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The Future of Low-Carbon Electricity

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DISCLAIMER

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Keywords

low-carbon electricity, renewable, nuclear, CO_2 capture and sequestration, grid integration, breakthrough technology

Selected Acronyms and Definitions

Biomass-CCS	biomass power with CCS
CCS	CO_2 capture and sequestration
CSP	concentrating solar power
DOE	U.S. Department of Energy
EGS	Enhanced geothermal systems
EOR	enhanced oil recovery
Fossil-CCS	fossil power with CCS
GHG	greenhouse gas
GW	gigawatt
HTGR	high temperature gas-cooled (nuclear) reactor
IEA	International Energy Agency
LMR	liquid metal (nuclear) reactor

MHK	Marine and hydrokinetic
NHES	nuclear hybrid energy system
OECD	Organization for Economic Cooperation and Development
PV	photovoltaic
R&D	research and development
SSP	space solar power
TWh	terawatt-hour
USD	U.S. dollar

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Abstract

We review future global demand for electricity and major technologies positioned to supply it with minimal greenhouse gas (GHG) emissions: renewables (wind, solar, water, geothermal and biomass), nuclear fission, and fossil power with CO_2 capture and sequestration. Two breakthrough technologies (space solar power and nuclear fusion) are discussed as exciting but uncertain additional options for low net GHG emissions ("low-carbon") electricity generation. Grid integration technologies (monitoring and forecasting of transmission and distribution systems, demand-side load management, energy storage, and load balancing with low-carbon fuel substitutes) are also discussed. For each topic, recent historical trends and future prospects are reviewed, along with technical challenges, costs and other issues as appropriate. While no technology represents an ideal solution, their strengths can be enhanced by deployment in combination, along with grid integration that forms a critical set of enabling technologies to assure a reliable and robust future low-carbon electricity system.

Introduction

According to the International Energy Agency (IEA), global demand for electricity is expected to grow from ~20,100 TWh/yr in 2013 to between ~30,000 and ~37,400 TWh/yr in 2040, depending on future policy assumptions (1). Most growth (>85%) is expected outside so-called Organization for Economic Cooperation and Development (OECD) countries,[i] with strongest growth in China and India. See Figure 1.

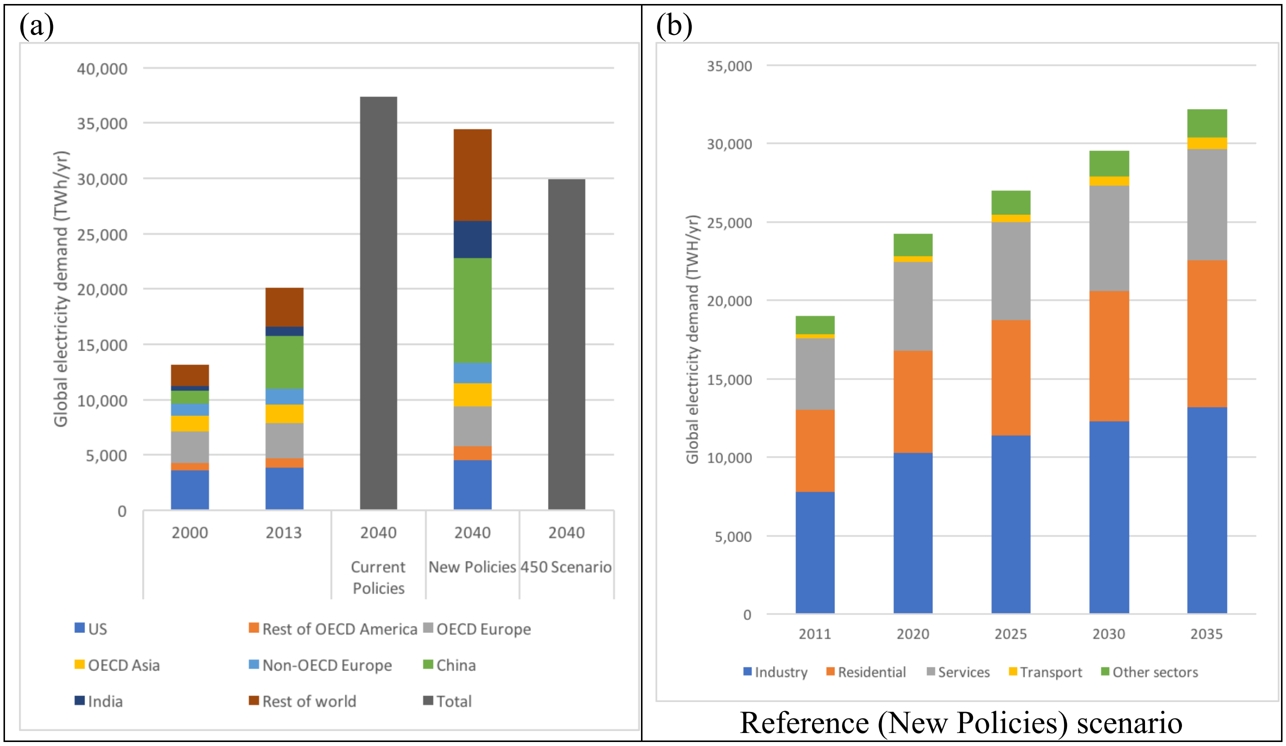

Figure 1. Global demand for electricity by (a) region (1) and (b) end use (2).

Increasing electrification of industrial processes helps spur demand in IEA scenarios, though all sectors contribute strongly. Transport electrification, while the fastest-growing sector at 3.9%/yr between 2011 and 2035 (2), is expected to contribute only 2.3% to future demand, with most growth coming from rail, not passenger electric vehicles (EVs). However, with aggressive climate policies (IEA's "450 Scenario"), EVs are projected to reach as much as 715 million by 2040, nearly five times the reference scenario level (3).

The rise in information and communications technology energy use globally may be especially rapid. In 2012, data centers consumed 270 TWh or ~1.4% of total global demand, while personal computers and communications networks each consumed >300 TWh. All three end-use categories are projected to grow significantly faster than overall demand (4). While data center

[i] Thirty-five countries comprise the OECD including the U.S., Canada, Mexico, Chile, many European countries, Turkey, Israel, Japan, South Korea, Australia, and New Zealand (2).

efficiency trends are also accelerating, at least in the U.S. (5), the growth of information technology services may become an important new end use category in the next few years.

Fossil resources have historically supplied most of the energy for electricity generation: 67% in 2013 (1). However, with adoption of the Paris Agreement (6), renewables are forecast to supply almost 60% of new electricity generation by 2040 under the IEA's reference scenario, and account for nearly 60% of all generation in the 450 Scenario (3). These scenarios contrast even more dramatically in greenhouse gas (GHG) intensity: 55% vs. 15% of today's global average (515 gCO_2/kWh). Both pathways also include growth of nuclear power, fossil power with CO_2 capture and sequestration (fossil-CCS), and displacement of coal with natural gas generation.

The electricity sector is perhaps uniquely positioned to dramatically reduce its GHG emissions faster than other sectors, so an important climate strategy is aggressive electrification, especially in transportation, industrial processes and building heating. With this growth comes additional demands on electricity supply, and a rapidly evolving grid whose temporal and spatial patterns could shift significantly compared to historical experience.

The 450 Scenario, consistent with the Paris Agreement goal of limiting global warming to 2°C (6), "puts the energy sector on course to reach a point, before the end of this century, when all residual emissions from fuel combustion are either captured and stored, or offset by technologies that remove carbon from the atmosphere" (3). To reach 1.5°C would require net-zero emissions between 2040 and 2060, and almost certainly widespread deployment of negative emissions technologies like biomass power with CCS (biomass-CCS; see biomass section).

