

## The Challenge of Decarbonizing the U.S. Power Sector: Encouraging Innovation and Aligning Stakeholder Interests

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### Review

This working paper was reviewed by multiple experts inside and outside the Nicholas Institute for Environmental Policy Solutions. However, this working paper has not undergone a formal review process as it is intended to present preliminary analysis, stimulate discussion, and inform debate on emerging issues. It may eventually be published in another form and its content revised.

### SUMMARY

Recent interest in and commitments to reduce greenhouse gas (GHG) emissions will require significant reductions of carbon dioxide (CO<sub>2</sub>) emissions from the U.S. power sector. Those reductions will in turn require a transformation in how electricity is produced, distributed, and consumed—a transformation possible only with intensive collaboration at all community scales, from local to state, regional, and national, and with attention to public, private, and government interests. Today's decisions about this national investment will affect ratepayers, the environment, and the economy for many decades, making transparency, participation, and technical, financial, and regulatory coordination crucial to optimize benefits and minimize costs.

This working paper describes current U.S. power sector trends and relevant environmental goals, ways that technology innovation could proceed or be interrupted, and three emerging low- and zero-carbon technologies generally considered leading options for meeting the decarbonization challenge. It concludes with ideas from a range of experts to meet GHG reduction goals and accelerate innovation to advance low-carbon generation. These ideas illustrate different perspectives on possible steps forward as well as the need for a venue or process for multiple stakeholders and experts involved in advanced energy technology, policy, investment, and implementation to collaborate in evaluating and prioritizing investments, policies, and broad efforts.

## OVERVIEW

The U.S. power sector is evolving and even deeper changes are likely to occur, creating both opportunities and challenges. Aging infrastructure presents a challenge; the decreasing costs of energy efficiency options and electricity generation from natural gas, solar, and wind power present an opportunity. Environmental drivers related to water resources, waste handling, and atmospheric emissions will affect the viability of power generation from each of these and other sources differently. In particular, recent international, domestic, and regional commitments to reduce greenhouse gas (GHG) emissions to mitigate climate change establish goals that will require significant reductions of carbon dioxide (CO<sub>2</sub>) emissions from the U.S. power sector.

The targeted level of greenhouse gas emission reductions will require a transformation in the market share of low-carbon electricity, as almost 70% of current generation comes from fossil fuel combustion, which emits greenhouse gases. Modeling has indicated that scenarios limiting climate change to a 2 degrees Celsius increase will require an 80% reduction in GHG emissions by 2050. This modeling reflects the widely held assumption that innovative technology will be developed to facilitate attainment of this goal (IPCC 2014a). This sort of advanced power generation transformation will affect generation at peak demand, base load, and everything in between, and it will require rapid technical and planning development, regulation and policy implementation, financing, and construction.

The United States relies on the availability of safe, dependable, and inexpensive electricity. Transforming how electricity is produced, distributed, and consumed will require intensive collaboration at all community scales, from local to state, regional, and national, as well as attention to public, private, and government interests. Today's decisions about this national investment will affect ratepayers, the environment, and the economy for many decades, making transparency, participation, and technical, financial, and regulatory coordination crucial to optimize benefits and minimize costs. Stakeholder involvement, outreach, and information availability must be supported throughout the power sector's evolution.

This paper discusses where progress is needed, across many disciplines, to transform and decarbonize the U.S. power sector and suggests an approach to overcome a wide range of obstacles. It focuses on the challenges specifically associated with large-scale zero- or low-carbon electricity generation, rather than the many important but smaller-scale approaches. Intermittent renewable sources of energy such as wind or solar ("renewables") are frequently cited as having enormous potential with declining costs and no GHG emissions (e.g., Mai, Sandor, Wisser, and Schneider 2012; Jacobson et al. 2015). However, here we address renewables in combination with energy storage because, among other reasons discussed below, many believe that advancements in storage are needed to support incorporation of these sources into grid-scale electricity.

This working paper describes current U.S. power sector trends and relevant environmental goals, ways that technology innovation could proceed or be interrupted, and three emerging low- and zero-carbon technologies generally considered leading options for meeting the decarbonization challenge. It concludes with ideas from a range of experts to meet GHG reduction goals and accelerate innovation to advance low-carbon generation. This range of ideas illustrate different perspectives on possible steps forward as well as the need for a venue or process for multiple stakeholders and experts involved in advanced energy

technology, policy, investment, and implementation to collaborate in evaluating and prioritizing investments, policies, and broad efforts.

## POWER SECTOR TRENDS AND ENVIRONMENTAL GOALS

### *Trends*

Within the U.S. power sector, five fuels—coal, natural gas (NG), nuclear power, hydropower, and wind—provide more than 90% of capacity and generation; the top two most utilized fuels, coal and natural gas, account for more than 90% of GHG emissions. Over the last decade, NG generation increased by some 300 terawatt hours (TWh), while generation from coal decreased by some 400 TWh (a trend not driven by GHG reduction requirements but by low NG prices). Over the same period, renewable generation, primarily wind, grew by more than 150 TWh. Table 1 shows 2015 capacity and generation for the five largest power-sector fuels.

**Table 1. U.S. power generation and associated greenhouse gas emissions by fuel in 2015**

Fuel	Summer capacity (GW)	Generation (TWh)	CO <sub>2</sub> emissions (MMmt)
Natural gas	476	1339 (33%)	524 (28%)
Coal	281	1355 (33%)	1340 (71%)
Nuclear	100	798 (20%)	-
Hydroelectric	80	247 (6%)	-
Wind	66	190 (4%)	-
All other		152 (4%)	27 (1%)

*Source: Various tables from Annual Energy Outlook 2016 (U.S. DOE EIA 2016).*

Deep infrastructure changes generally have long lead times and are long lasting. Important power sector trends, like the huge growth in natural gas generation, have and will continue to affect GHG emissions from the power sector for decades. In addition, setting policy, shaping regulatory structure, and implementing strategies to meet new policy goals can take decades before becoming operational. Current power sector trends appear to be aligned with short-term U.S. climate policy goals but are potentially at odds with longer-term goals.

U.S. electricity generation infrastructure is transitioning due to range of factors. Renewable and natural gas fuels make up most of the new power generation. Coal-fired power plants are aging, and their share of U.S. electricity production has dropped from 50% in 2005 to 33% in 2015. This reduction is due to declining costs of electricity generation from natural gas, solar, and wind power as well as to increased technical and financing options for energy efficiency improvements, increased difficulty in obtaining and maintaining cooling water and coal-ash waste storage sites, and declining national permissible limits for air emissions. By 2020, the U.S. Department of Energy (DOE) projects 20% less coal capacity than in 2014 and continued coal plant retirements (U.S. DOE EIA 2016). The outlook for coal is not helped by the uncertainty of electric demand growth (Monast and Adair 2014) or by past and future GHG reduction efforts.

The future of U.S. nuclear power is particularly murky. The U.S. fleet of nuclear reactors currently provides about 20% of U.S. electricity, and the already-extended licensing for 90% of this capacity will expire before 2050. Although emissions from nuclear power plants align with long-term emissions goals, it is unclear how many units will seek further relicensing due to economics and safety concerns about their original operational lifetime design of 30–40 years (World Nuclear Association 2016b). In the last few years, at least 12 nuclear units have announced plans to shut down. In 2013, the United States initiated construction of the first new nuclear power plant since 1977, breaking ground for four new units (two units each at Plant Vogtle in Georgia and at V.C. Summer in South Carolina). These new units, along with Watts Bar 2 in Tennessee—which first produced power in June 2016, 43 years after its construction began—have gone well beyond proposed costs and schedules, adding uncertainty to the likelihood of new nuclear power plants being built.

The future of the U.S. electricity sector may be affected by public and private sector commitments to reduce GHG emissions. State-level climate policies include some combination of enhanced building codes, energy efficiency requirements, and renewable portfolio standards (RPS), which are particularly significant because they target 10–50% of generation in 29 states. Quite a few other states have non-binding GHG reduction goals. Other significant sub-national climate policies related to the power sector are the Regional Greenhouse Gas Initiative (RGGI), a nine-state market-based program to reduce carbon dioxide emissions from power plants, and California’s multi-sector cap-and-trade program.

