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BATTEN REPORT
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PATH TO 2060:

Decarbonizing the Electric Utility Industry

The Future is Bright and Tailwinds Strong for Renewables

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SNAPSHOT

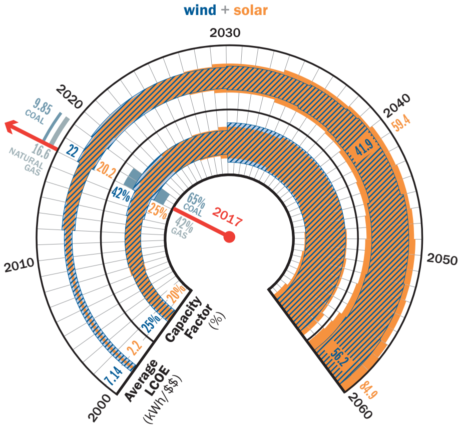
Scientists say that global warming must be kept below two degrees Celsius to avoid significant global disruption. Getting there will require near total decarbonization of economic activity by 2060.

In 2016, renewable energy sources represented 62% of new global generation capacity globally, driven by technology-cost improvements, government incentives, competitive pricing, and increasing demand for clean energy.

Decarbonizing the electric utility industry will likely take longer than 40 years as fossil fuels continue to be part of economic growth strategies around the world. Grid modernization and storage availability will facilitate a transition to renewable sources.

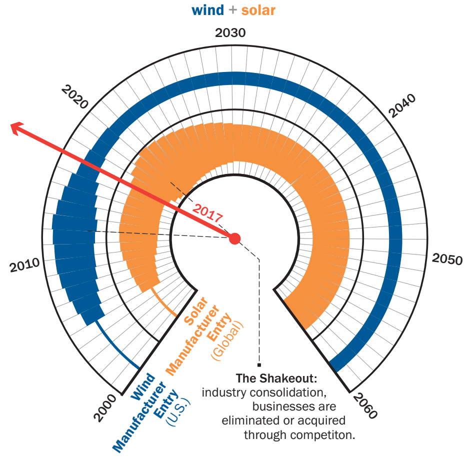
Technology Efficiency

wind + solar



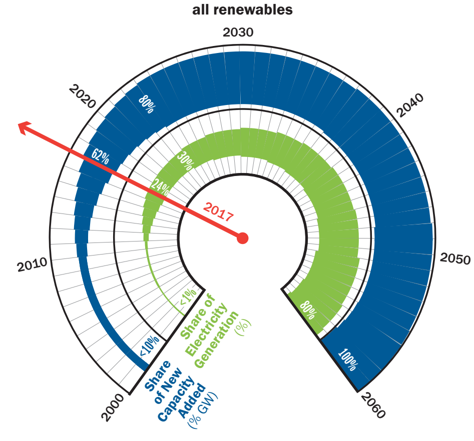
Competitiveness

wind + solar



Market Penetration

all renewables



This graphic is a representation of what could happen in the electric utility market, based on data and information made publicly available at the time of publication

* Recommendations and opinions stated in this report represent those of the authors and not the University of Virginia Darden School of Business or the Batten Institute for Entrepreneurship and Innovation.

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WHY 2060?

In the 2015 Paris Agreement, 175 countries pledged to commit to greenhouse gas emission reductions in order to limit global warning to no more than two degrees Celsius above preindustrial levels. According to atmospheric scientists, achieving this goal requires limiting total cumulative global emissions to 2,900 gigatons of CO_2. Since the Industrial Revolution, global CO_2 emissions have reached 2,100 gigatons; this leaves a carbon "budget" of 800 gigatons. Assuming the continued emission of greenhouse gases in the near future, staying within this carbon budget will require near-total decarbonization of global economic activity by 2060.[1]

IN THIS REPORT, WE ASSESS the potential for complete decarbonization[2] of global electricity generation by 2060. Today the burning of fossil fuels for electricity and heat production accounts for 25% of the greenhouse gases emitted globally[3]. The electric utility sector is one where much innovation is taking place and presents a potential opportunity for total decarbonization.

The report is organized into three sections. First, we review the technologies and innovations that have supported zero-emission carbon energy sources such as hydropower, nuclear energy, wind, and solar and we examine their potential growth as major players in the future energy mix. Second, we assess the levers that could determine the rate of renewable adoption moving forward. And, third, we offer some thoughts on the timing of decarbonization and the accelerators and roadblocks to meeting the 2060 goal.

UVA DARDEN'S BUSINESS INNOVATION AND CLIMATE CHANGE INITIATIVE

The Business Innovation and Climate Change Initiative at the University of Virginia's Darden School of Business facilitates a dialogue across a diverse set of stakeholders in business, non-profits, government, and academia about the role of innovation in addressing climate change. In support of this initiative, the Batten Institute for Entrepreneurship and Innovation is publishing a series of reports that explore technology innovation and the drivers behind the market disruption needed to decarbonize our economy. These reports synthesize research regarding industry sectors that hold the most promise for innovation and significant reductions in carbon-dioxide emissions, including: transportation, energy, and industrials.

Visit **www.darden.virginia.edu/innovation-climate** to learn more about the Business Innovation and Climate Change Initiative and to hear a podcast discussing the findings of this report.

ELECTRIC UTILITIES: THE ROAD TO DECARBONIZATION

DECARBONIZATION IN ELECTRICITY GENERATION will require a major disruption in current generation practices. While such a disruption may seem unlikely, it would not be the first. The first disruption in the electric utility industry was in 1910, when coal surpassed traditional biofuels as the primary feedstock for global energy production, serving as a leader for close to 100 years. Things began to change in 2000 when improvements in fracking[4] swung the pendulum away from coal to natural gas.

Natural gas now holds the largest share of U.S. and global electricity generation. According to the U.S. Energy Information Administration (EIA), shale resource development is 50% of U.S. natural gas production and, by 2040, it will increase to 70%. In China, it's estimated that shale development will account for 50% of natural gas production by 2040. While growth in natural gas consumption in Organization for Economic Cooperation and Development (OECD)[5] member countries is expected to slow, non-OECD countries facing industrial expansion and increased electricity demand will drive global growth[6].

While natural gas is currently ascendant, another disruption is percolating—the rise of renewables. Wind and solar have the potential to provide electricity at near zero production cost and to upend the ways electricity is generated, distributed, and priced. If current global adoption rates accelerate as expected, renewables will likely prevail as the dominant energy source. The critical question is: How long will this take?

According to the International Panel on Climate Change (IPCC), in order to have a significant impact on greenhouse gas emissions, the share of zero-carbon emissions generation must increase from the current 30% to more than 80% by 2050[7]. To get there, the global energy industry needs to continue to invest not only in cleaner technologies, but also in the electricity grid itself. This is particularly key for more intermittent and distributed renewables like wind and solar. Ensuring reliability at all points of the grid—generation, transmission, and distribution—will play an important role in accelerating widespread adoption of renewables.

The growth projections for renewable energy sources are impressive but turning over the entire global inventory of fossil fuel plants will likely take us well beyond 2060. Many agree that coal-fired power plants will be pushed out of the generation mix in the U.S. largely by competitive pricing. However, China and India will continue to build coal plants in response to a growing appetite for, and greater access to, electricity in those countries. Natural gas, viewed as a more environmentally friendly option compared to coal, will continue to be a contender for new capacity and coal replacement.

Even under the most optimistic scenario, in which all new capacity is met with renewables and fossil fuel plant retirements continue at recent rates, the industry will barely meet the 2060 target. In this report, we explore the factors impacting the speed of disruption and the levers that could be pulled so as to accelerate decarbonization. We will look not only at renewables such as wind and solar, but also at alternative zero-carbon emission technologies like hydropower and nuclear. We will ask which policies can help accelerate the adoption and advancement of zero-carbon emission technologies and which factors might threaten a clean energy future.

HYDROPOWER: THE WORLD'S FIRST RENEWABLE

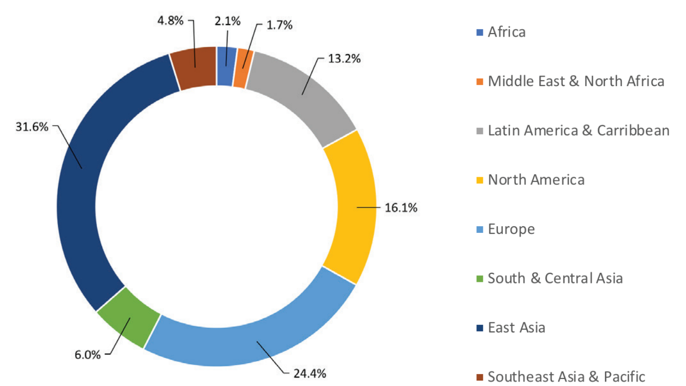
LOST IN THE EXCITEMENT OVER SOLAR AND WIND technologies is the "first renewable" power source: water. Hydropower electricity generation in the United States dates back to the late 1800s during the advent of the energy industry. The Niagara Falls plant, built in 1895, served as the first hydroelectric power plant providing major generation in the country[8]. It was the largest such plant in the world at that time[9].

A decade later, under the Reclamation Act, the U.S. Reclamation Service was created within the U. S. Geological Survey, with the charge to study the potential for water development projects in western states that included federal lands[10]. Power plants, seen as a by-product of water management, were built to help fund dam construction by selling electricity to existing local distribution networks. Much of the construction costs were covered by electricity sales[11]. Such reclamation projects continued during World War I, increasing hydropower storage capacity.

In 1933, President Franklin D. Roosevelt's New Deal policy gave a further boost to hydropower ushering in the so-called "big dam period". Construction of dams required large amounts of civil work and as such, fulfilled the New Deal's objectives to create jobs and reduce the unemployment rate. The result was a push for hydroelectric power projects including the Hoover Dam, which employed more than 20,000 workers.[12] By 1940, 40% of the nation's electricity was being generated by hydropower[13]. Over the next 30 years, hydropower would continue to gain investment increasing capacity and generation until the 1970s.

A similar story unfolded globally as other countries invested in large hydropower projects. The largest such project was the Three Gorges Dam built in the Hubei Province of China. Completed in 2012, the dam is the world's largest power station with an installed capacity of 22,500 megawatts (MW)[14]. Today, worldwide hydropower represents 71% of renewable energy and 16% of total electricity generation[15]. China is the leader with more than 380 gigawatts (GW) of capacity installed representing two-thirds of global hydropower capacity. Hydropower represents 20% of China's electricity generation[16]. Other countries topping the list of the most capacity include: Brazil, Ecuador, Peru, Turkey, and India. In Brazil, hydropower provides 70% of electricity generation[17]. A regional breakdown is provided in **Figure 1**.

