnerabilities. Private networks face cybersecurity challenges that increase with access to the Internet.

Economic security risks are related to price shocks and international supply disruptions of energy commodities, critical materials, and/or equipment. Globally traded energy commodities are subject to rapid price swings from a diverse range of geopolitical factors. These price shocks create uncertainty for energy-dependent businesses, which, in turn, can reduce investment and productivity. Major energy suppliers could manipulate the market by shifting output levels. Additionally, the manufacturing of large energy infrastructure components can be dependent on global supply chains that may be subject to long lead times, long-range shipping logistics, and price volatility.

Conflict-related security risks are related to unrest in foreign countries. Energy-related international security risks include those that involve unrest in locations that are critical to global energy supply, unrest driven by energy prices, and climate change-induced risks such as crop failure, water shortages, or extreme weather. These factors may increase risks to the United States.[51,52]

1.3.2 Economic Impacts

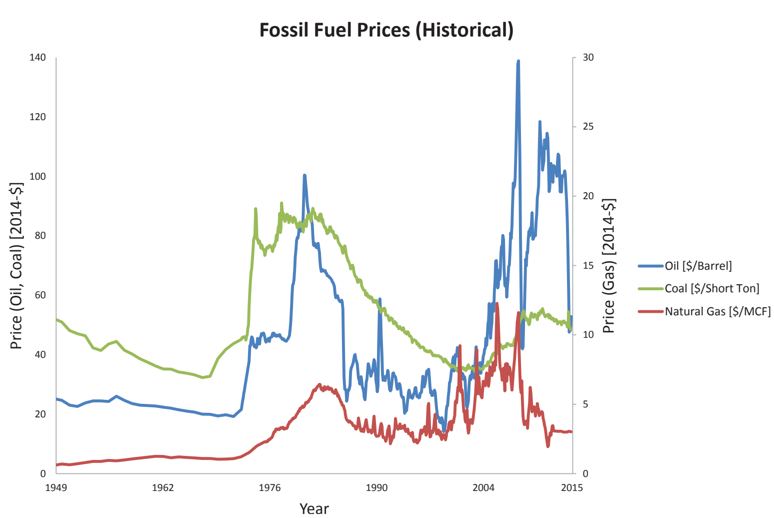
Energy costs are embedded in nearly every aspect of the U.S. economy. The total cost of energy supplies to end users in the United States was roughly $1.2 trillion in 2010,[53] or about 8% of the total gross domestic product.[54] Improved energy technologies can enhance economic activity by reducing energy costs, improving supply reliability, reducing energy imports, and expanding markets for energy technology.

Energy costs: The costs of energy are determined by a complex interplay of the primary energy commodity supplies available at a given price, the capital and operating costs of converting these supplies into energy services, and the demand for these energy services. This also leads to competition among energy resources and services, with alternatives that can serve as substitutes. The costs associated with security or environmental externalities are often not fully included in the market price.

Reduced energy costs generally contribute to improved performance in many sectors of the economy. In addition, cost-effective efficiency measures (e.g., appliance standards, weatherization) can provide more disposable income for individual consumers. Lower oil prices benefit consumers broadly but can reduce employment in the oil industry. Cost reductions for solar and wind electric power generation can affect the competition with other, more traditional generation options.

Energy systems all respond at different rates to changes in prices and technology developments. Energy prices respond to supply and demand in the market and are volatile, as illustrated in Figure 1.6, and notoriously difficult to predict. End-use fuel demand is relatively inelastic in the short term, in that small changes in supply can cause large shifts in prices. Factors as diverse as inventory adjustments, economic activity, geopolitical events, and market speculation can drive volatility on various timescales. This volatility complicates business planning, which could negatively impact the economy. Having a diversified portfolio comprising different energy supply and use technologies provides "options" value and can allow one to hedge the risk of being dependent on a single energy supply. Reducing fuel use through improved efficiency can also moderate steep price changes.

