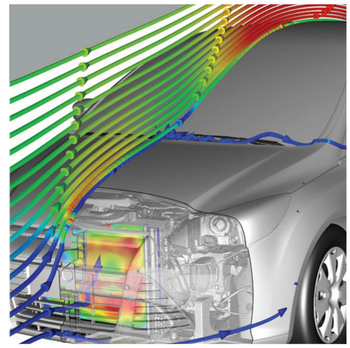
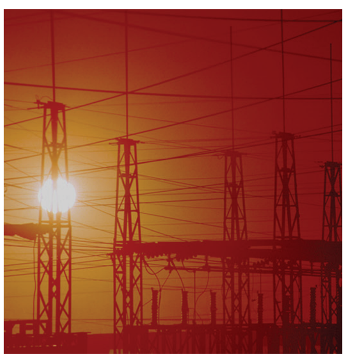
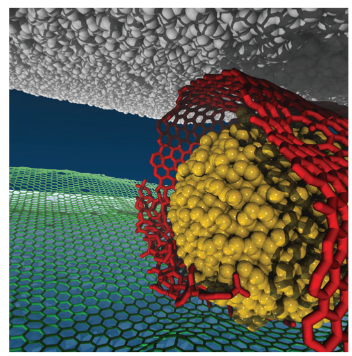




QTR





QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

Chapter 4: Advancing Clean Electric Power Technologies

September 2015

Issues and RDD&D Opportunities

- Electric power generation technologies are maturing to a new level of integration and interdependence that requires an expanded system approach and a global view to optimize integration, minimize risks, and maintain reasonable costs.
- There is potential in each of the technologies: more efficient coal and natural gas generation with carbon capture; advanced nuclear reactors; rapidly advancing renewable technologies, such as wind and solar; and developing technologies, such as fuel cell and marine hydrokinetic power.
- Common component developments offer opportunities for breakthroughs: advances in high temperature and pressure steam turbines, new supercritical carbon dioxide power cycles, hybrid systems matching renewables with nuclear or fossil, and energy storage.
- Advanced capabilities in materials, computing, and manufacturing can significantly improve electric power technologies cost and performance.
- A systems approach for the power sector (as described in Chapter 3) also enables innovation at the technology level, such as by identifying key characteristics needed in supply technologies to meet the changing requirements of the grid, including such factors as cost, efficiency, emissions, ramping rates, turn-down ratios, water use, and others. These can be approached through multivariable portfolio analysis.
- International cooperation greatly expands the collective research, development, demonstration, and deployment (RDD&D) investment in clean power technologies by governments and industry, accelerating the successful completion of demonstrations and full commercial deployment.

4 Advancing Clean Electric Power Technologies

4.1 Introduction

Clean electric power is paramount to today's mission to meet our interdependent security, economic, and environmental goals. While supporting aggressive emission reductions, the traditional market drivers such as reliability, safety, and affordability must be maintained and enhanced. The current portfolio of electric production includes a combination of reliable, but aging, baseload generation, evolving renewable resources, and new natural gas resources. Complementing this evolving generation mix are technologies to enable higher efficiencies and pollution control.

This chapter describes the current status and future outlook for power generation technologies and identifies a portfolio of RDD&D directions and opportunities that can be available to meet future regional demands. A combination of flexible technology options will be required to meet increasing power needs and the security, economic, and environmental challenges outlined in Chapter 1. The International Energy Agency (IEA) projects that world primary energy demand could grow by 37% between 2012 and 2040, assuming existing and planned government policies,[1] and during this period electricity demand is projected to grow by 78%. This review will not make regulatory and market policy recommendations as these are addressed by the Quadrennial Energy Review (QER).

Through 2050, most of the increased energy demand and carbon dioxide (CO_2) emissions are projected to be in non-Organisation for Economic Co-operation and Development (OECD) countries.[2] There will be interactions between energy technologies, international policies, and global market competitiveness. The Quadrennial Technology Review (QTR) focuses on technological advances to meet U.S. energy needs and challenges, recognizing that these also offer opportunities for cooperative research that will expedite the international deployment of these technologies. For example, there is significant ongoing cooperative research with China in pre-competitive areas on technologies such as carbon capture and storage (CCS), and there is progress toward cooperation in large-scale demonstrations that are expected to be complex and expensive, with long lead times.

4.1.1 Progress since the Last Review

The development of a robust portfolio of clean power technologies has seen major progress. Investments made through the American Recovery and Reinvestment Act (ARRA) are demonstrating returns in record levels of efficiency, flexibility, and lowered emissions. The ability to take on costly demonstration projects to advance technology, decrease developmental risks, and provide baselines for future deployment has been critical in making headway toward advanced technologies that require significant investment for demonstration, such as CCS and small nuclear reactors. Four years ago, only a single large-scale CCS demonstration project had begun construction in the United States. As of August 2015, one project is operational and three more are under construction. Globally, the number of large-scale CCS demonstration projects has doubled in this time frame, many with U.S. involvement, providing a wealth of data on CO_2 capture systems and CO_2 storage.

Since 2011, two passively-safe reactor designs have received certification from the U.S. Nuclear Regulatory Commission (NRC) under a new regulatory framework that requires a single approval for construction and operation. Three utilities received combined construction and operating licenses that are enabling the construction of the first four new reactors in more than thirty years in the United States. Additionally, renewable energy technologies have seen dramatic cost reductions, which have supported rapidly gaining market share as shown in Table 4.1. This increase in scale is bringing down costs further and leading to next-generation advancements which will result in even greater deployment.

Table 4.1 Electric Power Capacity and Production, 2010 and 2014

	Generation capacity 2010 (GW)	Generation capacity 2014 (GW)	Power production 2010 (TWh)	Power production 2014 (TWh)
Coal	316.8	300.4	1,847	1,586
Gas	409.7	430.3	999	1,122
Nuclear	101.2	99.2	807	795
Hydropower	78.8	79.2	260	258
Wind	39.1	66	95	182
Biopower	11.4	13.4	53	64
Solar	0.86	9.3	1.2	18.3
Geothermal	2.4	2.6	15	17
Fuel cell	0.06	0.2	0.3	1
Marine and hydrokinetic	0	0	0	0

Data from U.S. Energy Information Administration (EIA) *Electric Power Monthly* Feb 2015 Tables 1.1, 1.1a, and 6.1; 2010 Capacity from EIA *Electric Power Annual* Report 2013 tables 4.2a and 4.2b. Fuel cell data through June 2014 from Breakthrough Technologies Institute. EIA solar reporting does not represent about 8.5 gigawatts (GW) of distributed systems reported by SEIA in December 2014.

4.1.2 Balancing Drivers

To produce electricity, power companies assemble a portfolio of generation technologies that are selected in the context of myriad considerations, which are changing over time. The central requirement is that the power system must provide reliable power; to do this it must have the flexibility to respond to changes in demand and the resiliency to restore service following perturbations. Additionally, the power system must operate safely while protecting the environment and at a reasonable cost to the consumer.

Investment in the deployment of power technology is made on the local scale by power companies with state and federal review. In the past, selection of technologies was traditionally based on balancing regional customer demand, transmission availability, and resources of fuel and water. These siting characteristics would be evaluated based upon a specific location and the technology being considered. In recent decades, the need to address traditional criteria air pollutants, and more recently mercury and air toxics, was factored into the decision making around technology deployments. The evolving criteria for selecting power technologies is depicted in Figure 4.1.

Figure 4.1 Requirements and criteria have expanded over time.

Siting Characteristics				Environmental Criteria				Electric System		
Traditional Pollutants	Local Resources	Transmission Connection	Water Availability	GHG Footprint	Minimal Land Use	Water Impacts	Manage Waste	Load Following	Dispatch-ability	Security

As the electricity system evolves to address increased security, economic, and environmental challenges, the drivers that shape technology deployment decisions have expanded. The electricity system as a whole must be able to respond to variations in the level of output produced, maintain the ability to reliably generate power when needed, and do so while maintaining security against physical and cyber threats. Economic requirements motivate increased reliability and lowered costs. Environmental requirements include land impacts, water consumption and quality, waste management, and greenhouse gas (GHG) emissions. Finding a realistic balance between competing drivers (security, cost, environment, and societal energy demand versus acceptance) motivates new technology solutions that can match regional resources and local requirements.

4

Advancing clean electric power generation requires developing a full set of options, being cognizant of complementing strengths and weaknesses, and finding optimal system combinations to meet basic requirements and future criteria. Progress consists of advancements in technologies currently deployed, such as coal or nuclear; rapidly advancing renewable technologies, such as wind and solar; and technologies entering deployment, such as CCS, fuel cells, and, on the horizon, enhanced geothermal. The following sections review the strengths, challenges, and emerging opportunities for each electric power generation technology.

4.1.3 Technology Options in a Clean Electric Power Portfolio

For the electricity sector to meet all of its varied requirements, the characteristics of the individual technologies that comprise the generation system must be considered. Nuclear energy, for example, is capable of providing non-GHG emitting power, but is not well-suited to vary its output in response to the needs of the grid, and it generates nuclear waste that requires careful management. The development of coal with CCS addresses concerns about GHG emissions, but in doing so, significantly increases the water required for plant operations unless dry cooling is used. Wind power does not directly emit GHGs and requires little water, but the areas that have the most favorable resources may have limitations in their ability to access established transmission lines, and variation of power output also presents challenges. All of the technologies addressed in this chapter have differing attributes across these and other criteria.

While some shortcomings are inherent in the technologies themselves, RDD&D in these technologies can help to improve their performance characteristics. Nuclear fission will always produce radioactive wastes, but the development of new reactor technologies may make them more manageable. Feedstocks for biopower will need large areas for production, but RDD&D may lead to approaches that require less of it or use marginal lands. The discussion of the technologies in this chapter along with the accompanying technology assessments will provide a more complete picture of the RDD&D opportunities available.

The societal need for the electricity system to be cleaner and more robust and the market failure that arises from these externalities not being internalized by industry creates a role for government support through RDD&D. This builds upon long-established recognition that the public sector has an important role to play in advancing electricity technologies owing to the centrality of electricity to the national economy and the long timelines necessary to realize the benefits from investments in RDD&D. The government role in RDD&D for electricity technologies varies based upon the level of maturity and involves collaboration with the national labs and universities, and direct engagement with industry to identify and overcome the challenges facing technology development.

4.1.4 Portfolio Management

Even with RDD&D to improve the performance of electricity generation technologies, each technology still possesses strengths and weaknesses relative to the other. These varying attributes can be used to complement one another as they will be deployed as part of a portfolio of technologies that will comprise an electricity generation system. In this context, the shortcomings of one technology can be offset by the strengths of another in the system. Nuclear and coal as currently deployed are generally best-suited to run in full-time baseload operation rather than vary their output in response to changing wind or solar production, while the inclusion of natural gas or hydro in the portfolio leaves the system better suited to accommodate these changes. Ensuring stable and secure operation of the grid sets functional requirements of the entire system. A major change in the system could be achieved by different modes of operation including microgrids, hybrid systems, and energy storage. Utility-scale energy storage would address many of the shortcomings of variable power sources, as well as increase security and resiliency of the power system.[3]

The private sector generally makes the decisions about which technologies to deploy in the electricity generating portfolio. These companies must respond to the needs of the market, including customers' and shareholders', while operating within regulations established to govern the power sector. Depending upon these factors and the access to and availability of energy resources, the composition of regional energy portfolios, both domestically and globally, varies widely. In the United States, the federal government does not make deployment choices, but it can help shape them through regulation and policy. Environmental and reliability regulations can require companies to emphasize or value certain attributes of a technology, and subsidies or credits established in policy are intended to incentivize deployment of certain technologies. State governments often play a role in guiding deployment decisions, especially those that have regulated electricity markets, which require companies to receive state approval of plans to manage the electricity system.

4.1.5 Portfolio Approach

Electric power generation technologies are maturing to a new level of integration and interdependencies that require a system approach and a global view. As the industry evolves to meet growing electrification and GHG-reduction goals, challenges arise in optimizing the system, minimizing risks, and maintaining reasonable cost. Domestic choices on clean energy technologies also interface with global energy choices. Technologies are needed that will provide a portfolio of options for reliable, affordable, and clean power generation; available to meet regional needs; provide future flexibility; and enable a U.S. leadership role in global energy and environmental dialogue and markets. This chapter will identify key technical challenges and opportunities in RDD&D that can come to fruition by 2030 and be commercialized with significant impacts by 2050.

Figure 4.2 SaskPower Boundary Dam CCS Project: Pushing CCS Forward Internationally

Credit: SaskPower

4.2 Clean Power Technologies

The 2011 QTR stated that "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'. RDD&D will be most productive if it is conducted in a manner cognizant of these trends." This still remains the case, although the advent of abundant and affordable domestic natural gas supplies is having a significant near-term impact on new generation deployments.

4.2.1 Fossil Power with Carbon Capture and Storage

Fossil fuels currently supply 80% of the world's electric power. Globally, the demand for coal is projected to continue growth, but slowing to a rate of just 0.5% per year to reach 6,350 metric tonnes carbon equivalent in 2040, while natural gas has seen a near 50% rise in global production with recent advances in unconventional sources following a near-linear growth to 5,400 billion cubic meters in 2040.[4] Domestic projections for energy use are provided by the Energy Information Administration.[5] Domestically, coal and natural gas plants provide power generation and drive numerous industrial processes. However, it is critical to minimize CO_2 emissions from fossil power generation, while maintaining cost-effective power generation.

CCS technology is used to separate, capture, transport, and permanently store CO_2 emissions from power plants and industrial facilities. The IEA projects that CCS will be required for 14% of the global cumulative CO_2 emissions reductions by 2050, for a scenario with less than a 2°C rise in global temperatures.[6] In fact, without a CCS mitigation option, the United Nations Framework Convention on Climate Change projects that the costs of achieving this global goal would increase by 138%.[7]

The primary challenges to full implementation are experience and commitment to commercial-scale demonstration, establishing the basis for financial support through confidence in the technology and lowering costs, and implementing effective policy drivers to increase deployments. First-generation, large-scale CCS demonstrations are being demonstrated around the world. One example is the SaskPower Boundary Dam Project, shown in Figure 4.2. Another is the Southern Company Kemper Project shown in Figure 4.3. Such demonstrations establish that CCS can be integrated at commercial scale while maintaining reliable, predictable, and safe plant operations. As a positive

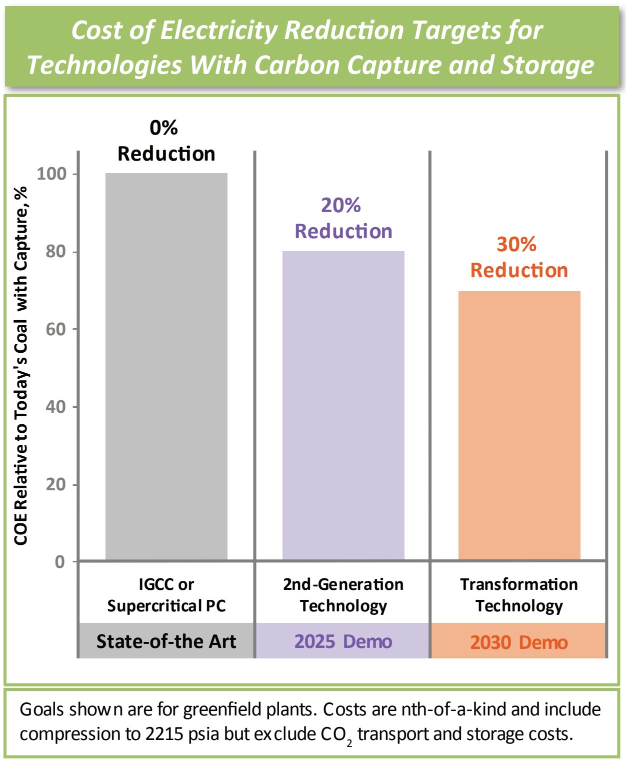
Figure 4.3 Southern Company Kemper Project

Credit: Mississippi Power

Southern Company Services, Inc. of Birmingham, Alabama, is developing an air-blown IGCC power plant large-scale demonstration project utilizing a coal-based transport gasifier. The project will deploy the Selexol physical solvent technology to demonstrate about 67% CO_2 removal, roughly three million tons per year. A sixty-mile CO_2 pipeline has been built to connect to an existing CO_2 pipeline used for enhanced oil recovery.

movement toward the next step, the SaskPower Boundary Dam project is the world's first large-scale, coal-fired, post-combustion carbon capture plant. The capture unit, based on Shell's Cansolv process, is a retrofit of Unit 3 at the Boundary Dam plant, and captures 90% of its CO_2 emissions, more than 1.1 million metric tonnes of CO_2 per year. The CO_2 is transported and used in the Weyburn oil fields for enhanced oil recovery. As shown in Figure 4.4, building upon these successes, technologies for coal power with CCS are pursuing aggressive levelized cost of electricity (LCOE) reduction targets.

Figure 4.4 Potential for Bringing Down Nth-of-a-Kind Cost Compared to First-Generation CCS Technology (as evaluated to define DOE CCS program targets)



Second-generation CCS technology includes a suite of improvements in capture performance, plant efficiencies, and component cost, and expanded characterization of storage options. These technologies are expected to become commercially available in the mid-2020s. Analyses of coal power with CCS conducted by the National Energy Technology Laboratory (NETL) show a 20% decrease in costs of mature units compared to first-generation CCS technology.[8]

Modeled deployment of transformational technology shows potential for a 30% reduction in LCOE. RDD&D of transformational technologies will make significant use of emerging capabilities such as integration of advanced manufacturing methods into supply chains for a variety of new technologies under development (e.g., high temperature alloys, high performance ceramics, and integration of ceramic to metal elements) to reduce cost and improve processing time. Advanced simulation will increasingly be employed to rigorously screen and evaluate new technologies and accelerate scale-up processes.

Large-Scale Integrated Demonstration and Deployment

Large-scale integrated technology demonstrations enable deployment of advanced CCS technologies by reducing technology risk at-scale. There are currently twenty-two large-scale CCS projects globally in the "operate" or "execute" stages (i.e., between detailed design and commissioning), and thirty-three projects in earlier stages.[9] Data on CO_2 capture systems and CO_2 storage are accumulating through these global CCS projects, which span power generation and industrial platforms representing various technology configurations, utilizing a diverse set of feedstocks, producing a variety of commodities, and accessing a range of permanent storage solutions.