### ***Environmental Goals***

GHG reduction is being pursued through a wide range and scale of efforts. In the United States, the public sector alone is pursuing it through the Paris Agreement, which was established by the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP); the U.S. Environmental Protection Agency’s (EPA) Clean Power Plan; nine northeastern states’ Regional Greenhouse Gas Initiative and California’s AB32; and the Conference of Mayors. The Clean Power Plan and U.S. participation in COP, which are mostly unrelated to the coal and nuclear trends discussed above, help define electricity decarbonization targets.

The Clean Power Plan addresses carbon dioxide emissions from the electricity sector. With respect to that sector, U.S. commitments submitted at the 21st COP (COP21) would likely require emissions reductions more stringent than those of the Clean Power Plan. Moreover, meeting the COP21 goals would require rapid development of large-scale low- and zero-carbon electricity generation as well as implementation of emissions reduction strategies in transportation, industry, and other sectors.

The UNFCCC was adopted at the Rio Convention in 1992 and entered force in 1994. In 2015, at COP21, representatives from more than 190 countries created an international agreement calling on countries to keep temperature rise to “well below” two degrees Celsius above pre-industrial levels by 2100. Approximately 163 countries submitted intended nationally determined contributions (NDCs) committing to GHG emissions limits, and, by surpassing a required ratification threshold, the Paris Agreement entered into force on November 4, 2016. The first session of the COP serving as the Meeting of the Parties to the Paris Agreement (CMA1) took place in conjunction with COP22 in November 2016 in Marrakech, Morocco.

To stay below the COP21 two-degree Celsius temperature rise limit, the Intergovernmental Panel on Climate Change (IPCC) estimates that global GHG emissions must be reduced by 41–72% by 2050 and

by 78–118% by 2100 compared with 2010 emissions (IPCC 2014b). The IPCC estimates that these reductions will require that, by 2050, at least 80% of electric generation come from renewable energy, nuclear energy, and the use of carbon capture and storage (CCS) and that fossil fuel power generation that does not utilize CCS technology must be almost completely eliminated by 2100. The U.S. NDC submitted at COP21 was a GHG emissions decrease of 26–28% below the 2005 level by 2025. This decrease can include reductions of the main recognized greenhouse gases of carbon dioxide, methane, nitrous oxide, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride from any combination of emissions source sectors. Of note, carbon dioxide emissions from the electricity sector comprise nearly a third of total U.S. GHG emissions.

Reducing power sector emissions by 80% in the next 35 years requires replacing most of the 757 gigawatt (GW) of fossil capacity (99% of power sector emissions and 2700 TWh of generation, from Table 1) with zero or low-carbon generation.<sup>1</sup> The DOE Energy Information Administration's (EIA) *Annual Energy Outlook 2016* anticipates that U.S. energy capacity provided by fossil-fueled power plants will grow with or without the Clean Power Plan and that coal retirements will be in the range of 60–100 GW by 2040. The report also forecasts demand to increase by some 1,000 TWh by 2040, with no additional emissions reductions beyond those possibly driven by the Clean Power Plan (~27%) between 2030 and 2040 (U.S. DOE EIA 2016). If so, 2,600–3,700 TWh of new zero- or low-carbon generation will likely be required to meet U.S. commitments to the Paris Agreement.

It is unlikely that this emissions target will be attained without significant innovation and very efficient deployment of low-carbon power generation technologies. The recent U.S. presidential election has increased uncertainty regarding federal policy related to greenhouse gases and highlighted the fact that although policy goals can be powerful drivers, innovation can also benefit from private investment, private action, and public-private partnerships.

## **INNOVATION FOR LOW-CARBON TECHNOLOGY DEPLOYMENT**

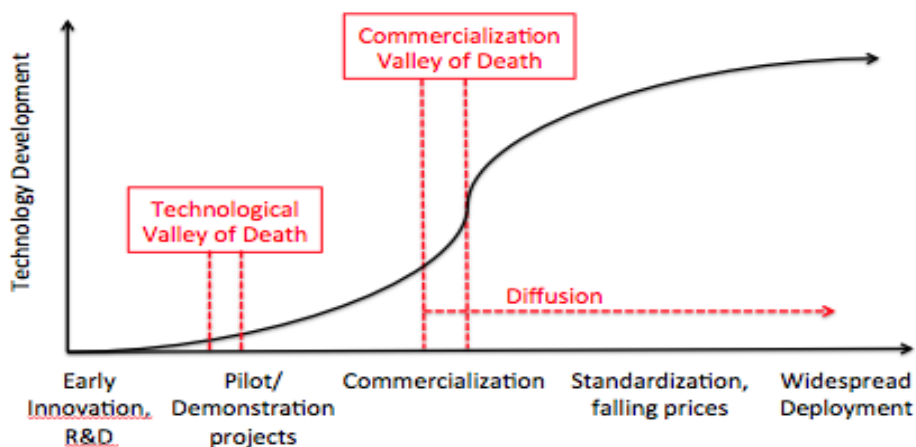
Energy technologies, even those already considered mature, are constantly evolving. For a transformation of the power sector within the next few decades—meaning large-scale deployment of technologies at early or demonstration stages such as, but not limited to, advanced nuclear, energy storage, and carbon capture and storage—innovation progress at a normal pace may not suffice. Progress in clean energy technology and ways to accelerate the early innovation-through-deployment process are discussed below.

The innovation process for electricity generation, which broadly refers to developing and advancing technologies that reduce economic costs, environmental costs, or both—has been widely researched (e.g., Gallagher Holdren and Sagar 2006; Gallagher et al. 2012; Popp 2010). It typically follows an S-curve pattern, including early-stage innovation, research and development (R&D); pilot-scale demonstration; and, if viable, commercialization and market diffusion to reach widespread deployment (Figure 1). Financial and policy incentives can help technologies, investors, developers, and regulators move through the process. They can also inadvertently hinder development; for example, uneven subsidies or regulatory requirements can distort the market. Like technologies, financial and policy incentives may require additional innovation.

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<sup>1</sup> COP goals are not 80% for each sector; an 80% reduction in the power sector is used for illustrative purposes. The power sector's share may need to be more or less than 80%. The extent to which electricity demand grows and to which other sectors electrify will be large determinants of how GHG emissions reductions need to be apportioned sector by sector to reach an 80% reduction.

Figure 1. Technology development and stages of advancement



In its nascent phase, a technology often develops slowly due to innovation challenges, high risks, and high costs (Popp, Newell, and Jaffee 2010). Once a technology crosses the “technological valley of death,” it still needs both demonstration projects and some commercial-scale success to cross the “commercial valley of death” to reach widespread deployment (Jenkins and Mansur 2011). Many technologies fail early on because materials or other technical requirements are not feasible at increasing scales. However, lack of capital funding or seemingly prohibitive regulatory hurdles can also disrupt progress at these milestones. As a commercial-scale technology is built and utilized, processes can become more efficient, lead to new breakthroughs, or both (Grubler, Nakicenovic, and Victor 1999), supporting further dispersion into use. Familiarization with a technology has been shown to have a positive effect on increasing investment (Popp, Hascic, and Medhi 2011) and acceptance. Further commercialization and diffusion enables standardization and mass production, which can further lower costs (Grubler, Nakicenovic, and Victor 1999) in a supportive feedback loop.

Agencies such as the U.S. DOE and the International Energy Agency (IEA) track clean energy technology innovation and progress and provide up-to-date analysis of current technologies, markets, and policies. Serial IEA reports such as *Tracking Clean Energy Progress* and *Technology Roadmap* give concrete examples of the advancement of clean energy technology innovation. The most recent reports align technology progress evaluation and advancement needs with the levels of innovation and deployment estimated to be required to meet the COP21 targets. Examples of how commercialization and diffusion (Figure 1) evolve are illustrated in *Tracking Clean Energy Progress 2016*, which points out recent cost declines for onshore wind (30%) and utility-scale solar (65%) since 2010. Solar photovoltaics are a good example of S-curve evolution; over 50 years, they’ve become more efficient, less costly, and more widely deployed, and they have resulted in technological learning.

Discussed below are three low-carbon technology categories—advanced nuclear, carbon capture and storage, and energy storage—each facing differing challenges along the development curve. For example, a main challenge (and investment risk) for advanced nuclear technologies is the regulatory, political, and geographical issues associated with getting pilot plants approved and built. For energy storage technologies, the high costs of demonstration are currently the main obstacle. For carbon capture and



storage, some technologies have reached the demonstration phase, but none have low costs at commercial scale (or a viable market). Therefore, to reduce power sector GHG emissions 80% by 2050, rapid innovation is needed for these three technologies or some other large-scale low-carbon approach. Rapid innovation will require both sustained progress for low-carbon technologies and a concerted stakeholder effort focused overcoming the valleys of death by increasing low-carbon investment and implementation of supportive policies to accelerate innovation.

