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An Innovation Agenda for Advanced Renewable Energy Technologies

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Innovation in renewable energy technologies, tapping solar, wind, geothermal, and water resources, could unlock massive decarbonization opportunities. But it will not happen without increased, sustained, and well-targeted federal investments.

KEY TAKEAWAYS

- Recent rapid progress in wind and solar power marks only the beginning of the renewables revolution. If clean energy is to supplant unabated fossil fuels, especially in the developing world, renewables must become even more affordable and reliable.
- There are many exciting opportunities to accelerate innovation in solar photovoltaics, wind, geothermal, concentrating solar, hydro, and marine power technologies.
- Advanced renewables that can provide firm power to alleviate the variability plaguing today's solar PV and wind systems are particularly important to pursue in light of the challenges that face alternatives like nuclear power and carbon capture.
- Federal research, development, and demonstration programs in each of the six advanced renewables technology areas should focus on a distinct set of challenges to bring innovations to maturity and jumpstart deployment.
- Federal investment must increase significantly if these challenges are to be surmounted rapidly enough for advanced renewables to contribute at scale to the transition to low-carbon energy in the coming decades.

INTRODUCTION

The clean energy success story of the 21st century is the astonishing rate at which solar photovoltaic (PV) and wind power have gotten cheaper and expanded around the globe, becoming mainstream sources of carbon-free electricity. In the United States, solar PV and wind have grown from a negligible share of electricity generation two decades ago to 2 percent and 7 percent, respectively, of electricity generation today.[1]

Yet, this progress marks the beginning rather than the end of the renewables revolution. The International Energy Agency's (IEA) Sustainable Development Scenario (SDS), in which global warming is limited to 2 degrees Celsius, envisions renewables—a grouping that stretches well beyond solar PV and wind—as the bedrock of the low-carbon economy, providing clean power, heat, transportation, and other vital services. By 2030 in IEA's scenario, a mere decade away, the share of the world's electricity drawn from renewable resources will have doubled. By 2040, it will be 72 percent.[2]

There is no doubt that achieving such ambitious objectives will require aggressive and immediate deployment of mature renewable energy technologies. But a strategy limited to deployment would be shortsighted.[3] Despite impressive improvements, renewables face constraints around affordability, availability, and reliability. If clean energy is to fully supplant unabated fossil fuels, especially in the developing world, these constraints must be overcome.

Innovation in advanced renewable energy technologies can catalyze a massive clean energy buildout and help draw down global emissions.

The possibilities are exciting. Thin, flexible solar panels could be manufactured at low cost and integrated into the architecture of dense, urban environments. Floating platforms could support massive wind turbines in deep waters far off the coasts. Geothermal reservoirs that are built, rather than discovered, could draw always-on power from the hot rock deep beneath the Earth's surface. These are just a few examples. Innovation can turn many of these possibilities into realities, unlocking massive decarbonization opportunities and complementing deployment of today's state-of-the-art technologies.

That state of the art owes a great debt to federal investments in innovation going back decades. All advanced nations, including the United States through its Congress and Department of Energy (DOE), should now build on that legacy and drive forward an ambitious renewables innovation agenda. DOE has already laid the groundwork in studies such as *Wind Vision*, *Hydropower Vision*, and *GeoVision*.[4] This body of work provides ample reason to believe that innovation in advanced renewable energy technologies can catalyze a massive clean energy buildout and help draw down global emissions.

This report puts forward an innovation agenda for solar, wind, geothermal, and water power. It organizes the key technologies into two categories: those that supply *variable energy*, which is only produced as a resource is available, and those that supply *firm energy*, which is available as needed. The technologies in each category have common roles, challenges, and opportunities. They also complement one another: Firm renewables enable very cheap variable renewables to provide more energy than they otherwise would. Within the two categories, each subsection summarizes the current status of a technology, describes its potential to contribute to decarbonization, and identifies opportunities for the federal government to accelerate innovation.

The report offers several overarching recommendations:

1. Congress should significantly increase DOE's funding for renewable energy research, development, and demonstration (RD&D), consistent with Information Technology and Information Foundation (ITIF) proposals for the entire federal portfolio.[5]
2. Congress and DOE should ensure wind and solar PV, the two major variable renewable technologies, can fulfill their promise to provide the bulk of new low-carbon energy capacity by driving RD&D to improve the efficiency of generating devices and promoting their integration into the electric grid.
3. Congress and DOE should support the improvement of firm renewable power technologies—such as geothermal energy, concentrating solar power (CSP), hydropower, and marine power—that would offer reliability and other benefits for a grid dominated by variable renewables, by ensuring they can be deployed in diverse locations at low cost.

Advanced renewable energy technologies are not magic bullets for climate and clean energy. Getting to zero emissions will require advances in grid technologies, solutions for hard-to-decarbonize sectors such as shipping and chemical manufacturing, and likely negative emissions technologies as well.[6] Other electricity generation technologies, such as nuclear power and fossil fuels with carbon capture and storage (CCS), might also play valuable roles and should continue to be pursued.

Advanced renewables are, however, indispensable. They will be the conduits linking the planet's inexhaustible natural resources to clean energy a thriving global society can depend on.

RENEWABLES: THE FOUNDATION OF A CLEAN ELECTRIC GRID

To avoid the worst effects of climate change, the world's nations must transform a global economy built on fossil fuels into one that emits little to no carbon, while supporting the livelihoods and aspirations of a growing population of almost eight billion. The electricity sector is a natural focus for this transformation. A large chunk of emissions will be eliminated if electricity generation is decarbonized and additional end uses such as transportation are electrified.

Electricity and heat are responsible today for about a quarter of all global greenhouse gas emissions.[7] As more consumers enter the middle class and already-wealthy consumers intensify their use of electricity-consuming devices such as computers and mobile phones, global demand for electricity is expected to continue to grow.[8]

Indeed, growth could accelerate if electric vehicles and heat pumps provide a rapidly rising share of transportation and heating energy services. Electricity may also be used to produce carbon-neutral fuels such as hydrogen for use in applications as diverse as long-haul trucking, process heat for chemical production, and long-duration energy storage.