U.S. private-public partnerships include the largest portfolio of large-scale integrated CCS demonstration projects in the world. Southern Company's Plant Barry has demonstrated the integrated performance of capture and storage on a portion of a coal plant's exhaust stream.[10] A 240 megawatt (MW) post-combustion project designed to capture 90% of its CO_2 flue gas emissions is under construction at NRG Energy's WA Parish facility. Southern Company's 582 MW Kemper Project (see Figure 4.4) plans to integrate CCS with advanced Integrated Gasification Combined Cycle (IGCC) units. Industrial sector projects include Air Products (CO_2 capture from steam methane reformers), Archer Daniels Midland (CO_2 capture from ethanol production), and Skyonics (mineralize CO_2 for saleable products).

CO_2 Capture Technology

Two approaches to carbon capture are post-combustion and pre-combustion capture. Post-combustion capture is applicable to the pulverized coal (PC) combustion and natural gas systems used in typical fossil fueled power plants today, while pre-combustion capture can be designed with an IGCC for a highly efficient, flexible-operation, advanced power generation system. Both separation techniques use solvents, sorbents, or membranes to separate CO_2. Key challenges for solvents and sorbents are reducing the energy required for releasing the CO_2 to regenerate the solvent or sorbent, increasing reaction speed, and reducing material cost. Improving durability and tolerance to contaminants, and CO_2 selectivity are critical for membranes. Advancements in manufacturing and process chemistry, integration with the power plant, and engineering and design all offer opportunities. In addition, novel research currently explores technologies such as electrochemical-based approaches, direct CO_2 phase change using passive nozzle designs, supersonic gas separation, and electrochemical capture. Such advanced concepts are focused on developing transformational systems that have the potential to realize step-change improvements in cost and performance beyond those seen using the more conventional solvents, sorbents, and membranes. First-generation systems, such as the Boundary Dam project, are operating now.

Small pilot-scale tests (e.g., one megawatt electrical [MWe]) of second-generation capture technologies, such as advanced solvents, sorbents, and membranes, are currently being conducted. Promising technologies, successful at the smaller scale, could be tested at large pilot-scale (10+ MWe) to advance the technology for possible first-of-a-kind demonstration by 2020. Additionally, transformational technologies, which have the potential for further cost reductions, are being tested at laboratory- and bench-scale and could be ready for commercial demonstration by as early as 2025.

High Efficiency, Low Cost Energy Systems, and Integrated Capture Concepts

Efforts to improve base plant costs and efficiencies are integral to CCS, and in some cases (e.g., gasification-based technologies) can have a greater impact on LCOE reduction for a fossil plant with CCS than improved capture technology. The non-capture components of a power plant offer opportunities for improving fuel conversion efficiencies, increasing plant availability, reducing water consumption, and achieving ultra-low emissions of traditional pollutants. For gasification and natural gas technologies, this includes low-cost air separation membranes, high efficiency hydrogen turbines, more efficient gas cleanup, and high temperature fuel cells. For pulverized coal plants, it includes advanced turbines, supercritical CO_2 (sCO_2) power cycles, and high-temperature durable materials.

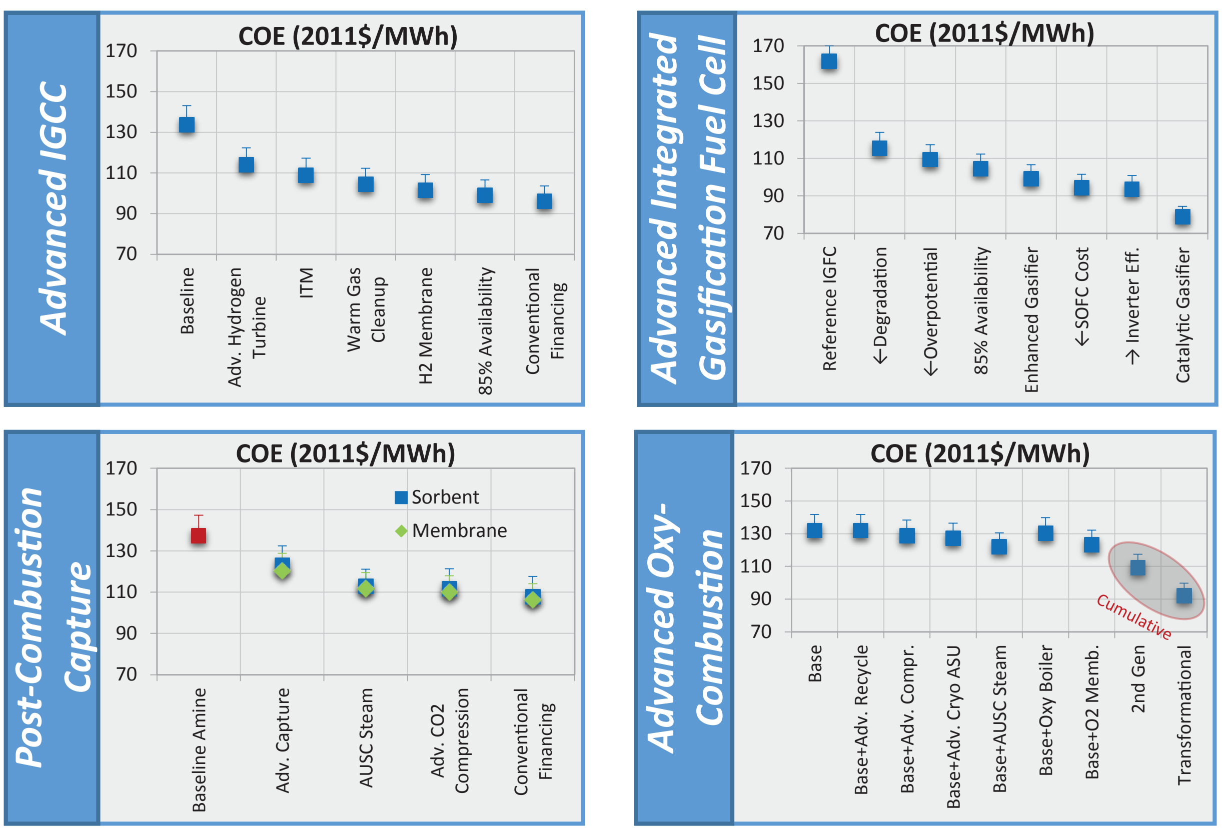
Alternative combustion processes are being explored. Oxy-combustion, which burns coal directly with oxygen creating highly concentrated CO_2, and chemical looping, in which oxygen is separated from air as an inherent part of the combustion process, are examples. Reducing the water footprint is of critical importance through the deployment of highly efficient power generation systems, development of novel systems that require very little water, and water treatment and reuse within the power generation industry. In addition, fossil energy plants may serve as sources or supplies for fresh water through application of novel and emerging technologies.

Examples of advanced systems include turbine-based cycles that operate at temperatures up to 3100°F with the potential to achieve 65% combined cycle efficiencies, but require advanced materials, system modeling, transition strategies and low nitrogen oxides (NO_x) combustion. Supercritical CO_2 power cycles have the potential to reduce the cost of coal-based power generation by 5%–15%. The goal is to pilot test a pre-commercial scale 50 MW sCO_2 power cycle unit, demonstrate reliable operation, and integrate with CCS and other transformational technologies to reduce the cost of CCS by 30% by 2025.

Analysis of the cumulative effects as multiple advanced components are integrated into a plant are used to evaluate the potential impacts, demonstrating that the pursuit of multiple combustion and gasification pathways is key to significantly improving the efficiency and decreasing the cost of electricity (COE) of fossil plants with CCS.[11] Figure 4.5 shows several such integrated evaluations of COE improvements, achieved along a variety of technology development pathways being pursued in CCS RDD&D. In this analysis advanced technologies have each been assessed individually and cumulatively in the appropriate combustion and gasification pathways to assess the impact to key metrics such as net plant efficiency and COE. Technologies evaluated are at varying technology readiness levels; thus, both the cost and performance data available to perform the evaluation and the anticipated date for commercial readiness vary significantly, and require RDD&D across multiple advanced technologies to be successful. Key conclusions include the following:

- Technologies providing improvement in power cycle efficiency (absorption heat transformer, solid oxide fuel cells, advanced ultra supercritical steam conditions) are key to each pathway through reducing operating and fixed costs per unit of net power generated.
- Reduction of auxiliary loads and cost improvements of supporting systems, such as oxygen production and gas cleanup, are critical to advanced oxy-combustion and IGCC.

Figure 4.5 Cost Projections for Advanced Fossil-CCS Plants. Integrated technology improvements and parallel pathways are required to drive down the cost of CCS on fossil plants and reflects nth-of-a-kind cost and performance. (Source: Gerdes et al. Energy Procedia 63 [2014] 7541–7557)

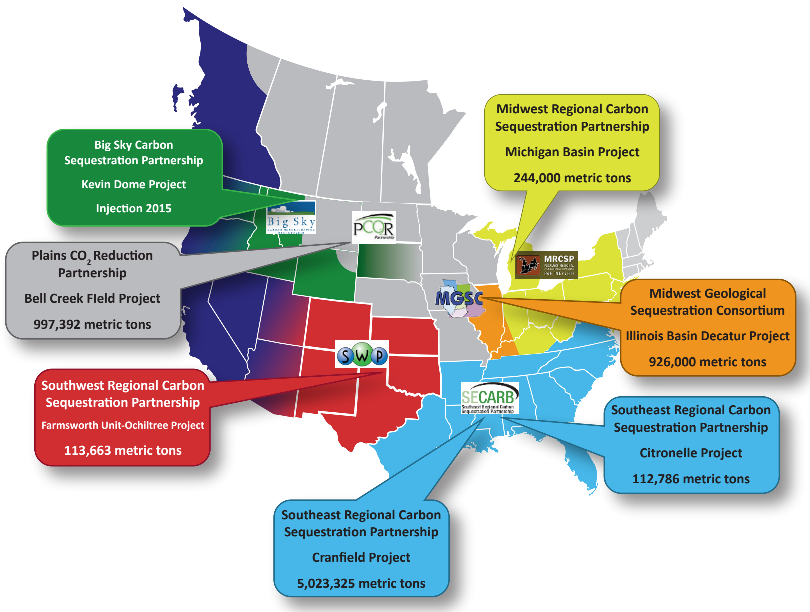


- Improvements in the energy penalty and cost associated with CO_2 capture technology play a significant role in the post-combustion capture pathway and are applicable to both greenfield and retrofit applications.

CO_2 Storage Technology

Development of a successful CO_2 storage industry will require storage that is safe and permanent. Both globally and in the United States, deep saline formations offer the greatest potential for the CO_2 storage necessary to provide meaningful reductions in carbon emissions. As the state-of-the-art technology for CO_2 storage has advanced, a growing number of CO_2 injection projects have been established around the world. In North America alone, more than 10 million metric tonnes of CO_2 have been successfully stored in large-scale field projects. While great progress has been made in saline formation storage over the past decade, work remains to be done.

Figure 4.6 Regional Carbon Sequestration Partnerships



CO_2 storage RDD&D leverages decades of experience from a range of industries such as oil and gas, industrial process fluid injection, and municipal fluid disposal and storage, which provide a basis of geologic characterization, modeling, and monitoring tools. Durable, robust, and cost-effective technologies are needed for geologic storage of CO_2, and field tests are necessary to validate technologies and address critical challenges such as long-term wellbore integrity, geomechanics (i.e., stress state), adaptive control of fluid flow and pressure management, and higher resolution characterization and mapping of the subsurface to identify fractures and faults that are natural or are a result of other subsurface activity. In addition, improved tools are needed to monitor and verify permanent storage of CO_2, mitigate potential risks, and increase storage efficiency. CCS subsurface challenges are closely aligned with those faced by other sectors that utilize the subsurface for energy production and storage or disposal of energy waste streams (see also the Supplemental Information for Chapter 7 on *Subsurface Science and Technology*). Activities such as the Regional Carbon Sequestration Partnerships (RCSP) conduct large-scale field projects in different storage types in various formation classes, distributed over different geographic regions, to provide a sound basis for commercial-scale CO_2 storage projects. The RCSP has seven partnerships encompassing forty-three states, four provinces and more than 400 organizations (see Figure 4.6).

Value-Added Products to Drive Down Cost

While technology advances are being pursued to decrease the cost to capture and store CO_2, there are opportunities for the utilization of CO_2 to help reduce CCS costs as an interim solution in moving toward full-scale storage. Enhanced oil recovery (EOR) is currently the largest and most profitable market for CO_2.[12]

A significant number of the oil reservoirs in the lower 48 are amenable to CO_2-EOR. In fact, 205 out of the 217 large reservoirs of the gulf coast hold as much as 17.7 billion barrels of 'residual oil in place' (ROIP) which is favorable to CO_2-EOR.[13] Crude oil production includes three phases: primary, secondary, and tertiary (or enhanced) recovery. Primary recovery, using natural pressure, produces about 10% of a reservoir's original oil. Secondary recovery can access 20%–40% of oil using injected water or gas. Tertiary, or EOR, techniques can increase output to 60%. As an example, the Dakota Gasification Company's Great Plains Synfuels Plant in Bismarck, North Dakota, has been capturing more than 1.5 million tons of CO_2 per year from a coal gasification plant and selling it for use in EOR for more than fifteen years. With technical validation and assessment, residual oil zones may offer a new opportunity for combined oil production and CO_2 storage.[14] However, additional research on technology and techniques of surface and groundwater monitoring and storage verification for anthropogenic CO_2 used for EOR is necessary for widespread adoption. Other CO_2 utilization options include mineralization and incorporation into building and construction materials (i.e., calcium carbonate or magnesium carbonate), CO_2 curing of concrete products to conserve energy and capture CO_2, and conversion into plastics and polymers. In addition, CO_2 can be used to promote indirect carbon storage through enhanced photosynthesis of algae for biofuels.

Emerging Opportunities

CCS RDD&D activities in the United States have historically focused on new-build coal-fired power plants, but there is opportunity in broadening this focus. All ongoing CO_2 storage and many CO_2 capture-related activities are applicable to CCS retrofit of existing coal power plants, natural gas-fueled power plants, and application to large industrial facilities.

Retrofit of plants with CCS technology: Post-combustion capture technologies represent the greatest potential for CCS retrofits and the development of second-generation and transformational CO_2 capture retrofit technology could enable the continued use of these existing assets with simultaneous reduction of CO_2 emissions. Existing post-combustion systems make use of processes such as amine-based scrubbing that can achieve CO_2 capture rates of 90% or more from flue gas. These are capital intensive and require significant thermal energy to drive the solvent regeneration process.[15] Nearly all of the current global growth in coal electric power generation is in non-OECD countries, creating a large, coal-based capacity projected to be less than twenty years old in 2030.[16] Close collaboration with China and India in demonstrating coal CCS retrofit technologies in those countries would support achievement of global climate goals.

Natural gas plants with CCS: CCS-based RDD&D has advanced the field of carbon capture for all fossil fuel applications. The technology transfer to natural gas for both new plants and retrofits would be relatively straightforward, though those plants will pose challenges due to lower concentrations of CO_2 (3%–4%) in the flue gas that could increase capture cost/tonne CO_2, and greater oxygen concentrations which can lead to degradation of solvents. Large-scale pilot test and demonstration projects are a natural next step in the application of CCS technologies to natural gas processes. With the abundance of natural gas from both conventional and now unconventional sources and the tightening environmental standards, natural gas plants are replacing many aging coal plants in the United States. Europe and other parts of the world, in collaboration with industry, are developing and demonstrating first- and second-generation carbon capture technologies for full-scale, natural gas-fired units.

Industrial plants with CCS: Industrial CO_2 emissions are produced both directly from fossil fuel combustion and indirectly from the generation of electricity that is consumed by industry. In the United States, as much as 27% of CO_2 from fossil fuel combustion in 2013 was from the industrial sector.[17] This is recognized as an area with potential for CCS application. The IEA projects that CCS in industrial applications can reduce CO_2 emissions by up to four gigatons (Gt) annually by 2050. Achieving this would require 20%–40% of all industrial and fuel transformation plants to be equipped with CCS by 2050.[18] Some industrial plants, such as ammonia and natural gas processing, produce high purity CO_2 streams that will enable lower capture cost and may already deploy carbon capture and separation as an inherent part of the process. However, other industrial CO_2 emissions sources such as cement, iron/steel, and refinery hydrogen production are attractive targets for advanced CO_2 capture technologies that will also provide greater opportunities for other technologies to contribute to overall CO_2 mitigation. For example, RDD&D to reduce the cost of oxygen used in gasification and PC oxy-combustion could also benefit potential use of oxygen in cement kilns, refinery fluidized catalytic crackers, and blast furnaces. The challenges for industrial processes are due to the smaller equipment sizes and reduced economies of scale, which can increase capture costs compared to power plant applications.

International cooperation addressing near-term CCS challenges: International collaborations offer opportunities for sharing data, testing transformational CCS technology, and demonstrating technologies. Activities like the International Test Center Network[19] facilitate the exchange of knowledge and expertise among the world's carbon capture test centers. These test centers, which are located in the United States and other countries, enable long-term, independent validation and verification of advanced capture technologies under real-world conditions, and thus play a vital role to bridge the gap between R&D and commercial deployment. International collaboration will likely play a key role in integrated demonstrations. Large-scale CCS demonstrations are complex and expensive, with long lead times. Working through international partnerships such as the Climate Change Working Group,[20] China, and the United States have agreed to coordinate on large-scale demonstrations for both CO_2-EOR and deep saline reservoir storage.

A great deal of progress has been made in advancing the state-of-the-art for CO_2 storage through RDD&D and the RCSP activities, which have culminated in ongoing million tonne CO_2 injection projects. However, the high cost of CO_2 capture has resulted in most large-scale injections focusing on EOR applications, as opposed to the deep saline injections that will be necessary for the development of a large-scale global CCS deployment. It will be important to develop sustained million tonne/year CO_2 saline injection projects in the United States and elsewhere where advanced storage technologies can be tested. The twenty-two countries of Carbon Sequestration Leadership Forum[21] are engaged in an initiative to identify potential test sites. In November 2014, President Barack Obama and Chinese President Jinping Xi jointly announced that the United States and China will lead a major new carbon storage project based in China and work together on a new Enhanced Water Recovery (EWR) pilot project to purify saline water extracted to control formation pressure during the process of injecting CO_2 into deep saline reservoirs.