Part of the challenge of bringing more investment to large-scale, low-carbon electric technologies is that these technologies are generally capital-intensive and take a long time to commercialize. Moreover, they are risky because a lower-cost, more reliable, or safer technology might emerge; anticipated regulations such as a restrictions on carbon emissions might not materialize; or costs for another power generation technique or fuel might decrease. Generally, the typical investor selects either high-risk, low-capital or low-risk, high-capital investment opportunities, making new large-scale energy investments relatively less desirable.

The challenges for rapid innovation are highly intertwined and interdisciplinary, but they can be grouped into two broad categories: the lack of a robust market for low-carbon electricity and the risks associated with technology or investment therein. Relatively few investors are interested in financing expensive (capital-intensive) and new (risky) technologies, especially given the long payback times involved. In addition, the lack of market signals, such as a set price on carbon dioxide or some value on the “externalized” impacts of GHG pollution undervalues GHG-free generation compared with the currently cheaper fossil combustion, further reducing interest in innovation backing.

Investors interested in clean energy technologies have typically focused efforts on measures such as energy efficiency, information technology (IT) smart meters, and small-scale renewables, which provide shorter-term implementation and lower capital investment opportunities.<sup>2</sup> The mismatch between new large-scale, low-carbon technology needs and private investor interests are often a result of misalignment of return-on-investment periods, policies, or incentive lifetimes. Some types of policies can help overcome this misalignment and can support continued investment through the technological or commercialization valleys of death by de-risking or incentivizing investment. Several broad national policies affect electric sector technology development, though many are not focused on GHG emissions.<sup>3</sup>

## **EMERGING ZERO- AND LOW-CARBON TECHNOLOGIES**

According to EIA estimates, approximately 2,580 TWh of energy would be sufficient to replace current coal-generated electricity and to meet projected additional demand. Comparing costs of power generated by different technologies is complex and would require many assumptions. Nonetheless, investing in zero-carbon technologies is projected to be much more expensive than business as usual. To achieve low-carbon goals at a reasonable cost, innovation will need to be accelerated and explored across a wide range of technologies and accompanying investments and policies. Moreover, regulatory adjustments will be required for implementation.

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<sup>2</sup> These renewables include wind and solar, which on a unit basis are often small even if significant in aggregate.

<sup>3</sup> The EPA’s Clean Power Plan, which is highly contentious and being litigated in the Supreme Court, is an exception, though as previously mentioned, it is more likely to accelerate the power sector transition than to usher in a transformation. The UNFCCC COP21 commitments may also encourage electricity sector research development, demonstration and deployment for GHG emissions reductions.

The most common low-carbon electricity generation technologies in use are hydropower, traditional nuclear, wind, and solar resources. A hot controversy is whether the 2050 GHG reduction targets can be met merely by expanding the use of these current technologies, even with rapid improvement in cost and performance. Explored here are three promising large-scale, low-carbon technology categories that may be needed in conjunction with expanded renewables and traditional nuclear generation.

Carbon capture and sequestration<sup>4</sup> (CCS), advanced nuclear power, and renewables combined with electrical energy storage (to enlarge the portion of intermittent sources that can provide reliable electricity) are three examples, not a most likely list. These technologies may help meet new demand and replace existing fossil generation by 2050, and they also illustrate differing challenges (and opportunities) to needed levels of deployment. Other options, such as advanced renewable energy sources, energy-efficiency improvements, and significant advancement in the transmission grid have large potential GHG reduction contributions, but for the sake of brevity are not addressed in this paper. Details on other low-carbon technologies are available in Appendix A.

### ***Technology 1: Carbon Capture and Sequestration***

Carbon capture and sequestration is a process of capturing, transporting, and storing carbon dioxide in such a way that it will not reach the atmosphere. Carbon capture technologies, including pre- and post-combustion as well as oxy-fuel combustion, have been used for industrial purposes for a number of decades and are estimated to have the potential to capture and sequester as much as 90% of carbon dioxide emissions from fossil-fueled electric power plants. Sequestration is generally planned to be in underground geological formations, such as depleted oil and gas wells or deep saline formations.

Based on regional assessments, the U.S. DOE estimates the storage potential for carbon dioxide as between 1,000 and 10,000 times the amount annually emitted (U.S. DOE 2015b), although geological storage potential, proximity, and transport cost will vary by power generation facility. Commercial-scale implementation of carbon capture and storage for power plants would allow for significant reduction of GHG emissions without the need to transition away from coal and natural gas use.

No large-scale CCS power plant projects are operating in the United States, but 13 states have financial incentives in place for implementing CCS technology (NCSL 2015). Three projects are under construction: the Kemper County Energy Facility in Mississippi, the Petra Nova Carbon Capture Project in Texas, and NetPower's demonstration plant in LaPorte, Texas. A few other projects are in planning phases (e.g., Texas Clean Energy Project in Texas and the Southeast Regional Carbon Sequestration Partnership project at Plant Barry in Alabama). All projects currently planned will use the captured carbon dioxide for enhanced oil recovery (MIT EI 2016). CO<sub>2</sub> emissions limits on new coal- or gas-fired power plants were set using New Source Performance Standards under section 111(b) of the Clean Air Act in August 2015. Although new gas-fired power plants can meet emissions standards with alternate technology, any new coal-fired plants will almost certainly require the use of carbon capture and storage. More stringent restrictions in CO<sub>2</sub> emissions through the adoption of the Clean Power Plan (for existing plants) may also play a role in the advancement and expanded adoption of carbon capture and storage.

CCS technologies have received both private and public funding. FutureGen, a \$1.7 billion CCS project in Illinois, was allocated \$1 billion in stimulus funds but was halted after spending only a fraction of the

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<sup>4</sup> Storage and sequestration can be considered equivalent.



award. Current projects, Kempur and Petra Nova, have both DOE funds and private funding from Southern Company, NRG Energy, JX Nippon Oil and Gas, and Texas Coastal Ventures. In 2016, NetPower, partnering with Exelon, CB&I, and Toshiba, broke ground on a 50 MW demonstration plant.

CCS innovation advancement has been slow for a variety of reasons. Primarily because there is little market value for CO<sub>2</sub> emissions reductions, the cost of CCS exceeds any economic value related to emissions capture (e.g., for enhanced oil recovery or any realized emissions reduction value). Cost overruns for early demonstration projects have added to the challenge of financing this capital-intensive technology. Multiple new CCS methods in the research phase are currently expensive and associated with safety concerns. Carbon dioxide can be harmful to both humans and the environment in high concentrations, leading to questions about transportation- and storage-related liability. Advances in materials, capture processes, and storage technologies are being explored to improve performance and safety and to reduce costs.

### ***Technology 2: Advanced Nuclear Energy***

The currently operating U.S. fleet of nuclear generators is composed of approximately 99 mostly thermal light water reactors (LWRs), each constructed sometime between 1964 and 1976 and each designed to operate for approximately 40 years. Although these plants produce virtually no carbon dioxide or associated emissions at the stack, they pose significant concerns regarding radioactive waste, potential nuclear accidents, and weapons proliferation. Furthermore, development requires very high levels of financial investment and long planning horizons. Reactors currently under construction have incurred significant cost and schedule overruns. Nevertheless, dozens of companies, entrepreneurs, governments, and international coalitions have taken on the challenge of developing the next generation of nuclear reactors.

Advanced nuclear designs aim to improve efficiency, safety, costs, and operational lifetimes. Advanced designs include advanced light water reactors and fast neutron reactors, which use molten salt, liquid metals, or high temperature gas rather than water for cooling. Small modular reactors (300 MWe, or megawatt electric, or less) are being designed to reduce the cost and time requirements for fabrication and transportation and to improve flexibility to hedge against future demand uncertainty. Other systems, such as fusion reactors, are still in very early research phases, and while gaining significant attention, their future potential viability is uncertain.