Renewable energy technologies are the best candidates to provide the majority of future low-carbon electricity, especially given the political and economic barriers facing other low-carbon power sources such as nuclear power and fossil fuels with CCS. IEA defines renewable energy sources as those "derived from natural processes" and "replenished at a faster rate than they are consumed."[9] IEA includes solar, wind, marine, geothermal, and hydropower; bioenergy; and hydrogen and other fuels derived from renewable sources in this category. IEA's SDS projects that these resources will supply 67 percent of global electricity generation by 2040, while unabated fossil fuels will fall to 21 percent.[10]

This low-carbon future will become more likely if innovation leads to improvements in the following areas:

- **Cost and performance:** Renewable technologies must provide energy that is cost-competitive with fossil fuels to accelerate the pace of their adoption, build political will for decarbonization, and incentivize deployment in parts of the world where lifting people out of poverty through energy access remains an urgent priority.
- **Resource access:** Technological improvements must allow renewable energy to be harnessed in a broader range of geographic locations, where resources are inaccessible or of insufficient quality to be developed now.
- **Grid integration and services:** Renewable technologies must become more reliable and flexible and provide other essential grid services to further decrease the cost of decarbonization and allow grid operators to make a smooth transition away from fossil resources.
- **Environmental impact:** Innovation must reduce the local and regional environmental impacts of renewable infrastructure and projects, which could be unsustainable if they are built out at a massive scale.
- **Global competitiveness:** By driving innovation in renewables, the United States can establish expertise, supply chains, and manufacturing capabilities that support domestic economic growth and demonstrate leadership on climate change.

AN INNOVATION AGENDA FOR VARIABLE RENEWABLE ENERGY RESOURCES

Solar PV and wind are variable electricity generation resources; they produce power only when the wind is blowing, or the sun is shining. The resources they are replacing are typically firm and able to produce electricity on demand regardless of the weather or time of day. The variable nature of wind and solar PV complicates their integration into the electric grid. Grid operators must balance supply and demand at all times. When variations in wind or solar PV output occur, whether for a few seconds or for many days, operators must adjust by bringing on additional supply or limiting demand.

Despite this drawback, solar PV and wind have emerged as the most promising candidates to supply low-carbon electricity to the world's grids. Solar PV is the fastest-growing form of new energy production, and is expected to dominate new electricity generation in the near future. IEA recently proclaimed solar PV "the new king of electricity," dethroning coal.[11] DOE estimates 970 gigawatts (GW) of domestic solar PV capacity could be in place by 2050, roughly equaling the current installed capacity for all power generation.[12] Wind power is currently the second-most widely deployed source of renewable power globally, after hydropower, and DOE has estimated that 400 GW of domestic onshore and offshore wind are achievable by 2050.[13]

A key reason for this growth, and optimism about the future, is both technologies have become inexpensive in much of the world, even compared with fossil fuels.[14] Since 2009, the levelized costs of unsubsidized, utility-scale solar PV and wind power have declined by 90 percent and 70 percent, respectively.[15] A recent report from the International Renewable Energy Agency (IRENA) found that over half of the renewable generation capacity added in 2019 will produce power more affordably than the cheapest new coal plants.[16]

Several factors have combined to drive down solar PV and wind costs and improve their performance, including technological improvements, favorable policies, rapid learning by doing, and competition.[17] Many of these factors are expected to continue to be present in the future. Solar and wind resources are abundant. The manufacturing and supply chain infrastructure needed to continue to scale up deployment are in place. These technologies have gained widespread public acceptance and entrenched policy support throughout the international community.

Yet, the demands that will be placed on solar PV and wind technologies are high: They must supply predictable power from unpredictable resources, while outperforming the fossil technologies around which society has been built. And there is plenty of room to accelerate progress.

Why Innovation Is Still Needed in Solar PV and Wind Power

Variability is the biggest challenge facing solar PV and wind power, and innovation can help address it. The hours of the day when solar PV and wind produce the most power do not neatly correspond to those when consumers want power. A common load profile in California, known as the "duck" curve for its appearance on a graph of daily power consumption, is a great example. Solar PV generation peaks at midday, but if there isn't enough demand at that time, grid operators may be forced to curtail generation, effectively wasting power. On the other hand, demand typically ramps up rapidly in the evening, just as the sun is setting, forcing operators to find firm electricity sources to meet it.[18] Although many solutions to the challenge of variability lie beyond the generating equipment itself (such as increased energy storage and transmission capacity, smart grid technologies, new pricing mechanisms, and improved planning and tools for grid operation), innovation that enhances these technologies' ability to provide reliable power and essential reliability services is a worthwhile objective.

Another reason innovation in solar PV and wind remains important is there are looming barriers to sustaining progress through economies of scale and learning by doing. Physical limitations such as the theoretical maximum efficiencies of crystalline-silicon (c-Si) solar cells and horizontal-axis wind turbines will constrain their current trajectories. Further, solar PV and wind power become less valuable as their penetration levels on the grid rise, not only because of phenomena such as the duck curve but also due to increasing costs of land.[19] Research by Saptarshi Das et al. finds that diminishing marginal revenue from increased penetration of solar PV and wind power may outpace declining costs due to technological progress. If that proves true, these technologies will lose their economic advantages in many places.[20]

A strategic federal innovation portfolio for solar PV and wind power should invest heavily to improve existing technologies, investigate alternative pathways, and lay the groundwork for variable renewable technologies to be developed in ways that are environmentally sustainable and supportive of the U.S. economy. Innovation in solar PV will help improve performance, increase the utility of solar resources for the grid, and continue driving costs down even at high penetration levels. Alternatives to c-Si materials are worthy of exploration in pursuit of these goals. Innovation in wind energy will allow developers and operators to continue to achieve cost declines by building larger, more efficient turbines, and to expand the growing market in offshore wind. Floating offshore wind, which allows wind-project development in deep waters, such as one finds off the U.S. west coast, is approaching commercial maturity and requires demonstration.

The following two sections explore the potential and innovation needs of solar PV and wind power in greater detail.

Solar Photovoltaics

Solar photovoltaic power uses special materials to convert incident photons from the sun into an electrical current. It has many attractive features. It can be installed almost anywhere. It is modular and can be built at hugely varied scales from utility-scale installations that provide hundreds of megawatts (MW) of power (see figure 1) to commercial and residential systems that support individual buildings. Solar PV is relatively simple to install and maintain, with no moving parts. Most importantly, PV in operation emits no carbon, and its lifecycle emissions are low.