4.2.2 Nuclear Power

Nuclear power provides 19% of the electricity in the United States and 60% of the non-emitting generation.[22] The U.S. nuclear fleet consists of ninety-nine operating reactors at sixty-one sites providing approximately 99 gigawatts (GW) of capacity, as shown in Table 4.2. Five reactors are also under construction. The operating plants have demonstrated a fleet-wide capacity factor of 89% over the last decade.[23] While the number of operating reactors

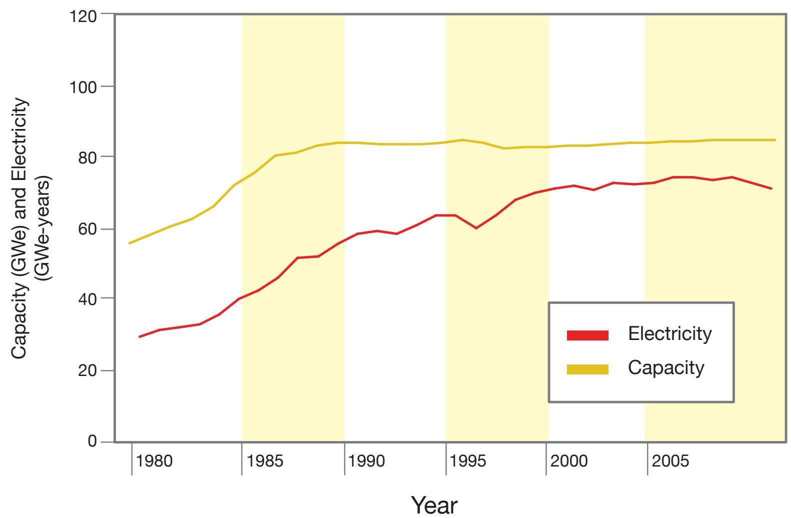
Table 4.2 Nuclear Power Capacity and Production, 2010 and 2014

	2010	2014
Reactors	104	99*
Capacity (GW)	101.2	99.2
Generation (TWh)	807	799
Capacity factor	91.1%	91.1%

*Value from 2015 (100 reactors were operating in 2014.)

All 2010 data and 2014 capacity and capacity factor data are from EIA *Electric Power Monthly*, Feb 2015, Table 8.1; Generation data for 2014 and reactors in 2015 from World Nuclear Association, World Nuclear Power Reactors and Uranium Requirements, June 2015 (http://www.world-nuclear.org/info/Facts-and-Figures/World-Nuclear-Power-Reactors-and-Uranium-Requirements/).

Figure 4.7 U.S. Nuclear Capacity and Generation Since 1980



Even without additional new builds, the capacity and generation of nuclear power continued to increase due to power uprates and improved efficiencies.[26]

has not increased for the last few decades, through power uprates and efficiency gains the contribution of nuclear energy to clean electricity generation continued to increase until 2014 (see Figure 4.7). As the new reactors start operation, the contribution of nuclear power will increase. The fuel cycle that supports these reactors is built around low-enriched uranium oxide fuel that will reside in the reactor for four to six years before being removed. Slightly more than 2,000 tons of used fuel are generated each year by the entire fleet. It is first stored in pools of water until it has cooled enough to be air-cooled above ground in welded stainless steel canisters placed in concrete casks prior to the anticipated eventual disposal of nuclear waste in a geologic repository.[24]

Nuclear power technology has attributes that make it attractive as a significant contributor in a transition to a low-carbon electricity system. Nuclear plants can provide significant quantities of baseload electricity production—a single 1,000 MW reactor can generate around eight million megawatt hours (MWh) of electricity annually without emission of GHGs. IEA's *World Energy Outlook 2014* forecasts global nuclear capacity as more than doubling by 2040 in its 2°C climate stabilization scenario. Reaching this level would entail deployments of up to 30 GW per year by the end of the next decade,[25] rates that have been seen historically but not in recent decades.

For nuclear energy to fulfill this potential, it must simultaneously address four key challenges that would otherwise limit its ability to widely expand. First, reactors must be recognized by regulators and the public as being a technology that will not pose a danger to nearby communities. This has been a primary driver for technology development for new nuclear reactor designs, a concern that has been heightened in the aftermath of Fukushima. Second, nuclear power plants must be economically attractive for companies making decisions about their generating portfolio. Nuclear plants require very large capital investments that can pose a significant financial risk for many companies. Advanced nuclear designs seek to create reactors that are more economical to construct, operate, and eventually decommission. Third, nuclear fission produces radioactive wastes that must be safely managed over a very long time horizon. While some nations have made progress on waste management either through recycling used nuclear fuel (UNF) or advancing geologic repositories for permanent disposal, the deployment of full-scale approaches to address this issue has proven difficult in many countries including the United States. Fourth, the widespread deployment of nuclear technology must not result in the proliferation of nuclear weapons. This is a particular concern with technologies used to produce nuclear fuel.

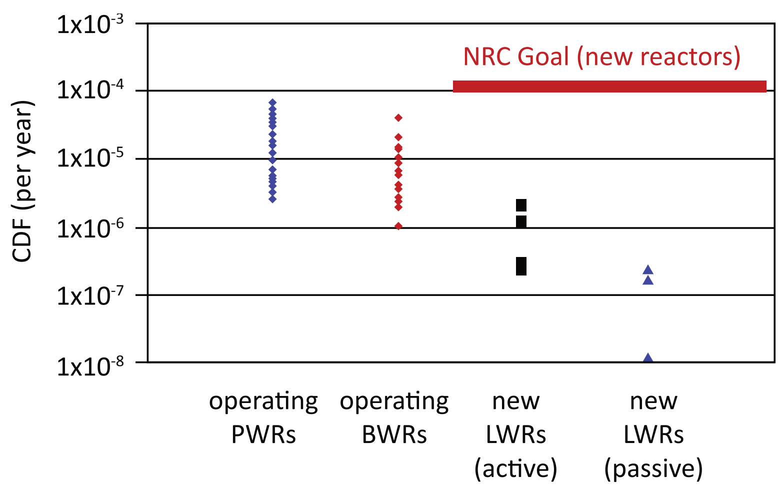
The RDD&D needed to address these challenges and enable continued nuclear deployment vary in relation to the time horizon of different nuclear technologies. The construction of large light water reactors (LWRs) that feature advanced safety attributes is underway, as are efforts to reduce costs that could expand their market potential. Small modular reactors (SMRs) currently being evaluated by the NRC seek to extend the safety and economic attributes of LWRs with the intent of commercial operation by the mid-2020s. Looking toward the 2030 time frame, RDD&D efforts are underway to develop advanced reactor designs that will enable new fuel cycles and widen the range of commercial applications for nuclear power—perhaps to be followed by fusion technologies (addressed in Chapter 9). Research on advanced reactors is an international endeavor, and collaborations such as the Generation IV International Forum have been established to leverage RDD&D capabilities. Fuel cycle RDD&D is to be pursued to facilitate the management of nuclear waste, while addressing concerns about proliferation. New approaches to integrate nuclear power are being investigated to allow better alignment with variable generation through more flexible operations. These will be addressed in greater detail below and in technology assessments.

Light Water Reactors

The predominant nuclear reactor technology is the LWR. In addition to the ninety-nine reactors in the United States, LWRs represent 259 of the 340 reactors deployed elsewhere in the world, as well as sixty-two of the sixty-nine units under construction.[27] LWR technology has seen consistent improvement from the current fleet through the reactors being developed today. In most electricity generation technologies, comparable technological advancements can be seen in reductions in cost or improvements in performance that translate into better economics. While there have been enhancements in LWRs that have translated into improved economics, a second dimension of advances is aimed at improving the safety performance of nuclear reactor systems. A key metric to measure safety performance is the core damage frequency (CDF) from internal events, as estimated through the probabilistic risk assessment methodology. Figure 4.8 shows that the effort being put into new designs, especially the passively safe LWRs, reflects significant improvements in the safety assessment of the reactors.[28] Additional RDD&D is underway investigating novel fuel options with enhanced safety characteristics (shortly referred to as accident tolerant fuels) and improved performance under normal operations.

Figure 4.8 Core Damage Frequency (CDF) Estimates of U.S. Reactor Types

Credit: U.S. Nuclear Regulatory Commission



Values for new light water reactor designs with more passive safety features are one to three orders of magnitude lower.

Current LWR Fleet

The current fleet of LWRs was built during a period in which reactor sizes escalated quickly. The oldest units in the fleet entered service before 1970 and are on the order of 600 MWe, though the units were quickly scaled up to over 1,000 MWe by 1978. Reactors have been deployed in both single- and multi-unit power plants ranging up to 4,000 MWe in total. These reactors (generally referred to as Generation 2 reactors) featured little standardization and increasing costs as designs became increasingly complex to enable larger capacities and respond to changing safety requirements. Though a downturn in the reactor orders began in the wake of the recession in the late 1970s, no new orders were placed following the accident at Three Mile Island though some of the units that were under construction were eventually completed.

The operational performance of the fleet was mediocre through the 1980s with capacity factors averaging 60% for the decade. Improved management and better fuels enabled a steady improvement in performance with capacity factors more than 88% by the late 1990s.[29] Improved performance and profitability led to additional investments to add capacity at existing units (uprates) and enable the long-term operation of the plants beyond the original forty-year license. The increased expenses to respond to newer safety and security requirements have put economic stress on plants in regions with low wholesale power prices stemming from inexpensive natural gas and renewable penetration. Five reactors have closed in the last three years as a result of economic pressures.

The technical challenge to the continued operation of the current LWRs stems from the need to understand and assess the effects of aging in a nuclear reactor. Many of the major components in a nuclear plant can be replaced as they wear out, but that is not the case for the entire system. DOE conducts cost-shared RD&D to understand the material degradation characteristics of the reactor pressure vessel and structural components under a high-temperature radiation environment. The experimentation and modeling done in this work will inform the analysis to determine the feasibility of extending reactor operation beyond the sixty years for which seventy-one of the U.S. reactors have already been licensed to operate.[30] If all of the reactors in the U.S. fleet operate for sixty years, the first units will begin retiring by 2030, and only a handful will remain after 2050.

New Builds

Four of the five reactors being built in the United States are modernized LWRs sold by Westinghouse as the AP1000. These Generation (Gen) 3+ reactor designs offer improved safety and economic attributes. These designs build, in part, upon R&D sponsored by DOE in the 1980s and 1990s, as well as DOE financial support to reach commercialization by completing the licensing process. In addition to the reactors being built in the United States, four more AP1000s are under construction in China with additional units expected.

A key safety advance for Gen 3+ designs was to simplify the safety-related systems and rely more on natural phenomena, such as gravity and natural circulation to ensure reactor cooling. This design approach minimizes the number and complexity of backup safety systems and substantially reduces the number of actions that an operator must take to ensure cooling in accident scenarios.[31] Rather than rely upon pumps that require electrical power to operate emergency cooling systems, water will circulate as a result of natural forces thereby obviating the need to keep pumps operating if external power is not available.

These designs are still large reactors and though the simplification of key systems has reduced costs, they are still expensive to build. All deployments of the 1,100 MWe AP1000 have been in two-unit configurations, while other systems such as GE Hitachi Nuclear Energy's are more than 1,500 MWe. With overnight construction costs in excess of $4,000/kWe, the total investment cost of a new Gen 3+ plant can be in excess of $10 billion. The development priority for the Gen 3+ systems is to reduce the costs to make them more economically attractive. The AP1000, in particular, has attempted to build upon modular construction techniques that enable more work to be performed away from the reactor site with major components manufactured in factories and delivered to the plant site. Supply chain issues have inhibited fully realizing the promise of this approach in the first Gen 3+ units being built in the United States. The identification of RDD&D opportunities to reduce construction costs is inhibited by the lack of publicly available data on cost components that would enable a more granular understanding of where RD&D could provide significant benefits. An effort to assess the costs of new nuclear plants would contribute to energy analyses and RD&D planning.

Small Modular Reactors

If the key advance with Gen 3+ designs was to take advantage of natural forces to enable the inclusion of passive safety systems, then SMRs are an extension of this approach that result in a different way of thinking about a nuclear power plant. Light water-based SMRs reduce the reactor capacity (small core) and increase the availability of water to make it even easier for the reactor to remain cooled in upset conditions. Some of these concepts, such as the NuScale design, go so far as to rely upon natural circulation for normal operations as well, eliminating the need for pumps entirely along with any risk that might come if they failed to work. Furthermore, key components that are external to the reactor in large designs, such as the steam generators and pressurizer, are integrated into the reactor vessel in many of the SMR designs, eliminating the possibility of certain failure modes such as large piping breaks that would inhibit the ability to cool the reactor fuel. In general, in the case of a potential upset condition in an SMR, the accident would progress more slowly due to the ability to cool the core with the relatively larger water volume, require few, if any, operator actions, and result in a lower off-site radiation dose due to the smaller radionuclide inventory. The smaller physical size of these units also permits a re-evaluation of how security at nuclear plants would be maintained. Many SMR designs feature below-grade construction to reduce the accessibility to the plants and to provide additional barriers to external threats. The principal challenge for SMRs is to determine whether power plants with smaller reactors can be built and operated at a cost that is economically attractive.

High-Temperature Reactors

This category of reactors would be operated at high temperatures that would permit more efficient generation of electricity. These designs would convert about 50% of the thermal energy into electricity compared to the 33% for LWRs. An additional potential market could be opened by new plant designs in a nontraditional application of using nuclear power for industrial process heat needs. Some industrial process heat applications require temperatures substantially above the 300°C–325°C outlet temperature of today's LWRs. High-temperature reactors could be deployed to meet more than 600 GW-thermal (more than 25%) of this process heat demand enabling the displacement of the emissions associated with this production.[32] Achieving higher outlet temperatures requires switching to a new coolant technology using gas, liquid metal, or molten salt. With these coolants, it may be possible to achieve outlet temperatures ranging from more than 500°C for liquid metal coolants to more than 900°C for helium or molten salt coolants.

Achieving high temperatures requires the development and qualification of fuels, materials, and instrumentation, particularly at the higher end of the temperature range. Ongoing research to qualify high temperature fuels and the graphite applicable to some of the designs is scheduled to be completed in the 2020 to 2022 time frame with additional testing and experimentation to follow. In addition, the use of coolants other than water will require the advancement of a variety of plant components and systems such as electromagnetic pumps for liquid metal coolants, compact heat exchangers for gas coolants, and chemical purification systems for molten salt coolants. These factors will impact the licensing process, including the current codes and standards.

Fast-Spectrum Reactors

Some advanced reactor technologies aim to change the reactor design to enable different characteristics of the fuel to run the reactor and to alter how the irradiated fuel is managed after it is removed. Fast reactors enable approaches that could reduce the waste disposal challenge by eliminating materials that provide long-term disposal issues. Transmutation is a process of turning some of the chemical elements in used nuclear fuel into elements with more desirable disposal attributes,[33] while keeping the fissile and fertile materials within the fuel cycle. Because of their neutronic characteristics, fast reactors make it easier to use recycled actinides in the fuel.[34] These approaches would produce power from fissile and fertile uranium and transuranic elements that otherwise would have required permanent geologic disposal. This category of reactors includes the more mature sodium-cooled fast reactor and the less mature lead-cooled fast reactor and gas-cooled fast reactor.

Key areas of RD&D for future systems include the following: high-performance materials compatible with the proposed coolant types and capable of extended service at elevated temperatures; new fuels (especially fuels using recycled actinides); and claddings capable of withstanding irradiation at high burnup.

Fuel Cycle

Nuclear fuel cycles encompass a number of system components and operational approaches, starting from the mining and milling of uranium, and ending with the sustainable disposal of used fuel and/or various waste forms. All elements of the nuclear fuel cycle are intended to support the commercial operation of nuclear plants and are critical to the sustainability of nuclear energy. A large number of technologies have been explored in the past, and based on the results of these studies and systems and options analyses,[35] DOE focuses on a number of activities that support the development and ultimate deployment of a sustainable fuel cycle.

Uranium resources: Historically, RDD&D on uranium resources has focused on improved methods for land-based uranium extraction and recovery of fissile isotopes from used fuel. Novel approaches of extracting uranium from seawater (which contains a large integrated quantity of uranium at very low concentrations) are currently under investigation.[36] Though uranium supplies have proven sufficient to date, if this technology proves to be economically feasible, it would greatly extend uranium resources worldwide. RDD&D work is continuing on advanced separation techniques that might enable economic recovery and possible recycling of key fissile isotopes and the removal of waste constituents for disposal.

Waste management: Nuclear waste management is a particular focus of DOE as the government bears the responsibility to safely manage these materials. The government strategy to address waste management[37] includes a call for a consent based siting approach for one or more interim storage facilities for spent nuclear fuel and the longer term development of a permanent geologic repository. A number of technical options have been explored for waste management, including using full recycle or limited recycle fuel cycles for transmutation of specific isotopes, developing waste forms for specific types of materials, used fuel storage, and used fuel disposition. To this end, DOE pursues a number of activities, including RD&D on separation techniques and advanced fuel forms for transmutation, waste forms adapted to these fuel cycles, and a safeguards development program, the latter in collaboration with the National Nuclear Security Administration, to support these initiatives. These RD&D activities are closely coordinated with the design and development of advanced nuclear reactors for energy production and waste management missions. Building upon decades of research into the safe long-term disposal of nuclear waste, DOE is also developing the technical basis for ultimate development of geologic repositories to be implemented as part of any future fuel cycle including the investigation of deep boreholes for certain types of material.

Used fuel storage and transportation: In response to the Administration's strategy, DOE has initiated a significant RD&D program on used fuel storage and transportation, including the characterization of used fuels and their behavior in long term storage media, and the development of logistics strategies for transportation, storage, (and ultimate disposal) of used fuel. This effort builds upon the commercial experience in moving used fuel between nuclear power plants to best manage the existing stocks.

Hybrid Energy Systems

The increased introduction of renewable sources (especially wind and solar) into the electricity grid may require nuclear plants to interface with a very dynamic grid. Nuclear power plants built around current technology are not well-suited to vary their output in response to the conditions of the grid. In periods of low demand and high variable renewable generation, nuclear systems are challenged to respond in an economically efficient manner. This RD&D is aimed at developing technologies and control systems that can follow the demand. An alternative is to be able to switch between electric and nonelectric (process heat) applications while maintaining steady and economical reactor power levels. While this effort is being pursued with nuclear as the focus for the energy production, this technology could well be applied to other power types that are suited to run full-time, such as coal with CCS.