In this review, we survey recent technical and market trends, as well as future prospects, for low-carbon electricity generation technologies including renewables, nuclear fission, fossil-CCS, breakthrough technologies, and grid integration challenges of widespread reliance on these technologies.

Renewables

The term "renewable" generally refers to energy sources that replenish over human timescales, as opposed to fossil resources which required millions of years to form. Renewables include energy provided directly or indirectly from the Sun (solar, wind, biomass and most forms of water power), gravitational interactions between Earth and Moon (tidal power), and energy from Earth's formation supplemented by radioactive decay (geothermal power) (7,8).

Renewables are by far the oldest human sources of energy, with biomass supplying heat energy for tens of thousands of years, wind power driving the golden age of exploration and trade, and water powering early mechanization. However, renewables are also the newest form of energy, with modern technologies efficiently harnessing renewable resources to produce electricity and heat, and in recent decades they have seen great improvements in technical performance and affordability (9,10).

Here we provide brief summaries of recent developments and future prospects for the major renewable technologies available for electricity production globally.

Wind

Installed wind power has more than doubled globally since 2010, reaching 433 GW at the end of 2015 (11). China leads the world at 145 GW, with the U.S. in second place (74 GW), followed by Germany (45 GW). 2015 was a "banner year" for wind, with record-level installations globally (63 GW). Capacity is forecast to grow to 792 GW by 2020 (11) and 926-1,684 GW by 2035, depending on policy assumptions (2).

Onshore average wind turbine capacity in the U.S. was 2.0 MW in 2015, with rotor diameters and hub heights averaging 102 and 82 m, respectively. These represent strong increases over the past 15 years, though hub heights have remained essentially level since 2007 (9). Increasing hub height allows turbines to access higher average wind speeds, increasing power. Larger rotor diameters also allow capture of more power. The largest diameters (>110 m), although representing 20% of new installations in 2015 (9), appear close to transportation infrastructure limits and are unlikely to grow further (R. Wiser, pers. commun., 2016). Another notable trend is the wider deployment of turbines designed for lower wind speeds. Along with this trend is a significant increase in turbine capacity factor (ratio of average to maximum power) for projects built recently, increasing power generated per installed turbine. Projects built in 2013 (37%) and 2014 (41%) were significantly higher than projects built in 2004-2011 (31%) (9).

Wind power is overwhelmingly produced onshore, but offshore capacity has been growing rapidly as well, and stood at 12.1 GW globally at the end of 2015. Ninety-one percent of offshore wind exists in Europe (mainly the UK and Germany), with the remainder in China, Japan and South Korea (11). The first U.S. installation began operating off the Rhode Island coast in December 2016 (12), with 23 projects totaling >16 GW in various stages of development (9). The average size of an offshore turbine is 4.2 MW and sits in 27 m of water, 43 km from shore (11). Because the cost of the foundation is high relative to onshore installations, cost-optimal designs call for larger turbine capacities, and 6-8 MW are expected to be deployed before 2020, with 10+ MW prototype designs developed by that year (13). Floating structures, which allow deployment in much deeper waters to reach higher-quality wind resources, are expensive (R. Wiser, pers. commun., 2016) and still at the pilot stage (13).

In the U.S., the cost of wind turbines has fallen ~20-40% relative to a 2008 high of 1,500 U.S. dollars (USD)/kW in 2015, despite increases in hub heights and rotor diameters, which in turn have reduced project costs and wind power prices. Average 2015 costs were ~1,000 USD/kW (9). An extensive expert elicitation study of future wind energy costs found that relative to 2014, levelized costs could fall 24-30% in 2030 for both onshore and offshore technologies (14).

For a discussion of high-altitude wind technology developments, see sidebar.

Solar

Solar electricity today is dominated by photovoltaic (PV) technology of various types, but includes small amounts of concentrating PV and thermal (concentrating solar power = CSP) technologies. Global solar PV capacity was 227 GW in 2015, with installations spread across

China, Japan, the U.S., Europe, and new markets around the world (15). It is expected to grow to 510-990 GW by 2035 (depending on policy assumptions), with large increases in most world regions (2). For CSP, capacity was 4.8 GW in 2015 (15), and is projected to grow to 35-224 GW in 2035 (2).

Current PV technologies span mono- and polycrystalline silicon (c-Si), gallium arsenide (GaAs), III-V multijunction, and thin-film designs (16,17). In the U.S., c-Si made up 94% of the 2014 market, with thin-film cadmium telluride (CdTe) comprising most of the remainder (18). GaAs is inherently more efficient than c-Si but also much more expensive; it is usually reserved for high-performance applications, especially space. Multijunction cells stack multiple material layers that absorb at different wavelengths in series to produce higher voltages and utilize more of the solar spectrum, increasing efficiency. Thin-film devices such as CdTe, copper indium gallium selenide (CIGS) and hydrogenated amorphous silicon (a-Si:H) utilize materials that absorb light more efficiently than silicon, allowing much thinner layers, but usually at the expense of lower efficiency. Emerging thin-film materials include copper zinc tin sulfide (CZTS), perovskites, organic semiconductors and quantum dots. However, large-scale deployment of some thin-film designs may be limited by elemental scarcity (17).

While PV can be as small as a few kW installed on residential rooftops, it is much more affordable at larger scales. For all scales, however, solar PV has seen a tremendous decrease in installed cost since 2009, falling in the U.S. by more than 50% to between ~2 USD/W_{DC} (≥500 kW) and ~4 USD/W_{DC} (residential-scale).[ii] This drop has been mainly precipitated by the large decrease in module prices, which for residential PV fell from ~4 USD/W_{DC} average in 2000-2008 to ~0.5 USD/W_{DC} in 2015 (10,16). Moreover, U.S. installed costs are high compared with other major markets, particularly Germany where they are ~50% lower (10).

At the utility scale, PV can be installed in a fixed-tilt or tracking configuration (16); the extra energy afforded by tracking is traded with increased capital cost and mechanical maintenance, and most solar PV installations are fixed-tilt. However, tracking now dominates new installations as its costs have fallen (~0.3 USD/W_{AC} at utility scale in 2015) (16).

While c-Si costs may fall further due to investment from a large-scale industry, thin-film technologies hold promise due to higher power-to-mass ratios and potentially lower ultimate costs. Jones-Albertus et al. (18) outline technological improvements needed for solar PV to achieve 60 USD/MWh levelized cost, which the U.S. DOE's Sunshot Initiative estimates it is >90% toward meeting for utility-scale PV (19).

CSP represents a fundamentally different approach to solar energy: using concentrated solar energy as a thermal source driving a steam turbine. CSP must inherently track the sun, and pointing stability is critical to maintain high operating temperatures. While CSP plants can store thermal energy for hours, providing dispatchable power, they are only suitable in regions with high direct insolation, and are currently costlier than PV (17). Largely experimental until recently, seven commercial CSP plants totaling 1.4 GW are now operating in the U.S. in Arizona, California, Florida and Nevada (16), using a mixture of single-axis (parabolic trough)

[ii] Solar PV power is usually measured by peak direct-current (DC) output or W_{DC}, though sometimes peak alternating-current (AC) output or W_{AC} is used. As module output is natively DC, subsequent conversion to AC incurs some losses, so $W_{AC} < W_{DC}$.

and two-axis (tower) concentration designs. However, while prospects are not as promising now due to lower solar PV costs, they are expected to improve in the longer term (1).

Water

Power from water—exploiting gravitational potential, kinetic or thermal energy—is among the oldest renewable technologies. Worldwide hydropower capacity was 1,064 GW in 2015, generating 3,940 TWh/yr (15) or ~19% of total demand (1), led by China, Canada, Brazil and the U.S. (15,20). In developed countries, most significant hydropower resources are already exploited; U.S. capacity is expected to grow modestly from 80 GW today to 93 GW in 2050, with ~50% growth from repowering existing facilities (21). Globally, however, growth to >1,600 GW by 2035 is expected (2,20).