Figure 1: Hydropower Installed by Capacity by Region 2016



Source: World Energy Council website (Energy Resources – Hydropower)

OTHER LOW CARBON ALTERNATIVES. *Other low carbon technologies—like wave, geothermal, and biomass—show promise particularly in specific regions of the world. Currently representing less than 2% of the global market these technologies will likely be small players in the generation mix, at least in the immediate future. There is an abundant amount of energy available in these natural resources but these technologies have yet to be commercialized on a massive scale. The best opportunities for these technologies are likely serving those regions where siting for wind and solar is unfavorable. Market analysts predict continued growth for these three technologies, and with continued investment in R&D and commercialization strategies there could be more significant growth over the longer term.*

THE FUTURE OF HYDROPOWER

While hydropower continues to play a significant role in global electricity generation, several challenges threaten its growth; these include high construction costs and concerns regarding impacts on local ecosystems. While hydropower is recognized as a clean energy source, as early as the 1970's environmentalists began to raise concerns about the wildlife and environmental impacts on local rivers of manipulating water sources. In the United States, changes to federal standards to protect water resources included new dam licensing requirements that required extensive environmental studies, delaying permitting processes and adding significant costs to projects. As a result, growth in U.S. hydropower capacity began to slow and the technology's share of overall electrical generation began to decline. By the start of the 21st century, the share of hydropower had fallen below 10% of total U.S. electricity generation. Today, it represents only 6.5%[18]. Similar trends have been observed in other developed economies. Ironically, climate change is accelerating these trends as it threatens the efficacy of hydropower in many parts of the world. Regional droughts can cause plant effectiveness to fluctuate within +/- 10% year to year[19].

Increasingly, the future of hydropower is tapping into existing capacity and innovating on a smaller scale. More than 90% of existing dams in the United States aren't being used to generate electricity. According to a 2012 U.S. Department of Energy (DOE) report, 12 GW of new hydropower could be generated by retrofitting existing, non-powered dams[20]. In 2013, the Hydropower Regulatory Efficiency Act signed by President Barack Obama aimed to facilitate retrofits by reducing the permitting burden for incorporating hydropower into existing dams[21]. This legislative action shifted focus from upgrades to non-powered dam retrofits[22]. By the end of 2016, U.S. DOE reported that 52% of new hydropower capacity proposed would come from retrofits[23].

Dam retrofits have led to an increase in "small-scale" hydropower, over the last decade. When compared to large hydropower plants, small-scale plants are less disruptive to the environment and less costly to build. Most small hydropower plants use a run-of-river approach, where water is diverted to pass through turbines and then returned downstream. The underlying technology is the same as in larger dams, but on a smaller scale. Run-of-river plants are typically installed in rivers that have sufficient head (or drop) and consistent flow to reliably generate electricity.

In Canada, where large hydropower already provides 60% of electricity, there is a focused effort to develop run-of-river sites to keep up with growing demand. Run-of-river has found a niche in Canada in remote areas, where diesel generators have historically provided electricity. In some applications, run-of-river is close to competing with the cost/kWh of large hydropower plants[24]. China also is investing in small hydropower generation. The country has long encouraged the use of small hydropower plants and community-level management of these resources with the goal of rural electrification. Between 2006 and 2012, China almost doubled its small hydropower capacity[25].

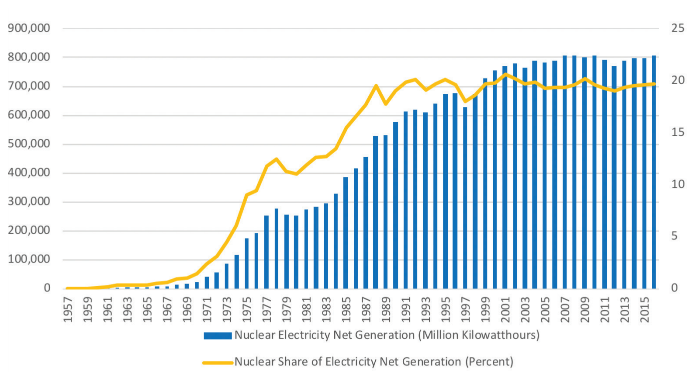
Overall, hydropower is a highly flexible energy source, offering both clean electricity generation and energy storage to support more variable renewables on the electric grid. Large hydropower will continue to serve an important role in the energy mix, particularly in regions that have access to significant hydro resources. Hydropower generation continues to grow worldwide by about 4% each year according to the World Energy Council[26]. The International Energy Agency[27] predicts continued, but slower, growth worldwide through 2022[28]. The U.S. EIA predicts slow growth in the U.S. over the next 20 or more years[29]. More significant growth will likely rely on continued innovation in smaller scale production. Countries around the world are currently tapping into less than 50% of their potential generation[30]. A report published by the World Energy Council[31] in 2016 suggests a potential generation of 10,000 TWh/year[32] if all hydropower resources are utilized.

NUCLEAR: FROM WEAPON TO CLEAN ENERGY

NUCLEAR POWER HAS LONG BEEN ADVANCED as the best clean-energy solution to our energy needs. After World War II, scientists were able to change their focus from nuclear weapons to the development of nuclear power generation. In 1951, the first small experimental nuclear reactor was started up by Argonne National Laboratory in Illinois. Two years later, in an effort to shift international focus away from building atomic arsenals, President Dwight D. Eisenhower announced his "Atoms for Peace" program to the United Nations. The program provided nuclear technology support and education to countries with an interest in building nuclear powered economies, helping to further commercialization of nuclear energy around the world[33].

In 1954, the U.S. Congress enacted the Atomic Energy Act, which gave organizations outside of the federal government the ability to build and operate nuclear power plants. At that time Congress also established the Atomic Energy Commission (AEC) as a watchdog over the commercialization of nuclear power[34]. Six years later, the first fully commercialized pressurized water reactor (PWR) plant in the U.S. was built in Massachusetts by Westinghouse Electric Corporation. The 250MWe Yankee Rowe operated from 1960 to 1992 when it was decommissioned. Around the same time the first boiler water reactor (BWR) plant—the 250MWe Dresden-1 built by General Electric—came online[35].

Figure 2: U.S. Nuclear Energy Generation



Source: U.S. EIA September 2017 Monthly Energy Review (Table 8.1)

Concerns over U.S. dependence on foreign oil in the 1970s and 1980s paved the way for increased growth in nuclear energy, which also offered environmentalists a clean energy alternative. In the span of 20 years, nuclear energy would grow to generate almost 10% of total U.S. electricity[36]. Nuclear plant start-ups in the country peaked at 12 new grid connections in 1974 and would surge again in the 1980s (see **Figure 2**). Yet by the 1990s, more nuclear plants were being retired than built. Between 1997 and 2015 the country saw no new construction of nuclear plants[37].

This was due partially to the accident at the Three Mile Island plant in Pennsylvania on March 28, 1979, which gave rise to concerns about the dangers of nuclear energy[38]. While no release of radioactive materials was detected, this accident would mark the beginning of slow growth in the years to come. In the nine years following Three Mile Island, 67 planned construction projects in the United States were canceled. Projects started prior to the accident continued through the early 1990s.[39] These projects would provide the capacity needed for nuclear to reach 20% share of overall generation but with no new construction planned in the U.S., this share remained relatively flat for the next 20 years[40].

A similar story played out globally. Nuclear energy saw a similar increase in new construction worldwide in the 1970s and its share of electricity generation grew beyond 10% by the mid-1980s[41]. Generation continued to grow as new plants were brought on-line and by 1996, the global share of electricity generated by nuclear energy reached 17%[42]. But the growth in new plants worldwide began to slow in the late 1980s following the Chernobyl incident. In 2011, a record number of plants were shut down following the Fukushima accident including 16 reactors in Japan alone. Nuclear energy hasn't kept pace with overall electricity generation growth and by 2016 it's share fell to 10% of worldwide generation[43].

Today there are over 400 commercial nuclear energy reactors operating in 31 countries, providing more than 350 GWe of capacity[44]. Collectively the United States, France, Russia, China, and South Korea represent 70% of global nuclear energy generation[45]. Of the 53 units under construction today, 20 are located in China[46]. In France, where 75% of electricity supplied is from nuclear reactors, recent new energy regulation reduces the use of nuclear to 50% and caps the total capacity at 63 GWe[47]. This will require older reactors to be shut down before the end of life[48].

THE FUTURE OF NUCLEAR POWER

Overall, nuclear plants around the world are a depreciating capital stock. More than half of the nuclear reactors operating today (58%) are at least 30 years old; 64 of those are 41 years or older[49]. Over the next 10 to 20 years, the increase in plant retirements will likely outpace new capacity additions. In the U.S., of the 99 reactors currently operating, 25 are in danger of being shut down by 2020[50]. The Nuclear Regulatory Commission (NRC) grants initial operating licenses for 40 years but it has granted 20-year extensions to 84 of the 99 reactors. Since 2013, 5 nuclear reactors have been retired and some utilities are deciding not to apply for 20-year extensions for others[51].

The cost to build a new reactor is significant. For example, the Watts Bar Unit 2 reactor, which was brought online in 2016 by the Tennessee Valley Authority, was estimated to cost $4.7 billion[52] and take 9 years to complete[53]; in the end the total investment was $6.4 billion and the time to complete was longer with many starts and stops. The Georgia Power's Vogtle Units 3 and 4, currently under construction and expected to be operational by 2021 and 2022, will cost $19 billion.

In 2005, the Energy Policy Act included a production tax credit[54] for new nuclear capacity as well as federal loan guarantees for advanced nuclear technologies and support for nuclear R&D efforts. By 2008, the loan program had received applications for 14 nuclear power plants that would provide a total 28,800 MWe of new capacity[55]. While U.S. DOE funding wouldn't be enough to cover all of the proposed projects, and many of the new plant projects were suspended, it did spur interest in advanced nuclear energy technologies and keep nuclear in the mix.

New construction has slowed over the last 20 years but investments have been made in improving existing plant efficiencies. In the United States, average capacity factor (the power generated compared to rated power) increased from 56% in 1980 to 90% by 2010[56]. A similar trend has occurred worldwide. According to the World Nuclear Association, 64% of reactors have a capacity factor greater than 80% compared to 24% of reactors in 1976[57]. These improvements have helped nuclear energy retain its share of generation. For example, in 2007, nuclear reactors worldwide produced an additional 210 Twh compared to 2000. Yet there was no net increase in the number of reactors; improvements in performance resulted in more electricity being delivered[58].

There is also work underway by U.S. DOE to extend the life of these reactors beyond 60 years, with R&D focused on materials aging and degradation, advanced control systems, risk-informed safety measures, and advanced light water reactor nuclear fuels[59]. Disposal of radioactive waste also continues to be a concern and work is underway to develop alternative fuel cycles, including partial uranium replacements and full recycling combined with advanced reactor designs.

The industry is continuing to improve the safety and reliability of reactors while attempting to reduce their footprint and cost. PWR is the dominant design used in the United States, France, Japan, Russia and China; overall, PWRs represent 65% of nuclear power plants worldwide. Two other technologies, BWR and Pressurized Heavy Water Reactors,[60] make up the majority of remaining reactors in operation today[61]. Both PWRs and BWRs are Generation II water-cooled and moderated reactors. Compared to the Generation I prototype reactors, which represent the first commercialized reactors of the 1940s and 1950s, these reactors are more economical and include new safety systems and a 40-year design life[62].