Safety has traditionally been an important concern for nuclear energy generation, but most advanced reactors are planned to be “passive” or “walk away safe”—that is, in the event of a malfunction, they should automatically shut down through systems triggered and controlled by natural processes such as melting and gravity. Reactors adhering to such a standard would have a significantly reduced probability of meltdowns, such as those experienced at Chernobyl, Three Mile Island, and Fukushima Daiichi.

In addition to being safer, many of the reactors currently under development are designed to significantly reduce the amount of discharged nuclear waste. For example, in lead-cooled reactors, uranium fuel can be used for decades without refueling, whereas the uranium fuel in traditional light water reactors can only be used for about four years. Sodium-cooled reactors can potentially reprocess current nuclear waste for usable electricity (Freed, Brinton, Burns, and Robson 2015), reducing the amount and potency of radioactive waste. One group expects its technology will produce just 2.5% of the waste of a traditional light water reactor (TransAtomic Power 2015).

Funding for the development of these technologies comes from both public and private sources; the DOE and venture capitalists are the primary contributors. Privately funded advanced nuclear companies include Terrapower (Bill Gates), NuScale (Fluor), Tri Alpha, General Fusion, Transatomic (Venrock, Acadia Woods, Armana Investment, and Founders Fund), and Helion. These companies are led by investors such as Paul Allen, Jeff Bezos, Jeff Skol, and Peter Thiel, with collective investments of some hundreds of millions of dollars. International government-backed programs include the Wendelstein 7-X stellarator in Greifswald, Germany, which has cost approximately \$1 billion and is mostly funded by the German government, and the largest current program, the ITER in Cadarache, France, which is backed by the United States and 34 other nations and which has exceeded original estimates and is now due for completion in the mid-2020s at an estimated cost of \$20 billion (Boyle 2016).

The potential for electricity generation from advanced nuclear reactors is theoretically large due to the abundance of uranium available for fuel (World Nuclear Association 2015). However, it is difficult to predict the extent to which nuclear power will contribute to electricity generation in the United States, largely because of uncertainties regarding permitting, costs, suitable plant locations, and other factors. Advanced nuclear innovation requires very high financial investment. Richard Lester, a nuclear expert from MIT's Department of Nuclear Science and Engineering, has suggested that commercializing a single new technology may require \$10 billion. Safety concerns over current nuclear technologies have partially led to a regulatory framework that may not be appropriate for encouraging innovative nuclear designs (Lester 2016). However, in May 2016, the Senate Environment and Public Works Committee cleared the Nuclear Energy Innovation and Modernization Act (NEIMA), which, if passed, will create a new licensing framework designed to more effectively assess advanced reactor designs.

### ***Technology 3: Bulk Energy Storage of Renewables***

Power generated using solar and wind is highly variable, or “intermittent,” over hourly, daily, seasonal, and other time scales. Dramatically increasing intermittent renewables' share of generation to decarbonize the power sector is appealing, but appropriate implementation and potential costs are somewhat controversial. Some studies suggest that by 2050 all global energy could be provided by water, wind, and solar (Jacobson and Delucchi 2011; Jacobson et al. 2015). Others suggest that bulk energy storage, defined as the capture of energy as it is produced for later use, could accommodate large-scale integration of variable (intermittent) sources (Beaudin, Zareipour, Schellenberglobe, and Rosehart 2010). Still others find that intermittent sources' capacity to meet variable load as renewables increase on the grid would require both massive renewable capacity and significant backup from conventional generation sources, creating both cost and transmission challenges (Brick and Thernstrom 2016). Without diving into these controversies, it is fair to say that developing and deploying bulk energy storage would be one way to support a significant increase in the fraction of renewably generated energy in the United States (currently 13%).

Currently, bulk energy storage comprises about 2% of the nation's generation capacity, mostly through pumped hydropower (96.2% of storage). Compressed air energy storage (CAES) and battery technologies comprise the remaining proportion of storage (3.8%). Dams and other water storage facilities are highly dispatchable, but their use is restricted by location and available water volume. Like pumped hydropower, cavern CAES systems are geographically limited (two are currently operating, one in Germany and one in Alabama). Next-generation systems may have wider potential, for example, a porous medium CAES is at an early fundamental research stage (U.S. DOE 2015b). With increasing market demand for energy

storage projected, significant research is focusing on battery storage technologies, which utilize electrochemical cell configurations to convert between chemical and electrical energy states.

Relatively small-scale battery services (e.g. electric vehicles, increased power quality, grid stabilization), have significantly improved, but batteries for bulk power management are not currently available. Conventional forms of solid-state batteries include lead-acid, sodium-sulfur, and lithium-ion, all varying in performance based on design goals. Characteristics that make batteries suitable for bulk storage include timely ramp rates (meaning the speed of adding stored electricity to the grid and ease of adjusting the rate), high energy capacity (in the range of approximately 100MW), long lifetime, and technological maturity. Several battery technologies appear to be progressing toward bulk power management viability. Each arrangement, however, comes with its own challenges, ranging from expense, unit lifetime, corrosiveness, safety and toxicity issues, and depth of discharge. Current battery research goals are to improve power output, energy capacity, materials, and potential discharge rates.

According to the DOE, four hurdles limit widespread deployment of electrical energy storage. First and foremost is cost-competitiveness of both storage components and whole systems. The other three hurdles relate to performance and safety, sometimes conflicting regulatory and market environments, and industry acceptance due to issues such as standardization and system integration (U.S. DOE 2015b). There are no validated performance and safety standards, making it difficult for investors and industry to gauge or compare the value of energy storage technologies. Bulk energy storage is part of the energy mix but will likely require significant R&D time and investment across any number of technologies before it can become a widespread source of low-carbon electricity. Manufacturing energy storage systems to meet projected global demand represents a large revenue opportunity for industrial energy interests. Navigant Research estimated the global market for grid energy storage at more than \$15 billion annually by 2024; IHS envisions 40 GW of grid storage by 2022 (U.S. DOE 2015b).

The carbon reduction potential of the combination of renewables and storage is large, but unlike advanced nuclear and carbon capture and storage, that combination has the additional challenge of needing to generate electricity and tolerate costs and losses while it is stored before use. However, the value of selling or using energy later—energy otherwise “shed”—if generated during times of low demand (i.e., excess energy) is gained. Some energy storage technologies satisfy valuable grid services other than bulk energy storage, such as transmission, distribution, and ancillary services, so these technologies are being pursued to meet multiple objectives beyond decarbonizing power generation. As a result, the value or benefit of these storage technologies—unlike targeted carbon reduction technologies such as carbon capture and storage—is only fractionally related to carbon reduction performance.

The three above-noted emerging technologies could contribute significantly to decarbonizing the power sector. Although these technologies are not ready to fully replace traditional fossil-fuel electricity generation, investment in them and similar technologies is accelerating, driven by domestic and international interest in meeting future electricity needs with clean, inexpensive energy.

## **ACCELERATING INNOVATION TO ADVANCE LOW-CARBON GENERATION**

To identify how new policies could influence additional investment and possibly lead to an accelerated innovation cycle, we interviewed approximately 20 energy experts with extensive experience in low-carbon electricity technology development, private and public financing, utilities, academia, and policy (see interview questions in Appendix B.) We wanted to surface ideas from a wide range of perspectives to

identify common approaches or to spark creative approaches to meeting decarbonization goals for 2050. Some of these ideas are described below without attribution, including a few approaches on which consensus is lacking.

On the topic of how to fund clean energy, expert analysis ranged from “only the government has enough patient capital,” to “foundations can help overcome the commercialization valley of death,” and “utilities [not regulators] will lead innovation... and we need to get PUCs to expedite R&D approvals for technologies like CCS.” Researchers at the University of Texas suggest that the clean energy sector could attract venture capital from a Food and Drug Administration-like, sequential approval process that would signal confidence to private investors. A few of the many other related or conflicting ideas included “mandates are critical,” “technology targets are needed,” “remove fossil subsidies,” and “rate-based cost recovery for utilities.”

The rest of this section describes a handful of ideas with broad support among the interviewees—ideas that could be important to build on, given the significant challenge of a low-carbon transformation of the power sector. The experts were asked broadly about meeting the 2050 low-carbon goals and specifically about overcoming innovation challenges for particular technologies. The resulting themes, along with relevant ideas found in literature, are organized here in reference to the two broad challenges mentioned in the previous section: creating a robust market for low-carbon generation and de-risking investment for low-carbon generation. Some broad takeaways about accelerating innovation are also presented.