Nuclear Energy Summary

The traditional approach to nuclear energy research is lengthy and expensive, discouraging most private investors from investing in innovative technologies without government support. To realize the full potential for nuclear technology development, it is important to create an RD&D paradigm that enables faster readiness for commercialization of innovative technologies. This will likely require the further development and demonstration of advanced reactor concepts before they will be adopted commercially. The RD&D paradigm also needs to be complemented by a consistent licensing paradigm that fosters commercialization of novel safe and efficient concepts.

DOE has recognized that demonstrations of nuclear technologies are often expensive endeavors and advanced modeling and simulation tools are being used in conjunction with smaller-scale, phenomenon-specific experiments informed by theory to reduce the need for large, expensive integrated experiments. Insights gained by advanced modeling and simulation combined with a strong verification and validation program can lead to new theoretical understanding and, in turn, can improve models and experimental design. Though the use of modeling and simulation may serve to reduce the need for experiments and demonstrations, it cannot supplant the need entirely. These facilities are beyond the capabilities of the private sector to develop and maintain. DOE maintains access to hot cells and test reactors as well as smaller-scale radiological facilities, specialty engineering facilities, and non-radiological laboratories. DOE core capabilities rely on irradiation, examination, chemical processing, and waste from development facilities. These are supplemented by university capabilities ranging from research reactors to materials science laboratories. However, not all capabilities exist within the United States. International partnerships have been developed to maximize the use of facilities in other countries that can be used to support RDD&D needs. The drive to develop advanced reactor designs may well require additional capabilities to test the fuels, coolants, and materials that will enable non-water reactor systems. DOE is assessing the future testing needs for advanced reactors and the attributes that a 21st century test reactor would need to possess to meet those needs.

4.2.3 Hydropower Technology

U.S. hydropower technology has provided reliable and affordable power for over a century, contributing on average 10.5% of cumulative U.S. power sector net generation over the past six and one-half decades (1949-2013).[38] With 78 GW of installed capacity and 22 GW of pumped-storage hydropower capacity, hydropower provides approximately half of all U.S. renewable power sector generation (47% in 2014),[39] and provides many strategically valuable ancillary benefits that are uniquely suited to support further integration of other variable renewable energy technologies.

Major Challenges

Market challenges: Hydropower development and operations are intertwined with water resources development and management, which presents unique deployment challenges among renewable energy sources. Metrics for sustainability of hydropower development and operations within this broader water resources context of the United States are neither well-defined nor universally accepted. In addition, competing uses for water resources besides hydropower—including species protection and restoration, drinking water supply, navigation, and recreational uses—impact hydropower development and operational decisions. Much of the existing hydropower infrastructure in the United States will evolve from an energy-production role to a mixed role of production and provision of ancillary services to enable integration of variable renewables. This mixed role for hydropower is at risk due to lack of investment in aging infrastructure and increasing environmental and multiple-use constraints on water releases. Large-scale pumped-storage development is constrained by the absence of market signals and assured revenue streams needed to support financing of initial construction costs.[40] Hydropower development has historically been a site-specific design, permitting, construction, and commissioning process with little standardization to reduce costs and uncertainty of development. Addressing siting, permitting, and environmental concerns result in long planning cycles and time to deployment.

Technology challenges: Large hydropower turbine-generator technologies are highly optimized, robust, and cost-effective designs, with peak energy conversion efficiencies of more than 93%.[41] However, they require economies of scale for energy revenues to support the cost of civil works. Advancements for small-scale turbine-generators must reduce technology cost and enable more compact support structures and smaller physical and environmental footprints to achieve economic feasibility. The remaining hydropower potential in the United States is comprised primarily of small-scale development opportunities that will require such advancements. The environmental performance of turbine designs continues to improve, in the form of blade shape enhancements to reduce injury to fish and aeration into turbine flow passages to improve the water quality of releases. However, these evolving designs engender trade-offs between energy conversion performance, environmental performance, and technology cost that are not thoroughly understood. They also require field testing to validate their environmental performance and achieve acceptance.

Current Status

Hydropower currently provides 7% of annual total U.S. electricity generation.[42] Pumped-storage hydropower provides vital grid reliability services for the U.S. power system and enables grid integration of new variable resources. Approximately half of U.S. hydropower capacity is owned and operated by federal agencies. The remaining half is owned and operated by investor-owned utilities, state and municipal utilities, and independent power producers. This diversity of ownership requires active cooperation among stakeholders to identify and accelerate technology advancement opportunities and to coordinate water management and hydropower scheduling in multiple U.S. river basins.

Factors Driving Change in Hydropower Technology

Environmental impact mitigation remains the overarching factor that drives hydropower technology advancement. Continued operation of existing facilities and new deployment will depend upon demonstration and acceptance of environmental mitigation technologies for facilities of all sizes—within the turbine and external to the turbine. Future drivers for hydropower and water storage could be impacts of climate change, with potentially increased water shortages—especially in the western states. There is approximately 65 GW of undeveloped stream resource hydropower potential in the United States.[43] Much of this potential capacity will require low-cost turbines operating at less than twenty-five feet of elevation difference. Small hydropower technology must become less expensive to manufacture, install, and operate if it is to see widespread deployment. Traditional powertrain, powerhouse, dam, and reservoir designs have footprints that may be too expensive with too many environmental impacts to be acceptable. There is opportunity to add up to 12 GW of capacity to existing non-powered dams.[44]

Hydropower Technology RDD&D Opportunities

With technology innovation, cost reductions, and favorable market mechanisms, hydropower could substantially contribute to emissions reductions of CO_2 and criteria pollutants as a substantial part of the U.S. power portfolio. Design, siting, and operation will also need to take into account potential changes in precipitation and evaporation under climate change. Technology RDD&D can help to sustain and enhance existing hydropower capabilities and achieve market-competitive LCOE for new hydropower development in the following four areas:

Integration of environmental mitigation technology into turbine designs: Environmental performance optimization requires advanced computational models of flow dynamics, fish kinematics, and gas transfer within turbine flow passages, as well as laboratory and field scientific experiments to inform those models. Such design tools will require advanced physics-based turbulence modeling and will need high-performance computing (HPC) power to incorporate fish passage and water quality objectives into the turbine design process.

Advanced powertrains: Innovations can reduce direct costs of low-head turbine components, as well as reduce the physical footprint of small low-head turbines that influence overall costs and environmental impacts of low-head hydropower project development. Key areas of interest include advanced materials and manufacturing for powertrain components, innovative hydrodynamic and mechanical concepts to reduce integrated turbine-generator size (diameter and length) and increase speed, embedded condition monitoring sensors, and powertrain design innovations that afford flexibility in selection of design objectives such as initial cost minimization, efficiency over a range of head and flow rates, and durability or ease of replacement.

Market acceleration and deployment: Opportunities exist for reduction of the cost and duration of market barriers, including fish and wildlife, environmental, and multiple-use concerns such as navigation and water supply. Potential market barrier technology solutions include: a) standardized technology packages and site civil layouts to reduce the uncertainty and complexity of environmental and safety reviews for new development, and b) decision support tools that integrate fish passage, water quality, and other environmental objectives more robustly into hydropower and power system scheduling.

Advanced grid integration: Large-scale studies of power systems can choose to include hydropower and pumped-storage facilities as a part of solutions to integrate variable renewables into the grid. The capabilities and operational constraints of existing and future hydropower technologies must be accurately represented in such studies and within the operational and planning models that electric utilities and other stakeholders rely upon for decision making. Further, the impact of altered operational strategies for hydropower will have operations and maintenance (O&M) impacts and costs that must be projected as part of decision making and O&M planning.

4.2.4 Wind Power Technology

Wind power has become a mainstream power source in the U.S. electricity portfolio, supplying 4.4% of the nation's electricity end use demand in 2014.[45] With more than 65 GW installed across thirty-nine states at the end of 2014,[46] utility-scale wind power is a cost-effective source of low-emissions power generation throughout much of the nation. There are more than 70,000 U.S. jobs in the wind industry at more than 500 manufacturing companies located in forty-three states in the U.S. wind energy supply chain.[47] Wind technology is cost-competitive today, without subsidization, in specific high wind speed locations with access to transmission capacity. The United States has significant sustainable land-based and offshore wind resource potential, greater than ten times current total U.S. electricity consumption, and various opportunities have been analyzed in future scenarios of high integrations of wind energy. Recent analysis highlights that through continued innovation in technologies and markets, wind technology can support large scale deployment in the U.S. power sector portfolio and could provide up to 35% of U.S. power requirements with high grid reliability by 2050.[48, 49]

Major Challenges

Market challenges: Varied wind capacity at traditional tower heights and electric energy value in utility markets across the U.S. strongly influence the competitiveness of wind power. With an increased ability to reach effective wind regimes, most regions would have wind energy capable of entering the regional market. Market valuation for carbon and criteria pollutant impacts would spur investment during periods of minimal demand growth. Increased transmission capacity from high quality wind resource locations is required.

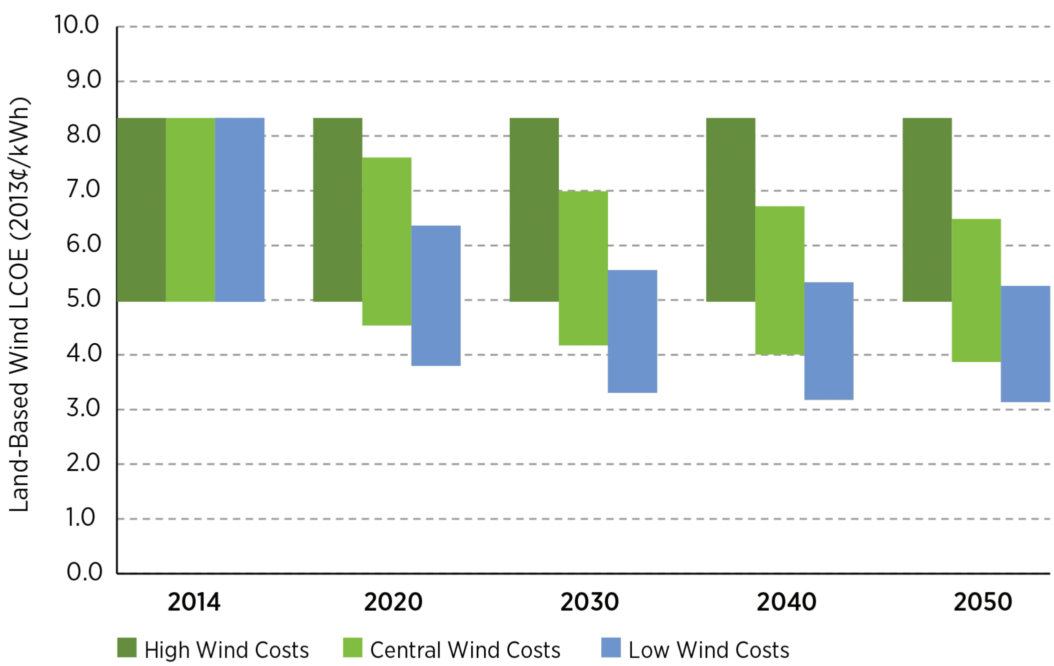
Technology challenges: Advanced understanding of fundamental atmospheric and turbine interaction physics, with optimized component designs, advanced sensors, higher hub heights, and plant controls have the potential to reduce LCOE.

Wind Power Technology RDD&D Opportunities

Technology RDD&D opportunities to achieve market competitive LCOE for both land-based and offshore wind exist in the following five areas:

Wind plant optimization: Optimization of wind plant performance involves minimizing wind plant cost of energy through wind resource characterization, complex wind plant aerodynamics R&D, advanced plant-level controls development, improved numerical weather prediction and power forecasts, and improved design and operation standards to enhance plant reliability. Considerations include access to high resolution weather data and leveraging HPC assets for high-fidelity atmospheric and wind plant modeling and data integration efforts; comprehensive scaled and full-scale measurement campaigns to validate model development; holistic plant design that includes innovative plant control strategies to enhance energy capture, improve reliability, and reduce LCOE; and characterization of risk and uncertainty to maximize the financial investment potential of wind plants. Figure 4.9 illustrates the range of land-based wind LCOEs represented in the 2015 *DOE Wind Vision* scenario framework for the interior region and related changes from 2014 to 2050.[50] Data shown represent the plant-level LCOE, excluding potential intraregional transmission needed to move the power to the grid and interregional transmission to move the power to load.

Figure 4.9 Land-Based Wind Changes in LCOE by Sensitivity (2014–2050, Interior Region)

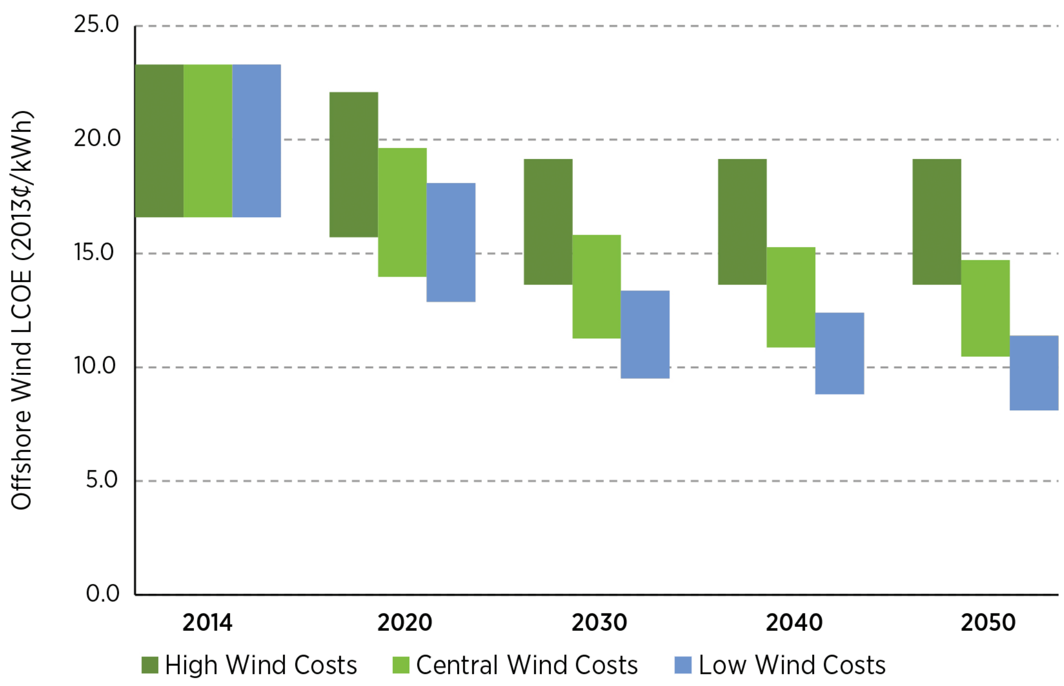


Wind turbine components and materials: Development of next-generation wind turbine components and materials requires research on advanced materials and key components to improve performance and reliability; development of new architectures for larger, light-weight turbines that reduce overall mass (reducing costs) and provide access to better wind resources (larger rotors, taller towers), and improved systems performance (capacity factor); improvements in turbine cost, strength, weight, and fatigue to reduce operations and maintenance (O&M) costs and reduce the failure rate for large components, such as blades, gearboxes, generators, power electronics, and collection systems; and innovations to solve transport and installation cost limitations for large scale turbine systems and components. Research in advanced materials and innovative manufacturing techniques such as additive manufacturing that show potential to address issues specific to wind turbine components could be useful.

Offshore wind technology: Expedited development of a U.S. offshore wind energy industry requires advanced technology demonstration projects to validate innovative technologies to reduce LCOE. Figure 4.10 illustrates the range, as a function of wind resource quality and water depth, of offshore wind LCOEs in the 2015 *DOE Wind Vision* scenario framework, and how these LCOEs change from 2014 to 2050. Data shown represent the plant-level LCOE, excluding the marine export cable, potential intraregional transmission needed to move the power to the grid, and interregional transmission to move the power to load. In 2012, DOE funded development of proposals for seven offshore wind advanced technology demonstration projects.[51] Three project proposals were competitively down-selected in 2014 for continued funding and are required to be grid-connected and producing power by the end of 2017. These proposed projects would demonstrate features such as innovative, U.S.-developed twisted jacket foundations, hurricane-resilient design, and floating semi-submersible foundations. These projects are currently seeking financing. As of the end of 2014, the U.S. Department of Interior has issued seven commercial wind energy leases on the Outer Continental Shelf, including those offshore of Delaware, Maryland, Massachusetts, Rhode Island and Virginia.[52]

4

Figure 4.10 Offshore Wind Changes in LCOE by Sensitivity (2014–2050)



Market acceleration and deployment: Reducing the cost and impact of market barriers that limit wind deployment involves resolution of considerations related to potential wildlife impacts, radar interference, workforce development, and public awareness. Opportunities exist to develop new scientific capabilities and technology solutions to enable sustainable wind deployment in more locations, including development of monitoring and mitigation tools necessary for the industry to obtain new permits required under the Bald and

Golden Eagle Protection Act; compliance with provisions of legislation such as the Endangered Species Act and offshore wind-specific legislation such as the Magnuson-Stevens Fishery Conservation and Management Act, and the Marine Mammal Protection Act; collaborations to help mitigate wind turbine interactions with civilian and military radar; and completion of national public acceptance baseline studies to provide the first quantitative assessment of the factors associated with public acceptance of wind energy development across the country.

Advanced grid integration: Optimizing grid integration (distributed and utility) and transmission for wind systems requires integration studies and operational forecasting tool development, including development of grid management and control systems that enable high penetrations of wind with high grid reliability. These tools would ensure reliable and economic system operations under high penetration levels of wind generation. Integration studies to fully understand the effect of wind on the U.S. power system would support the adoption of effective operational practices. Additional tool development would support planning and development of new infrastructure to allow access to high quality wind resources, evaluation of system response to uncertainties and electrical phenomena associated with wind power and development of operations practices for system operator use, and improvements to wind power controls to benefit grid power quality through activities such as voltage ride-through and frequency control.