Several countries aided the journey of solar PV from the lab to the mainstream energy. The United States was an early global leader, investing heavily in research and development (R&D) in the 1970s and 1980s. In the 1990s and 2000s, Japan and Germany advanced the technology by creating initial markets with innovative policies that drove demand. Over the past decade and a half, China has dramatically scaled up production, reducing manufacturing costs in turn.[21]

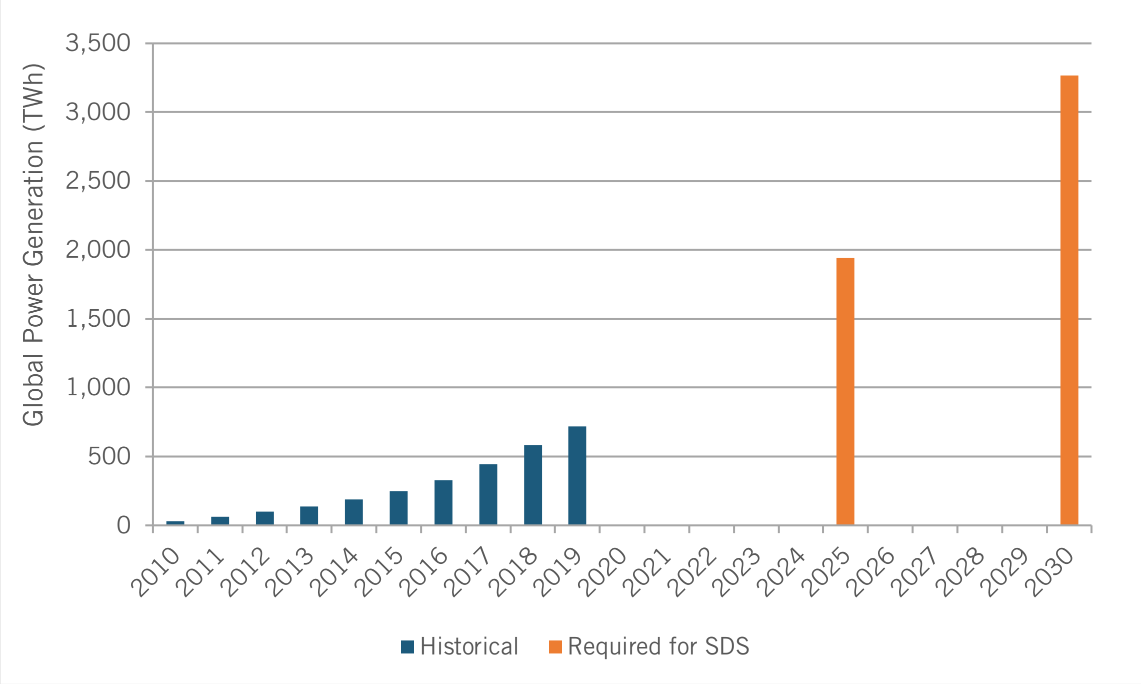
Solar PV deployment increased 36-fold from 2009 to 2019, and it now supplies almost 3 percent of global electricity. The most-conservative IEA scenario ("Stated Policies") projects that it will meet almost a third of global electricity demand growth through 2030.[22] A 2019 review article in *Science* estimates that 10 terawatts (TW) of solar capacity could be installed by 2030, and 30–70 TW could be installed by 2050, up from about 630 GW as of the end of 2019.[23]

Figure 1: The 550 MW Topaz Solar Farm in California is among the largest solar PV systems in the United States. Image courtesy of the U.S. Fish and Wildlife Service.[24]

Solar PV in IEA’s Sustainable Development Scenario (SDS)

Solar PV is among the few technologies IEA labels “on track” with its SDS. The SDS calls for solar PV generation to increase by 15 percent annually between 2019 and 2030. In 2019, solar PV generation increased by 22 percent to 131 Terawatt-hours (TWh).[25]

Figure 2: Solar PV in IEA’s Sustainable Development Scenario.[26]



The Case for Innovation in Solar PV

The future of solar PV is bright. Technological progress and economies of scale have caused prices to plummet. It is competitive with, if not cheaper than, fossil-fuel-powered generation in many parts of the world. There is every reason to believe that its cost and efficiency will continue to improve as the industry continues to grow. The question is whether the pace can be accelerated.

Varun Sivaram and his colleagues have argued that power may need to reach a price point of 25 cents per Watt if it is to fulfill the massive growth called for by deep decarbonization scenarios.[27] As of early 2020, the price of U.S. solar systems ranged from $1.50 to $4 per watt.[28] Crystalline silicon, the material used in more than 90 percent of solar modules today, may not be able to reach such low costs.[29] Soft costs of installation and balance-of-system (BOS) equipment, which are even more costly than modules in most systems, must be curbed as well.

As the solar PV manufacturing industry spends very little on R&D, it is unlikely to address many of these innovation challenges on its own.[30] China’s production surge in the 2000s, which ensured c-Si’s dominance, eliminated many innovative companies and shifted the technological trajectory away from alternative materials that might ultimately be less costly.[31]

Governments should move swiftly to address the private sector's shortcomings in solar PV innovation. Key priorities include lowering module costs by exploring alternatives to c-Si with superior attributes (such as theoretical maximum efficiencies), improving the integration of solar power into the grid, and reducing non-module BOS and soft costs.

DOE Portfolio in Brief

DOE's solar PV program is housed in the Solar Energy Technologies Office (SETO). It focuses on improving PV module efficiency and stability through R&D on advanced silicon processes and other cell materials and architectures; enhancing PV systems integration into the grid; reducing BOS and soft costs; and enhancing manufacturing and competitiveness.[32] Recent initiatives include a $20 million perovskite R&D program that targets device efficiency and stability, manufacturing, and validation and bankability, and a $3 million American-Made Solar Prize, which aims to help boost U.S.-based solar manufacturing.[33]

Innovation Challenges

Innovation Challenge #1: Develop new materials with the potential to be more efficient and lower cost than c-Si.

A federal RD&D strategy should seek to advance promising PV materials with properties that may lead to cheaper, more efficient solar cells, and could emerge as superior alternatives to c-Si in utility-scale applications or in specific markets such as building-integrated solar. There are a number of alternatives to c-Si. Organic PV materials composed of carbon-rich polymers capture light with high efficiency.[34] Quantum dots generate electricity using semiconductor particles a few nanometers wide and are easy to manufacture.[35] III-V semiconductors can achieve exceptionally high efficiencies (29.1 percent for single-junction cells) and have other advantageous physical properties. Combining these materials and others, including c-Si, in multi-junction architectures multiplies the opportunities.