Generation III and III+ reactors offer ease in operation, safety features aimed at avoiding environmental disasters due to core failure or other accidents (e.g., damage from a large plane), design standards to speed construction time and reduce cost, and a 60-year design life. These reactors have more than doubled the fuel burnup compared to Generation I designs, which means that more of the fuel is used, reducing the amount of toxic waste that then needs to be disposed. There are only a few Generation III reactors currently in operation and efforts are underway to develop Generation IV designs, which will focus on sustainability, safety/reliability, cost competitiveness, and protection of materials.[63]

Making Nuclear More Modular

More radical innovations are on the horizon. Small modular reactors (SMRs) show promise due to their potential to more quickly grow nuclear capacity. SMRs are defined by the World Nuclear Association as "nuclear reactors generally 300MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times"[64]. To compare, larger nuclear reactors scale up to 1,600 MWe.

SMRs offer significantly lower capital costs, shorter construction times, and greater flexibility for future expansion, providing utilities the ability to quickly scale and supporting the overall trend toward a more decentralized grid[65]. Smaller reactors would be easier to protect (the materials and the surrounding community in case of an accident) and could be assembled at the factory. Many SMRs are designed to be installed underground, providing greater security from terrorist threats, and due to their smaller footprint could be sited in place of decommissioned coal plants.

There are a few initiatives underway to develop and commercialize SMRs, primarily in the United States, China, and Russia. SMRs face several challenges to further commercialization including permitting and licensing fees, which aren't necessarily lower than that for larger reactors. The World Nuclear Association lists only three SMRs in operation globally, while five more are under construction in Russia, China, and Argentina[66]. Similar to large nuclear plants, SMR projects have been challenged by inflating costs, delays in construction, and waning interest by investors[67].

In the United States, DOE created the SMR Licensing Technical Support Program to provide funding for the development, certification, and licensing of SMRs. One company, NuScale Power LLC, was selected by U.S. DOE to site and build a 50 MWe SMR for demonstration[68]. The SMR will be sited on Idaho National Laboratory grounds, and the company is targeting a commission date of 2024[69]. Two other companies—Westinghouse and mPower—attempted to build SMRs but abandoned projects citing the absence of a viable market and further investment interest[70].

Nuclear Fusion: Harnessing the Power of the Sun

The ultimate disruptive technology is nuclear fusion. Fusion research dates back to the 1970s. Fusion utilizes hydrogen isotopes deuterium and tritium to offer four times the energy generated by traditional uranium fission. Deuterium, naturally occurring in seawater, is abundant while tritium, also naturally occurring, is radioactive and found only in trace amounts[71]. Compared to uranium, tritium has a shorter half-life and the gases used in the fusion reaction can be treated on-site. However, tritium released into the environment is hard to contain, which is a cause for concern. Longer term there is hope for scientists to produce a deuterium-deuterium reaction suitable for energy production, eliminating the need for tritium[72].

With regard to electricity generation, one challenge in nuclear fusion is the need to heat the fuel to high temperatures and confine it long enough to allow not only for the initial ignition but also for the sustained reactions needed to take place to produce energy. Another challenge is that fusion has a lower energy density than fission (gas versus solid fuel) and therefore, fusion plants would need to be bigger to meet the same generation capacities as uranium fission plants. For an industry already facing the challenge of cost-prohibitive new construction, a larger footprint will be a barrier to commercialization.

Overall, like hydropower, nuclear energy is a clean alternative to coal and natural gas, particularly in developing countries, and it could serve as a reliable base load generator but its share of the generation mix will likely be small. Advanced nuclear technologies are still nascent and unlikely to reach the level of commercialization needed to compete with low cost renewables. Upcoming retirements will take more nuclear capacity offline. Negative public perception of nuclear, along with high construction costs and delays, continue to be a barrier to wider adoption.

While nuclear energy currently represents 70% of zero-emission electricity generation in the United States[73], plant retirements will be responsible for a projected decrease across all OECD countries. The U.S. EIA estimates that nuclear energy will drop to 11% of total U.S. electricity generation by 2050[74]. Worldwide, it's projected that nuclear generation will continue to grow, albeit slowly over this time period, largely due to development in non-OECD countries, led by China[75]. Yet even with this growth, nuclear energy still faces the challenges of slow and costly new construction and lingering public concerns about safety and waste. Nuclear will be hard-pressed to challenge wind and solar for future market share without further innovation.

WIND: A MILLENNIUM-OLD TECHNOLOGY COMES OF AGE

IN THE U.S., THE USE OF WIND ENERGY to provide localized electricity dates back to the 1800s. However, utility-scale wind power wouldn't be demonstrated until 1941 when a 1.25 MW turbine was installed on top of a mountain called "Grandpa's Knob" in Vermont and then connected to the electric grid[76]. Aside from smaller and more specialized applications, such as powering German U-boats during World War II, mass commercialization of wind energy wouldn't be seen in the United States for another 30 years[77].

In 1974, Congress created the Energy Research and Development Administration (ERDA) with the purpose of expanding federal energy research and development, including the demonstration of new energy technologies. While wind energy wasn't a new technology, it required significant capital investment to prove concept on a larger scale. Under ERDA support, the first prototype large scale wind facility was constructed in Ohio in partnership with NASA to test components and collect performance data.

The door opened for commercialization in 1978 with the passing of the Energy Tax Act and Public Utility Regulatory Policy Act (PURPA), which provided: (1) a 30% investment tax credit[78] to residential consumers for solar and wind energy equipment and a 10% investment tax credit to businesses for solar, wind, and geothermal installations and (2) requirements that companies purchase a percentage of power from renewables. PURPA would open the door for smaller, non-utility generators to enter the market through requirements that utilities buy electricity from a "qualified facility" if less than the utility's own generation. PURPA diversified electricity supply, providing renewables the opportunity to compete with fossil fuels.[79]

Tax incentives were critical in the early days of wind energy deployment. President Ronald Reagan cut federal funding of wind energy projects by 90% in the 1980s. Despite this, a "wind rush" was underway in California, created by the California Public Utility Commission's first 30-year Standard Offer Contracts that required utilities to make long-term purchase agreements for alternative energy[80]. In 1986, federal tax incentives expired, driving most American wind turbine manufacturers out of business and halting further expansion of wind power.

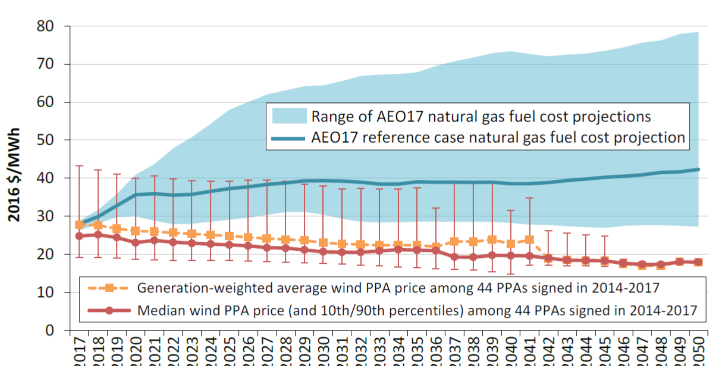
Hope in wind energy was restored when in 1992, President George H. W. Bush signed the Energy Policy Act that provided production tax credits to renewables, including a credit of $0.015/kWh for wind generation. Government research ramped up in the 1990s, primarily through the National Wind Technology Center which was built with the goal of reducing the cost of energy for wind to compete with other energy sources.[81] Favorable state mandates and renewed federal tax credits helped to increase U.S. wind generation capacity to 2,500 MW by 1999[82]. Entering into the 21st century, these incentives helped to put wind at the forefront of the renewable movement.

Several extensions of the tax credits over time have helped the overall growth of wind energy. In 2015, Congress passed a multi-year extension of the tax credits through 2019. By 2016, wind energy had grown to provide more than 5% of electricity to U.S. customers[83]. At more than 82 GW installed, wind has surpassed hydroelectric as the number one source of renewable energy capacity in the United States.

WIND IS A SERIOUS COMPETITOR

Interestingly, while incentives are helpful, particularly in some parts of the country, they may no longer be needed for growth in wind energy to continue. According to Lazard's Levelized Cost of Energy (LCOE) Analysis, onshore wind LCOE ranges from $30 to $60/MWh without government subsidies. In comparison, the range for coal is $60 to $143/MWh and gas combined cycle is $42 to $78/MWh. LCOE takes into account the costs of capital, fixed operations and maintenance (O&M), variable O&M, and fuel. The Lazard Analysis provides a longer term view of asset ownership as the costs to construct a fossil fuel plant may appear to be more favorable at the onset but are not cost effective over the lifetime of that asset, which is critical for utility planning. Since 2009, the Lazard Analysis shows that onshore wind LCOE has decreased 67%, due largely to technology improvements and declines in system component pricing[84].

Figure 3: Wind PPA Prices vs. Natural Gas Projected Fuel Costs



Source: U.S. DOE 2016 Wind Technologies Market Report (Figure 51)

What makes renewables like wind such attractive options is the fact that fuel costs are zero and not at the mercy of the variable pricing that fossil fuels face. As manufacturing and installation prices come down, choosing wind is a matter of simple economics. Lower installation prices and increasing wind turbine efficiencies have led to declining levelized Power Purchase Agreement (PPA) prices for wind projects (i.e., from $70/MWh in 2009 to $20 to $30/MWh in 2016[85]). While natural gas may be able to compete with wind today, longer term projections suggest that gas prices will rise over time while wind PPA prices locked in today will remain competitive (**Figure 3**).

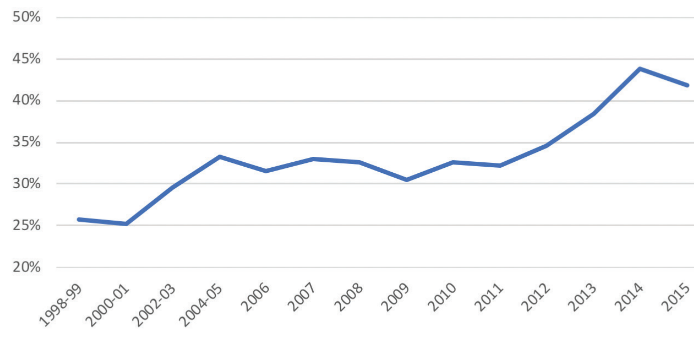
A POWER PURCHASE AGREEMENT (PPA) *is a contract between an electricity generator and buyer, where the developer (owner/operator) designs, builds, and operates the renewable asset, selling the electricity to a buyer at either a flat or a fixed escalator rate. These rates are locked in for 10–25 years and are typically less than projected utility prices. The buyer might be a utility or corporate entity. There has been an increase in the number of corporate PPAs as large corporations like Apple and Google look to become more sustainable. PPAs allow renewable projects to be financed while also providing end users long term price stability with potential for future savings.*

PPAs have facilitated the substantial growth in wind power generation across the United States, especially where climate and/or policy environments are favorable to wind. Growth in the interior United States and Great Lakes regions, which are favorable to wind, have reached 56% and 48% (respectively) of new capacity added during that time[86]. At the end of 2016, Texas was in the lead with regards to cumulative installed wind capacity while Iowa held the largest share of in-state generation at 36%; 14 states show wind energy penetration levels greater than 10%[87].