Figure 1.6 Energy Prices by Year for the Coal, Natural Gas, and Oil Markets. Note the substantial price volatility, which can be even more pronounced when examined over a shorter time frame.[55]



Disruption-related losses: Power outages cause substantial economic costs to the businesses they affect. A 2006 study by Lawrence Berkeley National Laboratory estimated that disruptions to the U.S. electric power system cost from $22 to $135 billion per year due to normal weather events, downed trees, and equipment failure.[56] A more recent study found outage-related costs ranging from $20 to $50 billion per year for weather-related outages alone. These estimates do not include the damage from extreme weather events, such as Hurricane Ike in 2008[57] or Hurricane Sandy in 2012.[58] Reducing these costs through improvements to the transmission and distribution system would benefit the economy as a whole.[59]

Energy imports: Expenditures for energy imports go to external producers and can be a substantial component of the U.S. trade deficit. Net petroleum imports cost the U.S. economy approximately $190 billion in 2014.[60] During the next twenty years, the International Energy Agency (IEA) projects substantial pressure on global oil markets as global demand continues to grow;[61] others project this can be managed.[62] With international sales of coal, natural gas, and refined products, the United States may become a net energy exporter, but crude oil imports will continue and U.S. oil prices will remain tied to global prices.[63] Reducing dependence on imports reduces the potential impact of supply disruptions by keeping more of the additional expenditures within the domestic economy.

Energy technology markets: Production and export of energy equipment represents a substantial market opportunity for the United States that would generate high-value jobs. For example, the IEA forecasts that clean energy will provide $7 trillion of the $10 trillion invested in electricity generation capacity growth over the next twenty years, of which $6 trillion will be in renewables and $1 trillion will be in nuclear power. Nearly two-thirds of this investment will be in the emerging economies. Energy efficiency investments will account for a further $8 trillion of investment.[64,65,66]

1.3.3 Environmental Impacts

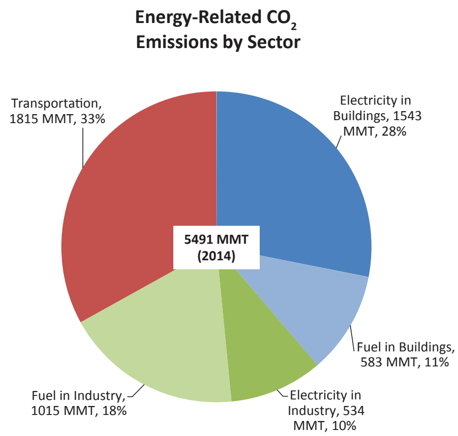
Energy production, delivery, and end use can have significant detrimental impacts on the environment. Air and water quality have historically been the primary concerns. More recently, issues of land/water availability, ecosystem health, and the global climate have joined the list.

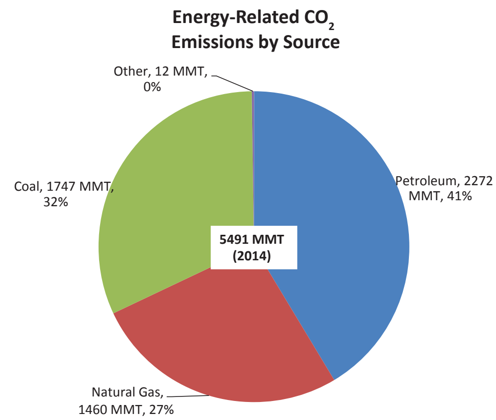
Air pollution: Criteria pollutants, such as sulfur oxides, nitrogen oxides, particulate matter, and volatile organic compounds, are released into the atmosphere by the combustion of fuels in power plants, vehicles, industry, and building equipment. Some pollutants are directly harmful to human health while others participate in atmospheric chemical reactions that generate harmful conditions such as ground-level ozone. Technology options for further reducing air pollution from energy systems can be made available through RDD&D on both systems that can control these emissions and through developing alternatives that do not produce pollutants.[67,68,69]

GHG emissions: Gases such as water vapor, carbon dioxide (CO_2), methane, and nitrous oxide increase the global temperature via the greenhouse effect.[70,71,72] The concentration of CO_2—the predominant long-lifetime GHG—in the atmosphere has increased from about 280 parts per million (ppm) by volume during pre-industrial times to about 400 ppm today, a 40% increase.[73] Figure 1.7 identifies U.S. energy-related emissions of CO_2 by source and sector. U.S. fossil fuel use currently results in the emission of about 5.3 billion metric tonnes of CO_2 into the atmosphere each year. This total includes uses for energy, non-energy (e.g., feedstocks), and industrial uses such as iron and cement production.

Climate change resulting from the the increase in GHG emissions in the atmosphere is already being observed and is projected to increase with the continued release of these emissions. Such changes include temperature increases, sea-level rise, and an increase in the frequency and intensity of certain extreme weather events (e.g., more intense regional precipitation and drought events).[74] In addition, increases in atmospheric concentrations of CO_2 inevitably lead to increased absorption of CO_2 by the oceans, which causes ocean acidification.[75] Addressing the climate and ocean acidification challenges requires the development and deployment of energy supply technologies that either control emissions, such as through carbon capture and storage, or that do not release GHG emissions, such as nuclear or renewable energy.