Perovskites are worthy of special attention. They are a class of hybrid organic-inorganic materials that have demonstrated high conversion efficiencies (over 25 percent as of 2020). They may be tuned to absorb different frequencies of light, are made of cheap and abundant materials, have the potential to be manufactured at low cost, and may be developed into thin films, applied as solar paint, or stacked with other materials into high-performance tandem architectures. The major drawbacks of perovskites are their tendency to degrade due to moisture, light, and heat, and the environmental impacts of the lead-based perovskite absorbers that are currently used. Importantly, perovskites are closer than most other novel materials to commercialization.[36]

- **Recommendation:** DOE should expand its support for R&D of new materials for solar PV cells and modules, with a strong focus on perovskites. A key goal should be improving the reliability of perovskites, which may be advanced by improving understanding of failure mechanisms.[37] Cell packing, which makes up a large component of the cost of flexible PV cells, may also be improved through R&D. DOE initiatives to advance perovskites should collaborate closely with the newly established U.S. Manufacturing of Advanced Perovskites (US-MAP) Consortium formed by National Renewable Energy Laboratory (NREL) and several academic centers.[38]

Innovation Challenge #2: Improve the efficiency of PV manufacturing.

Solar PV deployment could be accelerated if the cost of manufacturing declined further. However, factory-level demonstration of new manufacturing concepts will cost tens of millions of dollars, which is beyond the means of many companies that seek to pioneer new solar products. New manufacturing processes also have the potential to revitalize domestic manufacturing of solar PV cells. A study by Mathews and colleagues, for example, suggests that perovskites could be manufactured economically in a market with high labor rates, such as that of the United States. (It should be noted that RD&D initiatives alone cannot spawn new solar manufacturing industries, and such initiatives ought to be paired with demand-pull policies that target solar innovations.)

- **Recommendation:** DOE should establish a next-generation solar energy manufacturing initiative, as proposed in the Solar Energy Research and Development Act of 2019 (H.R. 3597). Such a program would award grants or cost-share awards to support advanced solar energy manufacturing technologies and techniques in solar cells, hardware, and enabling technologies.[39]

Innovation Challenge #3: Reduce BOS costs of solar PV, including hardware and non-hardware costs. Some 40 to 60 percent of the cost of solar PV systems comes from something other than the electricity-generating modules. BOS hardware includes the inverter and power control systems, which connect the system to the grid and ensure it is managed intelligently.[40] Such hardware also enables solar PV to provide more robust voltage, reactive power, and other essential reliability services. Non-hardware "soft" costs include installation, permitting, and financing.

- **Recommendation:** Congress should increase funding for SETO's soft costs team and programs that support BOS hardware, such as its work in power electronics. Given the outsized impact of these expenses on total solar energy cost, they ought to be a significant focus of federal investment, especially considering cost reductions here are easier to achieve than technological breakthroughs in solar PV materials or enhanced manufacturing techniques. Technical solutions to lower hardware costs include solar smart inverters and communication protocols to manage power from solar PV fleets.[41] Solutions to reduce soft costs include R&D on market and regulatory analysis, new techno-economic tools, and methodologies for distributed resources.

Innovation Challenge #4: Improve the integration of solar PV at high penetration in the grid. Grid integration will become a greater barrier to the deployment of solar PV as its penetration in the grid increases. The availability of solar power varies on second-by-second, daily, and seasonal timescales. These fluctuations must be dealt with. In addition, because solar output from generating resources in the same region peaks around the same time of day, its value tends to decline as penetration rises, which could lead to curtailment of production. Grid operators must also find ways for solar PV resources to provide grid services—for instance, using grid-forming inverters. Investment from DOE could help address such integration challenges.

- **Recommendation:** DOE should support the demonstration of microgrids and autonomous energy systems with high levels of solar penetration. Such projects could enable localities to develop the technical and regulatory tools needed to manage high penetrations of solar PV. The dissemination of lessons learned could help grid operators provide more reliable power as well as other grid services. The Senate Appropriations Committee recently proposed that DOE fund pilot "energy shed" management systems that would improve the performance of such systems. [42]

Innovation Challenge #5: Demonstrate solar PV in new environments, such as floating on hydropower reservoirs or integrated in buildings.

Solar panels are typically deployed in fixed arrays of panels in open spaces or on rooftops. New technologies and applications could broaden where solar PV may be deployed, offering the possibility of more deployment, placing solar power closer to where it will be used, and enhancing other grid attributes. Such innovations are particularly important in parts of the world with limited land area and dense cities, including much of the developing world.

For example, over 2 GW of solar PV have been installed in floating configurations on bodies of water. A recent study from NREL found that linking hydropower with floating PV could, in principle, produce the equivalent of 40 percent of the world's electricity while improving the attributes of both types of resources. Hydropower's firm production would increase the reliability of solar PV, while solar PV could be used to pump water into a reservoir for storage in times of surplus generation.[43] Solar power integrated into buildings is also a large and growing market, with 10 GW deployed as of the end of 2018. In-building applications of solar PV would benefit from the development of solar PV materials that can be applied in flexible, semi-transparent, and lightweight coatings.

- **Recommendation:** DOE should cost-share demonstration projects of PV in floating, architectural, and other non-standard applications. Specific needs in floating PV include better understanding of siting, reliability, and quantifying the value stack. Needs in architectural solar include achieving greater industry buy-in, the development of codes and standards, and educating the market.[44] DOE's recent request for information (RFI) seeking information on solar technologies to install in government buildings—intended to improve building health and resilience—is a good step in this direction.[45]

Wind Power

Wind power technologies use the wind's movement to spin the blades of a turbine, which drives a generator and produces electricity. Wind and solar power are often complementary. In many locations, the wind blows mainly at night and is calm at midday.

Horizontal-axis turbines are the best known and most widely deployed wind power technology. This technology's main advantage is that blades mounted horizontally can capture wind energy over a large radius while using relatively little material. Much less common vertical-axis turbines can capture wind coming from any direction because of their orientation, but their large, thick blades are less efficient.[46] Wind turbines may be deployed at utility scale in wind farms or in distributed applications, from small devices powering homes to larger devices powering manufacturing facilities.[47]

Onshore and offshore wind power systems differ in important ways. Onshore turbines have an average height of about 450 feet and typically have a capacity of several MW. Offshore turbines are nearly twice as tall and can generate up to 14 MW.[48] This enormous scale is possible because there are few constraints on transporting components to offshore sites. The wind blows more consistently offshore as well, leading to higher capacity factors (i.e., the percentage of time plants actually generate electricity) offshore than onshore. Most offshore wind turbines today are built in shallow waters on fixed foundations, but floating offshore wind turbines tethered to the seabed in deep waters are approaching commercial maturity.[49] An emerging approach to wind power takes to the sky. In airborne systems, tethered kites harness energy from high altitudes where the wind is stronger and steadier.