Hydropower is not universally considered "green": for instance, California does not count hydropower facilities as renewable unless they are <30 MW (22). In addition to displacing people and habitat when constructing reservoirs, dams may promote anaerobic decay of organic matter, generating the potent GHG methane; recent research suggests this effect could be even larger than estimated (23).

Marine and hydrokinetic (MHK) technologies are distinct from hydropower, exploiting energy from waves, tides, and river and ocean currents, and represent a number of potentially viable technologies (24). The U.S. has estimated MHK's technical potential as ≳50% of U.S. electricity demand (1,25). However, MHK is still immature and hence expensive, and has recently suffered technological and commercial setbacks (26); while the U.S. and other countries remain supportive (27), the future is uncertain. The IEA's global marine power forecast (includes some MHK technologies) is 9-23 GW in 2035 (2) and up to 36 GW in 2040 (1), growing from negligible levels today.

Geothermal

Large-scale geothermal energy is produced in high-temperature regions at shallow depths (typically >1 km), using either natural or injected water to extract heat from rock. This heat originates from residual energy of Earth's formation supplemented by natural radioactive decay (7,8). In contrast to small-scale geothermal heat pump systems utilized widely for homes and buildings, attractive locations for large-scale electricity production are very limited geographically, and most conventional potential in OECD countries has already been exploited, though much remains elsewhere (1). Global geothermal generation is projected to grow from 12 GW in 2013 to 32-63 GW in 2035 (2) and 43-78 GW in 2040 (1), depending on policy assumptions.

Conventional geothermal technologies require steam above 150°C for economic operation. However, the U.S. Department of Energy (DOE) has been funding research that takes advantage of lower temperatures and/or "coproduced resources" (hot fluids other than steam, such as oil or gas) for electricity generation. In some cases, so-called low-temperature fluids can improve plant economics by adding a secondary, lower-temperature application such as building heating, water purification, or mineral recovery (28).

Enhanced Geothermal Systems (EGS) are reservoirs engineered to create energy from "hot dry rock" that otherwise lack the water and/or permeability to be utilized. EGS has the potential to access geothermal resources at greater depth and could add >100 GW of capacity in the U.S. (29). A key enabling technology is hydraulic fracturing to increase permeability (30), similar to that used to produce unconventional natural gas. Strongly supported by the U.S. DOE, the technology is still at a research and development (R&D) stage, with goals to demonstrate a 5 MW system by 2020, and a cost-reduction pathway from ~240 to ~60 USD/MWh by 2030 (30).

Biomass

Biomass electricity comprised ~11% of total biomass energy utilization in 2013 (1), with the balance going to fuels production (mainly ethanol, biodiesel and biogas). Nonetheless, biomass electricity produces nearly zero net GHG emissions, and is often an excellent way to use biomass when feedstocks are abundant and economical to procure (1).

Total global biomass electricity generation was 108 GW in 2013 (1), and is projected to grow to 230-355 GW in 2035 depending on policy assumptions (2). The European Union had the most bioenergy capacity in 2014 (almost 40 GW), followed by North America (>20 GW) and Brazil (12 GW) (1). Technologies for biomass power are essentially the same as for fossil combustion (1).

In terms of raw biomass, the global technical potential ranges from <50 to >1,000 EJ/yr (~600-12,000 GW if used to make electricity[iii]) in 2050, with the largest uncertainty from estimates of dedicated biomass production on surplus lands. As a diffuse resource, biomass production is often limited by collection cost, and it is also constrained by competing uses of land for agriculture, grazing, urbanization, or preservation of biodiversity. Moreover, water resources and nutrients may limit productivity. Nonetheless, marginal or degraded lands as well as grasslands have considerable potential for biomass production (31).

With consideration of all these factors, the economic potential for biomass in 2025-2030 is estimated to be ≲100 EJ, with ~27 EJ/yr in Europe, ~15 EJ/yr in the U.S., ~25 EJ/yr in Brazil and ~20 EJ/yr in other parts of the world (31). These estimates assume the majority of biomass goes to fuels production (primarily ethanol), highlighting another important constraint on this resource: competing energy uses.

Biomass-CCS (sometimes called biomass energy CCS = BECCS) has recently become a focus of attention because of its potential for negative net GHG emissions. (For details on CCS technology, see fossil-CCS section). A 2011 report suggests that biomass-CCS could be used in a range of biomass technologies, including power generation (32). Sanchez et al. (33) showed that biomass-CCS could be cost-effective relative to other low-carbon technologies, and using biomass-CCS for electricity could reduce emissions >2× as much as biomass-CCS for cellulosic

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[iii] Assuming 30% thermal-to-electrical conversion efficiency and 80% plant capacity factor.

ethanol. Moreover, resources in the western U.S. were sufficient for >10 GW; in combination with significant renewables expansion and reductions in fossil fuel generation, biomass-CCS could reduce net electricity GHG emissions below zero by 2050 (33). Azar et al. concluded that biomass-CCS is important for lowering the global cost of reaching stable atmospheric CO_2 concentrations (with value increasing as concentration targets decrease), or conversely, could allow global CO_2 reductions 50-100 ppm lower at the same cost as without biomass-CCS (34). These are significant findings, but there is little recognition of the importance of biomass-CCS aside from these few studies; the IEA scenarios highlighted earlier make no mention of the technology (1-3). Before biomass-CCS can be deployed, GHG accounting rules must be expanded to allow the full benefits to be realized, including assurances that the biomass used is grown sustainably, with net zero GHG emissions from both direct and indirect land use (32).

Nuclear fission

Nuclear fission power is the leading low-carbon generation technology in the U.S. and OECD countries, and second-largest in the world, just behind hydropower (1). The global nuclear fleet generated more than 2,500 TWh in 2014, with 78% of this generation occurring in OECD countries (35). Nuclear electricity generation rapidly grew from 1970 to 1995, but since then has been relatively stagnant. Nuclear power reactors have predominantly been used for steady-state production of "baseload" (constant-output) electricity that is distributed broadly on the electric grid (36). These reactors have an exceptional operational and safety record in the U.S., with the lowest death rate (0.04/TWh) of all electricity generation sources globally (37). The average capacity factor of the U.S. nuclear fleet has been >90% since 1999 (38), significantly higher than either fossil energy systems (~50-60%) or renewable energy systems (~25-35%) (39). The challenges with nuclear energy are economics, sustainability and perceived safety.

The nuclear reactors presently in operation are mostly water-cooled and operate at high coolant pressure. These reactors use uranium oxide fuel pellets contained in zirconium-based cladding. In the U.S., reactors use uranium fuel with a ^{235}U enrichment of less than 5% (40). Typically, these power reactors are operated in a once-through fuel cycle, where the low-enriched uranium oxide fuel is "burned" (consumed) and disposed of without being recycled. However, there are exceptions internationally, such as the mixed-oxide (MOX) recycled nuclear fuel used in France (41). Water-cooled technologies were originally developed in the 1950s and 1960s for powering nuclear submarines. The majority of water-cooled nuclear power reactors are also water-moderated, where moderation is the process of slowing neutrons down from the energy at which they are released to the energy most likely to cause fission, a key feature for the safety of the reactor. However, some water-cooled technologies, such as the Reaktor Bolshoy Moshchnosti Kanalnyy (RBMK) from the former Soviet Union, and the Canada Deuterium Uranium reactor (CANDU), are moderated by graphite and deuterium oxide ("heavy water"), respectively.