### ***Creating a Robust Market***

One of the most common views expressed during interviews was skepticism about investment in low-carbon generation given low natural gas prices. The lack of economic drivers for low-carbon innovation was identified by almost every interviewee. Many mentioned the “simple” idea of congressionally mandating a price on carbon, through a carbon tax or through carbon caps to create a low-carbon generation market and to spur innovation. However, as that approach is considered unlikely in the existing political climate, discussions focused on strategies other than carbon taxes and caps.

A few experts favored creating a market for low-carbon generation by establishing state or national clean energy standards. Such standards are similar to renewable portfolio standards but cover more technologies and can send clear long-term policy signals about the value of zero- or low-carbon generation. Clean energy standards have been proposed in Congress, but it has been difficult to reach consensus on their details, for example, which relatively low-carbon generators should be subject to them. Another expert suggested that the government (federal or local) could create a market for dispatchable low-carbon electricity by becoming the market (i.e., purchasing only low-carbon electricity). A few experts recommended leveling the playing field for low-carbon technologies by removing fossil fuel subsidies. Any number of questions related to these ideas’ potential unintended consequences and ultimate effectiveness are worth exploring.

### ***De-risking Investment***

Multiple types of risk affect investors’ decision to invest in a clean energy technology; the first is often whether the technology will actually work. Another type of risk relates to whether the technology can be cost competitive and if it can attract a share of the market. As noted above, investing in clean electric technologies often seems to be high risk and not well suited to the typical investor profile. If measures

were put in place to reduce uncertainty for investors, it could be easier for them to become involved in clean energy technology. Interviewees offered many ideas for de-risking inherently risky technologies, but there was little consensus on solutions.

Quite a few experts suggested a significant role for the government in order to de-risk investment in low-carbon technologies. One expert suggested that the government should fund the “first-of-its-kind” commercial-scale unit for any low-carbon electric technology that meets predefined criteria. This support would help overcome a concern of many interviewees, namely that the government picks winners and losers. The idea that the federal government can help overcome the commercialization valley of death on a technology-neutral basis, however, would be difficult to implement because, as is well known, there are limited federal funds available for that activity.

Several government-related de-risking suggestions were more targeted than “fund the first commercial plant.” Richard Lester suggests that the federal government help de-risk nuclear investment and that the private sector ultimately fund commercialization of advanced nuclear technologies (Lester 2016). Another expert suggestion was for government at the both state and federal levels to show commitment to low-carbon innovation by establishing long-lasting regulatory policies, such as tax incentives or loan guarantees. Short-term policies, such as tax credits that last only a couple of years, did not appear to influence the investment decisions of any of the interviewees.

Another idea was to expand government loan guarantee programs to high-risk, low-carbon technologies, beyond nuclear, to attract capital. Quite a few experts alluded to the 2009 American Recovery and Reinvestment Act (ARRA) loans as a good approach to investing in risky technologies, even while noting that many technologies should not be expected to succeed. Despite the political football the ARRA program has become, particularly regarding Solyndra, interviewees thought the loans approach was on the right track.

### ***Increasing Investor Confidence***

One known risk for many investors, particularly those without appropriate expertise, is that highly technical and proprietary processes can be difficult to assess. From the interviews, one suggestion to overcome this barrier was for the government to support a third-party verification of proprietary technology to increase investor confidence and reduce the burden on investors to perform their own due diligence. A similar but different idea supported by a number of experts is to have more non-governmental intermediary groups to help bridge the information barriers associated with technology uncertainty.

Intermediaries play an expert role in information sharing and undertaking technical or other due diligence for parties that can benefit from, but may not possess, that expertise themselves. Some intermediaries match clean energy technologies with appropriate investors based on risk preferences.<sup>5</sup> Other intermediaries, such as Cyclotron Road and ARPA-E, work at the basic research level or introduce basic ideas to investors to create startup companies. Successful intermediaries can help match groups and funding in cases in which the two parties never would have been able to come together on their own. Although most interviewees were supportive of participation by intermediaries, a few viewed them as completely unnecessary.

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<sup>5</sup> See Appendix C for examples of this approach, such as by CREO syndicate, Aligned Intermediary, and Energy Options Network.

Interviewees representing the utility perspective identified completely different risk challenges than experts from other sectors. They were less interested in intermediaries, presumably because they have adequate resources to assess new technologies internally, and more interested in the fact that regulated utilities have no incentive to persuade their public utility commissions to build risky or expensive technologies. Regulated utilities' risk in pursuing innovative technologies extends to whether development and commercialization costs can be recovered in the event that a better (e.g., more efficient or less expensive) technology emerges. Investors frequently prefer predictable returns in restructured markets, which results in a conservative approach to new technologies. Interviewees were interested in finding ways to change this dynamic so as to encourage utility investment in innovative technologies.

### ***Technology Specific Challenges—Advanced Nuclear***

With respect to advanced nuclear risk, many interviewees said that the innovation challenge is uniquely acute in the United States, where regulatory hurdles have been blamed for creating a wide valley of death between the research and development stage and the demonstration stage. These hurdles increase costs and create high uncertainty about the likelihood of licensing. Nuclear Regulatory Commission (NRC) licensing guidelines that may work well for conventional light water reactors may not work well for other advanced designs, which may need a different approach for evaluation of safety and licensing decisions.

Many interviewees said that financing is a relatively small challenge compared with overcoming the NRC process. Although many are skeptical about whether regulatory reform is possible, the above-noted Senate Bill 2795 (Nuclear Energy Innovation and Modernization Act) was introduced to address this issue. Other countries are eager to commercialize advanced technologies if they can. The costs currently associated with advanced nuclear are leading companies to look to Canada, South Korea, and China for prototype development. One of the arguments for rethinking the regulatory form is that the outsourcing of nuclear development to other countries is likely to result in more dangerous development and heightened waste security concerns beyond U.S. control.

One policy, suggested by Thorcon Power, is for the government to establish a “protopark” to overcome regulatory reluctance to building nuclear pilot projects. The federal government would designate land as a user-pay prototype testing area with low-level disposal and high-level waste storage facilities. The user would have to obtain private insurance, which would also require them to find non-governmental (market) help to identify pilot projects worth testing. The approach would help overcome regulatory, licensing, and testing problems (Devanney 2015).

## **CONCLUSIONS**

Transforming to a low-carbon power sector will be no small feat, though progress is being made. Advanced nuclear, renewables with storage, and CCS technology each have different and significant obstacles to wide commercialization. Although many groups are working on low-carbon technologies, policies, and funding innovation, it is unclear which, if any, approaches will be successful.

The current rate of power sector decarbonization will not reach broad U.S. goals without more concerted efforts. This working paper explores trends in the power sector, decarbonization goals, and experts' ideas for more rapid advancement in the development of low-carbon technologies and the financing, policy, and regulatory support needed for widespread implementation. Although interviewees expressed desire to



bring investment to low-carbon technologies and to identify policies that would encourage innovation, consensus on a path forward was lacking. Also lacking: appropriate forums for dedicated low-carbon electricity sector stakeholders—developers and utilities, investors, academics, and policy and regulatory communities—to create a shared vision of that path, notably, forums at multiple scales of implementation to support rapid advancement of well-vetted technologies.

Three steps appear crucial to success: (1) building on the efforts of currently active groups (see Appendix C); (2) developing systematic, interdisciplinary approaches to identify gaps in the development process and to support promising low-carbon technologies, develop informed policies, and to improve regulatory processes; and (3) engaging a wide range of stakeholders in support of technology development to accelerate broad low-carbon commercialization and deployment. Transformation of electricity sector infrastructure will need to account for both known and unknown future needs and will need to recognize and take advantage of every significant technical advancement as rapidly as possible if the United States is to build a strong and long-lasting energy foundation for the coming century.

## **APPENDIX A: ADDITIONAL TECHNOLOGIES**

### ***Expanded Hydro***

Hydroelectric power currently accounts for approximately 7% of the electricity produced in the United States. In its *2015 Quadrennial Technology Report*, the DOE estimated that U.S. hydroelectric power capacity could be doubled. This expanded capacity could come, in part, from retrofitting electrified dams and by electrifying other dams, but the majority would be sourced from new dam sites known as low-impact new development. Despite the potential for expanded hydroelectric power, the combination of water use restrictions and a lack of capital investment in infrastructure have prevented growth in such development (U.S. DOE 2015b).