Overall, wind power represented 27% of capacity added to the U.S. electric grid in 2016[88]. Wind has accounted for an average 31% of new generation added over the last decade. Similarly, wind has been growing worldwide. Globally, there is more than 50 GW of wind energy capacity installed, which is almost double that installed just five years ago[89]. According to the Global Wind Energy Council, wind represents close to 4% of total electricity generation worldwide[90]. Similar pockets of significant growth in wind installations are also occurring globally, with Europe in the lead. In 2016, the share of wind power capacity installed across Europe increased from 6% in 2005 to 16% in 2016. Wind is now the second largest source of electricity generation in this region ahead of coal and on the heels of natural gas[91].

Continued growth in wind will be fueled by continued improvements in efficiency and cost. It is important to note that wind is a mature technology, with turbines already extracting close to the theoretical maximum energy conveyed by the wind of just under 60%[92]. Increases in nameplate capacity (rated capacity at full load), hub height, and rotor diameters over the last decade have led to an increase in average capacity factor from 25% in 1999 to more than 40% today[93]. **Figure 4** shows the capacity-weighted average capacity factor over time based on project vintage (data from more than 600 projects). These technological advances have allowed wind farms to be sited in areas with low wind speed, further expanding the potential reach of wind energy across the United States. R&D efforts are focused on making the blades more resilient under the increased stresses that might be experienced as hubs get taller and blades longer.

Figure 4: Capacity-Weighted Average Capacity Factor



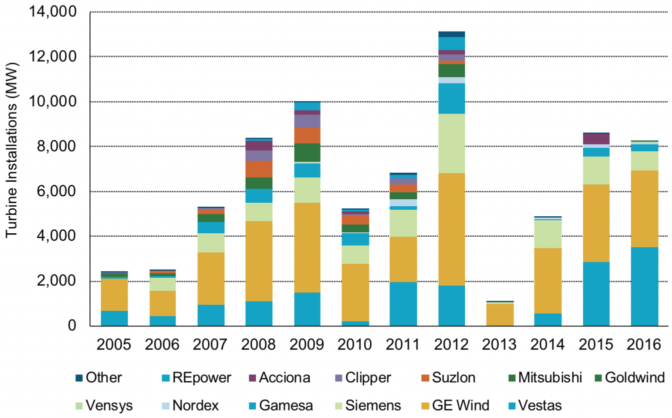
Source: U.S. DOE 2016 Wind Technologies Market Report (Figure 33 data file).

As presented in U.S. DOE's 2016 Wind Technologies Market Report, wind turbine prices were at their lowest between 2000 and 2002 at $800/kW but increased to $1,600/kW by 2008 due to several factors, including: "a decline in the value of the U.S. dollar relative to the Euro; increased materials, energy, and labor input prices; a general increase in turbine manufacturer profitability due in part to strong demand growth; and increased costs for turbine warranty provisions"[94].

Since 2008, due partly to increased competition among manufacturers and further innovation on behalf of turbine and component suppliers, costs began to decline, averaging in the range of $800/kW to $1,100/kW today[95]. Lower turbine prices have driven down installation costs; DOE estimates the capacity-weighted average cost of installation at $1,590/kW[96]. This estimate is in line with the U.S. EIA's *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2017*, which estimates that wind is the lowest cost zero-emission plant option and is competitive with conventional fuels[97].

Typical for an emergent industry, there has been significant turnover in wind turbine manufacturers over the past decade. As of 2016, two turbine manufacturers—Vestas and General Electric—supplied 85% of wind installations. Competition heated up between 2007 and 2012 as the number of manufacturers increased from 4 to 12 companies (**Figure 5**). However, due to recent consolidations[98] and companies exiting the market the number of manufacturers has returned to its 2007 level[99].

Figure 5: Annual U.S. Turbine Installation Capacity by Manufacturer



Source: U.S. DOE 2016 Wind Technologies Market Report (Table 3)

Worldwide, Vestas led the competition for turbine supply in 2016, followed by General Electric, Goldwind, Gamesa, and Enercon. Chinese turbine manufacturers continued to hold 4 of the top 10 spots but their growth has largely been in domestic projects. Only one U.S.-based turbine manufacturer, General Electric, is competing on a global scale[100].

THE FUTURE OF WIND POWER

Though wind technology is considered mature, efforts are underway to improve efficiencies and reduce the size and weight of future turbines. For example, direct-drive and hydraulic drivetrains could eliminate the gearbox all together, reducing size and weight. Incorporation of remote electronic controls could optimize wind production by using data to adjust blade pitch as wind conditions change[101].

In addition to siting turbines in low wind speed locations, there is also a movement to build in cold climate areas where wind resources are favorable and populations low. According to a World Energy Council Report, 52 GW of wind energy had been installed in colder climates around the world through 2016 with another 30 GW capacity expected by the end of 2017. Turbines employed in these sites require higher investment due to the need for de-icing capabilities and the potential for lower yield that might be caused by blade icing, leading to higher wind electricity costs[102].

Although a lot of work has been done to address the potential impacts of blades on wildlife (for example bat populations), efforts are also underway to design a radically different turbine. One startup company in Spain, Vortex Bladeless, designed a turbine that captures wind energy without blades. Instead, the turbine uses vorticity, causing the structure to oscillate and turning kinetic energy into electricity. An added benefit of this design is reduced material costs as the turbine doesn't need gears or bearings to work. However, the design will likely be limited in the total amount of power it can produce particularly at higher altitudes[103].

There are several efforts underway in airborne wind solutions. Google's Makani Power project uses a kite-like device attached to the ground that orbits similar to the blade tip of a horizontal axis wind turbine. Altaeros Energies, Inc. is working on a buoyant airborne turbine that suspends a traditional horizontal axis wind turbine from a helium filled shell. These inventions hold promise but are far from commercialization, facing challenges related to cable loading as well as impacts from storms and aircraft interference[104].

In 2008, U.S. DOE released a report that examined the possibility of wind providing 20% of electricity generation in the United States by 2030. At that time, U.S. DOE suggested that getting there would require improvements in transmission, streamlined siting and permitting processes, improvements in wind system reliability, and increased U.S. wind manufacturing capacity. While efforts are underway in all of these areas, a bigger opportunity to expand wind capacity lies offshore.

Tapping into Wind Resources Offshore

In 2011, U.S. DOE released the *National Offshore Wind Strategy* to reduce the cost of offshore wind energy through technology development and reducing deployment timelines. Challenges cited in that report include the high cost of energy, technical installation and interconnection challenges, and permitting challenges due to lack of data and experience. Lack of data also drives up the financing costs for offshore projects, another roadblock to commercial deployment[105].

High capital costs also challenge offshore wind installations, driven largely by turbine upgrades required for sea operation and additional costs of turbine foundations. U.S. DOE estimates installed capital costs for offshore wind at $4,250/kW.[106]

Similar to onshore wind, part of U.S. DOE's strategy is to facilitate deployment in U.S. waters, generating the experience and data needed to prove the technology and inform longer term strategies. U.S. DOE set a goal of growing offshore wind capacity to 54 GW and driving down the cost to $0.07/kW by 2030. In 2016, U.S. DOE released its Wind Vision Report, which set a goal of reaching 86 GW of offshore wind power by 2050 in multiple U.S. regions.[107] In December 2016, the first U.S. offshore wind facility was commissioned—the 30 MW Deepwater Wind.

While floating wind turbines are still in the proof-of-concept phase, if deployed they could open up additional wind resources off the coasts of major energy markets where depths below 60 meters are limited. U.S. DOE estimates that 58% of wind resources available to the U.S. coastline comes from deep water[108]. In California, 95% of the coastline's available 112 GW of offshore wind resources are in waters deeper than 60 meters[109]. How much energy could be tapped through offshore wind facilities? U.S. DOE provides an estimate of 2,000 GW of capacity, or 7,200 TWh of generation per year, which is nearly double the nation's current electricity use[110].

While off-shore wind is still emerging in the United States, the global market boasts more than 14 GW of capacity, with 88% of the installations located off the coasts of 10 European countries. In some of these markets, the cost of offshore wind is falling below that of onshore wind[111].

Small Wind Could Be Out of Reach

Small or distributed wind (<100kW) can benefit from the same incentives as larger wind farms; however, lack of education coupled with low turbine efficiencies and high installation costs have challenged their more widespread adoption.

Over the last five years, overall small wind sales have declined but sales of smaller units (<10 kW) have increased more recently. Most of these sales are for off-grid applications, which are less sensitive to market and policy changes. U.S. DOE estimates that the overall capacity-weighted average installed cost of small wind turbines in 2016 was $5,900/kW, which is significantly higher than that of larger turbines at $1,590/kW. The report claims that the average capacity recorded for small wind projects is 15%. Proper siting is one reason cited for the low efficiencies.

Growth in small wind will likely follow the same path as larger wind power, happening first in states and regions that have favorable net metering and distributed generation incentives[112]. However, high costs and the current trend toward installing turbines in remote locations will likely mean that small wind won't be a key player in the growth of wind energy.

Wind energy, currently led by larger onshore turbines, will continue to experience growth worldwide. In a 2016 report, the Global Wind Energy Council estimates that wind energy could represent as much as 36% of worldwide generation by 2050 if countries remain committed to goals set forth in the Paris Agreement[113].

Wind energy is the lowest cost zero-emission option today, competing with natural gas in the United States. Efforts to improve efficiency and greater accessibility to wind resources will continue to drive down the costs of this technology. Investments in new turbine designs that address reliability, harsher weather conditions, and wildlife impact concerns will only improve adoption as will the commercialization of offshore wind. Wind will continue to serve as a leading generator of renewable electricity, particularly in regions where siting is favorable.

SOLAR: EMERGING TECHNOLOGY TO LEADER

SOLAR ENERGY HOLDS POSSIBLY THE MOST DISRUPTIVE potential to the electric utility sector. Solar technology research dates back to the 1800s but the biggest breakthrough came in 1954 when U.S.-based Bell Laboratory scientists Daryl Chapin, Calvin Fuller, and Gerald Pearson developed the first photovoltaic (PV) solar cell capable of powering equipment. The first generation silicon solar cell came with a conversion (sunlight to electricity) efficiency of 4%. Bell Laboratory would improve on this efficiency claiming 11% in lab conditions.

Over the next 15 years, R&D efforts by Hoffman Electronics resulted in improvements in solar cell efficiency up to 14%. NASA served as a very important first customer and funder of the technology. During the 1960s, arrays were installed on several satellites, including: Vanguard I, Explorer III, Vanguard II, Explorer VI and Explorer VII. NASA also installed solar arrays on the first Orbiting Astronomical Observatory launched in 1966[114]. Yet solar PV technologies were still too costly for commercialization.