In the wake of the events at the Fukushima-Daiichi nuclear power station in 2011, there has been a global R&D effort to enhance the safety of today's water-cooled reactor technology by developing nuclear fuel and cladding materials with enhanced accident tolerance (42). These materials aim to increase high-temperature steam oxidation resistance versus the reference zirconium-based cladding materials that failed at Fukushima (43). In addition, high-performance fuel materials that enhance thermal properties are under consideration (44), such as thermal diffusivity, and improved retention of radioactive fission products (45), aiming to increase safety in severe accidents. The development of new materials for the extreme environment of a nuclear reactor is aiming to solve various scientific, regulatory, and operational challenges (39). The objective of developing these new materials is to enhance the accident tolerance of existing water-cooled nuclear reactor technologies.

The nuclear industry, especially in the U.S., is facing several economic challenges in the current energy environment. Today's reactors are large and designed to provide baseload electricity; large reactors are chosen to reduce overnight capital cost per kW installed compared to smaller ones (46). However, many developing countries or remote regions in developed countries are too small to support large-scale nuclear plants, so small modular reactors are under development to open these markets (47). Because nuclear power is inherently baseload, it can be difficult to integrate with renewables that are largely intermittent; as a result, nuclear must sometimes sell electricity at a loss (48). These economic challenges are compounded by relatively inexpensive fossil fuels, such as natural gas. The most significant economic challenge for nuclear energy is very high construction cost, exacerbated by substantial escalation during scale up—an example of so-called "negative learning" (49). Additionally, almost all operating nuclear reactors in the U.S. will be retired in the 2035-2055 timeframe (50), and must be replaced for nuclear power to maintain its share of electricity generation.

There has been a recent outburst of innovation in the nuclear energy sector, with the formation of a number of start-up companies and significant interest in advanced reactors (51). This interest has been summarized in a compelling report from Thirdway, a non-partisan think tank (52). The University of California, Berkeley and Nuclear Innovation Alliance held a Nuclear Innovation Bootcamp in 2016 (53) with the objective of bootstrapping disruptive innovation in the advanced nuclear energy sector.

There are applications for nuclear energy that expand beyond baseload energy production. These include several opportunities for better integration of nuclear energy and renewables. One such opportunity is the nuclear hybrid energy system (NHES), a multi-input, multi-output system whereby a nuclear energy source operates synergistically and flexibly with renewable energy sources (36). Energy input streams in a NHES would include both nuclear energy (thermal or electricity) and other sources, such as wind, solar, or biofuels (36). The general idea is that when wind and solar are generating more electricity, the energy coming from the nuclear reactor is diverted to generate valuable co-products (discussed below). This is a particularly useful model: it removes the need for battery storage for renewables, which can have large capital costs and environmental impacts of their own, and valuable co-products are created without GHG emissions.

To meet energy demand while reducing GHG emissions, several highly innovative advanced nuclear reactor technologies show promise. NHES can take advantage of existing fleets operating at ~300°C by using electricity generated for something else (e.g., desalination). However, advanced high-temperature nuclear reactors (>700°C) may be even better, reducing industrial-sector GHG emissions via a thermally-efficient and cost-effective integration with industrial processes requiring heat to accomplish their mission—heat that would otherwise most likely be generated by GHG-emitting technologies. Relevant industrial applications include process heat (54) and hydrogen production (55) for petrochemical and related industrial processes that require operating temperatures up to 900°C. Such an approach can be standalone or part of NHES.

The recent U.S. DOE Office of Nuclear Energy (DOE-NE) Advanced Demonstration and Test Reactor (ADTR) study identified several opportunities to expand the missions of nuclear energy beyond electricity production using non-water-cooled reactor technologies. The strategic objectives identified in the ADTR study include (56):

1. Deploy a high-temperature process heat application for industrial applications and electricity demonstration using an advanced reactor system, illustrating the potential for nuclear energy to reduce U.S. industrial sector GHG emissions
2. Demonstrate actinide management to extend natural resource utilization and reduce the burden of nuclear waste for future generations
3. Deploy an engineering demonstration reactor for a less-mature reactor technology with the goal of increasing the overall system technology readiness level for the longer term

The most flexible advanced reactor technology options for potential process heat applications are those with coolant outlet temperatures >700°C (45). Depending on the particular implementation, these technologies may include the high temperature gas-cooled reactor (HTGR), liquid metal reactor (LMR), and fluoride salt-cooled high temperature reactor (FHR). LMRs can be either sodium- or lead-cooled. Typically, sodium-cooled LMRs have outlet temperatures of ~500°C, although higher outlet temperatures (700°C) may eventually be possible in lead-cooled reactors if a cladding material with adequate corrosion resistance is found. Higher outlet temperatures enable a variety of process heat applications and also enhance conversion efficiency (57). Coolants like liquid metals (58) or molten salts (59) can also be applied in solar thermal systems and other high-temperature energy sources.

The ADTR study found that HTGR technologies were most promising for near-term application in high-temperature process heat missions because of high outlet temperatures (>700°C), flexibility, and technology readiness. It is also valuable to be able to consume actinides: heavy elements that contribute to the amount and duration of radioactivity from used fuel. LMR technologies are preferred, and in particular sodium-cooled fast reactors. These types of advanced reactors improve fuel cycle sustainability by enabling natural resource extension and burning long-lived actinides to reduce the burden of nuclear waste for future generations, further enhancing their benefits.

LMR and HTGR advanced reactor technologies are being pursued internationally. In Russia, LMR technologies are being commercialized (60); the BN-800 commercial demonstration plant was successfully started in 2015 in a plutonium disposition mission (61). HTGR technologies are being deployed in China with two modular HTR-PM commercial demonstration units (62) scheduled to come online in the near term, replacing coal-fired power plants (63). These examples are indicative of the promise of advanced reactor technologies in novel missions, and show strong potential for near-term commercial deployment (56).

Other technologies, such as FHR or lead-cooled fast reactors (LFR), are potentially promising but have a lower technology readiness level than gas- and sodium-cooled technologies. The FHR and LFR technologies are in need of engineering demonstration reactors to prove their viability. There is a significant R&D program in China pursing eventual deployment of FHR technology (64). All of these advanced reactor technologies may enable new markets that can reduce the energy sector's GHG emissions and expand applications of nuclear energy, with HTGR and SFR technologies being most promising for deployment by 2035 (49).

Another potential development area is "closing the fuel cycle." The present operation strategy of the U.S. and most other nuclear nations is a once-through fuel cycle based on low-enriched uranium. The recently completed U.S. DOE-NE Fuel Cycle Evaluation and Screening (E&S) (42) identified fuel cycle options that offer enhanced performance and sustainability versus the present nuclear fuel cycle. The E&S evaluated all possible fuel cycles (65) with respect to nine high-level criteria related to economic, environmental, safety, non-proliferation, security, and sustainability goals. The study found that, compared to today's approach, advanced reactors and fuel cycles could (39):

- Reduce waste generated by >10× and reduce waste radiotoxicity by >10×
- Reduce fuel needed per unit electricity output by >100×
- Reduce land required and lifecycle CO_2 emitted (already extremely low) by ~2×

The fuel cycles that offer the largest benefits versus the present U.S. fuel cycle are those employing continuous recycling of uranium and either plutonium (U/Pu) or all transuranic elements (U/TRU) in fast neutron spectrum critical reactors (42). These fuel cycles are considered promising predominantly because they enable better natural resource utilization (>30% of the mined uranium is fissioned, compared to <1% in the present U.S. once-through fuel cycle) and higher fuel burn-up (energy extracted per initial heavy metal mass). Fast spectrum systems have promising performance due to the larger number of fission neutrons released per neutron absorbed in the fuel relative to current systems. However, the potential transition from the present fuel cycle to a future fuel cycle represents a significant additional set of challenges (46). Although the E&S considered nuclear fuel cycles based on thorium (66) as well as externally-driven systems (e.g., accelerator-driven systems and fission-fusion hybrids) (67), those fuel cycles were not considered "most promising." This is because irradiating U/Pu- or U/TRU-based fuels in the fast spectrum provides higher internal conversion capability than thorium-based fuels in either a thermal or fast spectrum configuration (42). Additionally, the application of critical reactors that are capable of sustaining fission without the need for an external source of neutrons lowers development risk, safety challenges, and overall costs compared to externally-driven systems (42).