Figure 3: The National Wind Technology Center at the National Renewable Energy Laboratory has supported wind energy RD&D in partnership with industry over the past 40 years. Image courtesy of the National Renewable Energy Laboratory.[50]

Onshore wind power has become affordable, with a levelized cost of electricity that is competitive with fossil-fuel-powered generation in many circumstances.[51] As a result, it has grown rapidly and now generates almost as much energy globally as all other renewables combined, aside from hydropower. The United States and European Union each added about 9.1 GW of onshore wind capacity in 2019.[52]

Offshore wind power costs much more than its onshore counterpart, and is an order of magnitude smaller as a result. However, costs are declining quickly, and the industry is growing rapidly.[53] Some 197 GW of offshore wind capacity is in the global development and operation pipeline, an increase of nearly 50 percent this year.[54] China, the European Union, and the United Kingdom have led this surge, placing offshore wind power at the center of their national energy strategies.[55] For instance, U.K. Prime Minister Boris Johnson pledged in October that by 2030, offshore wind would supply enough electricity to power every home in the United Kingdom.[56]

DOE has estimated that with technology improvements and favorable policies, wind capacity in the United States could expand to 404 GW by 2050 (or 35 percent of end-use electricity demand).[57]

Wind Power in IEA’s SDS

More effort is needed in both onshore and offshore wind power to stay on track with the SDS. In 2019, onshore wind generation increased by 12 percent, and generation must continue increasing 10 percent per year through 2030 to meet the goals of the SDS.[58] Offshore wind generation increased by 20 percent in 2018, starting from a relatively small base and must grow even faster.[59]

Figure 4: Onshore wind in IEA's Sustainable Development Scenario[60]

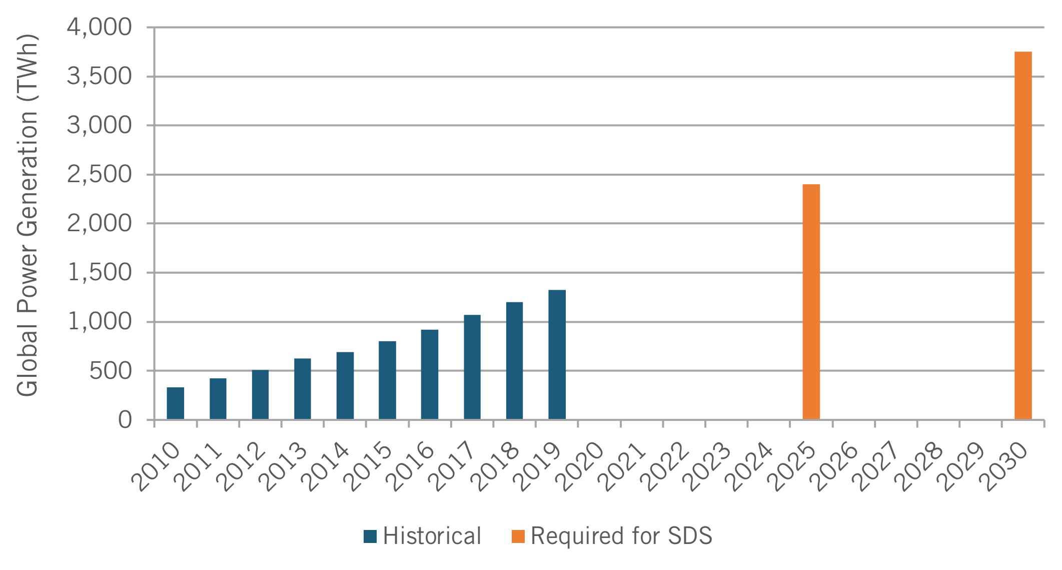
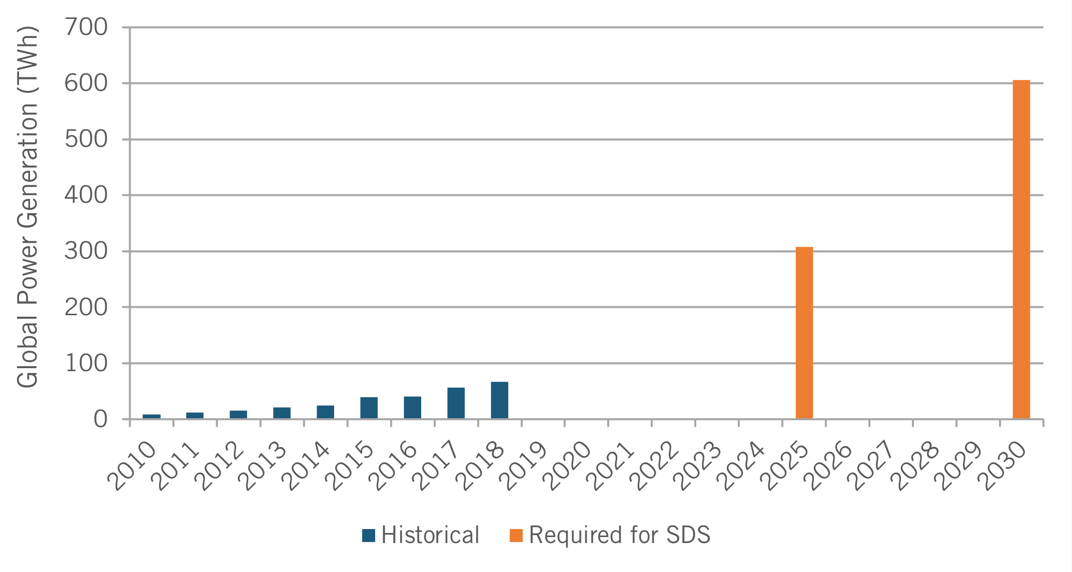


Figure 5: Offshore wind in IEA's Sustainable Development Scenario[61]



The Case for Innovation in Wind

Despite the progress and maturity of wind power, innovation to reduce its costs would further accelerate deployment in the face of looming constraints. As onshore wind power's penetration increases, land for optimal sites may become more expensive, even as the electricity that it generates becomes less valuable due to oversupply at certain times and seasons.[62] Fixed-foundation offshore wind remains much more expensive than coal and natural gas power. Floating offshore wind, which would allow for a massive expansion in potential sites, is twice the cost of fixed-foundation offshore wind and three times that of onshore wind.[63]

According to DOE's *Wind Vision* report, "[C]ost reductions do not depend on disruptive technological breakthroughs, but do rely on continued … improvements." Chief among these improvements is longer blades and taller towers. Bigger structures increase turbines' energy output by sweeping a larger area, and increase the capacity factor by capturing wind energy further from the Earth's surface where it blows more steadily. Optimizing plantwide operation of large wind farms is increasingly seen as an important frontier for cost reduction as well.[64]

DOE Portfolio in Brief

DOE's Wind Energy Technologies Office (WETO) manages its wind portfolio. WETO's work is divided into four program areas: onshore wind, offshore wind, distributed wind power, and systems integration, which seeks to enhance the contribution of wind farms to the grid.[65] In addition, the Advanced Research Projects Agency-Energy (ARPA-E) is currently supporting an initiative aimed at reducing the cost and mass of floating offshore wind platforms while maintaining performance.[66]

DOE maintains a National Wind Technology Center at NREL (see figure 3). The center provides a major test bed for the industry and has contributed to the advancement of utility-scale and small wind turbines for over four decades.[67] DOE also formed a $41 million National Offshore Wind R&D Consortium in 2018. It is administered by NYSERDA, New York State's energy R&D agency, and has begun issuing solicitations.[68]

DOE should continue to focus on reducing costs of offshore wind and enhancing the value and reliability of wind power by leading innovation in wind turbines and components, wind farm operation, and the contribution of wind energy to the grid.