Figure 1.7 U.S. CO_2 Emissions by (a) Primary Energy Source as a percent of total U.S. energy-related CO_2 emissions (in million metric tonnes); and (b) End Use Sector, including the share for industry and buildings that is from purchased electricity used in that sector, but not including self-generated electricity.[76] Other GHG emissions such as methane are not included here.





Water: Energy-related environmental impacts on water include pollutant discharges, thermal impacts of waste heat discharge, consumption of freshwater, and impacts on aquatic life. Pollutants include acids and toxics, and these can come from deposition of air pollution, acid runoff from mining operations, release of coal ash into lakes or rivers, contamination from energy resource extraction operations, absorption of the increased levels of CO_2 in the atmosphere, and other sources.[77,78] Continued emissions of CO_2 will further acidify the ocean with serious impacts on ocean life.

These potential impacts motivate energy RDD&D to develop technologies that, for example, reduce atmospheric emissions of pollutants (some of which ultimately go into water), control acids or toxics that go directly into water, reduce thermal loading from cooling systems by improving efficiencies and by switching to closed loop or dry cooling systems, and reduce emissions of CO_2.

Land: Environmental impacts on land can take many forms, such as deposition of atmospheric pollutants or direct discharge of pollutants (e.g., as coal ash) and physical disruption from fuel extraction/production or associated with energy plant and infrastructure siting. Physical disruption can take many forms, from mountaintop mining,[79] to land used for oil and gas operations,[80] to use of agricultural or other land to grow bioenergy crops, to placing wind turbines on farm or ranchland, each with differing degrees of disruption.[81] Another potential impact is induced seismicity (i.e., earthquakes) caused by injecting water into the subsurface (for hydraulic fracturing or disposal) associated with oil and gas extraction or waste water disposal, as well as geothermal energy operations.[82,83,84,85]

Over the last several decades, significant progress has been made in reducing pollution—atmospheric, water, land—from energy-related activities. Energy-related atmospheric emissions of conventional pollutants such as particulates, sulfur, and nitrogen compounds have been reduced through improved combustion strategies and “end-of-pipe” (e.g., scrubbers, catalytic converters) emissions controls. Additional progress has occurred by transitioning to cleaner fuels and renewable resources. These successes indicate what can be accomplished with RDD&D and policy. Advanced technologies can have a significant impact on the next generation of challenges, especially deep reductions in GHG emissions. The United States can demonstrate the viability of sustainable energy systems to the global community to provide leadership in creating vibrant economies, enhancing human progress, and assuring a sustainable biosphere.

1.4 Context for Evolving Energy Systems

There are many challenges to meeting the objectives of a secure, resilient, economically competitive, and environmentally responsible energy system. RDD&D opportunities should be considered in the context of the size and inertia of the energy system, as well as the costs to develop and deploy energy technologies. There are important public and private roles in helping the U.S. energy enterprise overcome these challenges.

1.4.1 Size

U.S. energy infrastructure is woven throughout the fabric of the economy. The costs required to modify these energy systems are proportional to the scale of the systems and compounded by their complexity, but moderated by the advanced age of many of these systems and the need to replace them.

Energy supply and infrastructure: The United States currently has about 1,000 GW of power plants,[86] with slightly more than 19,000 electric generators with individual capacities of one megawatt or more at about 7,000 operational sites and many more small, distributed facilities all connected to 640,000 miles of transmission lines and 6.3 million miles of distribution lines.[87] It also has about 140 refineries[88] and the associated infrastructure of wells, pipelines, and terminals. The transportation system depends on some 2.6 million miles of interstate and intrastate roads[89] as well as 140,000 miles of Class I railroads.[90] Each of these infrastructures is interconnected to non-energy systems such as water and communications.[91]

End-use: In 2012, there were more than 5.6 million commercial buildings with a total of 87 billion square feet of floor space;[92] about 115 million residential households;[93] and about 250 million light-duty vehicles,[94] which traveled a total of almost 2.7 trillion miles.[95]

Numerous stakeholders: A challenge of implementing new technologies is the number of actors that must be engaged, ranging from more than 600,000 firms involved in the construction industry, 250,000 companies across the manufacturing sector, 17,000 firms across the supply chains for appliances and vehicles, more than 3,000 electric utilities and cooperatives, and, of course, more than 300 million consumers.[96]

1.4.2 Inertia

The scale of the energy system inevitably results in significant inertia. It would take decades to fully replace existing assets with advanced energy technologies.