The door opened for solar commercialization in 1970, when Dr. Elliot Berman introduced a lower-cost solar cell using lower-grade silicon and cheaper housings, that drove down the cost from $100 to just $20 per watt[115]. Through the National Energy Act, solar would receive its first feed-in tariff[116] before the end of the decade.

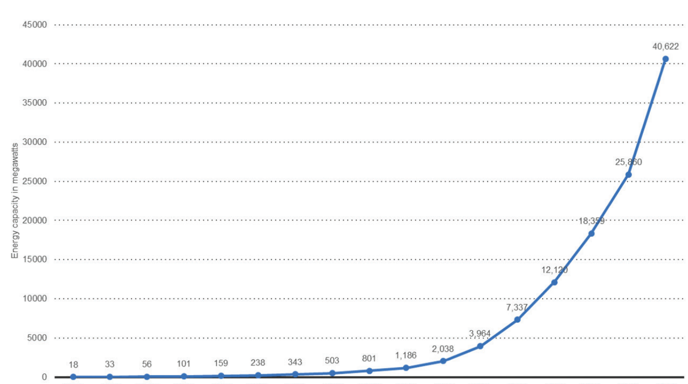
The 1980 discovery of thin-film solar cells provided yet another breakthrough in technology. Thin film offered flexibility and versatility in applications, along with the improvement of solar cell efficiency to 32%. Ten years later, Pacific Gas & Electric connected the first PV system to the electric grid in Kerman, California. Solar had gone from demonstration project to commercially viable technology.

Yet, investors were still hesitant to invest in utility-scale solar energy. The 2009 Recovery Act under President Obama provided the early investment funding needed for solar companies to get off the ground. U.S. DOE issued $4.6 billion in guaranteed loans to build the first five utility-scale solar plants in the United States.

The SunShot Initiative launched in 2011 set forth an aggressive mission: to reduce costs by 75% by 2020 for residential, commercial, and utility-scale solar. To reach this goal, U.S. DOE invested in the development of innovative, early-stage technologies aimed at lowering costs and improving reliability and efficiency on the grid.

By 2016 there were 28 utility-scale solar plants (larger than 100 MW) in the United States and the cost to build these plants had fallen by nearly 60% since 2008[117]. U.S. DOE met the median utility-scale grade solar panel target price of $0.06/kWh three years ahead of schedule—the price was $0.52/kWh just six years before—and is on track to meet residential ($0.10/kWh) and commercial ($0.8 /kWh) solar goals by 2020[118]. Since the creation of investment tax credits in 2006, solar has seen an average annual growth rate of 68%[119] and cumulative capacity surpassed the 40 GW mark in 2016 (**Figure 6**). For the first time, solar became the largest source (38%) of new U.S. capacity additions ahead of wind and natural gas. Utility-scale solar represented 70% of this share[120].

Figure 6: Cumulative Solar PV Capacity in the United States from 2000 to 2010



Source: Statista, U.S. Solar PV Industry

Globally, there has been a similar growth curve for solar installations. According to data provded by the World Energy Council, solar capacity in 2008 was 14.5 GW with 71% attributed to Europe. By the end of 2015, total capacity had reached 227 GW with Asia experiencing the most growth[121]. Solar is leading renewables in new capacity growth worldwide; according to a REN21 report, renewables added 62% of new capacity in 2016 with solar PV representing 47% of that new capacity[122].

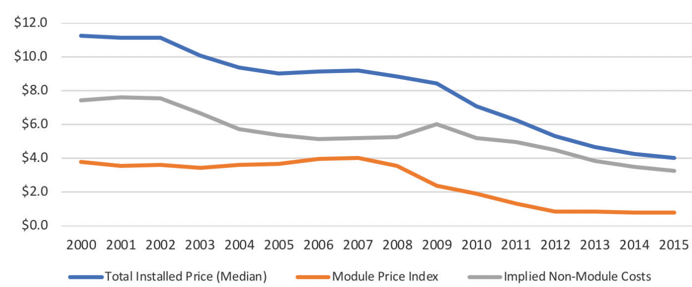
SILICON IMPROVEMENTS DRIVE DOWN COSTS

Today, crystalline silicon (c-Si) is the most commonly used solar cell in commercialized solar panels. In 2011, these cells represented 85% of worldwide PV sales. C-Si cell efficiencies have improved from 14% in 1960 to 22% in 2015, but manufacturers note reaching a development ceiling with the technology. Multi-c-Si cells are cheap to produce and since 2007, have driven down installation prices across all solar applications: residential, commercial, and utility-scale (**Figure 7**).

THE SOLYNDRA VENTURE. *The first to receive a U.S. DOE-guaranteed loan of more than $500 million promised under President Obama's stimulus program, Solyndra promised solar modules more expensive than polysilicon but less expensive to install. With polysilicon prices rising the company appeared to be a good investment. Yet due to the decline of polysilicon prices created largely by the entry of cheaper Asian solar cells and modules, higher than anticipated installation costs, and poor management of the company overall in 2011, Solyndra filed for bankruptcy. Such entrepreneurial failures are not unheard of, but the use of taxpayer money to cover these losses politicized the failure and led to condemnation of the entire clean energy sector, threatening to derail clean energy initiatives. Yet despite Solyndra and a few other defaults, the U.S. DOE loan program portfolio, which includes wind and other alternative energy investments, began to show profits of $30M by 2014. The estimated loss ratio on the loan program portfolio was 2% of total commitments, which is better than most venture capital firms.*[123]

According to Lazard's Analysis, utility-scale solar LCOE ranges from $43 to $53/MWh. In comparison, the coal LCOE range is $60 to $143/MWh and gas combined cycle is $42 to $78/MWh. Since 2009, utility-scale LCOE has decreased by 86%, even without subsidies due largely to declines in system component pricing. As a result of lower installation prices and increasing panel efficiencies, levelized PPA prices for utility-scale PV fell by $20 to $30/MWh each year between 2006 and 2012 and continued to decline through 2016, most recently at or below $50/MWh with some projects at $30/MWh.[124] In 2011, PPA prices were well over $100/MWh[125].

Figure 7: Installed Price Solar Panels: Residential (2015$/W)



Source: LBNL Tracking the Sun IX, Installed Price of Residential and Non-Residential Photo Voltaic Systems in the United States, August 2016 (Figure 8)

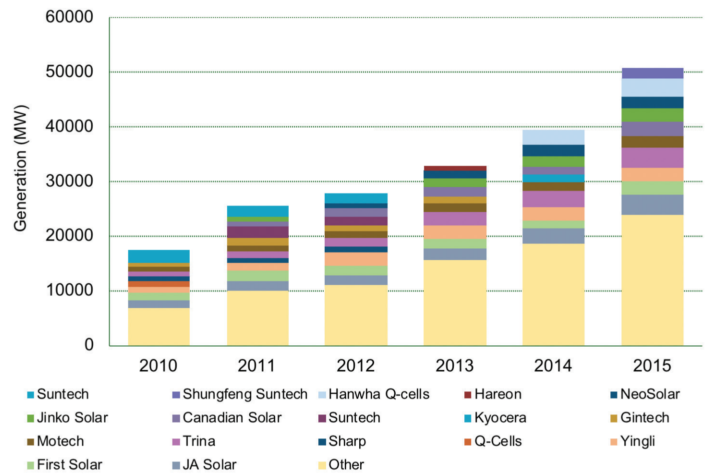
Cost-competitive modules coming out of China are behind these price decreases, putting large scale U.S. solar PV manufacturing out of business. China's rise to the top started in the 1990s when Germany, overwhelmed by increasing demand in rooftop solar created by government incentives, provided the capital, technology, and expertise to Chinese manufacturing to meet this demand. Supported by government investment in expanding solar manufacturing and low coat solar materials, China created a worldwide glut, which it addressed through its own feed-in tariff program that generated high demand domestically. China became the global leader in solar module manufacturing, essentially setting the price worldwide and making it difficult for U.S. manufacturing to compete[126].

U.S. TARIFF THREATENS SOLAR GROWTH. *Early in 2017, U.S. based solar manufacturers Suniva and Solar World Americas requested an investigation into the undercutting of silicon PV solar cell and module prices by Chinese manufacturers. In the Section 201 case brought to the International Trade Commission, the companies requested a $.25 per watt tariff on cells and $.32 per watt tariff on modules plus an import minimum of $.74 per watt. In November, the commission recommended a tariff of 35% to the Trump administration. In January 2018, the administration approved a 30% tariff, which would gradually decline to 15% by Year 4. Each year, the first 2.5 GW of imported cells will be excluded from the tariff. A tariff on imported solar cells and modules will increase capital costs and possibly halt projects awaiting financing, slowing new construction and eliminating solar jobs in the United States. The tariff is expected to impact utility-scale projects more than rooftop applications, but it won't derail the growth of solar longer term according to industry sources. Rapidly increasing global demand, largely due to supportive government regulation and incentives, will continue to push volume, decreasing price and making solar a cost-effective solution for new capacity.*

Industry rankings of the top 10 global solar manufacturers reveal two things: (1) Asia, led by China, is dominating the market and (2) a manufacturer shakeout is emerging that could take years to complete. Between 2010 and 2015, the leaderboard has changed every year with some top manufacturers claiming bankruptcy (**Figure 8**)[127]; although in the last three years, the top 5 manufacturer ranking has been more consistent[128].

In 2017, 9 out of the top 10 solar module suppliers were based on China, representing close to a 60% share of global shipments[129]. While this might suggest consolidation on the horizon, analysts argue that this isn't yet the case. Over the last two years the industry has seen more companies come into the space than exit; 2018 promises even more new ventures[130]. Analysts predict that the top 10 companies will continue to hold their positions in ranking and that China will continue to dominate solar manufacturing, at least in the near future. Potential disruption could come from shifts in technology as the industry looks to go from commodity to higher quality performance products[131].

Figure 8: Global Top Ten Solar Manufacturers 2010–2015



Source: Paula Mints, "2015 Top Ten PV Cell Manufacturers," Renewable Energy World, April 8, 2016.

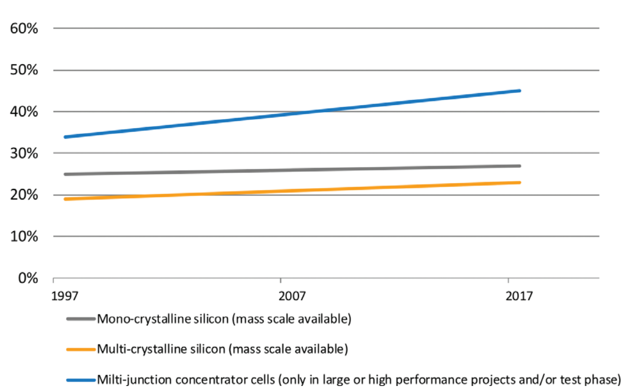
The predicted long term growth of renewables is one that cannot be ignored and could threaten the profits of major oil and gas companies. A 2016 report from Wood Mackenzie estimates that under a carbon-constrained scenario renewable revenues could be nearly three times greater than fossil fuels in the United States by 2035[132]. After suspending or abandoning renewables efforts in 2011, oil and gas companies are getting back into the game, largely through acquisitions[133]. For example, in December 2017, BP announced purchasing a 43% share in Lightsource Renewable Energy, Europe's biggest solar developer. Royal Dutch Shell also announced last year a $1 billion/year investment in clean energy as well as an acquisition of energy supplier MP2Energy. Other major oil companies are investing in various clean energy projects and companies[134].