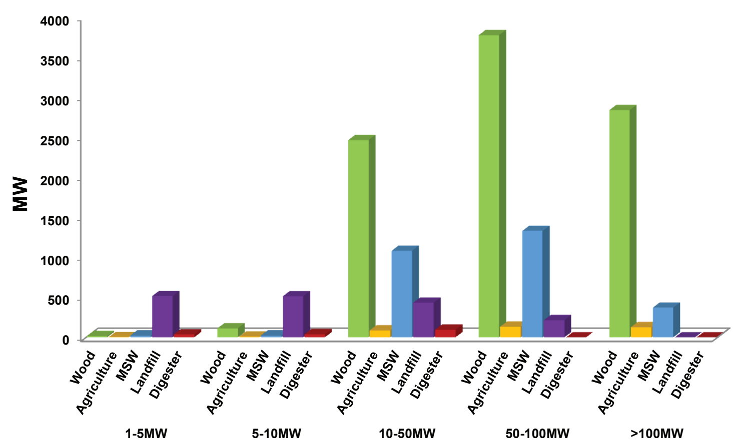
Deployment: Technology innovation and LCOE reductions, along with policy stability and transmission availability, are necessary to enable U.S. wind power to sustainably contribute to the reductions of CO_2 and criteria pollutants with reduced water consumption as a substantial part of the U.S. power portfolio. U.S. wind power could achieve up to 35% of U.S. power generation by 2050,[53] with benefits in reduction of lifetime GHG emissions of U.S. power generation; reduction of criteria air pollutants (e.g., sulfur oxides [SO_x], NO_x, and fine particulate matter [PM]$_{2.5}$); reductions of water consumption by power plants; reductions in U.S. electricity rates; and additions of U.S. wind-related jobs in U.S. manufacturing, operations, and induced jobs.

4.2.5 Biopower

The use of biomass to generate heat and power when coupled with CCS has the potential to be a significant source of carbon-negative renewable energy in the United States.[54] The IEA GHG R&D Programme found that biopower via gasification with CCS has the potential to reduce global GHG emissions by more than 2.5 Gt per year by 2050.[55] The forest products industry has been using biomass for heat and power for many decades, yet the use of biomass to supply electricity to the U.S. power grid and other applications is still limited, contributing 1.7% of total generated electricity in the United States according to the U.S. Energy Information Administration. In 2012, the nation-wide portfolio of biopower included 13.4 GW of installed capacity that produced 64 million MWh of electricity. These units are typically fired with opportunity fuels such as sorted municipal solid waste (MSW), agriculture and wood residues, sewage sludge, and pulp and paper industry black liquor. The heat produced by the combustion of this biomass is converted to steam, which is typically used to drive simple Rankine power cycles. The typical rating for these plants ranges from 2–100 MWe as seen in Figure 4.11.[56]

Figure 4.11 Scale of Biopower Plants in the United States

Credit: National Renewable Energy Laboratory



Biopower, as a baseload or dispatchable technology, has been considered as a potential electricity supply option in all past Intergovernmental Panel on Climate Change (IPCC) assessments. Under the right circumstances, biopower can accomplish three goals: 1) provide secure electricity using domestically-sourced biomass, 2) provide low-cost power when the cost of feedstock is competitive with alternative clean power generation sources, and 3) reduce atmospheric CO_2 emissions, compared to conventional fossil power, when biomass is obtained from managed plantations. Further, CO_2 that is taken up during the growth of biomass could be effectively fixed in a geological reservoir following combustion in a power plant equipped with CCS. If combined with CCS, the potential exists for reduction of atmospheric CO_2.

Major Challenges

Expansion of biopower in the U.S. is currently limited by the 1) availability and cost of feedstock, 2) reliability and consistent quality of feedstock, 3) combustion behavior in existing and advanced power plants, and 4) economies of scale (i.e., logistics) that are financially feasible with or without CCS. There are significant RDD&D opportunities to address all of these factors. Expansion of domestic biopower may be viable when biomass production in the United States increases significantly to ensure a reliable and economic feedstock source. Costs may also decrease with improvements to biomass production and supply logistics, or incentives to expand renewable energy, including the potential to reduce atmospheric CO_2 concentrations through biopower linked to CCS. Therefore, biopower will continue forward, drawing on the benefits of feedstock development for biofuels (see Chapter 7).

Current Status

The present opportunity for utility-scale biopower with CCS involves co-firing in CCS ready coal-fired power plants where preconditioned biomass is fed along with coal into the power plant through the existing coal conveyance and milling/grinding operations, or through a dedicated biomass feed system that requires a retrofit of the existing plant burners and burner registers. The biomass must be pretreated to meet the combustor specifications with respect to particle size, grindability, heating value, and ash content. The industry has investigated a series of biomass/coal cofiring tests over the past twenty years. Boiler feedrates of 5%-10% biomass have been successfully demonstrated. Recent research evaluated the technical feasibility and the cost/benefits of co-firing biomass ratios up to 20% in boiler units rated up to 500 MWe. The projected LCOE was 18% higher for co-firing wood with coal in a typical power plant in Alabama, while the projected LCOE rose 54% when co-firing switchgrass with coal in a power plant in Ohio.[57] These cost increases resulted from the higher production and preprocessing costs of biomass.

Factors Driving Change

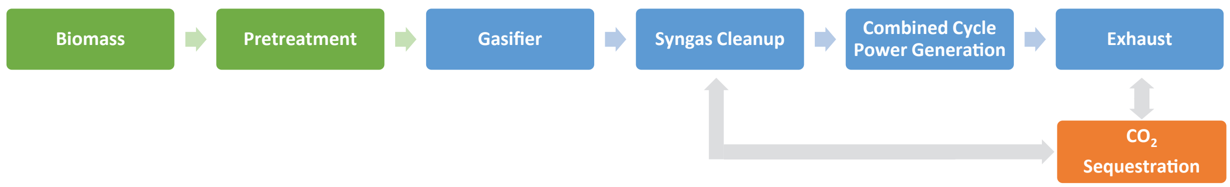
Given the promise of significantly higher efficiencies of combined gas combustion/steam turbine power cycles, combined cycle power generation is a target technology for biopower. Biomass gasification with CCS (BGCCS) could be developed in the 2025 to 2035 time frame by leveraging transformational technology supported by DOE's Office of Fossil Energy. The technology developed for coal could be progressively developed for biomass. As the amount of biomass cofiring increases, the coal conversion technology could be adapted or re-engineered to best exploit the characteristics of biomass feedstock in consideration of supply logistics and costs.

Biomass also offers the benefit of reducing SO_x, NO_x, and CO_2 emissions. Biopower plants release very little SO_x because of the low sulfur content of biomass; biopower plants may apply a selective non-catalytic reduction system for NO_x reduction. A mechanical collector and baghouse or electrostatic precipitator can be equipped to control PM emissions.[58]

Technology RDD&D Opportunities

Among the more promising biopower with CCS technologies is integrated gasification/combined cycle with CCS. However, gasification of biomass is uniquely different from coal due to feedstock characteristics that impact feed injection into a pressurized reactor, higher biomass thermal conversion reactivity, and mineral matter behavior that may impact reactor fouling and slagging behavior. Biopower gasification could therefore leverage ongoing advanced combustion and gasification technology development for coal to address specific biomass technical development challenges. Feed systems and reactor design may be adapted and optimized for higher biomass feedrates, leading up to 100% biomass feed as seen in Figure 4.12.

Figure 4.12 Biomass Gasification with CO_2 Capture and Combined-Cycle Power Generation



In consideration of the costs/benefits of BGCCS, feedstock format development should focus on the nominal supply for approximately a 200 MWe scale biomass gasifier. This scale of gasifier could meet the power requirements of a community of 100,000–200,000 persons, while co-producing a stream of CO_2 that is large enough to accomplish CO_2 storage. An LCOE of <$75/MWh (2014$) is a reasonable goal for utility-scale biopower. This amounts to approximately a 30% cost reduction from the average of current, limited-scale biopower co-firing studies.

4.2.6 Solar Power Technologies

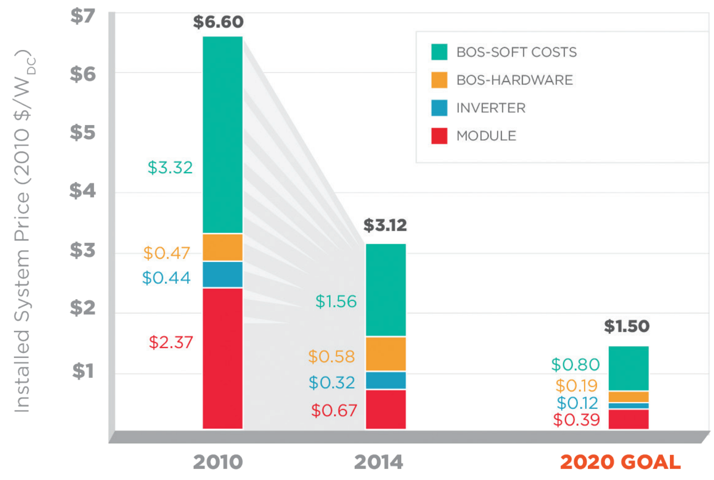
For 2014, the EIA reports 9.3 GW of solar capacity and 18.3 TWh of generation, which does not include distributed systems (see Table 4.1). Other analysts report that solar energy provided 2% (20 GW) of the U.S. electricity-generating capacity in 2014, an eleven-fold increase since 2008, when distributed systems are included.[59] As Figure 4.13 shows, hardware prices for solar photovoltaics (PV) have dropped by more than 60% since 2010; however, additional reductions, particularly surrounding the “soft costs” of solar will be required for solar to be cost competitive with traditional energy resources. Solar is being deployed on both utility and distributed scales to provide peak load power, and concentrating solar thermal power (CSP) plants have been coupled with thermal energy storage to provide power into the evening hours. Challenges for solar technologies include reducing “soft costs” (e.g., permitting, financing, interconnection), improving integration into the grid, and increasing reliability, while continuing to lower hardware costs.

Major Challenges

Several challenges for solar PV exist across the technology spectrum. In the near term, continued module cost reductions of roughly 30% by 2020 and power soft-cost reductions indicated in Figure 4.13 would fuel continued growth of the industry.[60] In the longer term, increasing cell and module efficiencies and reliability, addressing integration-related challenges associated with high penetration, and streamlining installation through plug-and-play designs will be important. Improving the efficiency of converting sunlight to electricity has the benefit of both reducing the cost per watt (W) of PV modules and many soft costs as well. Building integrated photovoltaics (BIPV) also has the potential to reduce costs by reducing installation labor and building materials costs. Additionally, improving the life-cycle sustainability of

PV modules and system components, through either improved recycling techniques or modules made from earth abundant materials, will contribute to reducing the LCOE from PV systems and minimizing the long-term environmental impact of PV as the technology becomes more mature.

Figure 4.13 Utility PV Cost Reductions Since 2010 and Required Reductions for Cost Competitiveness (Source: SunShot 2014 Portfolio Book)



For CSP, the largest barriers to adoption are the high overall costs of the systems (in particular the collector field and thermal storage systems), and the cost of capital, which increases the overall LCOE of a system. In the long term, technical challenges, including increasing the temperatures at which CSP plants operate, as well as the thermal efficiency of plant materials, such as heat exchangers and recieivers, need to be addressed in order to significantly reduce costs. Additionally, increasing the lifetime of plant materials, either through more resilient materials or less corrosive heat transfer fluids, has the potential to significantly decrease O&M costs.

Finally, significant challenges exist with respect to integrating solar into the grid and reducing non-hardware "soft costs." A combination of developments in PV and CSP technology and changes to the electric grid will need to be implemented in order to accommodate high penetration levels of solar on both distribution and transmission networks. Additionally, by developing innovative and scalable solutions to streamline processes and enable robust and sustainable market solutions, the soft costs of solar, which in 2012 represented 64% of a distributed PV system's total cost, can likewise be reduced.[61]

Current Status

Solar deployment has been growing rapidly. From 2009 to 2014 the compound annual growth rate was 31%, and currently there is more than 20 GW of solar, 18.3 GW of PV and 2.7 GW of CSP, operational across the United States, representing about 2% of the nation's generating capacity. These systems produce roughly 33 terawatt-hours (TWh) annually, about 0.9% of U.S. demand. Additionally, solar has proven to be a significant job creator. By the end of 2014, 174,000 workers in the United States were documented as employed by the solar industry.[62]

Factors Driving Change in the Technologies

Significant investments in technology innovation, both in the private and public sectors, have advanced technology in recent years. The installed costs of a PV system declined more than 50% between 2010 and 2013. Module price reductions have played a key role in driving system-level cost reductions and overall growth in the PV market. Module prices declined from approximately $1.95/W in 2010 to $0.67/W in 2013 (66% reduction).[63] Financial subsidies and loan guarantees have made new CSP technologies commercially viable. Since 2010, four trough plants have come online, and the Ivanpah Project became the first operational CSP tower on a commercial scale in the United States.

Technology RDD&D Opportunities

Despite the rapid increase in deployment, significant work remains before solar achieves unsubsidized cost competitiveness with conventional energy sources. Novel processes for integrating solar generation into the grid must be developed. Supporting advanced inverter technologies, using next-generation storage, and developing electricity market solutions to ensure that solar energy can be utilized in a safe and reliable manner will become an increasingly important area of focus, as larger amounts of solar energy is deployed. "Soft costs" represent an increasingly large fraction of system cost (64% as of 2012) and must be reduced.[64] Hardware innovations also have the potential to significantly increase solar deployment. For PV, manufacturing improvements could increase efficiencies and reliabilities, and lower costs. CSP has a very large technical potential, as described below, but needs to realize significant improvements in performance and cost reductions to be competitive in the near-term. Lowering capital costs (e.g., heliostats field and construction costs) and increasing access to low cost financing would impact CSP deployment.

Solar Power Opportunities

Solar power has a vast resource base and incredible technical potential. For example, PV panels on 0.6% of the nation's land could supply enough electricity to power the entire United States.[65] PV is flexible in size and deployment and can be integrated into the built environment on building rooftops and facades, parking lots, and abandoned or degraded land close to population centers. Additionally, placing CSP in suitable and available land in seven southwest states could theoretically provide four times the current U.S. annual electricity demand. CSP also provides a stable and cost-effective form of energy storage, and it can cogenerate with on-site fossil energy sources.[66]

Target Outcomes

Solar will become economically competitive nationally when the unsubsidized LCOE of solar energy reaches roughly $0.06/kilowatt-hours (kWh) at the utility scale (PV and CSP), $0.08/kWh at the commercial scale, and $0.09/kWh at the residential scale.[67] In addition, finding ways to integrate variable generation into the electric grid will enable widespread deployment. This outcome would require installed costs to reach roughly $1/W for utility-scale PV systems, $1.25/W for commercial rooftop PV, and $1.50/W for residential rooftop PV, and $3.60/W for CSP (including thermal energy storage).[68] Since 2010, the industry has progressed by more than 60% of the way toward these targets, and costs continue to drop year after year.[69]

4.2.7 Geothermal Technology Development

Geothermal power taps into Earth's internal heat as an energy resource. While geothermal power generation currently constitutes less than 1% of total U.S. electricity generation,[70] it is regionally much more significant in the western United States, supplying 4.4% of total system power in California in 2012.[71] Geothermal power plants have a small surface footprint and produce low-carbon baseload electricity. The challenges for geothermal power are to discover new resources, translate resources to reserves, lower early stage risk, and reduce costs in order to increase the scale of power generation and make geothermal a viable source of power in more regions.

Vast amounts of heat are contained in the interior of the earth from the slow decay of radioactive elements and the heat remaining from Earth's formation. Specific locations have a favorable combination of high heat flow and natural fluid circulation that make them suitable for geothermal power generation. The naturally circulating, hot fluid can be tapped into to generate power in these naturally occurring hydrothermal systems. Enhanced geothermal systems (EGS) are engineered reservoirs created to produce electricity from geothermal systems that are not otherwise economical due to lack of water and/or permeability.[72] In an EGS, fluid is injected into the subsurface, which causes pre-existing fractures to reopen. This increases permeability and allows fluid to circulate throughout the rock and transport heat to the surface, where electricity can be generated. The U.S. Geological Survey (USGS) estimates that there are nine gigawatt-electric (GWe) of identified geothermal resources and an additional 30 GWe of undiscovered geothermal resources.[73] With EGS, the USGS estimates a mean electrical power resource of 517 GWe in the United States.[74]

Major Technological Challenges

In geothermal energy development, two areas are identified as major technological challenges: 1) developing the subsurface engineering technologies and practices necessary for economic deployment of EGS, and 2) reducing the cost and risk associated with accessing the subsurface through characterization technologies that can improve drilling success rates and/or developing technologies to directly reduce drilling costs.[75] The high upfront costs, particularly drilling costs, are a major challenge for geothermal development because they occur when risk is still high. The result is that it is difficult to obtain financing for new geothermal developments.[76] These challenges have close ties to those faced by other energy sectors that utilize the subsurface for fuel extraction or for storage and disposal of energy waste streams, leading to opportunities for cross-sector collaboration.[77]

Current Status of Geothermal Technologies

The majority of the geothermal systems that can be readily identified by their surface expression have been developed or are in development. The future of geothermal in the United States lies in identifying "blind" hydrothermal systems through new innovative exploration technologies and in advancing technologies for EGS. Adopting technologies and practices from the oil and gas industry is a promising strategy to improve geothermal exploration. One example is translating the Play Fairway Analysis concept to inform the exploration decision-making process. The application of EGS techniques has been expanded from developing new geothermal sites to enhancing existing hydrothermal sites. Success has been achieved in stimulating noncommercial or "dry" wells within or on the margins of existing hydrothermal fields to increase their productivity and make them commercially viable.[78] These successes are an important step toward achieving the ulitimate goal of EGS: to create a geothermal system where none existed before.

Factors Driving Change in the Technology

The need to translate more resources to reserves, reduce early-stage risk, and lower costs for develoment are driving changes in geothermal technology. Some of the key areas of RDD&D that have the potential to impact geothermal deployment are: resource characterization and exploration technologies, purposeful control of subsurface fracturing and flow, improved subsurface access technologies, and additional value added to operations through mineral recovery and hybrid systems. The Frontier Observatory for Research in Geothermal Energy (FORGE) is a new DOE initiative that will address some of these areas. Informed by foundational Hot Dry Rock experiments[79] and the current DOE demonstration portfolio, DOE has launched the FORGE initiative, which will become a dedicated test site.