### ***Offshore Wind***

Offshore wind is a recently commercialized technology in Europe, which has more than 11,000 MW of capacity, 3,000 MW of which was added in 2015 (EWEA 2016). In the United States, the offshore wind market is still developing. The DOE funded seven demonstration projects in 2012. In 2014, three were selected as offshore wind advanced energy demonstration projects and received a second round of demonstration funding (U.S. DOE EERE 2016a). Each of these projects will test separate innovations and are supposed to be grid connected by the end of 2017 (U.S. DOE 2015b). NREL has estimated the technical potential, at 90 meters in height, for offshore wind of more than 4,000 GWh per year (Schwartz, Heimiller, Haymes, and Musial 2010). There are many challenges to overcome before the United States will have significant offshore wind installations. Necessary cost reductions and research development, demonstration and deployment advancements not only go hand and hand but should also follow from any learning from domestic demonstration projects and the European experience.

### ***Enhanced Geothermal Systems***

Enhanced geothermal systems (EGS) is a technology that artificially replicates the conditions that are favorable for traditional geothermal energy generation. This technology will allow for the expansion of geothermal energy production, providing a baseload energy source with little to no GHG emissions. It has been estimated that EGS could contribute 100 GW of capacity to the U.S. grid within the next 35 years (U.S. DOE GTO 2012). Although the technology is primarily in the R&D phase, five demonstration projects are funded through the Department of Energy. The total DOE funding for these projects is \$40.5 million (U.S. DOE EERE 2016b).

To be competitive in the market, certain essential component EGS technologies need to be developed and improved. There are also some concerns about some systems inducing seismic activity, although the extent of these concerns is not well known (U.S. DOE GTO 2012).

### ***Traditional Nuclear Energy***

Nuclear generation accounted for about 20% (797 TWh) of U.S. electricity generation in 2015. Nuclear units emit little or no greenhouse gases or associated stack emissions; however, the process of building these units is both costly and lengthy, and there are safety concerns related to waste handling and potential nuclear accidents. Delays and increasing costs can partially be attributed to the complexities of designing and building a nuclear facility, but cost stress is further exacerbated by the lengthy permitting process required by the NRC. In the past, technical specifications were not required for a construction

permit. This approach would sometimes result in required changes during the construction process to meet certain safety standards, which then caused delays and additional costs (Council on Foreign Relations 2011). Although progress has been made to streamline and reduce uncertainty, the process still takes at least five years to complete (Nuclear Energy Institute 2014). Partially as a result of the complex permitting process, nuclear capacity has seen no growth over the past 30 years. However, due to the changes discussed above, seven new units have been issued licenses by the NRC and four are under construction: two units at the Virgil C. Summer Nuclear Generating Station in South Carolina and two units at the Vogtle Electric Generating Plant in Georgia (Nuclear Energy Institute 2016). Public concerns over the safety of nuclear reactors in addition to problems associated with nuclear waste storage and management also remain major obstacles for the expansion of nuclear energy.

### ***Ammonia***

Ammonia combustion to generate electric power is in the R&D stage. Ammonia could function like pumped storage, storing energy when there is excess supply. Energy is needed to combine nitrogen and hydrogen to produce ammonia. If ammonia is manufactured with clean energy, it could be used as a storage and transportation mechanism for renewable energy technologies. Space Propulsion Group, Inc. is one group evaluating ammonia for use as an alternative to natural gas in gas turbines. The technology has been successfully demonstrated; however, no large-scale power generating units burn ammonia. Given that ammonia is a toxic substance, safe and reliable transportation and storage are needed to protect workers and the public. For ammonia to become a widespread fuel source, significant infrastructure would need to be developed and implemented (Thomas and Parks 2006).

### ***Nuclear Fusion***

Nuclear fusion is the process of combining hydrogen atoms to produce helium, which releases a massive amount of energy. This technology has been considered promising since the 1970s. Despite some important breakthroughs in the technology, many are skeptical that it will ever reach commercial viability (World Nuclear Association 2016a). Once sufficiently developed, nuclear fusion could provide an abundance of safe and reliable energy with no GHG emissions and a very small amount of waste. Fusion reactors should be safer than traditional nuclear reactors, presenting no risk of a serious meltdown. However, a major challenge is that it is difficult to efficiently initiate a fusion reaction. There has yet to be a fusion technology demonstration that has produced a net gain in energy (Laberge 2014). Fusion reactor technology is primarily in the R&D phase. Fusion research and development is funded by millions of dollars from both public and private investors. Funding is mostly supplied by energy venture capitalists and the Department of Energy.

## APPENDIX B: QUESTIONS FOR EXPERTS

### *Interview Questions for Investors*

1. Can you give an overview of your background, especially if it includes anything in the electricity field?
2. What stage of technology/innovation do you invest in?
3. How does the riskiness of an investment impact the attractiveness of your strategy?
4. Does your investment strategy include goals towards the environment, especially clean energy technologies?
5. Is there a typical scale of investments that you make?
6. The electricity sector is currently undergoing a lot of change. What do you think the energy mix will look like in 20 years?
7. Do you invest in any clean energy technologies at present?
8. Have you had any failed investments in clean energy technologies? What investment lessons did you take away?
9. Are there any reasons you avoid clean electricity investments?
10. How do you think big investments, like CCS and nuclear, should be financed?
11. How do current clean energy policies influence your investment approach?
12. Do you think there should be additional clean energy policies to stimulate investment?
13. Under what conditions would you or others invest in pre-commercial expensive and possibly risky technologies?

### ***Interview Questions for Technology Experts and Entrepreneurs***

1. Can you give an overview of your background, especially as it is related to energy/electricity technologies?
2. Can you briefly describe your technology?
3. How would you describe your market potential to investors?
4. What are the main hurdles to advancing your technology?
5. Does risk associated with your technology contribute to innovation [funding] challenges you face?
6. What private/public financing are you exploring?
7. What types of investors do you approach?
8. Do you approach investors for project finance, equity stake, or both?
9. Would specific policies help your technology?
10. How/Would an increase in DOE funding help your technology?
11. Has an accredited group helped to validate your technology? Would quality assurance or credentials help support your technology?
12. Do you think an intermediary organization would help your technology?
13. How do you think big investments, like CCS and nuclear, should be financed?

## **APPENDIX C: RELATED CLEAN ENERGY INNOVATION, POLICY, AND FINANCING EFFORTS**

Various groups are working in the disruptive technologies funding and clean-tech innovation ecosystem. They include universities, think tanks, and government organizations, and their work ranges from the purely theoretical to the practical (i.e., actual implementation of solutions). This appendix provides some insight into that work.

### ***Harvard Business School***

Although Harvard Business School does not appear to have an initiative devoted to energy, many of its faculty are interested in the topic. For their 2010 working paper “Venture Capital Investment in the Clean Energy Sector,” Shikhar Ghosh and Ramana Nanda interviewed a number of venture capitalists on the topic of clean energy investment. Their paper discusses the structure of venture capital investment, why it is not ideal for investing in energy startups, and possible solutions to that problem. The authors found that venture capitalists would prefer to exit their investment before energy startups have fully matured. They argue that although this timing issue has been addressed in other industries, such as biotechnology and communications networking, similar measures in the clean energy industry are unlikely given utility companies’ uniqueness, particularly the degree to which they are entrenched in the market due to economies of scale, required infrastructure, and current regulation. The authors advocate for government intervention to accelerate the change needed to eliminate the valley of death for commercialization. The proposition is to develop an active mergers and acquisition market that will allow for venture capitalists to exit their investment earlier than in the current energy innovation ecosystem (Ghosh and Nanda 2010).

### ***University of Texas at Austin***

Although the University of Texas has the Energy Institute and the Kay Bailey Hutchison Center for Energy, Law, and Business, it has no groups or projects specifically dedicated to energy innovation or finance. It does have faculty members who are conducting research on this topic. In their 2015 working paper “Venture Capital in Clean Energy Innovation Finance: Insights from the U.S. Market during 2005–2014,” Varun Rai, Erik Funkhouser, Trevor Udwin, and David Livingston explored how policy might spur venture capital investments in clean energy technology. They conducted semi-structured interviews with venture capitalists, members of regulatory groups, and investment houses that are involved in clean energy technology investing. Their main finding is that venture capitalists and policy makers have been learning and are well positioned to accelerate funding for clean energy technologies. The authors also challenge conventional wisdom that the scope of investment has been a deterrent for investment in large-scale projects, asserting that the larger issue is the type of risk involved. They point out that proving a technology works is highly capital intensive. In short, it entails a high price for a high risk. The authors also point to a lack of information on rate of return as another barrier to effective investment in clean energy technologies. They offer policy insights that are designed to provide a framework through which government seed money does not pick “winners” and “losers” to increase transparency about the effectiveness and feasibility of clean energy technologies and to decrease uncertainty in the market by creating a mechanism through which successful startups can exit the market (Rai, Funkhouser, Udwin, and Livingston 2015).