Electric power: In electric generation, transmission, and distribution systems, the need to replace aging equipment opens the door for introducing significant new technologies to address the challenges facing this sector. However, equipment can last three or four decades or more, slowing the introduction of advanced technology. Siting generation, transmission, and distribution systems can also take long periods.

Buildings: Given lifetimes of buildings of sixty to eighty years, turnover in the building stock itself will have limited impact on energy use in the near- to mid-term. Technologies to retrofit buildings for much higher efficiency at low cost will be important to capture significant energy savings and emissions benefits in the near term that otherwise would wait decades before the existing building stock was replaced. RDD&D on energy technologies for new buildings is also important because buildings that are designed for optimal energy performance and flexibility can capture decades of energy savings. In contrast, the furnaces, appliances, and other equipment within buildings last approximately ten to twenty years, so the RDD&D focus for them can be on advancing new equipment rather than retrofits.

Manufacturing: In the industrial sector, the high energy intensity of producing commodity materials encourages the introduction of new processes, plants, and equipment; partial retrofits may deliver energy and emissions returns much lower than the potential, while also missing many of the productivity and performance benefits of the improved production process. However, replacing capital equipment can be difficult given the low returns on commodity materials. RDD&D to develop clean processes that also lower capital costs and increase productivity and performance are then particularly important.

Transportation: For the transportation sector, the typical fifteen-year lifetime of vehicles means the vehicle fleet in the United States will turn over multiple times by 2050, allowing the introduction of several new generations of technology. More challenging is the modernization of the fueling, vendor, and service infrastructures to sustain the vehicle fleet—a process that may require longer periods. The underlying infrastructure of roads, rails, airports, and waterways will change even more slowly, constraining system evolution.

The energy infrastructure that evolved over the past century was designed for conventional technologies. New fuels and systems that are not adequately compatible with the existing infrastructure, such as hydrogen fuel cell vehicles, would require new infrastructures for fuel production and delivery, as well as new supply chains for equipment manufacture. This poses a "chicken-and-egg" dilemma: without a widely distributed fueling infrastructure it is harder to convince potential vehicle purchasers to buy, and without sufficient vehicles it is hard to pay for a large refueling infrastructure. This can impede technology introduction.

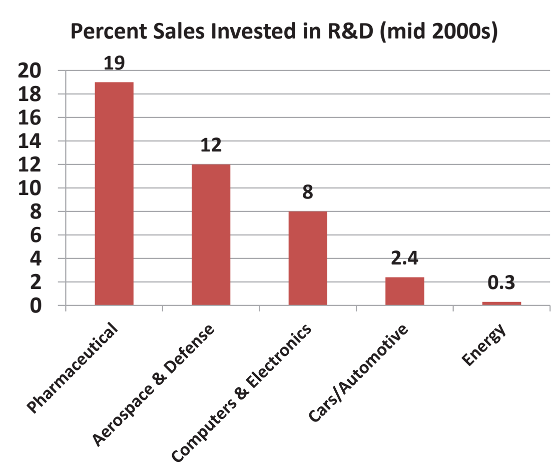
Finally, the time required to conduct energy technology research varies by technology and sector, but can be many years. While turnover of existing energy system assets limits the demand for new energy technologies, the pace of advanced energy technology innovation, a function in part of the resources devoted to RDD&D, affects the supply of new technologies to energy markets.

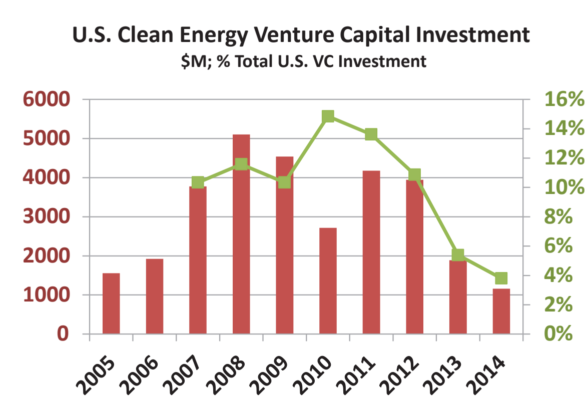
1.4.3 Research and Development Investments

Overall, the energy sector makes relatively limited R&D investments in comparison with other sectors (Figure 1.8a). Corporate investments in clean energy R&D have remained in the range of $3 to $4 billion from 2006 to 2014.[97] Venture capital funding has generally declined from its peak in 2008 (Figure 1.8b). In part, this may be due to the long time frames for returns on energy R&D. Directed basic research and early applied R&D can require as much as a decade or more to demonstrate bench-level results, indicating that a useful technology might be developed. Then, successful technologies for producing fuels or electricity, for example, are competing in low margin commodity markets and thus face a significant challenge in generating high returns. These pose challenges for private investors.