Advanced nuclear reactor technologies offer unique advantages for ensuring that increasing energy demand worldwide can be satisfied while simultaneously meeting GHG emission targets. While nuclear energy is the second-largest low-carbon contributor to electricity production today, challenges include economics, sustainability and perceived safety. Several advanced reactor technologies and advanced nuclear fuel cycles offer the potential to enhance the flexibility, market penetration, and sustainability of nuclear energy. However, these solutions are not yet ready for the marketplace and require appropriate investment in R&D to enable large-scale deployment.

Fossil-CCS

As discussed earlier, fossil fuels dominate the global electricity system today, and emitted >13 $GtCO_2$ in 2013 (>40% of energy-related CO_2) (1). If fossil generation is to remain part of the future electricity system, it will need to be equipped with CO_2 capture and sequestration[iv] (CCS) technology. In CCS, CO_2 that would otherwise be released to the atmosphere during fuel combustion is captured, compressed, and transported to a suitable storage site, where it is injected deep underground and retained in the subsurface through natural trapping mechanisms (68,69). There are generally three different approaches to integrating CO_2 capture with power generation: pre-, post-, and oxyfuel combustion (oxy-combustion).

In pre-combustion processes, hydrocarbon fuels are converted to a mixture of hydrogen and CO_2 (via gasification or reforming combined with the water-gas shift reaction) and the CO_2 separated from hydrogen, the latter being used as fuel for power generation (70). Integrated gasification combined cycle (IGCC) plants equipped with CO_2 capture, such as the Kemper County Energy Facility in the United States (582 MW), are one example of this process. In contrast, in post-combustion processes CO_2 is separated from low-pressure flue gas—largely a mixture of nitrogen, water and CO_2—rather than from the fuel (71). Post-combustion capture can be applied to conventional pulverized coal (PC) boilers and natural gas combined cycle (NGCC) plants. The most prominent examples of post-combustion capture are the Boundary Dam Power Plant in Canada (110 MW), operating since 2014, and the W.A. Parish Power Plant in the U.S. (240 MW), scheduled to begin operation in early 2017. The third approach is oxy-combustion, in which coal or gas is burned in a mixture of oxygen and CO_2 rather than air (72). Oxy-combustion avoids the need for a CO_2 separation step, but requires separation of oxygen from air. As of 2016, there were no operating commercial-scale examples of oxy-combustion; however, oxy-combustion of coal has been successfully demonstrated at scales up to 30 MW (72), and cryogenic air separation is fully commercial technology, with thousands of units operating worldwide at equivalent power generation capacities up to 300 MW (73).

The option to retrofit CCS to existing plants is particularly valuable in rapidly-developing countries with large, relatively-young fossil generation fleets and growing demands for electricity. For example, Chinese electricity demand more than doubled between 2005 and 2015, while over the same period the installed capacity of coal-fired power plants in China rose from 272 GW to ~900 GW (74). In addition to retrofitting existing capacity, new CCS-equipped generation could be valuable as a means of providing baseload capacity in markets with increasing shares of variable renewables.

CO_2 can be transported by truck, train, ship, barge or pipeline. All these transport modes are commercially practiced today, although only pipelines are used at scales necessary for CCS from power generation (~1-10 $MtCO_2$/yr per plant). In the U.S., there were ~8,500 km of CO_2 pipelines operating at the end of 2016 (75) that, in recent years, moved ~70 $MtCO_2$/yr from

[iv] While there has been some debate over the distinctions between storage and sequestration, the terms "CO_2 capture and storage" and "CO_2 capture and sequestration" tend to be used interchangeably.

mainly natural CO_2 sources for enhanced oil recovery (EOR) (76). There has been growing interest in CO_2 transport by ship, particularly from Japan and countries around the North Sea, and several studies have examined large CO_2 carrier designs in detail (77,78).

The principal options for geologic CO_2 sequestration are injection into deep brine-filled aquifers, and oil or gas reservoirs (including CO_2-EOR operations) (69). The technologies involved in CO_2 sequestration, such as those found in injection wells and used for monitoring, are largely borrowed from oil and gas operations and adapted for use in CO_2 sequestration. CO_2 sequestration has one critical distinction, however: large volumes of buoyant fluid (CO_2) are injected into the subsurface rather than withdrawn. This means that pressure in the receiving formation increases over a large area, and existing brines are displaced away from the injection site (79). Thus, pressure build-up limits practical storage capacity in many cases (80,81), which has spurred development of pressure management concepts generally (82), and brine withdrawal plans at the Australian Gorgon sequestration project specifically (83). Regulations also recognize the novel aspects of sequestration, typically requiring thorough understanding of site-specific risks (84), which has driven much research into the potential impacts of CO_2 sequestration and risk assessment (85,86).

There are several notable CO_2 sequestration projects operating today, most of which store CO_2 from industrial processes and natural gas processing rather than from power generation. Examples include the Canadian Quest project, which began injecting ~1 $MtCO_2$/yr from hydrogen production in 2014 (87), and the Illinois Basin Decatur Project in the U.S., which injected ~1 $MtCO_2$ from ethanol production in 2011-2014, and parts of which are being incorporated into a 1 $MtCO_2$/yr commercial project (88). In addition, older projects continue to generate knowledge, including the Norwegian Sleipner (1996-present) and Snøvhit (2008-present) projects, which together inject ~1.5 $MtCO_2$/yr separated from natural gas under the North Sea (89), and the Canadian Weyburn project, which sequesters ~3 $MtCO_2$/yr captured from coal gasification (90).

Rubin et al. (91) found that costs of first-generation CCS-equipped power plants have been higher than early cost projections suggested, a well-known problem for new, capital-intensive technologies (92). However, capital cost projections of fossil power generation, with or without capture, have also increased over time; increases are attributable to rapid growth in commodity costs between 2000 and 2008, changes to capture system designs, and greater detail in cost estimates themselves (91). A review of normalized capital and fuel costs, providing representative levelized cost of electricity estimates for a range of CCS-equipped plant types (Table 1), found that increases in capital costs are offset by other factors such as falling fossil fuel prices.

Table 1. Levelized cost of electricity (LCOE) estimates for a range of CCS-equipped plant type

Parameter	**NGCC with post-combustion capture**	**SCPC with post-combustion capture**	**SCPC with oxy-combustion capture**	**IGCC with pre-combustion capture**
Reference plant without CCS				
LCOE[a] (USD/MWh)	42-83	61–79	56–68	82-99
Power plant with capture				
Increased fuel requirement per net MWh (%)	13-18	21-44	24-29	20-35
CO_2 captured[b] (kg/MWh)	360-390	830-1080	830-1040	840-890
CO_2 avoided[b] (kg/MWh)	310-330	650-720	760-830	630-700
CO_2 avoided[b] (%)	88-89	86-88	88-97	82-88
Power plant with capture, transport and geological sequestration				
LCOE[a] (USD/MWh)	63-122	95-150	92-141	112-148
LCOE[a] increase for CCS (USD/MWh)	19-47	31-71	36-75	25-53
Increase (%)	28-72	48-98	61-114	26-62

[a] *Costs in constant 2013 USD. Abbreviations: natural gas combined cycle (NGCC), supercritical pulverized coal (SCPC), integrated gasification combined cycle (IGCC), CO_2 capture and sequestration (CCS), U.S. dollars (USD), megawatt-hours (MWh).* [b] *CO_2 avoided accounts for the reduction in generation output due to parasitic loads from CO_2 capture equipment, and is thus lower per MWh than CO_2 captured. Source:* 91.