### ***Carnegie Mellon University***

Carnegie Mellon has two organizations working on energy. The Scott Institute for Energy Innovation is dedicated to achieving a sustainable energy economy through multidisciplinary research on technology development. The Center for Climate and Energy Decision Making focuses on the public policy and private decision making necessary to reach a low-carbon economy. This group appears to do some work on energy innovation finance (Center for Climate and Energy Decision Making 2015).

### ***Duke University—Duke Energy Initiative***

The Duke Energy Initiative at Duke University has not done much work on energy innovation finance, but its former head, Richard G. Newell, has done a large amount of research on energy innovation, some of it captured in *Accelerating Energy Innovation: Insights from Multiple Sectors*, which was written in collaboration with Rebecca Henderson. To explore how energy innovation can be accelerated by public policy, Newell and Henderson explored four industries that have seen rapid acceleration of innovative growth: life sciences, agriculture, information technology, and chemicals. Their main finding is that public policy can be effective in helping to accelerate innovation, as long as it is well integrated into the complex ecosystem of the market (Henderson and Newell 2011).

### ***New York University Law—Guarini Center***

The Frank J. Guarini Center for Environmental, Energy, and Land Use Law at the NYU School of Law focuses on market-based approaches to environmental and energy issues in an effort to reach a sustainable economy. The Guarini Center has several initiatives, including the future of the electric utility sector, exploring structures for global climate action, and ensuring sustainable low-carbon development in developing countries. The project on the future of the electric utility sector focuses primarily on electric utility regulation from a grid-scale perspective. It addresses changes to the electric grid, along with distributed energy production, instead of changes in baseload electric generation technology.

One particularly relevant effort is the New Renewable Finance Project (Guarini Center 2015a). It focuses primarily on reducing the capital costs of developing renewable energy technology through the use of various financial tools. A fact sheet by Jonathan Schrag and Seth Silverman outlines the inadequacy of federal tax credits in incentivizing investment in renewable energy projects, and it proposes adaptation of existing financial tools, such as master limited partnerships, real estate investment trusts, asset backed securities, and yieldcos. These tools are essentially all methods to create a portfolio of renewable technology companies that are broken into smaller publicly tradable portions of the portfolio. Both of these methods help to avoid the problem of capital intensive and long return on investment projects from deterring investment in renewable energy technologies, by allowing investors to diversify their risk and leave the market at their convenience (Guarini Center 2015b).

### ***Massachusetts Institute of Technology Energy Initiative***

The MIT Energy Initiative (MIT EI) focuses its research on the future of energy and how the global system can reach both a sustainable supply and use of it. Part of this research focuses on energy transformations, which the MIT EI defines as, “Developing alternative energy sources that can supplement and ultimately displace fossil fuels, transforming the energy marketplace.” Although much of this research is focused on the technology involved with these transformations, the MIT EI employs a multidisciplinary approach. This approach involves research on policy, environmental impact, economics, and financing of energy. Within the research on financing, there is a particular focus on how to most

effectively utilize energy research funding. Although MIT has produced studies titled “Utility of the Future,” “The Future of Coal” and “The Future of Nuclear Power,” which draw from a group of international companies to address broad questions of the future of the global electricity market, with a focus on new and emerging technologies, it does not address the funding of clean energy companies. However, some research conducted through the MIT Energy Initiative is worth mentioning (MIT EI 2015).

In her June 2015 thesis, “An Analysis of How Climate Policies and the Threat of Stranded Fossil Fuel Assets Incentivize CCS Deployment,” Victoria Clark makes the case for carbon capture and storage as a critical piece of deep decarbonization. Although Clark touches on the financing for CCS projects, she does not focus on private investors. Instead, she highlights the need for government policies, such as a carbon tax, to make carbon capture and storage more competitive. She also discusses the need for direct financing, through grants or loans, to CCS companies from the government, specifically arguing that carbon capture and storage needs funding on par with renewable technologies. She acknowledges that CCS projects typically require more capital, but she asserts that this need makes it even more critical that they receive support from the government (Clark 2015).

“Closing the Energy-Demonstration Gap” makes the case for a decentralized approach to energy technology funding and development. The authors acknowledge that private funding sources are inadequate for funding transformative energy technologies due to the scale, risk, and regulatory climate in the space. They also argue that the Department of Energy has seen mixed results and is not the best mechanism for financing transformative energy technologies because they are too risk averse. One solution is a regionally based funding network. Each regional group would be run by technology and project investors and would be funded through state money coming from climate change mitigation funds, an electric grid utilization tax, federal money, and eventually private funding. These Regional Innovation Demonstration Funds (RIDFs) would theoretically trigger competition both among each other for federal funds and among technology innovators for RIDF funding. This strategy would allow for an array of promising technologies to receive the funding that they need to develop, demonstrate, and deploy their technology. Failure would be more tolerable within this framework, allowing more innovative technologies, which the DOE may not have invested in, to demonstrate their potential (Lester and Hart 2015).

### ***Energy Innovation Reform Project***

The Energy Innovation Reform Project is a nonprofit group focused on advancing energy technology innovation in the United States. The group argues that the combination of market failures and ineffective government regulations have hampered energy innovation. To accelerate innovation, they argue that the solution is to refocus government subsidies of renewable energy to fund R&D projects, restructure the DOE to be run more effectively, and remove some of the regulatory burden on nuclear energy (Energy Innovation Reform Project 2015).

### ***Massachusetts Institute of Technology Industrial Performance Center***

The Energy Innovation Project is run through the MIT Industrial Performance Center. This project focuses on a multidisciplinary approach to overcoming funding problems for innovative energy technologies after the R&D phase. It approaches this problem by looking at energy innovation systems and considering “incentives, regulations, markets, and public and private interests against which

development, demonstration, early adoption, and diffusion of new energy technologies take place” (MIT IPC 2015).

In a working paper for this project, “America’s Energy Innovation Problem (and How to Fix It),” Richard K. Lester argues that the changes necessary to curb the effects of climate change will not be realized in the current energy innovation climate. He dismisses a price on carbon as politically infeasible. He then makes the case for public support for additional public and public-private institutions that will accelerate development of costly energy innovation projects, an apparent precursor to the scheme he presented in “Closing the Energy Demonstration Gap” (Lester 2009).

### ***Stanford University—Steyer-Taylor Center***

Stanford’s Steyer-Taylor Center for Energy Policy and Finance has several projects on clean energy technology funding. One of these projects, Increasing Capital Flow to Clean Energy, focuses on gaining insight from policy, finance, and industry leaders to spur investment in renewable energy. At several roundtable discussions, renewable energy and financing experts concluded that securitization would minimize costs and allow for a broader range of investors to enter the space. They also concluded that development of an easily accessible database that has information on both companies’ long-term power production capability and likelihood of default would help investors make better decisions and increase the likelihood that they would invest. Finally, the experts concluded that there needed to be some standardization in the contractual documents used in this space to help streamline the investment process (Schwabe, Mendelsohn, Mormann, and Arent 2012).

One of Steyer-Taylor Center’s other projects is the Electric Power Commercialization Finance Project, which explores the technological, regulatory, and financial barriers to commercialization for electric power technologies. This information will be used to assess the effectiveness of commercialization financial tools. In 2013, the center held a conference with policy makers, entrepreneurs, investors, and customers to discuss this topic. They did not publish information from this conference (Stanford Law School 2015b).

The Steyer-Taylor Center’s Philanthropic and Long-term Sources of Capital in Clean Energy Finance project works with these investor groups to develop new financial strategies to fund clean energy technology. In February 2015 it held a conference on climate science, energy policy, investment information, and investment tools for family offices interested in investing in cleantech, renewable, and environmental opportunities (CREO). This event did not have sufficient space for everyone who wanted to attend. It led to a similar conference with pension fund investors and to plans for conferences with university endowments and foundation endowments (Stanford Law School 2015a).