Technology RDD&D Opportunities

To address the challenges summarized above RDD&D is needed in the following key areas:

- **Subsurface characterization:** Efficiently and accurately locate target subsurface geologic environments and quantitatively infer their evolution and enhance their operation over time. Advances in downhole tools that can withstand high temperatures (>300^{o}C) could improve the ability to characterize geothermal systems. New technologies to measure stress in the subsurface are needed.

- **Accessing:** Safely and cost-effectively construct wells in challenging subsurface conditions. High-impact technology advancements, such as advanced and tailored drilling methods, new casing and zonal isolation materials, and high-temperature directional drilling could facilitate improvements for the geothermal and other sectors.
- **Engineering:** Create the desired subsurface conditions in challenging high-pressure/high-temperature environments. For EGS to succeed, methods are needed to create or enhance fracture networks that allow enough fluid flow through the subsurface to allow requisite production rates but avoid uneconomically rapid thermal drawdown.
- **Sustaining:** Maintain these conditions over multidecadal time frames throughout complex system evolution. The ability to control fluid movement in the reservoir is essential to EGS and will require advanced wellbore methods to control injected and produced fluids.
- **Monitoring:** Improve observational methods to advance understanding of the multi-scale complexity throughout system lifetimes. Improved surface-based and downhole diagnostics methods and tools (hardened for severe geothermal conditions) are being developed and are needed.

Another potentially important technology option is utilizing CO_2 as the geothermal working fluid, or heat transmission fluid; previous and current attempts to create and operate EGS in the United States, Japan, Europe, and Australia have all employed water. A number of studies indicate that CO_2 is superior to water as a heat transmission fluid, achieving somewhat larger heat extraction rates when the same injection pressure is applied. An ancillary benefit to CO_2 EGS is the potential for CO_2 sequestration as precipitated carbonate minerals and feldspar to clay conversion at the fringes of a CO_2 EGS reservoir. An anticipated RDD&D challenge associated with the use of CO_2 as a working fluid lies in the likely requirement that the reservoir needs to be completely dried before CO_2 is injected in order to avoid problems associated with the formation of carbonic acid.

4.2.8 Stationary Fuel Cells

Fuel cells are well-suited to stationary applications because they are efficient even at small scale, have low emissions, are scalable from a few kilowatts (kW) to multi-megawatts,[80] operate quietly, have low maintenance, and can use a gamut of fuels (various hydrocarbons, hydrogen). Several types of fuel cells are applicable for stationary power generation, including polymer electrolyte membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs),[81] molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) (see Technology Assessment supplement for more information).

- PEMFCs are good for quick startup and transients and operate at 50°C–100°C, a relatively low temperature range with a solid electrolyte, conditions that reduce the risk of corrosion.
- PAFCs operate at 150°C–200°C and are more expensive than PEMFCs, but have increased tolerance to fuel impurities.
- MCFCs (600°C–700°C) are highly efficient with higher fuel flexibility than the previous two fuel cell types.
- SOFCs (500°C–1000°C) have even higher efficiency, scalability, and fuel flexibility, but their higher operating temperatures affect durability.

Both MCFCs and SOFCs can be integrated with a gas turbine in an ultra-high efficiency (>70%) combined cycle configuration. The challenge for fuel cells is achieving cost parity with conventional technologies through increased durability, higher power density, reduced cost of contaminants removal, and manufacturing cost reductions.

Distributed generation (DG) is an attractive pathway to fuel cells deployment with electric power applications (e.g., grid strengthening, prime power for data centers, and online backup power), and combined heat and power (CHP) for commercial, institutional, municipal, and residential buildings. The Technology Assessment discusses synergy with electrolyzers and reversible fuel cells for producing and using hydrogen in support of the electric grid.

Major Challenges

Technical challenges, beyond the need to reduce capital costs,[82] are listed in Table 4.3.

Table 4.3 Technical Challenges for Fuel Cell Types

Fuel cell (FC) type	Technical challenge
Polymer electrolyte membrane (PEMFC)	Very high cost for contaminant removal from fuel streams; durability needs to increase; efficiency needs to increase to MCFC and SOFC levels
Phosphoric acid (PAFC)	Low power densities; cost for contaminant removal from fuel streams; high cost of balance-of-plant; efficiency needs to increase to MCFC and SOFC levels
Molten carbonate (MCFC)	High system costs due to stack life and low power densities; cost for contaminant removal from fuel streams; high cost of balance-of-plant; long start-up
Solid oxide (SOFC)	Stack lifetime; performance stability (e.g., seals, interconnects, active materials); cost for contaminant removal from syngas; limited ability to thermal cycle; long start-up

Current Status

Production costs have come down from $6,000/kW in 2006 to projected high volume costs as low as $2,400/kW[83] in 2013. Customers have realized up to 60% reduction in GHG emissions compared to coal power and 20% compared to natural gas combined cycle. Other benefits driving demand for fuel cell power include high electrical efficiency (>60% lower heating valve [LHV] in some cases[84]), nearly silent and vibration-free operation, high reliability, and low maintenance. Grid-scale deployment started with Dominion's 14.9 MW fuel cell plant in Bridgeport, Connecticut. U.S. exports enabled the world's largest fuel cell park (59 MW) in South Korea.[85]

Factors Driving Changes in the Technologies

Cost-effective gas cleanup is an increasing priority with the growing use of low-carbon biogas. For stationary PEMFCs, a growing market for PEMFC-based material handling equipment, backup power and fuel cell vehicles would synergistially accelerate the rate of manufacturing cost reduction. For grid modernization application, R&D is also needed on advanced sensors, controls, and associated system architectures needed to manage a diverse set of resources and grid assets.

Technology RDD&D Opportunities

Table 4.4 shows the cost targets resulting in under $0.10/kWh LCOE[86] for deployment in commercial and multifamily residential buildings.

Table 4.4 Cost Targets versus Current Status – Medium-Scale (0.2–5 MW) Fuel Cells

	2020 targets	Current (2013) status
Installed costs	$1,500/kW (natural gas) $2,100/kW (biogas)	$2,400–$5,500 /kW[87] (natural gas) $4,900[88]–$8,000/kW (biogas)
Durability	80,000 hours	40,000–80,000 hours (depending on fuel cell types)

For large SOFCs, targets for industrial-scale DG and utility-scale generation (natural gas, coal, etc.) include high-volume production at $900/kW and durability >50,000 hours. SOFC power systems have the potential to achieve greater than 60% electrical efficiency and more than 97% carbon capture. The NETL projects that SOFC power systems could become cost-competitive by 2020.[89]

For the various fuel cells, RDD&D is needed on materials, stack components, balance-of-plant, and integrated fuel cell systems—targeting increased power density, lower cost, and enhanced durability, with an emphasis on science and engineering at the cell level and also on overall system integration.

While hydrogen production is covered in Chapter 7, high temperature fuel cells operating in trigeneration mode can also be used to produce hydrogen, heat, and power. However, cost reduction and durability, particularly in the case of internal reforming, need to be addressed. International collaboration should continue since progress is being made also outside the United States. Complementary activities should be pursued (e.g., codes and standards, demonstrations, and performance data collection and analysis of pre-commercial technologies).

4.2.9 Marine and Hydrokinetic Power Technology

Marine and hydrokinetic (MHK) technologies convert the energy of waves, tides, and river and ocean currents into electricity. With more than 50% of the U.S. population living within fifty miles of the nation's coasts,[90] MHK technologies hold significant potential to supply renewable electricity to consumers in coastal load centers, particularly in areas with high costs of electricity. MHK resource assessments identify a continental U.S. technical resource potential[91] of up to 538–757 TWh of generation per year from ocean wave,[92] ocean current,[93] ocean tidal,[94] and river current energy.[95] For context, approximately 90,000 homes can be powered by one TWh of electricity generation each year.[96] A cost-effective MHK industry could provide a substantial amount of electricity for the nation due in large part to its unique advantages as a source of energy, including its vast resource potential, its close proximity to major coastal load centers, and its long-term predictability and near-term forecastability.

Major Challenges

The following describe the major challenges to commercial deployment of MHK technology in the United States:

- Capital cost reductions and performance improvements are challenges for MHK to be competitive on a regional basis. The high initial costs of today's MHK prototypes are due in large part to the cost structure per unit power generation.
- Cost-competitiveness of MHK energy will require that individual devices capture more than double the amount of energy than current prototypes for the same device size.[97]
- Lack of available test facilities, in particular multiberth, full-scale, grid-connected open water test facilities for wave energy devices, to support the anticipated acceleration in U.S. MHK market growth.
- Lack of scientific information, for example baseline environmental data, and high monitoring costs can drive environmental and regulatory expenses to 30%–50% of total early-stage MHK project cost.

Current Status

- While tidal barrage energy has been employed for several decades, overall MHK technologies are in the early stages of development, with a wide variety of designs and architectures.
- Despite a significant increase in renewables generation and a diverse set of MHK technologies, there are currently no commercial MHK technologies deployed in the United States.

- As of the end of 2014, four companies held licenses from the Federal Energy Regulatory Commission for MHK technology deployment projects, with eleven other projects in the development pipeline (holding a preliminary permit or in prefiling for a license).[98]
- Internationally, the first phase of the Meygen tidal energy project in Scotland's Pentland Firth, with four turbines totaling six megawatts, is scheduled for commercial handover in the final quarter of 2016.[99]

Factors Driving Change in MHK Technology

Improving performance and reducing cost through technology advancements, demonstrating reliability and survivability, and addressing uncertainties regarding potential environmental impacts in order to reduce permitting barriers are key focus areas in reaching commercialization.

MHK Power Technology RDD&D Opportunities

MHK has significant opportunities to provide a substantial amount of electricity for the United States in areas where it is needed most. Opportunities exist for RDD&D in the technologies with the most abundant resources that have potential for techno-economic viability and can be deployed in markets with high energy costs, while supporting next-generation, game-changing technologies. Critical technology RDD&D can generate breakthrough technology innovations and identify the most promising ones, improve their performance, lower the costs, and accelerate their deployment. Opportunities for MHK RDD&D include the following four areas:

Technology advancement and demonstration: Provide the ingredients for and incentivize incubation of revolutionary concepts. Prove technical credibility, catalyze device design evolution, and optimize performance through, for example, application of optimized controls, power takeoff, and structure components to double annual energy production and increase availability.[100]

Testing infrastructure and instrumentation: Strengthen MHK device quality and reliability, provide affordable access to facilities for testing, and develop robust instrumentation and sensors.

Resource characterization: Classify the U.S. MHK resource, disseminate resource data among stakeholders, and develop numerical modeling tools to predict loading conditions. Quantify and classify environmental conditions to reduce siting risk.

Market acceleration and deployment: Environmental research and risk mitigation boost investor confidence and reduce regulatory barriers. Research of effects on aquatic organisms (blade strike, collision, entanglement, noise, electromagnetic fields, species behavior) and research of effects on physical systems (hydrodynamic and sediment transport dynamic modeling for both wave and current) are needed.

Specific opportunities for MHK power technology RDD&D include:

- Applied RDD&D to greatly improve today's technology through innovation in energy capture, operational efficiency, structural performance and reliability, and demonstrate capabilities through testing to prove readiness for early, near-term markets.
- Development of next-generation component technology designed specifically for the challenges of the marine environment. These technologies would drive the costs down for multiple energy conversion system solutions, including advanced controls to tune devices to extract the maximum energy from each sea state, compact high-torque, low-speed generator technologies, and corrosion- and biofouling-resistant materials and coatings.
- Development of fully-validated MHK open source advanced engineering/physics-based codes and design tools for modeling and simulation, and improved controls to spur innovation and collaboration in the MHK technology development community.

- RDD&D efforts to minimize the cost and time associated with permitting and deploying MHK projects, including RDD&D on new instruments to identify, mitigate, and prioritize environmental risks, providing data to accelerate permitting time frames and drive down costs, and engage in ocean planning.
- Provision of access to testing facilities that would enable a systematic progression toward commercialization, thereby reducing the cost and risk of technology demonstration for developers.
- Development of a wave classification scheme analogous to the resource classifications used by the wind industry. This would allow device developers to understand the operating conditions they would face in different regions and which regions to target for deployment in order to capture the maximum amount of energy with the minimum amount of load on the MHK device, maximizing the lifetime of the device and reducing LCOE and investor risk.

4.3 Creating Crosscutting Technology Solutions

As the industry develops to meet growing electrification and carbon reduction goals, there is a recognition of the value of increasing coordination, connections, and interdependencies. Opportunities exist in advancing common technologies, such as turbines and power cycles, in utilizing advanced capabilities, such as computing and advanced manufacturing, and also in sharing approaches, such as private-public and international partnerships. Technologies being developed for a specific energy source may be applicable to a broader range of energy systems. An example could be the hybrid energy systems presented in Section 4.2.2 that are being developed with a focus on nuclear technologies, but could well be expanded to address other thermal power sources.

4.3.1 Advancing Common Technologies

Technologies that can be applied to electrical generators share a number of common challenges, which are being addressed by creative solutions that cross the boundaries of specific technologies. Improved energy conversion systems in thermal power, expanding subsurface knowledge and manipulation capabilities, and water usage technologies are a few examples.

Supercritical Carbon Dioxide in Thermal Power

The sCO_2 Brayton Cycle energy conversion system is an innovative concept that transforms heat energy to electrical energy through the use of a supercritical fluid rather than through steam and water. In this cycle, the sCO_2 is maintained near the critical point during the compression phase of the cycle. This allows a higher gas density, closer to the density of a liquid than of a gas, where compressor work is significantly reduced, with the potential to reach thermal efficiencies of 50% or greater. The significantly higher-efficiency power cycles of sCO_2 systems coupled with other technology attributes could result in large potential reductions in capital and fuel costs, decreased GHG emissions, and reductions in cooling water consumption within the energy industry, specifically in the fossil, solar, nuclear, and geothermal sectors.

RDD&D in sCO_2 has made progress, but there are significant technical challenges remaining. For example, determining the set of operational parameters, component designs, and system configuration that results in adequate efficiency for commercialization are major uncertainties that will require modeling, component research, and rigorous systems engineering. Critical technology and component development will require science investigation of the effects of unavoidable impurities in the sCO_2 working fluid, dynamic processes within the system, and pressure waves and acoustics.

To address the technical risks for scaling up to higher temperatures, RDD&D would normally be phased by demonstrating an operational model at temperatures up to 550°C. As the technology advances, enabling operational temperatures to increase beyond 750°C, potential market opportunities would expand further to include CSP and fossil fuel direct heating. Over the longer-term, as operating temperatures and scalability increase, potential market opportunities could grow to include large nuclear and fossil fuel plant designs.

Advanced Combustion

While pressure gain combustion offers efficiency advantages, there are several challenges that must be overcome. Mechanical issues such as durability and integrity of valves and seals, thermal management (i.e., combustor cooling), and integration still need to be resolved. Fuel injection, fuel-air mixing, and control of the detonation wave/direction must be addressed. Significant testing at lab and bench-scale and scale-up to demonstration is a necessary part of the RDD&D process to realize the performance opportunity that this technology offers. DOE is beginning to pursue novel concepts and options to address these challenges. For example, Advanced Research Projects Agency-Energy (ARPA-E) had a project with Aerojet Rocketdyne on a rotating detonation engine combustor, which leveraged previous work under the Defense Advanced Research Projects Agency. Under the DOE Fossil Energy Advanced Turbines Program, two projects were awarded in fiscal year 2014 that will evaluate the technical and economic feasibility of pressure gain combustion and provide the technical basis for future development of the technology.

Subsurface Technology RDD&D

Energy resources originating from the earth's subsurface provide more than 80% of total U.S. energy needs today. Finding and effectively exploiting these resources, while mitigating impacts of their use, is critical to the nation's low-carbon and secure energy future. Next generation advances in subsurface technologies will enable access to more than 100 GWe of clean, renewable geothermal energy, as well as safer, less environmentally-impactful, development of domestic natural gas supplies. The subsurface potentially provides hundreds of years of capacity for safe storage of CO_2 and opportunities for environmentally responsible management and disposal of hazardous materials and other energy waste streams. The subsurface can also serve as a reservoir for energy storage for power produced from variable generation sources, such as wind and solar.

RDD&D opportunities in wellbore integrity, subsurface stress and induced seismicity, permeability manipulation, and new subsurface signals could lead to a future of real-time control or "mastery" of the subsurface. Achieving this goal could have a transformative effect on numerous industries and sectors, impacting the strategies deployed for subsurface energy production and storage.

Wellbore integrity: Well integrity is regarded as the single most important consideration for protecting groundwater resources that coexist with oil and gas production. As hydrocarbon reservoirs are increasingly found in deeper and hotter locations, chances of seal integrity failure increase considerably. Wellbore integrity is also critical to ensure safe injection of CO_2 into the subsurface and to optimize geothermal energy generation. RDD&D aimed at new materials and practices associated with wellbores can address these challenges.

Subsurface stress and induced seismicity: Knowledge of the subsurface stress state is required to predict and control the growth of hydraulically-induced fractures, reopening of faults, and induced seismicity potentially associated with subsurface energy production, storage, and waste disposal applications. RDD&D on new tools and techniques for stress measurement will lead to improved understanding of risk to minimize uncertainties and lost opportunities to take advantage of the subsurface for energy production and waste storage.

Permeability manipulation: The challenges involved in selectively and adaptively manipulating permeability in the subsurface result from the difficulty of characterizing the heterogeneous deep subsurface and incomplete understanding of the coupled processes related to fluid flow, geomechanics, and geochemistry over scales from nanometers to kilometers. RDD&D into new technologies and techniques for selectively enhancing, reducing, and eliminating permeability in the subsurface can contribute to all subsurface energy sectors. In particular, technologies to minimize water use and reduce risk for induced seismicity when operating in the subsurface present significant opportunity.

New subsurface signals: New signals have the potential to transform our ability to characterize subsurface systems by focusing on four areas of RDD&D: new signals, integration of multiple datasets, identification of critical system transitions, and automation. A focus is on co-characterization of physical, geochemical, and mechanical properties using multiple datasets and on leveraging advancements in materials science, nanomanufacturing, and HPC.