Table 1 also indicates the amount of CO_2 avoided relative to similar plants without CO_2 capture (82-97%). These estimates, however, did not consider CO_2 emissions from the entire electricity production lifecycle. Including these emissions results in net CO_2-equivalent emissions reductions of 47-97% depending on the fuel type, and conversion and capture technology assumptions (93). Moreover, application of pre- and post-combustion capture to both coal- and gas-fired power plants often results in an increase in eutrophication and acidification over the lifecycle (93).

Substantial research into new power generation cycles that integrate CO_2 capture, as well as improved capture systems for existing conversion technologies, is ongoing (94,95). Examples include: solvents with lower regeneration energy, lowering the energy penalty of pre- and post-combustion capture, and favorable absorption kinetics (71,96); improved integration of capture systems with power plants to minimize energy penalties and increase operating flexibility (96); chemical looping combustion systems that eliminate the need for air separation (97,98); and CO_2-based power cycles, such as the Allam and Clean Energy Systems cycles (99) that could substantially lower the cost of capture for gas-fired generation. Both improvements in technology and reductions through “learning-by-doing” (e.g., standardization, development of supply chains) are expected to contribute substantial cost reductions for future fossil-CCS plants (91), and may also reduce non-GHG impacts.

A key conclusion of an influential 2005 report on CCS (68) was that proven pre-combustion capture technologies were commercially available and economically feasible “under certain circumstances"; this was applicable for transport and sequestration as well. Subsequent research, development and demonstration activities have substantially improved understanding of all parts of the CCS process. Today, the main challenge facing fossil-CCS is that policies for incentivizing emission reductions from power generation remain too weak or are absent. Conditions exist to drive CCS forward in certain niches, e.g., when EOR pays for CO_2 (100), but moving fossil-CCS into the mainstream will require focused government action.

Breakthrough technologies

While a number of advanced electricity generation technologies in development could be considered "breakthroughs" if successful, two—space solar power and nuclear fusion—stand out as having sufficient potential for transformative impact worldwide, as well as steady technical progress over the years coupled with recent commercial investment that may signify an increase in prospects. We discuss each in detail here.

Space solar power

Ground-based solar power output is limited by the diurnal cycle and absorption by clouds, water vapor and dust in Earth's atmosphere. By comparison, solar generation in space can continuously utilize the full solar flux of ~1,370 W/m^2. Mankins (101) estimates that putting solar PV panels in space could harness 10-20× ground-based PV energy annually per unit area, and >40× when storage inefficiencies are considered. First formally proposed by Glaser (102), space solar power (SSP) is now undergoing serious development by the Japanese, Chinese and U.S. governments (103-105), as well as several private entities (101,106,107).

Converting electricity to microwave or radio frequencies for transmission to the surface is 40-50% efficient today and expected to exceed 80% eventually, while reconversion on the ground is already >80% efficient. Efficient laser transmission in visible or near-infrared wavelengths is also possible, but clouds block this light, while they are transparent to longer wavelengths, so there is little advantage to laser transmission (101) other than smaller receiver areas (see below).

SSP altitudes can vary from ~250 km (low Earth = LEO) to ~36,000 km (geosynchronous = GEO) orbit or beyond, with a capacity factor in GEO of nearly 100% (101). Objects in GEO remain at the same location over the Earth, a distinct advantage in providing continuous power, but constellations of lower-orbiting spacecraft could confer similar performance at lower cost. Ground receiver stations are inexpensive, requiring little hardware, and could even sit atop existing solar power stations and utilize their rectification and interconnection infrastructure (101,107).

SSP could transform solar electricity from an intermittent to baseload power source, with huge operational advantages. Not only is the electricity more reliable than ground-based solar PV, it can be sent to any location with a ground receiver (101), allowing rerouting around power outages or "wheeling" power across state or national boundaries, reminiscent of Buckminster Fuller's global superconducting transmission grid (108). This same capability could also reach remote areas currently without power, such as poor regions yet to be electrified, avoiding traditional development of expensive transmission infrastructure much as mobile phones leapfrogged landlines (107).

Aside from technical performance, the greatest challenge in making SSP a reality is getting to orbit. Historically, it cost ~10,000-20,000 USD to place 1 kg in LEO (109) (and ~2.5× to GEO), but recent innovation by private companies such as SpaceX has reduced this cost to <3,000 USD/kg in LEO (110), with ~200 USD/kg as an eventual goal (109). Designs such as Mankins' (101) rely on very low launch cost to make it cost-competitive with ground-based systems. A complementary strategy, pursued by Caltech (107) and the U.S. Naval Research Laboratory (NRL) (105), is to radically increase power-to-mass ratio through ultra-lightweight components and high efficiency cells. Caltech's ambitious goal is 100 g/m^2, far lighter than paper. Assuming 40% efficient cells achievable in multi-junction PV today (111), Caltech could achieve >5 kW/kg, many times that of existing space-based systems (112).

For high efficiency transmission, the product of transmitter and receiver apertures must exceed R • λ / π, where R = transmission distance and λ = transmission wavelength. For microwave transmission from GEO, this product is ~1 km^2 (for near-infrared transmission, it is ~10 m^2). A small SSP system would require a huge receiving antenna, so large-scale systems are generally envisioned, to match solar collection and transmission areas. Energy intensity is also a safety consideration; most designs limit transmitted intensity to ~1,000 W/m^2, comparable to full sunlight (101). The Caltech design employs 2,500 satellites occupying 9 km^2 (107), and most other efforts also envision multiple-km^2 sized systems (101,103,104), with microwave receiver apertures of several hundred m.

An operational challenge is how to maintain system efficiency when the angle between the Sun-pointing PV array and Earth-pointing transmission antenna varies as the satellite orbits (103). Many designs physically decouple the solar collection and transmission elements, allowing each to maintain their respective orientations, with solar power transmitted by mirrors, or electricity through wires, but this adds mass and complexity. Others (e.g., Caltech and NRL) take a modular approach where solar conversion and transmission is integrated in a single package. Despite flexibility in steering microwave beams off-axis, this approach suffers from unfavorable Sun-Earth alignment during portions of each day. Solutions include beaming power to varying locations, or using multiple, widely separated satellites to maximize power utilization.

SSP's viability prospects are increasing, but launch cost remains a major impediment. Together with the harsh radiation and micrometeorite environment in space, inaccessibility in case of mechanical failure, and demanding mass constraints, the engineering challenges remain formidable. The next few years, however, should see prototype SSP systems launched and tested, and possible small-scale commercial ventures undertaken. If SSP's advantages are demonstrated, market forces should welcome its contribution to a low-carbon electricity future, and if it becomes sufficiently cost-competitive, could even supplant existing technologies.

Nuclear fusion

Fusion is an alternative nuclear energy source to nuclear fission that produces roughly four times the amount of energy per unit mass of a fission reaction with no associated radiotoxic spent fuel transuranic elements,[v] allowing only a few kilograms of fuel to operate a potential reactor annually. Fusion is the most energy-dense reaction humanity can harness, with no GHG emissions, and the potential to produce reliable baseload power. The most feasible fusion reaction for future power plants combines two hydrogen isotopes (deuterium and tritium) to kilo-electron-volt temperatures (15 KeV or ~10^8 K):

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + n^0$$

Deuterium is readily found in seawater, and tritium is bred in situ (from lithium-6) in most reactor designs, as it is radioactive with a half-life of about 12.5 years and therefore not naturally occurring on Earth. About 80% of the energy from the fusion reaction goes into the neutron (n^0), which is captured for energy generation via conventional steam turbine systems, and the remaining 20% of the energy in the alpha particle ($^{4}_{2}He$) goes toward heating the plasma for further reactions. However, no material is capable of contacting such a hot substance, so the plasma is held in space away from the reactor walls (e.g., using spiraling magnetic fields).