THE FUTURE OF SOLAR

High volumes and low prices of multi c-Si cells have created a commodity market for PV modules. This has helped to drive down installation prices. Industry analysts note a shift in focus away from multi c-Si to developing mono-c-Si, which is more efficient. Mono-c-Si has been around but used mostly in high-tech space products and thus, was costly. That is expected to change, driven again by China. Mono c-Si offer a slight increase in efficiency to 26%[135]. However, the price gap is narrowing between multi and mono c-Si cells; according to one source, it is less than $0.10 per watt between the two technologies[136].

The biggest breakthrough in efficiency may come from Multijunction III-V solar cells, which use multiple bandgaps that can be tuned to absorb specific regions of the solar spectrum, delivering efficiencies as high as 45% (**Figure 9**). The benefits of multijunction cells include high efficiency, spectrum matching with different absorbers, and similar structure as crystalline cells. However, these cells are still very early in their development and could take years to commercialize[137].

Figure 9: Silicon Solar Cell Efficiencies in Laboratory



Source: Fraunhofer ICE, others

The challenge with solar cells is finding materials that are low cost, abundant, reliable, tunable (i.e., able to adjust frequency to maximize absorption), and that yield high efficiencies. There are no solar cells commercially available yet that offer all of these characteristics. While the currently popular crystalline silicon benefits from maturity, reliability, efficiency, and abundance of raw material (silicon) there are challenges in low defect-tolerance, which requires high levels of purity in manufacturing. Efforts are underway to explore other solar cell technologies[138].

Cadmium telluride (CdTe, thin film) modules are less costly and easier to manufacture but offer lower efficiencies; 22% in the laboratory and 16% mass produced. Copper indium gallium diselenide (CIGS, thin film) is a promising new technology, offering a laboratory efficiency of 20% but a commercialized efficiency of 12% to 14%. Copper zinc tin sulfoselenide (CZTS) is abundant and low cost, but yields a lab efficiency of 10% and has not yet been commercialized. Hybrid organic-inorganic perovskite offers competitive efficiencies (20%), low costs, abundancy, and ease in manufacturing. Organic photovoltaic (OPV) cells offer lower material costs but also low efficiencies and are very early in the R&D phase.[139]

Tracking the Sun

In addition to efficiency, energy production of a solar system depends on mounting of the panels. Fixed panels, while the least expensive are not able to be adjusted to respond to the angle of the sun, which changes based on season and time of day. Adjustable panels provide flexibility to adjust the angle throughout the year producing as much as 25% more energy than fixed arrays. Tracking panels automatically adjust to follow the sun's movement, maximizing the additional energy produced to 30%; but they come with a high cost.[140]

Market analysts are predicting significant growth in tracker installations, in the United States and globally. GTM Research forecasts that by 2021, tracker installations will increase to 38 GW, which will be close to half of all ground-mount solar systems. Ground-mount systems are expected to represent as much as 75% of solar installations over the next five years[141].

As solar module prices decline and tracker volume grows, costs are falling. According to the National Energy Renewable Laboratory (NREL), the cost for utility-scale one-axis tracking systems ranged from $0.03 per kWh to $0.06 per kWh for utility-scale one-axis tracking systems in 2017[142].

While innovation continues on solar cells and panels, forward-thinking companies like Tesla, are looking to incorporate solar into roofing products. The cost of a Tesla solar roof is expected to be significantly higher than installing traditional solar panels but when packaged with the offer of on-site battery storage and an electric vehicle offer homeowners the unique opportunity to live independent of the grid.

The Solar Energy Industry Association (SEIA) estimates that by 2022, solar will represent 5% of U.S. electricity generation. Globally, solar is the fastest growing renewable energy source and is estimated to remain in the lead for the next five years, according to the International Energy Agency[143]. China, representing half of the PV global capacity and 60% of the global solar cell manufacturing base, will continue to influence future solar pricing and demand[144].

While a dominant technology has emerged in multi c-Si cells, efforts continue to focus on increasing cell efficiency and lowering manufacturing costs; results of these efforts will play out in the years to come. These technology improvements coupled with increasing volumes will continue to drive down solar panel costs.

The ability of solar to scale from residential and commercial to utility applications gives it a distinct advantage over other electricity generation sources. With the help of investment tax credits, it's doing so cost effectively. Yet in several climate favorable regions, utility-scale solar is at grid parity with other energy sources without these incentives. Further, with emerging community solar developments this technology is reaching customers who wouldn't otherwise have to access clean, affordable energy. The future is bright for solar, energy but like wind, intermittency presents a barrier to widespread adoption. A greater number in distributed solar energy sources also puts a strain on a not yet modernized grid.

LEVERS FOR A RENEWABLE FUTURE

WITH THE HELP OF MARKET INTERVENTIONS—like government incentives—and fossil fuel pricing volatility, many alternative energy technologies are competing with traditional energy sources for capacity on the grid. Wind and solar, both now cost-competitive with natural gas plants in many instances, have the most potential for growth. The speed at which the electric utility industry decarbonizes will depend on several factors, four of which we explore below.

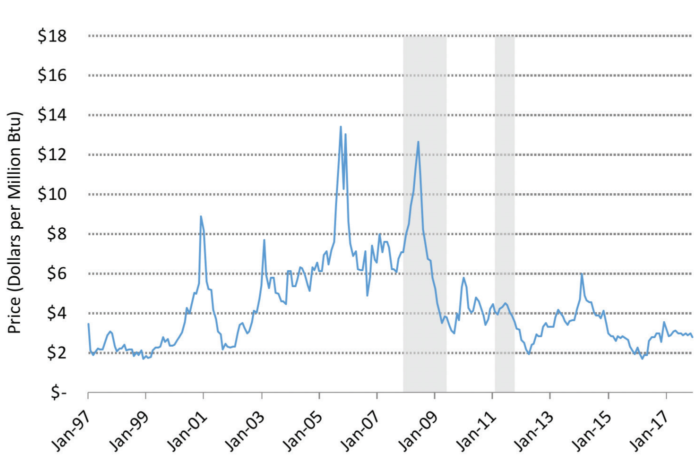
NATURAL GAS PRICING

The economic favorability of renewables such as wind and solar depend on their price relative to the next best alternative. Today, that alternative is natural gas. If natural gas prices rise, renewables become more attractive. If they fall, renewables might find a more challenging marketplace.

When the oil embargo hit in 1973, it elicited fears of oil and natural gas shortages. The nation needed immediate access to new energy sources and coal was in the best position to supply those needs with both deep reserves and the ability to scale production quickly. Over the next few years, coal's share of U.S. electricity generation jumped from 46% to 56%[145]. In fact, of the coal capacity available today in the United States, 36% was added during this decade[146]. This increased demand led to coal prices doubling between 1973 and 1975; prices would stay high until the early 1980s[147].

Meanwhile, natural gas reserves in the United States and abroad were drying up and so were company profits. Companies like Exxon and Chevron attempted to tap into shale gas but failed. Then in 1998, Mitchell Energy, which had been applying fracking techniques for years, provided a breakthrough with a new "slick water" fracturing technology that would prove to be profitable, opening up the Barnett shale formation in Texas. By 2000, shale production began to ramp up. A flood of new companies entered shale gas production and as a result, overall natural gas production increased from 4% in 2005 to 24% in 2012[148]. With increased supply, natural gas prices began to respond (**Figure 10**), falling below the price of coal in 2009 and staying there. By 2015, natural gas surpassed coal as the leading generation source in the United States.

Figure 10: Henry Hub Natural Gas Spot Price 1997–2018



Source: U.S. EIA, Natural Gas data tab (grey areas indicate recessions).

In a wholesale electricity market, low natural gas prices are setting the price of electricity. In these markets, pricing is determined through an auction process designed to match supply with demand using the lowest price of generation. At auction, generators offer a specific capacity into the market at a price representative of facility operation. Independent system operators (ISOs) sort the bids from lowest to highest, selecting generation sources available until the demand is met with available capacity. Once demand is met, the most expensive generator in the mix sets the clearing price. Given their low cost to operate, wind and solar are dispatched first but often cannot meet the total demand; natural gas is the next lowest cost resource and makes up the difference.

Low natural gas prices are creating a market in which coal plants just can't compete. In many cases, coal plants are retiring ahead of schedule, citing poor economics. This trend will continue under a low cost natural gas scenario. Natural gas plants have largely replaced retiring coal plants but with forecasts of rising prices these plants will not be able to compete with renewables, which are seeing rapidly declining construction costs and zero fuel costs. The same gas plants being constructed today could be retired early as natural gas prices increase over time.

WHAT ABOUT CLEAN COAL? *Technologies are available to make coal cleaner, including high efficiency low emission (HELE) coal and carbon capture and sequestration (CCS). HELE plants in China and Japan, with the help of government subsidies, are surpassing 40% efficiency making them competitive with natural gas combined cycle plants. CCS represents several technologies that remove the CO_2 created during the fossil fuel combustion process, transporting it to be stored long term in bedrock or used to enhance other manufacturing processes (e.g., biomass) or oil recovery. The U.S. Petra Nova CCS project completed in 2017, captures 90% of CO_2 post combustion, sending it to the nearby Hilcorp Energy Company's oil field, increasing production by 300 barrels a day. While the technology holds promise the fact is that it will always add cost that could only to be recovered through a secondary CO_2 market (e.g., oil recovery) or price on carbon. The profitability of projects like Petra Nova are dependent on oil prices. Petra Nova sites a $50 per barrel minimum for investors to recuperate their money, at least until a price is placed on carbon. Government investment will play a critical role for CCS projects. Petra Nova received significant financial support from private investors and $190 billion from U.S. DOE. There are several bills in the U.S. House and Senate that would provide tax incentives for CCS technologies. However, it could be too little too late as renewables and natural gas plants pull ahead.*

PUBLIC INTERVENTIONS

The electric utility sector has long been impacted by various government interventions to promote one technology or another. Government support for new technologies can come in several forms. For renewables, tighter environmental regulations on traditional energy sources, utility restructuring and deregulation, and tax incentives aimed at increasing market adoption of alternative energy sources have served as primary drivers.

Fossil Fuel Regulation. Since the Clean Air Act of the 1970s, emission and safety standards have put pressure on coal plants now struggling to compete with natural gas and renewables. For example, the U.S. EIA cites the 2015 Environmental Protection Agency's Mercury and Air Toxic Standards as the reason why 30% of coal plants retired in April of that year[149]. Coal's fate seemed to be sealed on August 3, 2015, when EPA finalized the Clean Power Plan. For the first time, CO_2 emission performance rates were established for fossil fuel electric steam generating units and natural gas combined cycle units. While states had flexibility in the means by which to meet the new standards, EIA estimated that switching from coal to natural gas-fired generation would be the "predominant compliance strategy"[150].