Energy-Water Nexus

Water is used in all phases of energy production and has direct links with two of the nation's energy-linked challenges: environment and security. Thermoelectric power generation accounted for 45%, or 161,000 million gallons per day, of the water withdrawals in the United States in 2010.[101] Surface water withdrawals accounted for nearly 100% of thermoelectric-power withdrawals, and 73% of the surface water withdrawals were from freshwater sources. With climate change affecting precipitation and temperature patterns in the United States and population growth and migration anticipated to continue in arid regions such as the Southwest, managing energy and water resources will increase in complexity. Although there is significant uncertainty regarding the magnitude of climate effects on water availability, predictability, and temperature, shifts in precipitation and temperature patterns will likely lead to changes in water availability that may impact hydropower and thermoelectric generation and biofeedstock production. For the electric power sector, RDD&D opportunities in utilization of waste heat, advanced cooling, hybrid cooling, and water treatment could reduce freshwater needs and potential vulnerabilities to changes in climate conditions.[102]

Utilization of waste heat: According to 2011 data, only about 30% of the energy content of the fuel in a conventional steam power plant emerges from the plant as electricity. The remaining 70% is dissipated through losses to flue gases or is rejected through cooling operations at thermoelectric power plants.[103] Improvements in the efficiency of power cycles can reduce waste heat generation. Combined cycle power plants can have efficiencies close to 60%, and advances in thermoelectric materials and heat exchangers can increase utilization further. Numerical models have shown that energy recovery systems using solid-state thermoelectric power generators could increase overall power plant output by approximately 6.5%.[104]

Advanced cooling: Once-through cooling systems accounted for 94% of thermoelectric water withdrawals in 2010. Although cooling towers withdraw far less freshwater than once-through cooling, they currently consume more freshwater per Joule of cooling in operation. For example, for natural gas combined cycle plants, cooling towers typically withdraw 150–760 gallons per megawatt-hour (gal/MWh) with a median of 250 gal/MWh and consume 47–300 gal/MWh (median 210 gal/MWh) of water, while once-through systems withdraw 7,200–21,000 gal/MWh (median 9,000 gal/MWh) and consume 20–230 gal/MWh (median 100 gal/MWh).[105] Replacing conventional cooling towers with air-cooled condensers could reduce water use by 80% for pulverized coal plants and 40% for pulverized coal plants with CCS.[106] However, challenges with dry cooling include higher capital costs, larger physical footprints, and reductions in power outputs on the hottest days—often when demand is highest. Opportunities for RDD&D in advanced dry cooling include early-stage breakthrough air-cooled heat exchanger technologies, which in small-scale applications have shown performance improvements of 12%–14%.[107, 108]

For wet-cooled systems, where evaporation accounts for 75% of cooling tower losses, water recovery systems have reduced evaporative consumption losses by 19%.[109, 110] The low concentration of total dissolved solids in the recovered water suggests that, with modifications, cooling towers could be freshwater sources. Other improvements, such as increasing the cycles of concentration in cooling towers from four to five, could decrease blowdown, or wasted water, by 25%.[111] Blowdown controls the concentration of dissolved solids in cooling towers; therefore, there are potential performance tradeoffs associated with reducing blowdown and water consumption and increasing dissolved solids concentration. Improved monitoring and control of blowdown can avoid potential risks to the system from scale or corrosion.

Water treatment technologies for power applications: The use of nontraditional waters could further reduce freshwater withdrawals and consumption. Cooling water needs for 81% of proposed plants could be met with water from publicly owned treatment works within a 10-mile radius, or 97% with a 25-mile radius.[112] For some areas of the United States, the costs for treatment of municipal wastewater effluent have been found to be within the range charged for alternative sources of cooling water, such as river water withdrawal with filtration and chemical conditioning and is below the national average rate for potable city water.[113] Advanced continuous nanofiltration technologies can further reduce consumption by as much as 40%.

4.3.2 Utilizing Technical Advances

The utilization of broad technical advances provide opportunity to increase the pacing of technology readiness, and accelerate the time required to scale up. The opportunities cover a range of disciplines that are addressed in greater depth in other sections of the QTR, but a handful are of notable interest in the development of clean power technologies. Advanced modeling and simulation enabled by HPC (Chapter 9) can provide the capability to reduce the time required to design and test new technologies by providing a virtual environment for exploring design trade-offs, minimizing the need to test multiple configurations and enabling the more efficient use of experimentation by validating theoretically derived codes. The development of advanced materials (see Chapter 6 and its Technology Assessments, and Chapter 9) holds the promise of reducing cost and improving performance of a range of technologies that are limited by the ability of structures to withstand the range of conditions to which they would be exposed. Modern manufacturing capabilities (Chapter 6) can drive down the cost to build clean generation capacity. Since life cycle costs of these technologies are less dependent upon fuel inputs, reducing the upfront capital cost to deployment could have a significant impact.

4.3.3 Leveraging Interfaces

The RDD&D environment of electrical power generation has a human interface on many levels. Not only is the end result to provide a consumer product, but throughout the RDD&D process there exists public-private collaboration and international coordination to enable this development.

Private/Public Roles

The traditional electric power generation industry has a long history of power supply planning and meeting evolving needs. Through an interaction of market and state regulation the private sector makes a selection of technologies based on local parameters, and more recently additional criteria and requirements, such as carbon constraints. The federal role of enabling and enhancing technology advancement includes assessing future security, economic, and environmental considerations, and ensuring power supply options are available to meet a broad set of societal goals. The role of public technology leadership lies in leveraging foundational science expertise to innovate, overcome development barriers in investment and public acceptance, and provide data and information in concert with policy and to achieve societal goals.

The scale and type of public investment evolves over the cycle of technology development. Early research may be heavily supported by public investments where concepts are far from commercial deployment. As technologies become more mature and closer to market the degree of public support is often reduced as private firms seek to reach commercialization and reap the benefits of widespread deployment. Technologies that require large-scale demonstrations before they will be commercially deployed, such as nuclear and CCS, may require the government to share in the cost of early demonstration that would otherwise be too risky for private firms to be expected to bear.

International Partnerships and Markets

DOE participates in a variety of international agreements, including major multilateral agreements with the IEA and the Nuclear Energy Agency of the OECD, the International Renewable Energy Agency, and the International Atomic Energy Agency. Bilateral and multilateral agreements typically focus on promoting the safe deployment of clean energy technologies, as well as RDD&D considered pre-commercial or in markets lacking commercial drivers.

CCS has been an especially productive area for international RDD&D cooperation because market drivers for this technology do not exist in most countries, and CCS may be the most economical approach for dealing with a portion of the CO_2 emissions attributable to fossil fuels, which account for 80% of global energy. Recent CCS international initiatives include the International Test Center Network, which will facilitate the sharing of knowledge and expertise amongst the world's carbon capture test centers. In November 2014, President Obama and Chinese President Xi jointly announced that the United States and China will lead a major new carbon storage project based in China, and work together on a new EWR pilot project to produce fresh water from CO_2 injection into deep saline reservoirs.

Nuclear power technology development has similarly been shaped by international engagement. The first AP1000 reactors are being built in China, which is enabling U.S. projects to learn from these experiences. Collaborative RDD&D is part of the approach to developing new nuclear technologies as some key facilities and capabilities (such as fast neutron sources for fuel testing) may reside in only a handful of locations, thus requiring cooperation. The Generation IV International Forum has been established to facilitate collaborative RDD&D on advanced reactor concepts.

For the last twenty years, renewable technologies have been developing irrespective of national boundaries. Numerous bilateral and multilateral agreements have engaged research centers in Europe, Asia and North America to collectively develop fuel cells, wind, hydropower, solar, and geothermal capabilities. Marine RDD&D is a newer area where researchers have also worked across national boundaries to make recent advances. Scientific and engineering experts are working today on every continent to develop and deploy an appropriate portfolio of clean power technologies to match locally available resources.

4.4 Conclusion

This review provides an assessment of the status and challenges, and it also identifies opportunities for each technology to advance further or expand its respective contribution toward meeting overall system requirements and criteria. In addition, underlying common developments have potential to enable innovative breakthroughs, including the areas of materials, computing, data management, multivariable portfolio analysis for power generation, energy-water nexus, and energy storage. Both system and technology development opportunities are summarized in Table 4.5.

Table 4.5 Opportunities in Clean Electric Power Technology Development

Opportunities in clean electric power technology development	
Carbon capture and storage	Second-generation pilot demonstrations of carbon capture and advanced energy systems for new build and existing plants and field tests addressing critical challenges such as pressure management, induced seismicity, and storage permanence
	Demonstration of CCS technologies on retrofit fossil fuel burning plants
	Application of CCS to natural gas and industrial plants, and need to address differences in CO_2 and O_2 concentrations and the effects on CCS technologies
	International partnerships continue opportunities for shared knowledge, expanded demonstration, and broad impact
Nuclear power	Light water reactors: Characterize reactor material aging, drive down costs of new construction, improve analysis tools to better characterize safety margins
	High temperature and fast reactors: Advanced materials/fuels, modeling and simulation with validation experiments to demonstrate performance
	Fuel cycle technology: Improved understanding of material degradation under extended storage of high-burnup fuels; assessing alternate repository geologies and long-term interaction effects with waste forms; research and testing of actinide-bearing fuels
	Hybrid systems: Dynamic modeling and demonstration of subsystem interfaces
Hydropower	Materials and turbine designs, modularization, technology-based footprint reduction
	Supporting research needed in hydrologic, ecological, environmental, hydrodynamic, hydromechanical, operations, and power system data collection, monitoring, modeling, and analysis
Wind power	HPC model development, verification, and validation of high-fidelity physics-based atmospheric and complex flow models to improve wind farm design and operation
	Effective grid integration, including high-resolution short-term resource forecasting
Biopower	Utility-scale biopower with CCS to improve power production efficiency and offer a cost-competitive GHG reduction alternative
	Use and integration of biogas processes
Solar (PV and CSP)	PV: Innovation that will enable low cost manufacturing in the United States
	CSP: Lower capital cost for large-scale deployment
	Systems integration: Integration with storage solutions and energy management systems
	Nonhardware soft cost: Solutions to streamline processes and drive down costs of permitting, interconnection, finance, and customer acquisition
Geothermal energy	Develop advanced remote resource characterization tools to identify geothermal opportunities without surface expression
	Purposeful control of subsurface fracturing and flow
	Improved and lower $/MW subsurface access technologies
	Develop mineral recovery and hybrid systems to provide second stream of value
Fuel cells	Drive down costs through research into membrane processes and materials
	Focus on gas cleanup for increased fuel flexibility, advanced materials, hydrogen production, and manufacturing technology
	Modeling and simulation with technology validation to demonstrate performance
Marine hydrokinetic power	Next-generation component technology RDD&D designed specifically for the challenges of the marine environment, including advanced controls to tune devices to optimize energy extraction, compact high-torque low-speed generator technologies, and corrosion and biofouling resistant materials and coatings
	Development of open source, fully validated MHK modeling and simulation codes
	Collection of technology performance and cost data through device demonstrations

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

[See online version.]

Endnotes

[1] *World Energy Outlook 2014*. Paris, France: International Energy Agency, 2014.

[2] *Energy Technology Perspectives—2014*. Paris, France: International Energy Agency, 2014.

[3] "Grid Energy Storage." (2013). Washington, DC: U.S. Department of Energy, 2013. Available at: http://etc/www.energy.gov/oe/downloads/grid-energy-storage-december-2013.

[4] *World Energy Outlook 2014*. Paris, France: International Energy Agency, 2014.

[5] Energy Information Administration, U.S. Department of Energy, Annual Energy Outlook 2015, with Projections to 2040, DOE/EIA-0383(2015) April 2015. Available at: http://www.eia.gov/forecasts/aeo/.

[6] *Energy Technology Perspectives 2014*. Paris, France: International Energy Agency, 2014.

[7] "The Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2014. Available at: http://www.ipcc.ch/report/ar5/index.shtml.

[8] Gerdes, K.; Stevens, R.; Fout, T.; Fisher, J.; Hacket, G.; Sheldon, J. "Current and Future Power Generation Technologies: Pathways to Reducing the Cost of Carbon Capture for Coal-fueled Power Plants." *Energy Procedia* (63), 2014; pp. 7541–7557. Available at: http://www.sciencedirect.com/science/article/pii/S1876610214026058.

[9] "Global Status of CCS 2014." Melbourne, Australia: Global CCS Institute, 2014. Available at: http://www.globalccsinstitute.com/in-focus/global-status-ccs-2014.

[10] "MIT CCS Project Database: Plant Barry Fact Sheet." Carbon Capture and Sequestration Technologies at MIT, 2015. Available at: http://sequestration.mit.edu/tools/projects/plant_barry.html.

[11] Gerdes, K.; Stevens, R.; Fout, T.; Fisher, J.; Hacket, G.; Sheldon, J. (2014). "Current and Future Power Generation Technologies: Pathways to Reducing the Cost of Carbon Capture for Coal-fueled Power Plants." *Energy Procedia* (63), 2014; pp. 7541–7557.

[12] "Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Onshore Gulf Coast." ARI, 2005. Available at: http://www.netl.doe.gov/kmd/cds/disk22/F-ARI%20Basin%20Oriented%20Strategies%20for%20CO2/gulfcoast_report.pdf.

[13] "U.S. Oil Production Potential from Accelerated Deployment of Carbon Capture and Storage." Arlington, VA: Advanced Resources International, 2010. Available at: http://www.adv-res.com/pdf/v4ARI%20CCS-CO2-EOR%20whitepaper%20FINAL%204-2-10.pdf.

[14] Ibid. IEA, "World Energy Outlook—2013." Available at: http://www.worldenergyoutlook.org/.

[15] "DOE/NETL's Carbon Capture R&D Program for Existing Coal-Fired Power Plants." DOE/NETL- 2009/1356, 2009. Available at: http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=0a636ca9-cab5-43a7-8e12-31cc33ba919c.

[16] Ciferno, J. P.; Fout, T. E.; Jones, A. P.; Murphy, J. T. "Capturing Carbon from Existing Coal-Fired Power Plants." DOE/NETL-2009/1356. Pittsburgh, PA: U.S. Department of Energy/National Energy Technology Laboratory, 2009. Available at: http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/DOE-NETL-2009-1356-CarbCaptRDProgExistCFPP-Overview0209.pdf.

[17] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013." Washington, DC: U.S. Environmental Protection Agency, 2015. Available at: http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[18] "Technology Roadmap: Carbon Capture and Storage in Industrial Applications." Paris, France: International Energy Agency, 2011. Available at: http://www.iea.org/publications/freepublications/publication/ccs_industry.pdf.

[19] "Re-energizing Global Momentum for CCS and Identifying Key Actions Needed for CCS Deployment." Carbon Sequestration Leadership Forum Ministerial Meeting Communique. Washington, DC, 2013. Available at: http://www.cslforum.org/publications/documents/Washington2013/MinisterialCommunique-Washington1113.pdf.

[20] "U.S.-China Climate Change Working Group Fact Sheet." U.S. Department of State, 2013. Available at: http://www.state.gov/r/pa/prs/ps/2013/07/211768.htm.

[21] "About the CSLF." Carbon Sequestration Leadership Forum, 2015. Available at: http://www.cslforum.org/aboutus/index.html.

[22] "Monthly Energy Review." DOE/EIA-0035. Washington, DC: U.S. Energy Information Administration, September 2014; Table 7.2a. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351409.pdf.

[23] Ibid. Table 8.1.

[24] "On-Site Storage of Nuclear Waste." Nuclear Energy Institute, 2015. Available at: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/On-Site-Storage-of-Nuclear-Waste.

[25] *World Energy Outlook 2014*. Paris, France: International Energy Agency, 2014.

[26] "Nuclear Energy Research and Development Roadmap: Report to Congress." Washington, DC: U.S. Department of Energy, 2010. Available at: http://energy.gov/sites/prod/files/NuclearEnergy_Roadmap_Final.pdf.

[27] "Power Reactor Information System." International Atomic Energy Agency, 2015. Available at: https://www.iaea.org/pris/.

[28] "Modifying the Risk-Informed Regulatory Guidance for New Reactors." SECY-10-0121, Rockville, MD: Nuclear Regulatory Commission, 2010. Available at: http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2010/secy2010-0121/2010-0121scy.pdf.

[29] "Monthly Energy Review." DOE/EIA-0035. Washington, DC: U.S. Energy Information Administration, January 2015. Table 8.1. Available at:

http://www.eia.gov/totalenergy/data/monthly/archive/00351501.pdf.

[30] U.S. Nuclear Regulatory Commission. An Additional 18 Units Have Applications Under Review for License Renewals and the Remaining Five Are Expected to Apply Prior to 2019. Available at: http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html.

[31] General Electric Reported That Its ESBWR Reactor Eliminated 25% of the Pumps, Valves, and Motors of Its Previous Version. Available at: https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/esbwr.html.

[32] "Ultra Safe Nuclear." HTGR Economic/Business Analysis and Trade Studies. USNC-NIA-G00001, 2013.

[33] The radiotoxicity of used nuclear fuel exceeds that of the original uranium ore for about 300,000 years. Converting long-lived transuranic elements into shorter-lived fission products as part of the process of running a fast reactor results in a waste that reaches the original level of radiotoxicity in just several hundred years. "Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary, Report to Congress." Washington, DC: U.S. Department of Energy, Office of Nuclear Energy, Science, and Technology, 2005. Available at: http://web.missouri.edu/~suppesg/book/AFCI_RptCong_ObjApp%5BTechSummMay2005.pdf.

[34] Additional reactor concepts have been proposed that could enable transmutation without operating completely in a fast spectrum. These approaches tend to rely on fuels dissolved in molten salts that allow for a window of transmutation in the fast spectrum before a neutron moderator has the opportunity to slow the released neutrons into a thermal spectrum that would help to maintain a chain reaction.

[35] Wigeland, R; Taiwo, T.; Ludwig, H.; Todosow, M.; Halsey, W.; Gehin, J.; Jubin, R.; Buelt, J.; Sockinger, S.; Jenni, K.; Oakley, B. "Nuclear Fuel Cycle Evaluation and Screening—Final Report." INL/EXT-14-31465. Idaho Falls, IS: Idaho National Laboratory, 2014. Available at: https://inlportal.inl.gov/portal/server.pt/community/nuclear_science_and_technology/337/nuclear_fuel_cycle_evaluation_and_screening_final_report/11118.

[36] Initial work in Japan had indicated that uranium could be recovered from seawater at a cost of $1,000/kg, but recent research by DOE has demonstrated feasibility at about $600/kg with designs of driving costs much lower until closer to the upper range of spot market prices seen over the last decade, around $200–$300/kg. Schneider, E. A.; Lindner H. D. "Energy Balance of Uranium Recovery from Seawater." *Science & Global Security* (21:2), 2013; pp. 134-163.