Innovation Challenges

Innovation Challenge #1: Improve the size and efficiency of individual horizontal-axis turbines.
The physical laws governing turbine operation place constraints on the extent to which they may be cost-effectively scaled up: Energy production scales with the square of blade lengths, whereas blade volume, and hence material costs, are tied to the cube of blade lengths.[69] Still, significant opportunities to improve wind turbine technology remain. Larger, more efficient turbines that are better able to tolerate high loads with less material would help to continue driving down costs.

- **Recommendation:** DOE should increase its R&D support for projects at universities, national laboratories, and other institutions to increase hub heights and rotor diameters, decrease component weight, reduce loads on turbine components, and add innovative power electronics.[70] New materials and manufacturing methods could push turbines to attain larger sizes and operate in more challenging environments.[71] Efforts to address barriers to deployment for turbines with blade lengths over 75 meters are important as well, including improvements to tower and blade transport and onsite fabrication.

- **Recommendation:** DOE should demonstrate novel wind turbine designs in partnership with wind developers. Innovative turbines may offer step change enhancements in operation, such as more flexible blades oriented downwind. However, companies are typically unwilling to be first movers without federal support because of the high costs and risks involved. Relatively immature wind technologies such as vertical-axis turbines and airborne wind systems are also worthy of exploration, but should not be prioritized at the expense of critical research on horizontal-axis turbines.[72]

Innovation Challenge #2: Build industry support for and understanding of wind performance in the ocean environment necessary to give rise to a robust offshore wind market.

Offshore wind offers a huge opportunity for wind technologies because of rich and steady wind resources, proximity to population centers, the ability to deploy larger turbines, and minimal competition for space. The major technical challenges facing offshore wind are associated with surviving an ocean environment, including corrosive saltwater, severe storms, surface icing, and the rolling and pitching caused by waves and currents.[73]

Floating offshore wind technologies would open up development in waters over 200 feet, which are characteristic of many coastal regions in the United States and other countries. Floating installations use less material and are simpler to build and decommission than fixed-foundation installations, which could eventually lead them to be less expensive.[74]

- **Recommendation:** DOE should invest with industrial partners in cost-shared demonstration projects to refine floating wind technology and accelerate industry adoption. DOE is currently supporting a 12 MW project off the coast of Maine, which was developed by the University of Maine.[75] Future projects should seek to develop design criteria and validate alternative designs such as the spar buoy, tension leg platform, and buoyancy-stabilized semi-submersible platform. Vertical-axis turbines may also offer advantages in the offshore environment given their low centers of gravity and need for relatively fewer parts.[76]
- **Recommendation:** Congress should establish research facilities focused on advancing offshore wind deployment, as called for by the Wind Energy Research and Development Act of 2019 (H.R.3609). Such facilities could support characterization of the ocean environment and atmosphere, as well as testing of support structure components and systems.[77]

Innovation Challenge #3: Improve understanding of atmospheric dynamics within and among wind plants to optimize wind plant operation.

A key question for wind researchers involves how systems of wind turbines may be optimized. Even if individual turbines approach maximum efficiency under optimal conditions, they may fall far short of that when operated in arrays. For instance, turbulent wakes from the first row in a wind farm array can diminish energy production downwind by as much as 40 percent.[78] These problems may be improved through research on atmospheric flows through wind farms, the impacts of turbulent wakes within individual farms, and the impacts farms have on one another.[79]

- **Recommendation:** DOE should expand computational and other efforts that seek to optimize wind farm operations. Its existing Atmosphere to Electrons initiative conducts systems-level research on siting and operations, focusing on plant performance and financial risk assessment, atmospheric science research, wind plant aerodynamics modeling, and next-generation wind plant technology development.[80] Future R&D should focus on atmospheric dynamics on finer time scales, such as during diurnal transitions (e.g., day to night) and the spatial scale of one to five kilometers (or "terra incognita," as it is known in the wind R&D community), which is increasingly relevant as individual turbines get bigger. Additionally, enhanced remote sensing technologies such as lidar may help wind farm operators apply research findings in real time.[81] The facilities and resources at NREL's National Wind Technology Center are well-suited to help advance understanding in these areas.

Innovation Challenge #4: Enhance the contribution of wind energy to the grid.
Wind energy's variability, resource uncertainty, and distributed nature complicate its integration into the grid at high penetration.[82] While turbine capacity factors are increasing and wind farms are increasingly able to offer critical grid services such as synthetic inertia, better tools to match supply and demand will become necessary as grids draw more and more heavily on variable resources.[83]

- **Recommendation:** DOE should support the demonstration of microgrids and autonomous energy systems with high levels of wind penetration. Such projects could enable localities to develop the technical and regulatory tools needed to manage such systems, and the dissemination of lessons learned could support larger utilities and governments as penetration rises across wider areas. Specific technical solutions that could be tested in these efforts include enabling wind energy to ride through faults, multi-scale integration of control systems, and advanced ramping services.[84]

AN INNOVATION AGENDA FOR FIRM RENEWABLE ENERGY TECHNOLOGIES

Firm electricity resources are available to be dispatched as needed, over long durations and in all seasons. Such resources have traditionally operated as the foundation upon which a reliable electric power system was built.[85] Many scenarios for decarbonizing the global energy system envision supplanting firm, carbon-intensive coal and natural gas resources with cheap, variable solar PV and wind resources. However, a significant body of research suggests that this strategy has limits, and there will be benefits to incorporating low-carbon firm resources along with variable ones in the zero-emission grid of the future.[86]

Over the past few years, Congress has worked on legislation to promote advanced nuclear power and CCS for fossil fuel plants, which could provide firm, low-carbon electricity. Less attention has been devoted to another set of opportunities: next-generation, firm renewable energy technologies.