Figure 1.8 (a) Percentage of Gross Sales Invested in R&D for Selected Sectors of the U.S. Economy.[98] (b) U.S. Clean Energy Venture Capital Investment. The investment in RDD&D is low for energy compared with the other sectors listed, and is also a low and recently declining share of venture capital investment.[99]

Credit: (a) National Science Foundation (b) American Energy Innovation Council





1.4.4 Economies of Scale and Learning

Economies of scale: Economies of scale occur in several forms. Conventional power plants and refineries, for example, are built in scales of hundreds of megawatts to multiple gigawatts to capture economies of scale and improve efficiency in generating power or refining fuels. For some applications, however, larger scales have been found to increase costs due to the extensive on-site fabrication required, and the cost of integrating multiple complex systems.

Economies of scale are also realized in manufacturing, where large-volume production of individual devices provides savings. For example, more than 40% of the cost reduction in silicon photovoltaic production from 1980 to 2001 was due to economies of scale in the plant size.[101] To capture economies of scale, a company needs to have some expectation that it will be able to sell product from a larger plant over a sufficient period to get a return on its investment. Very large plants needed to capture economies of scale can be extremely capital intensive and pose substantial, often multibillion dollar risks for companies.

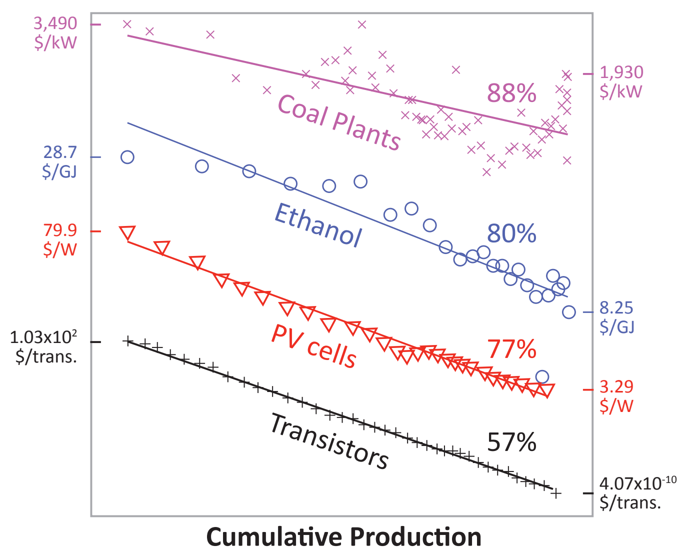
Economies of learning: In general, the cost of a given technology declines as cumulative production increases and, thus, with deployment (Figure 1.9). This is interpreted as "learning by doing" to drive cost reduction.[102] The pace of learning varies by technology. For example, photovoltaic modules have demonstrated cost reductions per kilowatt of about 20% with each doubling of production over the past forty years; wind turbines demonstrated about 15% for each doubling from 1980 to 1995; and natural gas-fired combined cycle turbines have demonstrated about 5% learning for each doubling over the past twenty years.

R&D is important within this framework, as its ability to lower costs and improve performance can have an important impact on deployment. In addition, R&D may impact the ability of the technology to benefit from economies of scale—particularly in manufacturing—and learning.

The need for large-volume production poses a chicken-and-egg problem for manufacturing. On the one hand, large volumes are required to drive prices down; on the other hand, low prices are required to sell into the market and achieve these volumes.