In 2016, the Supreme Court issued an 18-month hold on the plan which is in the process of being repealed by the Trump Administration. States didn't wait to see what would happen and moved quickly to start implementing plans. Today, 35 states are on track to meet or beat their own emissions goals, reducing CO_2 emissions by 27% to 35% below 2005 levels by 2030[151].

Tax Incentives. There is no question that tax incentives for renewables have supported their growth. In general, the energy sector is no stranger to government subsidies. According to one independent study, between 1950 and 2010, the U.S. government provided more than $850 billion in energy subsidies with 47% given as tax incentives followed by regulatory compliance and R&D at 19% and 18%, respectively. The oil and gas sectors received the most financial support over this time period in the form of tax incentives, representing 80% of total funds allocated across the energy industry[152].

Government investment in renewables increased significantly under the Obama administration. In 2009, the American Recovery and Reinvestment Act brought $90 billion in clean energy investments and incentives to the market[153]. Most notably, the Act authorized a 30% tax credit for more than 180 advanced energy manufacturing projects; provided $25 million to fund more than 100,000 wind, solar, geothermal, and biomass projects; extended production tax credits for wind, geothermal, and hydroelectric generation; and boosted funds to U.S. DOE's guaranteed loan program for clean energy projects[154]. The Act also provided $10 billion to efforts to modernize the grid and ensure reliability[155].

Utility Deregulation. In 1978, PURPA redefined electricity generation, requiring utilities to purchase from "qualifying facilities." Qualifying facilities can be small power production facilities or qualifying cogeneration facilities. This requirement was a game changer, essentially diversifying electricity supply and opening the door to competition[156].

The Energy Policy Act of 1992, intended to be an amendment to PURPA, created a new class of generators: exempt wholesale generators (EWGs). The Act allowed EWGs to engage in interstate wholesale electricity transitions without SEC oversight and removed restrictions on the price charged for wholesale[157]. It paved the way for deregulation of utilities in the United States and by 1999, states like California and Texas were starting to deregulate energy services—by 2017, 48 states were partially deregulated[158].

State Incentives. Regional demand for wind and solar is largely being driven by state renewable portfolio standards that require investor-owned utilities, and in some cases municipal utilities and cooperative utilities, to produce a percentage or amount of renewable energy. In 2017, 29 states, three territories, and Washington, DC had adopted renewable portfolio standards.

In the short run, public interventions can have a big impact on the growth and decline of the various technologies in play. Clearly, past subsidies for renewable energy have helped push those technologies down the learning curve, lowering costs, and improving their economic attractiveness. Interestingly, however, the influence of such subsidies and interventions may be waning as costs come down dramatically for solar and wind making them the potential low-cost option even in the absence of subsidies.

EMISSIONS TRADING

Another public regulatory approach is to effectively put a price on greenhouse gas emissions. Creating a market where companies buy and sell greenhouse gas emission permits and credits would facilitate greater adoption of renewables. This "pay-to-pollute" approach encourages fossil fuel plants to explore new, clean technologies and rewards renewable energy sources by offsetting capital investments.

There are two cap and trade programs currently operating in the United States along the East Coast and in California. The Regional Greenhouse Gas Initiative (RGGI) is jointly operated by Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont. Started in 2009, RGGI only covers CO_2 emissions from fossil fuel plants 25 MW or larger. A cap is established covering the RGGI region and covered power plants are required to obtain an allowance for each ton of CO_2 emitted annually. Plants comply by purchasing allowances at auction, purchasing allowances from other generators in the region that have excess allowances, or financially supporting offset projects. Since the launch of RGGI, reductions in CO_2 emissions in RGGI states are 16% greater than in other U.S. states, according to a report published in 2016 by the Acadia Center. The report also cites fuel switching from coal to natural gas and the increase in renewables generation as reasons behind the 37% emissions reductions to date[159]. By 2020, RGGI is projected to contribute to a 45% reduction in emissions[160].

California's cap and trade system is broader in scope, covering power plants, industrial facilities, and fuel distributors that emit 25,000 metric tons or more of CO_2-equivalent (standard unit of measure used to compare all greenhouse gases using their global warming potential). In addition to allowances being sold at auction, California also provides some for free, although that will phase out over time[161]. The program has received some criticism over the years, especially when only 11% of the allowances offered at auction in February 2016 sold, yet it's hard to dispute its impact; the state is well ahead of its 2020 emission reduction goals, putting forth new goals of 40% reduction by 2030 compared to 1990 emissions[162]. In 2016, electricity generation from hydropower and other renewables increased significantly compared to the previous year; although some critics point to renewable portfolio standards and weather conditions as the drivers responsible for these increases rather than cap and trade[163].

Globally, similar carbon trading schemes are emerging in Europe, South Korea, and Canada, and programs are under development in Mexico and Japan. According to Bloomberg, 40 countries or jurisdictions have plans for cap and trade programs[164]. China is evaluating the potential for a national cap and trade program through pilot programs operating in several provinces across the country. Once a national program is in place in China, 25% of global emissions will be covered by carbon pricing[165].

The European Union program was the first to market with a carbon pricing program and it is serving as a lesson learned for other countries; 10 years after launching the program, carbon prices fell 80%. In the United Kingdom, where the carbon price is four times that in Europe, carbon pricing helped to reduce 60% of annual coal consumption in 2016[166]. The World Bank estimates that carbon pricing needs to be between \$40/ton and \$80/ton to achieve the Paris goals. Most of the existing programs show prices of less than \$25/ton and many under \$10/ton[167]. There is some movement toward the connection of cap and trade schemes across country borders. California currently connects to a similar trading scheme in Québec, Canada allowing for trade across borders.

MODERNIZED GRID

The intermittency that comes with wind and solar generation sources presents a challenge for an electric grid designed to dispatch base-load sources available 24 hours/day. Discussions are underway in the industry around how much energy could be supplied by wind and solar reliably without storage. Estimates range from 20 to 40% of total generation, but there is consensus that these technologies will reach a generation ceiling without changes to grid infrastructure.

As electricity generation becomes more distributed and the amount of renewable energy coming on-line grows, there is a critical need for a smarter, more nimble electricity grid. At the core of grid modernization is the need for two-way communication, advanced metering, and responsive pricing. Consumer choice in the source of electricity delivered is complicating what used to be a simplified demand-supply decision made and controlled by the utility.

As the industry has been shifting away from a centralized-utility model, there has been an explosion of innovative activity at the grid-edge[168]. According to GTM Research, annual investments by North American and European companies in companies providing distributed energy services have tripled since 2010, reaching a total of $2.9 billion in 130 individual companies. Investments made in 2016 alone represented $1 billion[169]. Digital technologies on the grid such as smart switches and sensors and artificial intelligence are providing the system reliability needed to support a modernized grid. Significant investment is being made in "direct customer engagement" solutions, like advanced energy management systems[170].

The electric grid as we know it today hasn't changed much since its inception. The purpose of the grid, and the driving motivation for utilities serving it, was to provide reliable access to electricity. Customers didn't ask for much more.

Change was set into motion with PURPA. For the first time, customers would have a choice in generation providers. New Federal Energy Regulatory Commission (FERC) orders created in the years that followed PURPA aimed to increase access to renewables, reduce grid congestion, provide incentives for energy storage, and ensure reliability. These orders would facilitate the shift from centralized to more distributed generation. As states became de-regulated, utilities were forced to step out of the generation business and focus on transmission and distribution services.

Choice in electricity source is changing the dynamics of the utility-customer relationship. Customers are looking for more customized services and holistic solutions from their energy suppliers. They want a cleaner energy mix and more specificity around source. Providing this level of specificity has required innovation in the way the industry tracks, buys, and sells electrons on the grid. Unless the electricity is being generated on-site, once the electrons are added to the grid, there is no way to identify them as "green".

One solution is renewable energy certificates (RECs), which track each MWh of renewable generation that can then be sold or traded to comply with renewable portfolios standards or support corporate claims of investment in clean energy. The REC and electricity delivered represent two different revenue streams, assigning social and environmental values to clean energy generation.

To date, certifying and managing RECs data has been manual and thus, costly and subject to human error. Blockchain technology—an open-source database that operates across a computer network to authenticate and record transactions in real-time eliminating the need for centralized control and ensuring data redundancy—is emerging as a solution. New digital currencies able to encrypt data (cryptocurrencies) are being introduced that could work within blockchain to allow for peer to peer energy transactions.

Peer-to-peer transactions gave rise to the term "prosumer," i.e., households that produce and consume electricity. Community microgrids using peer-to-peer trading platforms are enabling residents to buy and sell electricity generated from residential solar PV sources. How does the electric grid, and those operating and maintaining the balance needed to ensure reliability, respond to this level of distributed generation?

This is a work in progress. Organizations such as the Solar Electric Power Alliance (SEPA) are working to develop standards for distributed energy resource management systems, which will facilitate communications between these resources and utility systems. One of the biggest challenges is private sector reluctance to support an open standard software platform. Companies are choosing proprietary solutions over industry-wide collaboration. But the challenge goes even deeper, the traditional utility business model needs to change as well, from one that rewards revenue based on generation to one that rewards services while continuing to ensure reliability and security on the grid.

STORAGE

While efforts are underway to facilitate smart grid communication, investments in energy storage are aimed at addressing intermittency renewable concerns. Some in the industry argue that renewables could meet all of the energy needs in the United States without significant storage if the industry can more effectively distribute the electricity[171]. But as discussed above, solving the distribution issue will take time; more immediate solutions are necessary. Energy storage solutions are available today with significant investment going into technology improvements. Similar to what solar experienced in the last five years, storage costs will continue to come down as demand rises and more storage is deployed. According to Lazard's Levelized Cost of Storage Analysis, some of these technologies are nearing cost-competitiveness with gas peaker[172] power plants today[173].

Several storage technologies are vying for a place in the energy market. Some of the more commercially viable include: lithium-ion (Li-ion), flywheel, compressed air, and pumped hydro. Application is a key indicator of which energy storage solution will be more effective.

Unlike generation which has one purpose, storage offers multiple uses for "in front of the meter" and "behind the meter" applications[174]. Storage used for the former case is primarily deployed for frequency regulation but with the rise in intermittent renewables like wind and solar, there will be an increasing need for peaker replacement, PV integration, transmission grid support, and distribution services.[175] Storage deployed for "behind the meter" applications is more nascent but the increasing ownership of electric vehicles could change that growth trajectory.

Today, Li-ion is the leader in storage deployment but high costs have been a barrier to more widespread adoption. Efforts in the automobile sector to improve Li-ion batteries and drive down costs through increasing volumes will benefit energy storage. According to Bloomberg New Energy Finance (BNEF), utility-scale battery systems could fall from $700/kWh in 2016 to less than $300/kWh by 2030[176]. Other analysts like McKinsey& Company are projecting costs as low as $160/kWh by 2025[177].