Firm, dispatchable power can be derived from several flows of energy in the environment. Geothermal power draws heat from the Earth's core, concentrating solar power (CSP) captures radiation from the sun and accumulates it with thermal storage, and water power technologies harness energy from the motion of water being propelled by gravity or oceanic forces. These resources are tremendously abundant; however, with the exception of hydropower, they comprise tiny fractions of the U.S. and global electricity supply. Innovation is a key element to unlock the potential of all these firm renewable energy technologies.

The Role of Firm Resources

Firm electricity resources make it easier for grid operators to do their most essential job: balancing supply and demand. When energy consumption or the output of wind and solar PV fluctuate, firm resources can often fill the gap, avoiding brownouts and blackouts. The more flexible such resources are—for instance, the more quickly they can start and stop—the more value they can provide in this respect.

Firm resources also provide *capacity* and *essential reliability services*. Capacity services provide insurance that is purchased years in advance to avert shortfalls of available generation resources. Essential reliability services are drawn upon by grid operators to respond to rapid or unexpected changes in their systems.[87] Variable resources have greater difficulty providing these services, although they may be combined with storage technologies to do so more effectively.

Firm resources also complement variable renewables by lowering the cost of decarbonizing the power sector. A review of 40 deep decarbonization studies by Jesse Jenkins and his colleagues finds, "Firm low-carbon resources are a consistent feature of the most affordable pathways to deep decarbonization of electricity."[88] Many models suggest that penetrations of variable renewables of up to 80 or even 90 percent may be cost-effective, but the cost of decarbonizing the last 10 to 20 percent is very expensive.[89] If firm resources are not available, an emissions-free electricity grid typically requires a total capacity of five to eight times its peak demand in order to function effectively. But if firm resources are available, the required total capacity could be reduced to only 1.3 to 2.6 times peak demand.[90]

Utilities and local governments recognize the value of firm, low-carbon power. Duke Energy's plan to achieve net-zero emissions anticipates that "zero-emitting load-following resources"—in other words, firm resources—will account for 12 percent of capacity and 30 percent of generation in 2050.[91] An official with the Los Angeles Department of Water and Power, the nation's largest municipally-owned electricity system, noted that it may need "resources like geothermal that can produce around the clock" if it is to achieve its goal of a 100 percent renewables-based system without natural gas.[92]

Advantages of Firm Renewable Energy Technologies

A number of technologies—both renewable and non-renewable—can provide firm power. A well-balanced federal RD&D portfolio ought to hedge against the risks that any given technology will fail to perform as expected.

The two most prominent families of firm power technologies—nuclear and CCS—present such risks. The only nuclear plants currently under construction in the United States, at the Vogtle site in Georgia, have run over budget and schedule. Advanced reactor designs are being fast-tracked through the regulatory process, and federally subsidized demonstrations are planned, but nuclear power's track record in recent years does not bode well for the future.[93] Meanwhile, CCS will likely struggle to be widely competitive in the absence of a carbon price. The recent mothballing of Petra Nova, the only U.S. CCS project at a power plant, serves as a case in point.[94]

While nuclear and CCS warrant continued public RD&D investments, comparable investments in firm renewable technologies will increase the likelihood governments and power providers will have the tools they need to offer affordable low-carbon electricity in the coming decades.

Firm renewable technologies offer other advantages as well, especially in remote locations and in the developing world. These technologies avoid most public health risks associated with fuel transport, handling, and disposal. They may afford localities greater energy security and autonomy by reducing dependence on resources extracted elsewhere. And they insulate electricity prices from energy market volatility.

Finally, a review by Charlie Wilson and his colleagues finds that "granular" technologies, which are physically small and individually low cost, and can be used in a distributed manner, are likely to accelerate decarbonization. Many of the firm renewable technologies discussed in this section fit this description (along with some variable renewable technologies such as solar PV), whereas nuclear and CCS do not.[95]

Overview of Firm Renewable Sources

Each of the next four sections describes a promising set of firm renewable energy technologies: geothermal power, CSP, hydro power, and marine power. They are discussed in order of their potential importance. In brief:

- Geothermal power can harness the Earth's heat to provide up to 60 GW of firm, flexible power to much of the United States by 2050.[96] Innovation is needed chiefly to develop enhanced geothermal systems (EGS), or engineered reservoirs, that would make geothermal resources available to much of the country. EGS that operate at very high temperatures, so as to improve productivity and reduce costs, are a longer-term objective.
- CSP captures solar radiation by heating a working fluid to run a turbine, and stores it as thermal energy as well, which can be drawn upon when the sun is not shining. It has the potential to supply the United States with some 25 to 158 GW of power by 2050, if innovation makes it more affordable.[97] A key area of research is increasing storage and operating temperatures to boost plant efficiencies. CSP pairs well with solar PV because of its availability at night—and it can also produce low-carbon heat for some industrial processes.
- Hydropower, which draws energy from the controlled flow of water powered by gravity, is the most mature and widespread renewable energy technology. While opportunities for new hydropower infrastructure are limited, the efficiency and contribution of existing electricity infrastructure can be boosted substantially. In addition, up to 36 GW of new long-duration pumped storage may be made available by 2050, benefiting the integration of variable renewables.[98] Innovation programs should seek to improve the cost, capacity factor, longevity, and sustainability of hydropower infrastructure and develop novel approaches to pumped storage.
- Marine power, which draws energy from waves, currents, and tides, is still relatively immature. While its ultimate potential is large, due to the enormous resources that might be tapped into near population centers, only modest gains are likely in the medium term. Innovation is needed to identify successful technology pathways and reduce costs. One immediate goal should be to integrate marine energy technologies into niche applications

where they are cost-competitive or offer new capabilities, such as powering ocean observation equipment or remote communities.

Geothermal Power

Geothermal energy technologies draw heat from the Earth's subsurface to create steam that spins a turbine. There are two main types of geothermal resources. Traditional hydrothermal resources are natural pockets of heat and fluid close to the Earth's surface, with enough permeability for heat to transfer between the two. EGS resources are engineered by injecting fluid into hot rock in the subsurface to create fractures that enhance permeability and heat exchange.

Geothermal energy can be used for a diverse set of applications in addition to electricity generation. Geothermal heat pumps enable buildings to exchange heat with the ground and, through connection to a standard HVAC system, can heat and cool buildings. District heating systems pump geothermally heated water to localities for heating services. Geothermal resources can also serve agriculture and industry, for instance, by providing heat for greenhouses and paper mills.[99]

Figure 6: The Geysers complex in northern California comprises 18 geothermal power plants providing over 900 MW of electricity. Image courtesy of the U.S. Department of Energy.[100]

The Case for Innovation in Geothermal Power

The Earth radiates heat continuously, allowing geothermal units to provide firm power to the grid. Their capacity factors are often over 90 percent. These units can also be designed to operate flexibly, adding to their value for renewables integration.