Figure 1.9 Learning Curves for Selected Technologies[100]

Credit: National Academy of Sciences



1.4.5 Demonstration and Deployment

Mobilizing capital for clean energy demonstration and deployment faces many challenges. Energy supply technologies often take years to commercialize, require relatively large front-end capital investments, and then supply commodity fuels or power with relatively low margins. This means that net returns on major capital projects can be negative for long periods of time. For advanced energy efficient technologies, capital costs are generally higher than for the incumbent technology even though their life cycle costs typically are lower. Purchasers are generally wary of high capital costs, and this sensitivity is increased for a relatively new technology, which may have performance risk or uncertainty due to immaturity. These finance challenges can occur at several development stages described below:

- Basic feasibility stage, where new technologies are translated into early functioning hardware
- Demonstration stage, where the technology is scaled up to demonstrate performance at a commercial scale
- Commercial viability stage, where the new technology can enter markets
- Economic viability stage, when the technology can provide significant return

These stages pose challenges in mobilizing needed resources and requiring considerable time to realize a return. The volatility of energy markets and changing policies can complicate these challenges.

Finally, once a technology is demonstrated as viable, it is much easier for a competitor to copy it or find alternative approaches to achieve the same thing. This can sharply reduce the financial return for the innovator as well as the incentive to invest.

The various steps of research, development, demonstration, and deployment have many interactions and feedbacks among all of them as the work progresses, making it more of an interwoven tapestry of activities than the conventional linear depiction.[103] Thus, in the following chapters, the term RDD&D is typically used rather than individually identifying a particular stage within this process.

1.5 Energy Technology Assessments

As described above, current patterns of energy use pose substantial challenges, but developing new energy technologies can address these challenges and open new market opportunities. This QTR identifies many important technologies to do this. Countless technologies could be considered, so criteria were employed to narrow this set down to the manageable number addressed in the subsequent chapters. Building on the work of QTR 2011, the following criteria were used to select energy technologies for QTR 2015:

- **Maturity (and time period):** Technologies should have the potential for significant advances in cost, performance, or other key metrics with further RDD&D that can lead to commercialization in the mid-term and beyond.
- **Materiality (impacts):** The system and associated technologies, in aggregate, should have the potential to save or supply at least 1% of the primary energy of the United States or of a region, or similarly impact a key energy-linked challenge such as reducing carbon emissions.
- **Market potential:** The system or technology should have significant potential to succeed in competitive markets, recognizing that markets are driven by economics and shaped by public policy.
- **Public benefits:** The system or technology should have significant public benefits, such as improvements in public safety and security; much lower emissions of CO_2 or other pollutants; reductions in environmental impacts to land, water, or biota; or others.
- **Public role:** The system or technology should be one that provides value to the public, that the private sector is unlikely to undertake the RDD&D at sufficient scale alone, and for which the public contribution can make a significant impact in advancing the technology.

Technology areas discussed in the subsequent chapters are examined and evaluated against these criteria, with occasional adjustment to allow for differences in regional energy needs and resources or for technologies with very long development cycles (e.g., fusion).

In addition, the following attributes were considered:

Crosscutting applicability: Inevitably, many technology themes transcend specific application areas. Advances in one area can lead to benefits in others. These crosscutting opportunities span numerous energy systems such as grid integration, subsurface science, advanced materials, modeling and simulation, data and analysis, decision science, cybersecurity, energy storage, and broadly considered efficiency. A more comprehensive discussion of crosscutting activities can be found in Chapters 2 and 11.

Improved services: New energy systems developed for improved efficiencies can often provide better services. A recently commercialized example includes solid-state, light-emitting diodes (LEDs), which can deliver a better quality of light than their fluorescent or incandescent predecessors at significantly lower energy consumption.

Price advantages: The availability of low-cost energy supplies within the United States can provide a market advantage for U.S. production of energy-intensive products, such as chemicals or forest products. Efficiency measures that reduce energy demand help reduce market pressure on energy prices.

Energy technology exports: As a leader in R&D on many energy technologies, the United States has the opportunity to lead the world in developing and manufacturing new clean energy technologies, although it currently does not take advantage of this.[104] Global clean electricity supply and energy efficiency markets are estimated by the IEA to total $7 trillion and $8 trillion, respectively, by 2035. Producing for such large markets, together with technology and manufacturing advances, can move new energy technologies rapidly down the learning curve to lower costs.[105,106] Those countries and companies that are able to drive these costs down first may capture a large first-mover advantage. Further, they develop the advantages of building strong supplier networks for the needed inputs, a skilled workforce, and the downstream companies that integrate the energy technology into systems for sale in markets around the world. Production and export of energy equipment represents a substantial market opportunity for the United States that would generate high-value jobs; conversely, if the United States ends up importing much of its energy technology, this could impact the U.S. trade balance, taking the place of fuels that are imported today.

Supplemental Information

Additional Information on Energy Challenges

Agency Information

Representative DOE Applied Energy Program Workshops

[See online version.]

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