[37] Following the recommendations of the "Blue Ribbon Commission of America's Nuclear Future," the administration issued the "Strategy for the Management and Disposal of Used Nuclear Fuel and High Level Radioactive Waste." "Blue Ribbon Commission of America's Nuclear Future—Report to the Secretary of Energy." Washington, DC: U.S. Department of Energy, 2012. Available at: http://energy.gov/ne/downloads/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy.

[38] "Annual Energy Review." EIA, OE/EIA-0384, Washington, DC: Energy Information Administration, 2011. Available at: http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf. See also "Electric Power Monthly." Washington, DC: Energy Information Administration, 2014. Available at: http://www.eia.gov/electricity/monthly/current_year/march2014.pdf.

[39] "Monthly Energy Review." DOE/EIA-0035. Washington, DC: Energy Information Administration, March 2015. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351503.pdf.

[40] For more information see "Quantifying the Value of Hydropower in the Electric Grid: Final Report." DE-EE0002666. Washington, DC: Electric Power Research Institute, 2013. Available at: http://www1.eere.energy.gov/wind/pdfs/epri_value_hydropower_electric_grid.pdf.

[41] Tagliaferre, L. "Renewing Interest in Hydropower." 2008. Available at: http://www.buildings.com/article-details/articleid/6276/title/renewing-interest-in-hydropower.aspx.

[42] "Monthly Energy Review." DOE/EIA-0035(2015/06). Washington, DC: Energy Information Administration, June 2015. Table 7.2b. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351506.pdf.

[43] Kao, S. C.; McManamay, R. M.; Stewart, K. M.; Samu, N. M.; Hadjerioua, B.; DeNeale, S. T.; Yeasmin, D.; Pasha, M. F. K.; Oubeidillah, A.; Smith, B. T. "New Stream-reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States." GPO DOE/EE-1063. Washington, DC: ORNL/DOE, 2014. Available at: http://nhaap.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf.

[44] Hadjerioua, B.; Wei, Y.; Kao, S. C. "An Assessment of Energy Potential at Non-Powered Dams in the U.S." DE-AC05-00OR22725. Oak Ridge, TN: Oak Ridge National Laboratory, 2012. Available at: http://www1.eere.energy.gov/water/pdfs/npd_report.pdf.

[45] "Monthly Energy Review." DOE/EIA-0035. Washington, DC: Energy Information Agency, March 2015. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351503.pdf.

[46] "U.S. Wind Industry Fourth Quarter 2014 Market Report." Washington, DC: American Wind Energy Association, 2015. Available at: http://www.awea.org/Resources/Content.aspx?ItemNumber=7150.

[47] Wiser, R.; Bolinger, M.; et al. "2014 Wind Technologies Market Report." Lawrence Berkeley National Laboratory for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, August 2015. Available at: http://energy.gov/eere/wind/downloads/2014-wind-technologies-market-report.

[48] "Wind Vision: A New Era for Wind Power in the United States." DOE/GO-102015-4557: U.S. Department of Energy, 2015. Available at: http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf.

[49] "U.S. Wind Industry Fourth Quarter 2014 Market Report." Washington, DC: American Wind Energy Association, 2015. Available at: http://www.awea.org/Resources/Content.aspx?ItemNumber=7150.

[50] "Wind Vision Scenario Framework." Washington, DC: U.S. Department of Energy, 2015. Available at: http://www.energy.gov/eere/wind/maps/wind-vision.

[51] "U.S. Offshore Wind: Advanced Technology Demonstration Projects." U.S. Department of Energy Wind Program Office, 2012. Available at: http://www1.eere.energy.gov/wind/financial_opps_detail.html?sol_id=473.

[52] "Fact Sheet: Renewable Energy on the Outer Continental Shelf." Bureau of Ocean Energy Management, 2015. Accessed March 5, 2015: http://www.boem.gov/BOEM-Overview-Renewable-Energy/.

[53] "Wind Vision: A New Era for Wind Power in the United States." DOE/GO-102015-4557: U.S. Department of Energy, 2015. Available at: http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf.

[54] Sanchez, D.; Nelson, J.; Johnson, J.; Mileva, A.; Kammen, D. "Biomass Enables the Transition to a Carbon-Negative Power System Across Western North America." *Nature Climate Change* (5), 2015; pp. 230-234.

[55] "Potential for Biomass and Carbon Dioxide Capture and Storage." Stoke Orchard, UK: International Energy Agency Greenhouse Gas R&D Programme, 2011. Available at: http://ieaghg.org/docs/General_Docs/Reports/2011-06.pdf.

[56] "NREL Biopower Atlas, 2014." National Renewable Energy Laboratory, 2014. Accessed November 17, 2014: http://maps.nrel.gov/biopower.

[57] Boardman, R.; Cafferty, K; Nichol, C.; Searcy, E.; Westover, T.; Wood, R.; Bearden, M.; Cabe, J.; Drennan, C.; Jones, S.; Male, J.; Muntean, G.; Snowden-Swan, L.; Widder, S. "Logistics, Costs, and GHG Impacts of Utility-Scale Cofiring with 20% Biomass." Technical Report. INL/EXT-12-25252 and PNNL-23492, 2013. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23492.pdf.

[58] Bain, R. L.; Amos, W. A.; Downing, M.; Perlack, R. L. "Biopower Technical Assessment: State of the Industry and Technology." Technical Report. NREL/TP-510-33123, Golden, CO: National Renewable Energy Laboratory, 2003. Available at: http://www.nrel.gov/docs/fy03osti/33123.pdf.

[59] The EIA figures previously cited only include utility scale solar, the 2% of capacity 20 GW of deployed solar, and 1% of generation figures cited in this section represents the utility and distributed sources of solar energy. See, for example, GTM Research and SEIA. *U.S. Solar Market Insight 2014 Year-in-Review*. Boston, MA, 2015.

4

[60] Friedman, B.; Ardani, K.; Feldman, D.; Citron, R.; Margolis, R.; Zuboy, J. "Benchmarking Non-Hardware Balance-of-System (Soft) Costs for U.S. Photovoltaic Systems, Using a Bottom-Up Approach and Installer Survey. Second Edition." NREL/TP-6A20-60412. Golden, CO: National Renewable Energy Laboratory, 2013. Available at: http://www.nrel.gov/docs/fy14osti/60412.pdf.

[61] Feldman, D.; Barbose, G.; Margolis, R.; Darghouth, N.; James, T.; Weaver, S.; Goodrich, A.; Wiser, R. "Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections." 2014 Edition, 2014. Available at: http://www.nrel.gov/docs/fy14osti/62558.pdf.

[62] "National Solar Jobs Census, 2014." Washington, DC: The Solar Foundation, 2015. Available at: http://www.thesolarfoundation.org/wp-content/uploads/2015/01/TSF-National-Census-2014-Report_web.pdf.

[63] Feldman, D.; Barbose, G.; Margolis, R.; Darghouth, N.; James, T.; Weaver, S.; Goodrich, A.; Wiser, R. "Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections." 2014 Edition, 2014. Available at: http://www.nrel.gov/docs/fy14osti/62558.pdf.

[64] Friedman, B.; Ardani, K.; Feldman, D.; Citron, R.; Margolis, R.; Zuboy, J. (2013). "Benchmarking Non-Hardware Balance-of-System (Soft) Costs for U.S. Photovoltaic Systems, Using a Bottom-Up Approach and Installer Survey. Second Edition." NREL/TP-6A20-60412. Golden, CO: National Renewable Energy Laboratory, 2013. Available at: http://www.nrel.gov/docs/fy14osti/60412.pdf.

[65] "SunShot Vision Study." Washington, DC: U.S. Department of Energy, 2012. Accessed December 2014: Available at: http://energy.gov/eere/sunshot/sunshot-vision-study.

[66] Ibid.

[67] Ibid.

[68] Ibid.

[69] Friedman, B.; Ardani, K.; Feldman, D.; Citron, R.; Margolis, R.; Zuboy, J. (2013). "Benchmarking Non-Hardware Balance-of-System (Soft) Costs for U.S. Photovoltaic Systems, Using a Bottom-Up Approach and Installer Survey. Second Edition. NREL/TP-6A20-60412. Golden, CO: National Renewable Energy Laboratory, 2013. Available at: http://www.nrel.gov/docs/fy14osti/60412.pdf.

[70] "Annual Energy Outlook 2014." DOE/EIA-0383. Washington, DC. U.S. Energy Information Administration, 2014. Available at: http://www.eia.gov/forecasts/archive/aeo14/.

[71] Matek, B.; Gawell, K. "Report on the State of Geothermal Energy in California." Washington, DC: Geothermal Energy Association, 2014. Available at: http://geo-energy.org/events/California%20Status%20Report%20February%202014%20Final.pdf.

[72] "Enhanced Geothermal Systems." U.S. Department of Energy Geothermal Technologies Office, 2015. Available at: http://energy.gov/eere/geothermal/enhanced-geothermal-systems-0.

[73] Williams, C. F.; Reed, M. J.; Mariner, R. H.; DeAngelo, J.; Galanis, S. P., Jr. "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States." Geological Survey Fact Sheet 2008-3082. Washington, DC: U.S. Geological Survey, 2008. Available at: http://pubs.usgs.gov/fs/2008/3082/.

[74] Ibid.

[75] "Enhanced Geothermal Systems." JSR-13-320. McLean, VA: MITRE Corporation, 2013. Available at: http://www1.eere.energy.gov/geothermal/pdfs/jason.final.pdf.

[76] Ziagos, J. P.; Phillips, B. R.; Boyd, L.; Jelacic, A.; Stillman, G.; Hass, E. (2013). "A Technology Roadmap for Strategic Development of Enhanced Geothermal Systems."Proceedings of the 38th Workshop on Geothermal Reservoir Engineering, Stanford, CA. February 11–12, 2013; pp. 11-13. Available at: https://www1.eere.energy.gov/geothermal/pdfs/stanford_egs_technical_roadmap2013.pdf.

[77] "Subsurface Characterization Letter Report." JSR-14-Task-013. McLean, VA: Mitre Corporation, McLean Virginia, 2014. Available at: http://www.energy.gov/sites/prod/files/2014/09/f18/2014%20SubTER%20JASON%20Report_1.pdf.

[78] "Enhanced Geothermal Systems Demonstration Projects." U.S. Department of Energy Geothermal Technologies Program. Available at: http://energy.gov/eere/geothermal/enhanced-geothermal-systems-demonstration-projects.

[79] "A History of Geothermal Energy Research and Development in the United States: Reservoir Engineering 1976–2006." Washington, DC: U.S. Department of Energy Geothermal Technologies Program, 2006. Available at: http://energy.gov/sites/prod/files/2014/02/f7/geothermal_history_3_engineering.pdf.

[80] Scales include small DG (<20–30 kW, commercial/industrial [0.2 to a few MW], utility scale [10s–100s MW]).

[81] PEMFC and PAFC operate at lower temperatures than MCFC and SOFC (see Chapter 4Q. "Stationary Fuel Cells" Technology Assessment).

[82] Industry investment in advanced manufacturing processes can potentially reduce costs but is more likely in a high-demand situation. In the early commercialization phase, low demand is a barrier across fuel cell types.

[83] Wei, M.; McKone, T. "A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications." Presentation at the 2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review,2014. Available at: http://www.hydrogen.energy.gov/pdfs/review14/fc098_wei_2014_o.pdf. Confidential information from a major U.S. fuel cell company was provided to the Fuel Cell Technologies Office in 2014.

[84] SOFCs can achieve this efficiency. MCFCs can achieve this efficiency only in hybrid cycles that capture waste heat to produce steam to drive a turbine to produce electricity. While modern NGCC plants have LHV efficiency in the high 50 percentile, they do not have an outlet for their waste heat and are also penalized with nearly 7% loss associated with transmission and distribution.

[85] "World's Largest Fuel Cell Plant Opens in South Korea." Power, February 2014. Available at: http://www.powermag.com/worlds-largest-fuel-cell-plant-opens-in-south-korea/.

[86] "Levelized Costs of CHP and PV." Record #14003. Washington, DC: U.S. Department of Energy Offices of Solar Energy Technologies and Fuel Cell Technologies, 2014. Available at: http://www.hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf.

[87] "Medium-scale CHP Fuel Cell System Targets." Record #11014. Washington, DC: U.S. Department of Energy Hydrogen and Fuel Cells Program, 2012. Available at: http://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf.

[88] Ibid.

[89] Vora, S. D. "Office of Fossil Energy's Solid Oxide Fuel Cell Program Overview." 15th Annual SECA Workshop, July 22–23, 2014. Pittsburgh, PA: National Energy Technology Laboratory, July 2014. Available at: http://www.netl.doe.gov/File%20Library/Events/2014/2014%20SECA%20workshop/Shailesh-Vora.pdf.

[90] "Oceans and Coasts."National Oceanic and Atmospheric Administration, 2015. Accessed February 11, 2015: http://www.education.noaa.gov/Ocean_and_Coasts/.

[91] Technical resource potential refers to the portion of a theoretical resource (annual average amount of physical energy that is hypothetically available) that can be captured by using a specific technology.

[92] Jacobson, P.; Hagerman, G.; Scott, G. "Mapping and Assessment of the United States Ocean Wave Energy Resource." Report Number 1024637. Palo Alto, CA: Electric Power Research Institute, 2011. Available at: http://www1.eere.energy.gov/water/pdfs/mappingandassessment.pdf.

[93] Haas, K.; Fritz, H.; French, S.; Neary, V. "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines." DE-EE0002661. Atlanta, GA: Georgia Tech Research Corporation, 2013. Available at: http://energy.gov/sites/prod/files/2013/12/f5/energy_production_ocean_currents_us_0.pdf.

[94] Ibid.

[95] Ravens, T.; Cunningham, K.; Scott, G. "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States." Report Number 1026880. Palo Alto, CA: Electrical Power Research Institute, 2012. Available at: http://www1.eere.energy.gov/water/pdfs/riverine_hydrokinetic_resource_assessment_and_mapping.pdf.

[96] Based an average annual U.S. residential electricity consumption of 10,837 kWh in 2012 (EIA).

[97] Li, G.; Weiss, G.; Mueller, M.; Townley, S.; Belmont, M. "Wave Energy Converter Control by Wave Prediction and Dynamic Programming." *Renewable Energy* (48:0), 2012; pp. 392–403. Available at: http://www.eng.tau.ac.il/~gweiss/art101_RenEnergy.pdf.

[98] FERC, Licensed Marine and Hydrokinetic Projects; FERC, Issued Hydrokinetic Projects Preliminary Permits.

[99] "MeyGen on Pace for 2016 Launch." reNEWS. Accessed March 4, 2015: http://renews.biz/84853/meygen-on-pace-for-2016-launch/.

[100] Availability refers to the proportion of time a system is in a functioning condition.

[101] "Summary of Estimated Water Use in the United States in 2010." Fact Sheet 2014-3109. Washington, DC: U.S. Geological Survey, 2014. Available at: http://pubs.usgs.gov/fs/2014/3109/pdf/fs2014-3109.pdf.

[102] "The Water-Energy Nexus: Challenges and Opportunities." Washington, DC: U.S. Department of Energy, 2014. Available at: http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities.

[103] Ibid.

[104] Silaen, A.; Wu, B.; Fu, D.; Zhou, C.; Yazawa, K.; Shakouri, A. "Numerical Model of Thermoelectric Topping Cycle of Coal Fired Power Plant." ASME 2013 4th Micro/Nanoscale Heat & Mass Transfer International Conference Proceedings. December 11–14, 2013. Hong Kong.

[105] Meldrum, J.; Nettles-Anderson, S.; Heath, G.; Macknick, J. "Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature." *Environ. Res.* Lett. (8), 2013. Available at: http://iopscience.iop.org/1748-9326/8/1/015031/pdf/1748-9326_8_1_015031.pdf.

[106] Zhai, H.; Rubin, E. S.; Versteeg, P. L. "Water Use at Pulverized Coal Power Plants with Postcombustion Carbon Capture and Storage." *Environ. Sci. Technol.* (45), 2011; pp. 2479-2485.

[107] Johnson, T. A.; Staats, W. L.; Leick, M. T.; Zimmerman, M.; Radermacher, R.; Nasuta, D.; Martin, C.; Kalinowski, P.; Hoffman, W. "Development and Testing of an Integrated Sandia Cooler Thermoelectric Device (SCTD)." SAND2014-20146. Albuquerque, NM: Sandia National Laboratories, 2014. Available at: http://prod.sandia.gov/techlib/access-control.cgi/2014/1420146.pdf.

[108] "Department of Energy Announces 23 New Projects to Improve Efficiency and Create New Technology Pathways for Energy Innovation." Advanced Research Projects Agency—Energy, 2015. Available at: http://arpa-e.energy.gov/?q=news-item/department-energy-announces-23-new-projects-improve-efficiency-and-create-new-technology.

[109] Zhai, H.; Rubin, E.S. "Carbon Capture Effects on Water Use at Pulverized Coal Power Plants." *Energy Procedia* (4), 2011; pp. 2238-2244.

[110] Mortensen, K. "Use of Air2AirTM Technology to Recover Fresh-Water from the Normal Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants." Overland Park, KS: SPX Cooling Technologies, 2009. Available at: https://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/NT42725_SPX-Cooling_Final-Report.pdf.

[111] Zhai, H.; Rubin, E. S. "Carbon Capture Effects on Water Use at Pulverized Coal Power Plants." *Energy Procedia* (4), 2011; pp. 2238-2244.

[112] Vidic, R. D.; Dzomback, D. A.; Hsieh, M.; Li, H.; Chien, S.; Feng, Y.; Chowdhury, I.; Monnell, J. D. "Reuse of Treated Internal or External Wastewaters in the Cooling Systems of Coal-Based Thermoelectric Power Plants." Pittsburgh, PA: University of Pittsburgh, 2009. Available at: http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/42722FSRFG063009.pdf.

[113] Theregowda, R.; Hsieh, M.; Walker, M. E.; Landis, A. E.; Abbasian, J.; Vidic, R.; Dzomback, D. A. "Life Cycle Costs to Treat Secondary Municipal Wastewater for Reuse in Cooling Systems." *Journal of Water Reuse and Desalination* (3:3), 2013; pp. 224-238. Available at: http://www.iwaponline.com/jwrd/003/jwrd0030224.htm.