In order for fusion to occur, the hydrogen plasma must be very hot (~10^8 K), very dense (~800 g/cm^3, greater than the Sun's interior), or some optimized combination of the two. Therefore, several different approaches to fusion technology have been developed in the public sector historically, and private sector much more recently. Magnetic confinement devices called stellarators (113) and tokamaks (114) produce very hot plasmas confined by magnetic fields that are not very dense. Conversely, inertial confinement fuses hydrogen isotopes by implosion using very powerful pulsed lasers (>500 TW) (115).

The most conventional type of fusion machine is the tokamak due to its relative simplicity to manufacture and engineer, and it has been the primary focus of the U.S. government fusion efforts such as DIII-D at General Atomics (116), C-Mod at the Massachusetts Institute of Technology (MIT) (117) and NSTX-U at Princeton Plasma Physics Laboratory (118). The National Ignition Facility's inertial confinement project at Lawrence Livermore National Laboratory (119) has also made notable progress. Private sector fusion experiments by General Fusion, Tri Alpha Energy, Lockheed Martin and others (120-124) have sprung up more recently, and many are exploring unique ideas combining standard magnetic and inertial confinement principles.

To date, there has been no fusion reaction that has generated more power than it consumed, but current fusion devices were not designed for this goal but rather for research. The current path to commercial fusion is an international effort to build the ITER reactor (125), designed to be the first fusion machine to reach ignition and output 10× its input power. Beyond the ITER

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[v] There is some indirect production of radionuclides from fusion neutrons activating structural materials surrounding the reactor. These can be relatively radiotoxic for ~50 years, but decay quickly to low-level waste in ~100 years, compared to ≳10,000 years for nuclear fission spent fuel.

experiment, the next planned stage is to build DEMO (126), which will be a demonstration system connected to the grid. This will serve as a blueprint for a potential fleet of fusion reactors that could be installed around the world. Alternative concepts include compact, high magnetic field tokamaks at MIT (124) and the use of fusion to destroy spent fuel from fission reactors at Georgia Institute of Technology (127).

Oil shortages in the 1970s spurred the U.S. DOE to allocate ~1 billion inflation-adjusted USD/yr for fusion, leading to many breakthroughs initially. When oil prices recovered, however, the budget for both domestic research and U.S. vested interest in ITER was cut to ~4 million USD/yr. The recent increased interest in fusion through various start-ups as well as advanced research initiatives (e.g., Helion) (122) through DOE's ARPA-e program are inspiring to the fusion community, which signal that energy markets may be ready to pursue the technology, and perhaps diverge from the public-sector path. Competition through the private sector would bring a welcomed alternative to the slow, multi-national, publicly-funded path toward fusion, which could possibly accelerate the timeline. There are still many technical hurdles to address to make fusion feasible and economically competitive with other technologies, but fusion appears to have a bright future ahead.

Grid integration

The transmission and distribution grids were designed to deliver power to customers, reliably and efficiently, from large rotating machinery via a series of interconnected electrical wires and transformers. As discussed earlier, power has historically been generated via large, centralized coal, nuclear and hydropower plants, with natural gas or oil primarily providing peaking capacity to balance load variability. Frequency and stability is maintained on a sub-second basis, with consistent balancing between load and generation.

However, a new paradigm for the delivery of bulk power is emerging worldwide, with an increase in customer-owned, behind-the-meter generation and load control, and a societal desire to shift toward cleaner, sustainable electricity generation. Along with this desire is a frequent disparity between renewable resource locations and population centers, however, often resulting in costly (even prohibitive) electrical transport investment (128). Moreover, many renewables—particularly wind and solar and, to a more limited extent, hydropower and MHK—suffer from supply variability and forecasting issues, whereas other clean resources discussed in this paper have predictable, typically baseload output. In all cases, the need to supply controllable generation during peak load periods remains, increasing with high penetrations of these resources (129).

Without integrated ramping and variability management strategies, additional load-balancing resources such as natural gas turbines providing "spinning reserves" (short-time responsive generation) and peaking plants will be needed to meet, for example, evening ramp-ups in generation as solar output decreases and load increases (130,131). However, GHG and other pollutant emissions from these generators must decrease to meet increasingly stringent policy targets. Strategies to reduce reliance on these emissions-intensive resources include: 1). greater connectivity with neighboring regions to provide geographic diversity of renewable resources, 2). use of energy storage technologies to replace load-following generation, 3). automated, distributed, demand-side load management including both interruptible[vi] and scheduled loads (e.g., washing machines) (132), 4). use of low-carbon fuel substitutes for natural gas (e.g., biogas or hydrogen), which can be used in existing turbine equipment or, for hydrogen, high-efficiency fuel cells (133), and 5). co-production of heat or other products (e.g., NHES). Each of these technologies has a different time scale for integration and control; for example, balancing between regions as well as many forms of electricity storage can occur in <1 to ~a few seconds, whereas demand response at present technology levels requires scheduling >1 hour ahead. While less balancing capacity may be needed to integrate significant levels of baseload compared with intermittent generation, an increased reliance relative to today will still be required.

Investment in grid infrastructure has traditionally been driven by an urgency to supply power to customers, such as the widespread blackouts in the U.S. Northeast in 2003 (134) or Southwest in 2011 (135). Transmission events, such as tripping of large transmission lines or equipment, inherently have the potential to cause outages on a regional scale; for utilities, avoiding penalization is usually incentive enough to invest and maintain the system. Transmission—the high-voltage transport of bulk power across large distances—is typically monitored closely using a combination of sensors and state estimation/forecasting tools ("visibility"), enabling operators to respond in foreseeable circumstances and emergency scenarios (136). However, there is much less visibility at the distribution level, where smaller amounts of power are transported at lower voltage across shorter distances. Also, outages at the distribution level typically affect smaller numbers of customers, so the economic incentive to improve visibility is less. However, a greater reliance on resources at the distribution level (e.g., rooftop solar PV) is driving a need to invest in monitoring, but solutions must be carefully balanced with applications. In contrast, large centralized generators are monitored heavily, and infrastructure investments are clearly justified at this level of generation.

At present, there is a drive in the U.S. toward defining advanced distribution management system architecture through the grid modernization initiative (137), which if enabled would provide a suite of information to planners, operators, and engineers for both human-in-the-loop management and monitoring of future automation. Ubiquitous but interoperable sensing, transformation of this data into useful information, and getting that information to the right people quickly is essential. While efforts toward management of the distribution grid are often focused on one resource, i.e., EVs or residential solar, a holistic multi-pronged approach, considering all of the above with diversity of loads, is essential.

Lessons learned at the transmission level are often directly applicable at the distribution level, but differences in application of information is a significant barrier. For instance, through the mass deployment of Phasor Measurement Units (138), a device measuring voltage magnitude and phase angle, the California Independent System Operator is aware of the presence, impact and mitigation strategy of an imbalance in load and generation between regions through phase angle deviations. While this is not relevant to a distribution system operator, as they are not managing large rotating machines, the resulting actionable information—a prediction of possible

[vi] In addition to large industrial loads, these may include residential and commercial loads such as electric space conditioning and water heating, refrigeration and to a limited extent, lighting.

outage or control of a cluster of distributed resources for a global system goal—may have extreme relevance.