The Steyer-Taylor Center has partnered with two organizations, Prime Coalition and MIT Sloan Management, to release two reports about the proper strategies for funding technologies to achieve significantly reduced GHG emissions. The first report, *Impact Investing in the Energy Sector: How Federal Action Can Galvanize Private Support for Energy Innovation and Deployment* (October 2015), makes the case that there is underutilized opportunity in the clean energy sector for private investment. The authors argue that there is plenty of interest among family offices and philanthropists to invest in clean energy but that a lack of knowledge about the industry and a few high-profile failures have resulted in a slow entrance into the market. As a solution, the authors advocate for a private-public partnership. This partnership would involve a private-led task force, whose job is to help collect and share information

relevant to investors and to advocate for policies that will foster investment in clean energy technologies. It would also involve public grant funding that would help spur investor confidence in the clean-tech industry (Kearney, Seiger, and Berliner 2015).

The second report, *Energizing the US Resource Innovation Ecosystem: The Case for an Aligned Intermediary to Accelerate GHG Emissions Reduction* (June 2016), makes the case for an aligned intermediary, which is analogous to the above-described task force. The report frames the problem as a lack of long-term investors in clean energy technologies that will help avoid the negative impacts of climate change. The solution is the proposed aligned intermediary that would create a climate that is favorable for long-term investors, such as pension funds, endowments, and family offices, to invest in clean energy technology. The theory is that the aligned intermediary will be able to provide accurate information about risk and rates of return. The success of long-term investors committed to a low-carbon future will attract other long-term investors, resulting in an influx of investment for promising clean energy companies. By providing accurate information to investors and providing an avenue for entrepreneurs to connect with investors, the aligned intermediary will reduce information asymmetries and reduce transaction costs, all resulting in a climate favorable for significant and meaningful investment in clean energy technologies (Monk, Kearney, Seiger, and Donnelley 2015).

### ***Aligned Intermediary***

The above-mentioned Aligned Intermediary group has been launched as nonprofit looking to help channel long-term investors' capital into innovation projects involving energy, water, and waste at all stages of development and implementation. The group works with long-term investors to properly screen and vet innovative technologies, with the goal of meeting desired rates of return. Current partners are the University of California Regents (university endowment), New Zealand Suprannuation Fund (sovereign wealth fund), TIAA-CREF (financial service group), and Tamarisc (single family office) (Aligned Intermediary 2015).

### ***Energy Options Network***

Energy Options Network is a nonprofit focused on development of zero-carbon energy technologies. It collaborates with technology entrepreneurs, investors, and regulators to promote promising clean energy technologies as attractive investment opportunities. Energy Option Network is primarily focused on technologies that can be deployed in developing countries, in anticipation of these areas seeing the largest growth in energy demand. The technologies that the group currently endorses are advanced nuclear reactors, carbon capture and storage, and ammonia (Energy Options Network 2015).

### ***CREO Syndicate***

CREO Syndicate is a non-profit collection of like-minded family offices and private investors that have an interest in clean tech, renewable energy, and environmental opportunities. With the belief that private capital is critical for solving environmental issues, CREO Syndicate seeks to increase investment in the space through increased education, cooperation, and collaboration among investors. The syndicate has more than 100 family offices and private investors (CREO Syndicate 2015).

## ***Clean Energy Trust***

Clean Energy Trust seeks to accelerate clean energy technology in the Midwest through early-stage investment in promising technologies. The investments range from \$50 to \$500,000 and are typically used to help technologies reach the next stage in development and secure additional investment from other investment sources. The organization is a self-proclaimed impact investor, with an actual designation as a 501C3 public charity (Clean Energy Trust 2015).

## ***U.S. Government***

In February 2015, the White House launched the Clean Energy Investment Initiative. The goal of this initiative is to spur private investment in innovative technologies that can help to reduce the impact of climate change, including technologies that have the potential to decarbonize the energy industry. As part of this initiative, in June 2015 the White House held a Clean Energy Investment Summit. At the summit, the White House announced a commitment of \$4 billion by various private groups to help fund innovative energy technologies and provided guidance for impact investors seeking to invest in clean energy technologies (Moniz 2015). During this summit, the White House also announced that the Department of Energy (DOE) had created the Clean Energy Investment Center to foster private-sector investment in clean energy projects, with the goal of overcoming current gaps in the energy innovation ecosystem. The investment center will achieve this goal by providing information to private investors about clean energy technologies and will make the Department of Energy's information more accessible and easier to understand. It will also tap into other governmental resources, such as the Department of Transportation, the EPA, and the National Science Foundation, to provide the most in-depth and useful information (U.S. DOE 2015a).

The Department of Energy also provides loans for clean energy technologies through two programs, the Loan Programs Office and ARPA-E. The Department of Energy's Loan Programs Office provides billions of dollars in loans and loan guarantees to innovative clean energy technologies. The team that administers these loans is comprised of technical, financial, environmental, and legal professionals. The goal of the loans is to provide capital for the development of utility-scale low-carbon energy technology, while providing job growth and reducing U.S. dependence on foreign fossil fuels (U.S. DOE Loan Program 2015). APRA-E provides early stage capital to jump-start promising innovative energy technologies to carry them to the point of attracting private investment.

The Department of Energy is not the only government agency involved in clean energy financing. On October 20–21, 2015, Secretary of State John Kerry held a forum to discuss the importance of public and private investment in clean energy projects in the fight against climate change. The forum brought together, investors, corporations, policy makers, and philanthropists to address the topic. The forum had four main goals: (1) highlighting the role that private investors can have in helping to direct the flow of capital, (2) sharing success stories of private investments leading toward a low-carbon economy, (3) exploring the intricacies of private sector investment in clean energy projects, and (4) identifying opportunities for collaboration between public and private groups (U.S. DOS 2015a). Several projects were highlighted as positive examples of investment projects that will facilitate the shift to a low-carbon economy. Among these projects is the Clean Energy Finance Facility for the Caribbean and Central America. This facility focuses on providing early-stage investments for clean energy projects (U.S. DOS 2015b).

### ***Mission Innovation and Breakthrough Energy Coalition***

On November 30, 2015, Mission Innovation and the Breakthrough Energy Coalition were launched. Mission Innovation is a commitment by 20 countries to double their energy innovation spending over the next five years in an effort to accelerate the energy technology innovations necessary to move toward a low-carbon economy. This funding primarily focuses on early-stage research development through national labs (Mission Innovation 2015). The Breakthrough Energy Coalition is a collection of private investors, led by Bill Gates, who are committed to driving meaningful innovation in the clean energy sector. This coalition will provide private long-term investment to energy projects that are emerging from the national labs in order to help bridge the valley of death and create scalable solutions to the world's low-carbon energy needs (Breakthrough Energy Coalition 2015). The idea is that this private-public partnership will accelerate development of low-carbon and potentially disruptive energy technologies. The initial 28 investors in the Breakthrough Energy Coalition hope to set an example for other investors that will lead to a growing group of patient, long-term investors in the clean energy market.

### ***PRIME Coalition***

PRIME helps philanthropists support new GHG emission reduction ventures. A nonprofit organized in 2014 as a charity, it focuses on overcoming investment barriers for climate innovation. Its stated intention is to “unlock the floodgates of charitable investment for early-stage climate investment.” The organization assesses thousands of climate mitigation investment opportunities by impact, priorities, and other screens such as venture capital misalignment to narrow its focus. It promotes a small number of companies (seven in 2016) to philanthropic investors. It also works to educate stakeholders about innovation financing gaps (PRIME Coalition 2016).



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### **Nicholas Institute for Environmental Policy Solutions**

The Nicholas Institute for Environmental Policy Solutions at Duke University is a nonpartisan institute founded in 2005 to help decision makers in government, the private sector, and the nonprofit community address critical environmental challenges. The Nicholas Institute responds to the demand for high-quality and timely data and acts as an “honest broker” in policy debates by convening and fostering open, ongoing dialogue between stakeholders on all sides of the issues and providing policy-relevant analysis based on academic research. The Nicholas Institute’s leadership and staff leverage the broad expertise of Duke University as well as public and private partners worldwide. Since its inception,

the Nicholas Institute has earned a distinguished reputation for its innovative approach to developing multilateral, nonpartisan, and economically viable solutions to pressing environmental challenges.

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