BNEF predicts that the global energy storage will double six times leading up to 2030, providing a total of 125 GW of storage support[178]. Storage seems to be following in the footsteps of solar with regards to exponential growth—between 2000 and 2015, solar's share of total electricity generation doubled seven times[179]. The U.S. market represents 25% of BNEF's 2030 growth prediction and over the next five years, it is expected to grow 12 times the size of the market in 2016[180].

In the United States, there have been recent efforts to create tax incentives to storage but such incentives were ignored in the two-year budget bill signed in early February. Incentives for storage packaged with solar are available today but the pairing is still quite expensive. While incentives could speed storage deployment, the economics are strong for storage technologies longer term.

Grid modernization is in an era of ferment, and while the flurry of innovative activity in this space is promising, more progress is needed at a faster pace to provide the standardization and support needed for renewables to dominate the generation landscape.

AVAILABILITY OF MATERIALS

One challenge that may slow the growth of renewables is rising costs due to shortages of necessary components, such as rare earth elements in wind turbines and solar panels. These shortages may be caused by simple resource scarcity or global trade barriers.

Trade barriers became an issue in 2011, when prices for rare earth metals spiked after China, which represented 98% of global production, restricted its exports. These restrictions were lifted by 2015 but in response, the industry began looking for other sources for rare earths and substitutes[181]. While new rare earth deposits have been found around the world, it can take a decade to create an extraction and processing supply chain that can compete with China. Rare earths, despite their name, are fairly abundant; the challenge is extracting enough of the metals to make them economical. Industry and governments are looking at potential mitigation strategies regarding rare earths, ranging from reuse and recycling to material substitution and increased mine production.

Organizations like the U.S. DOE Ames Laboratory's Critical Materials Institute are leading research "on technologies that make better use of materials and eliminate the need for materials that are subject to supply disruptions"[182]. Five specific rare earth elements have been identified by U.S. DOE as critical to clean energy development: dysprosium, terbium, europium, neodymium and yttrium, as well as lithium and tellurium. The Critical Material Institute is conducting research on potential substitutes for these elements.

For wind turbines, dysprosium and neodymium are used in in permanent magnets for the production of high-performing generators[183]. For solar cells, silicon is abundant and widely available, and therefore not seen as a threat to further growth. However, some solar cell types do use rare earths and may be subject to shortages. One example is thin-film, which uses indium and tellurium.

Copper used in many electronic controls and wiring, including wind and solar, could also be affected over the next 20 years, as demand for the metal increases because of increased demand for electric vehicles and other electronics products[184].

Battery energy storage also faces potential challenges with regards to the supply of cobalt and lithium. Cobalt, which can represent from 10 to 20% of the cost of lithium batteries, doubled in price in 2017 and suppliers are indicating shortages in existing stock, driven primarily by the increased demand for electric vehicles[185].

ACHIEVING A FULLY DECARBONIZED ELECTRIC UTILITY SECTOR: A MATTER OF TIME?

RENEWABLES, LED BY WIND AND SOLAR, will likely grow to dominate the electric utility sector in the coming years. Hydropower and nuclear energy will play supporting roles but face challenges as facilities age. Small-scale generation solutions in hydropower and nuclear energy hold promise, but are still far from widespread commercialization. Natural gas will continue to be a vital part of the new generation mix but will find it difficult to compete longer term with renewables as capital and installation costs come down for wind and solar, even under a low-price gas scenario. Low natural gas pricing is putting coal out of business. Without incentives to defray the additional costs of carbon capture and storage (CCS) technologies, coal won't be able to compete with natural gas or renewables in the new clean energy economy.

Wind and solar technologies are quickly moving up the technology S-curve[186]. Wind is more mature and is cost-effective with fossil fuels today when considering capital, installation, and operation costs over the lifetime of the asset. Yet there is still room to improve. R&D efforts continue, aimed at improving turbine efficiencies and expanding wind into less optimal climates. Off-shore wind offers significant capacity not yet tapped by the United States but in Europe, prices are starting to compete with those for on-shore wind. Exciting new off-shore designs are emerging that could open up shorelines once commercialized.

Solar competes with wind in terms of market development. Today, c-Si dominates the solar cell market but new, more efficient technologies are on the horizon. There has been continued turnover in competition, as top 10 manufacturer rankings shift and China comes to dominate the manufacturing market. Today, solar is cost competitive in favorable climates. As efficiencies improve and costs decline, solar will become the cheaper option in residential, commercial, and utility-scale applications. Analysts predict that solar will lead renewables into the clean energy future. Yet solar can't do it alone and needs the partnership of wind and storage technologies, along with supportive grid solutions, to grow.

Industry analysts predict that energy storage technologies will be cost-competitive in four years, following a technology adoption curve similar to that of solar. While Li-ion batteries have emerged as an early leader, benefiting greatly from R&D efforts in the automobile industry, it faces cost barriers and potential technical limits with regards to scaling as well as concerns over material supply and waste disposal. Like automobiles, there could be an opportunity for hydrogen and fuel cells in this sector but technologies are still nascent.

At the end of the day, our ability to scale renewables will depend heavily on an electric grid that can handle two-way communication and vast amounts of distributed resources and data, all while ensuring that the lights stay on. The time it takes to build out the new energy grid will determine how quickly the electric-utility industry can decarbonize.

ACCELERATORS AND ROADBLOCKS

In the U.S., federal government investment in R&D and tax credits have helped to accelerate commercialization of wind and solar technologies. Today, even without subsidies, these technologies are cost competitive with fossil fuels in many applications. Incentives are helpful but will be phased out over the next few years at which time wind, solar, and storage are expected to be cost competitive without them. In lieu of federal government standards, state renewable portfolio standards have created a demand for renewables nationwide. Many states have goals of 25% or greater renewables generation share within the next 10 years. Federal government incentives help accelerate these dynamics, but increasingly are becoming less critical to the success of renewables.

That being said, federal actions aimed at subsidizing fossil fuels could slow down progress. Recently, U.S. DOE Secretary Rick Perry, citing resilience, asked FERC to issue a rule that power plants that keep a 90-day supply of fuel on-site receive subsidies. FERC denied that request and instead, opted to work with ISOs and Regional Transmission Organizations (RTOs) on identifying needs for ensuring a reliable and resilient electric grid moving forward. Solar tariffs, positioned as a way to save U.S. solar manufacturing, will have little impact on U.S. global competitiveness and will cause delays in new construction as the price of imported solar panels rises. Ironically, tariffs may destroy more U.S. jobs than they create, as most U.S. jobs in renewables are in the construction and installation of solar projects. For renewables, federal government engagement may be more of a hindrance than an accelerator under proposed rules.

Meanwhile, governments in other countries are moving forward with renewable energy plans. Demand for renewables in China is driving the growing global market, accounting for 40% of total renewable energy growth in 2017. China, India, and the United States are expected to represent two-thirds of renewables growth through 2022[187]. In the U.S. and abroad, commitments to reduce carbon footprints being made by large and influential companies are driving demand for wind and solar. Major technology companies, such as Facebook and Amazon, are requiring that renewable energy be part of bids presented for prospective new construction locations. Companies are joining together under the World Resources Institute's Renewable Energy Buyers Alliance (REBA) to create a large pool of demand and connect this demand to renewable energy sources. More progressive electric utilities are moving ahead with plans to expand renewable capacities and invest in grid solutions in response to increasing corporate and consumer demand. Micro and remote grids are forming around the world, bypassing the need for utilities completely. Disruption is happening not only with generation technologies but also in the way electricity is distributed. Utilities that fail to shift their business models to a service-based approach may be left out.

Low natural gas pricing will continue to impact renewable sources, forcing coal plants to retire, and serving as a direct competitor to renewables for new capacity. Many countries, including the U.S., see natural gas as a clean alternative to coal and as a key component of their future generation portfolio. Ironically, with lower demand for coal, its price will drop and become more competitive with natural gas. Critical are the drivers of future natural gas prices. Innovations, such as the fracking of shale gas, could potentially increase supply and lower gas prices further. On the other hand, wars and embargos can limit supply and raise global oil and gas prices. For these reasons, the U.S. Department of Defense is investing in renewables to build resiliency to global disruptions.

Wind and solar are growing at a rapid pace but will hit a market penetration ceiling if issues around intermittency and distributed generation are not addressed. Intermittency requires a means for storing renewable energy when it exceeds demand and then deploying the electrons onto the grid during times when supply is limited such as cloudy days. Yet, even with cost-effective storage, the grid itself needs to be nimble and flexible to handle distributed distribution on a massive scale. A modern grid is needed but what defines "modernization" is still being debated.

Grid edge technologies are being introduced to enable two-way communication and to process potentially billions of energy transactions. Standardization of communications on the grid and between smart products is necessary to ensure a shared "language". Data analytics and artificial intelligence hold promise for enhancing grid reliability and functioning. Blockchain and currency tracking technologies may allow customers to more effectively trade "green electrons". A national grid that connects regional grids could further facilitate access and energy trading. While the cost for renewable "fuel" is essentially zero, transmission and distribution costs can be substantial and cost prohibitive without a more connected and modernized grid. While the future of wind and solar looks bright, grid modernization could be perhaps the biggest roadblock to their speedy adoption.

GLOBAL ENERGY DECARBONIZATION IS POSSIBLE, BUT NOT GUARANTEED

Electricity generation represents a significant portion of greenhouse gas emissions worldwide. It touches every major sector, from buildings to industrials and, increasingly, transportation as vehicles electrify. Innovation in this sector can have a significant impact on the speed at which the global economy decarbonizes. The trajectory of renewables, specifically solar and wind, suggest they could become the dominant low-cost technology in the near future giving us hope for a decarbonized electric utility.

Yet with countries like China and India still building coal plants to keep up with rising demand in consumption, and with natural gas generating capacity continuing to grow due to low pricing, decarbonization will take time. Globally, coal still represents the largest share of the generation market—40% in 2015[188]—driven largely by China. In July 2017, there were 6,700 coal fired power plants operating around the world with 530 more under construction. While China has scaled back plans for significant new coal generation, China and India still represent 40% and 50% of these new plants, respectively[189]. The U.S. EIA predicts that India will increase its coal production by 90% by 2040 due to new demand for electricity generation. Efforts in China and the United States to scale back coal consumption will balance out growth in India and other countries but coal's share of the worldwide generation market will fall only slightly to 31% by 2040, according to U.S. EIA estimates[190].

Disruption on the scale of natural gas fracking is needed if there is any chance of meeting the Paris Agreement goals by 2060. Owners of coal and natural gas plants must be willing to walk away from these assets even before planned retirement. Federal governments need to a look at the longer-term gains to society, support work training programs, and focus on the renewable energy sources of the future. Significant and widespread innovation is also needed on the grid and in energy storage to facilitate greater adoption of renewables.

In the end, as long as the wind blows and the sun shines, renewables will become increasingly attractive, decarbonizing the electric utility sector. It's basic economics. The question is how long will this technology transition take? Various institutional players can accelerate or hinder this disruption. Their choices are critical, and 2060 is looming.

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ENDNOTES

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