The issues presented at both the transmission and distribution levels must be treated similarly, rather than solving different problems at all timescales, for a successful grid transformation. For example, utilities at the distribution level currently provide service based on power used and reliability. As solar PV developers integrate with the grid, centralized generation increasingly becomes leased or permanently reduced. Many existing regulatory and ratemaking approaches are not aligned with supporting a transition from centralized generation and system planning to more decentralized electricity delivery. However, some utilities are considering new rate structures such as "pay to play" to ensure cost recovery of distribution-level assets, and innovative business models are emerging to enable new rate structures as distributed energy resource penetrations grow (139).

Load management, as an integral piece of behind-the-meter resource availability, has potential to enable customers without rooftop PV to benefit from new distributed resource markets. In addition, there is growing desire for customers to choose the type of generator(s) supplying their power (140), which could be extended to include centralized low-carbon resources. Automated, shorter timeframe services that can provide distribution support in the future, following expected changes to present regulations including local voltage and load management (132) and system-level frequency support. For instance, behind-the-meter inverters cannot currently regulate voltage at the point of connection due to industry standard IEEE 1547 (141), but changes are expected in 2017 enabling utilization of these schemes. Each of these services requires automation, continuous monitoring, and support service that responds within seconds of either operations or distributed control requests.

Energy storage technologies encompass another set of developments that can enable lower-carbon grid integration. Historically, pumped hydropower represented the most cost-effective electricity storage technology, but implementation is very limited geographically. While numerous storage technologies exist in various stages of development, those with the most promise in recent years include flow battery technologies such as vanadium redox, advanced compressed air energy storage, as well as several emerging technologies with very low cost per stored kWh (142). Lithium ion batteries are also promising for grid storage because they are high-volume consumer products that currently cost half as much as flow batteries (V. Battaglia, pers. commun., 2016). The emergence of low-cost electricity storage will be pivotal to reducing reliance on fossil-intensive load balancing technologies, lowering grid emissions associated with higher levels of low-carbon generation.

Besides flexible demand and energy storage, few other low-carbon grid integration options exist except for NHES and a few renewable technologies. CSP is one option, as intrinsic thermal storage provides several hours of flexibility after solar production ceases at night. Biomass electricity plants offer another option as they operate much like fossil fuel plants (1). Hydropower has some inherent storage and has long been used to balance loads, but it has limited capacity and is constrained both by water availability, which can vary with season and year, and considerations of aquatic health. Low-carbon fuel substitutes can be used similarly to natural gas, but these currently have limited availability and/or high production costs. Finally, SSP offers interesting, and possibly profound, possibilities for shifting supply over large distances, but has no inherent storage capability.

In summary, major issues to overcome are:

- Lack of distribution grid visibility, transformation of large-scale measured data into useful actionable information, security of supply in a highly distributed environment
- Institutional challenges for grid management: customer-owned resources, regulatory barriers, future functional role of the utility with distributed generation ownership
- Commercial integration with government regulation including developing a qualified workforce for new generation technology

A future low-carbon grid is possible, but must be balanced among centralized baseload generation, large-scale intermittent generation, and decentralized, customer-driven generation and controllable loads, facilitated by flexible, reliable, cost-effective grid integration technologies.

Discussion

We have reviewed the major technologies available to deliver low-carbon electricity globally, constrained by strong climate policy. Of the major categories—renewables, nuclear, and fossil-CCS—none represents an ideal solution, and some combination is likely needed in most regions, along with grid integration technologies, to assure a reliable and robust future electricity system. Breakthrough technologies represent exciting, but uncertain, additional options for low-carbon generation, and come with drawbacks of their own.

Renewables are the preferred option among many environmentalists, and are strongly embraced in Germany, Denmark, California, Hawaii and elsewhere. Moreover, most types of renewables continue to decrease in cost as markets mature. However, renewable resources vary considerably by location, and capacities of some types of renewables (in particular, geothermal, hydropower and MHK) are inherently limited compared with the ample wind and solar resources, though EGS promises to greatly expand geothermal capacity. More importantly, renewable resources—particularly wind and solar, but also hydropower on a seasonal and inter-annual basis—are intermittent and therefore not always available when power is needed. A significant increase in load balancing and other grid integration technologies and strategies are needed to successfully operate an electricity system heavily dependent on renewables. There is also concern about the "gigawatt-day" problem: generation deficits lasting several days or weeks, beyond the capacity of most storage technologies (143). Interconnectivity across wide geographic regions, multi-day bulk energy storage, backup generation using renewable fuels, or hybrid solutions such as NHES can contribute toward eliminating this problem.

Nuclear power carries a number of challenges from regulatory, economic, environmental and technical perspectives. However, it is the leading low-carbon electricity generation source in the U.S. and OECD countries, and second largest worldwide. While perceived safety is often cited as a concern for nuclear power, evidence indicates it is among the safest forms of electricity generation. Large nuclear plants are often sited far from consumers, in common with renewables installations such as large wind farms, but the reward per GW of transmission investment is significantly higher due to high capacity factors. The baseload nature of nuclear does not currently support a move toward clean ramping technologies, however.

While the hazards and risk magnitude associated with the nuclear fuel cycle are very different, fossil-CCS technologies share many similar challenges with nuclear: in particular, relatively high capital costs, waste disposal siting, and challenges inherent in long-term waste isolation (144). In addition, fossil-CCS technologies carry the burden that they still emit GHGs (~5-15% of CO_2 generated, and even more when the full lifecycle is considered). Nonetheless, CCS may allow a rapid reduction in electricity-sector GHG emissions without discarding established fossil fuel infrastructure, particularly when nuclear plant siting is difficult and renewable resources are scarce. In order to progress fossil-CCS technology, capture system cost reduction through technology innovation and learning-by-doing needs to be accompanied by pipeline infrastructure development and geologic sequestration sites (100).

The breakthrough technologies reviewed—SSP and nuclear fusion—present exciting challenges and opportunities. Both promise essentially unlimited supplies of clean, reliable, baseload power at a cost that may eventually be lower than existing technologies. While cautious of the claim of "too cheap to meter" first applied to nuclear fission (145), and mindful of the stigma "always 30 years away" often applied to nuclear fusion (146), commercializing either of these technologies could profoundly benefit society, and are thus important to track as they approach reality. In particular, the ability of SSP to transport power effortlessly across the planet qualifies as a game-changing technology in itself, and could become as important as space-based electricity generation. The global applicability of these technologies is another compelling feature that distinguishes them from most other options discussed in this review. Much development work remains, however, for these breakthrough technologies to be realized.

Sidebar

High altitude wind represents another potential game-changing technology, as wind speeds are much higher and more constant above 250 m, and available almost anywhere on Earth. However, harnessing this resource requires a fundamentally different approach—an airborne energy harvester—as conventional tower designs become prohibitively expensive at these altitudes. Mearns provides an excellent review on this topic (147). Two complementary approaches exist: 1. airborne energy conversion with electrical transmission to ground via conductive wire, and 2. ground-based energy conversion with mechanical transmission via tether. Two leading companies, Makani (148) and KiteGen (149), have designs resembling an airplane wing with multiple propellers, and a large kite, respectively; other companies with variant designs also exist (147). Both approaches keep aloft utilizing some harvested energy.

Concepts are still in development, but appear technically sound due to advances in sensor, global positioning system and computing technologies; the main challenge is safety (147). While high-altitude wind cannot provide baseload power, it delivers much higher capacity factors than conventional wind turbines. It is too soon to determine potential costs, but KiteGen's energy return on energy investment, a useful sustainability metric often anticorrelated with cost, is estimated at >300, much higher than other renewable technologies (147,150).

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