In addition, geothermal power plants have modest land footprints—less than one-seventh the size of a comparable coal plant or solar PV farm. Jobs in the geothermal industry can leverage transferrable skill sets that are valued in the oil and gas industry, which may ease the transition away from fossil fuels. Geothermal plants may also offer additional value streams, such as lithium extracted from brine. Research that examines whether geothermal reservoirs could be used for energy storage is ongoing.[101]

The geothermal industry is well-established, but small and growing slowly. The United States leads the world in total deployment.[102] Yet, U.S. geothermal power capacity is just 2.5 GW, or about 0.4 percent, of utility-scale electricity generation.[103] The majority of these resources are located in Western states, where hydrothermal resources are more plentiful. The largest complex, the Geysers, provides over 900 MW to northern and central California (see figure 6).

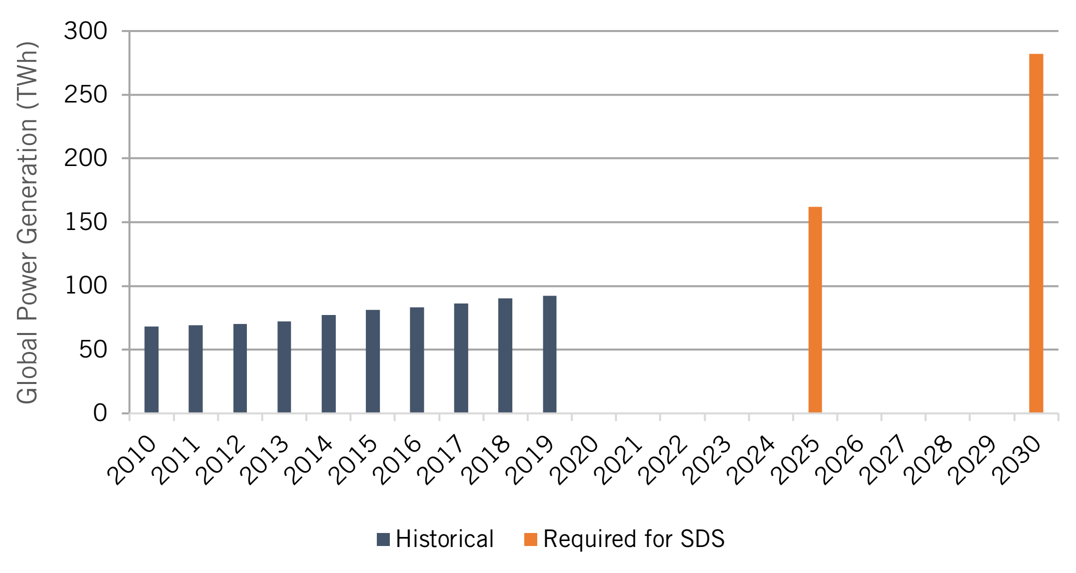
One barrier to the deployment of geothermal energy is its high upfront costs. A 2019 Lazard analysis finds that a new utility-scale geothermal plant has a levelized cost of energy between $69 and $112 per megawatt-hour (MWh), compared with $32 to $44/MWh for utility-scale solar PV. However, because geothermal energy is dispatchable, this comparison may be misleading. A 2016 Center For Energy Efficiency And Renewable Technologies (CEERT) study finds that geothermal power plants could bring in over $20/MWh more in revenue than a comparable solar PV plant, even one with bulk storage, because of their high capacity factors.[104] Recent power purchase agreements suggest that geothermal power may now actually be $40/MWh more valuable.[105] As noted above, these plants may also derive additional revenue from services other than electricity generation.

Exploration and permitting are the biggest components of geothermal power's cost. Exploration and resource confirmation alone account for nearly 40 percent.[106] Permitting for a single site can require up to six separate environmental reviews—which is a major reason geothermal project development can take up to a decade.[107]

Geothermal Power in IEA’s SDS

Geothermal power is not on track, according to IEA’s SDS. The scenario calls for a 10 percent annual increase in geothermal generation from 2019 to 2030, growing from 92 TWh to 282 TWh. In 2019, geothermal power generation increased by only 3 percent, slightly slower than in the previous five years.[108]

Figure 7: Geothermal power in IEA’s Sustainable Development Scenario[109]



Even though the geothermal power industry is over a century old, it has the potential to grow dramatically. The U.S. Geological Survey and NREL estimated that there are 30 GW of undiscovered hydrothermal resources and 5,000 GW of potential EGS resources.[110] While these theoretical potentials are not reachable, DOE has estimated that technological advances and favorable policies could unlock 60 to 120 GW of geothermal capacity by 2050.[111]

The majority of these additions would come from EGS technologies, which greatly expand access to geothermal resources. Indeed, if one drills deep enough, geothermal resources are available anywhere on Earth. However, accessibility in principle is not the same as affordability in practice. Innovation is needed to improve EGS technology to the point a material level of resources becomes commercially viable. DOE’s goal is $60/MWh by 2050, which it has argued would be cost-competitive with other sources of firm power.[112]

Super hot rock geothermal technologies, which involve developing very deep reservoirs where the subsurface is over 400°C, are particularly promising. Higher temperatures mean an order of magnitude more energy per well, along with increased efficiency. According to the geothermal company AltaRock, a 100 MW geothermal plant would require more than 40 wells operating at 200°C, but only 3 at 400°C.

However, difficult problems must be solved before resources at great depths and very high temperatures can be accessed routinely. Current technologies work down to about 7 kilometers below the surface. Super hot rock geothermal resources are only found at these depths in a few locations around the world, and these are often volcanic and tectonically active. Developers would need to go down 7 to 20 kilometers to build EGS plants in more geographically diverse locations. That is comparable to the deepest hole ever drilled, a Russian scientific project that reached 12 kilometers.[113]

DOE Portfolio in Brief

DOE's Geothermal Technologies Office (GTO) advances geothermal energy through its program areas in hydrothermal R&D; EGS; low-temperature and co-produced resources; and data, modeling, and analysis.

DOE has supported several EGS demonstration projects as well as a new field laboratory in Milford, Utah, the Frontier Observatory for Research in Geothermal Energy (FORGE). FORGE will be operated by a coalition of academic, private sector, and government entities led by the University of Utah, and will allow for experimentation in EGS while developing a functioning EGS reservoir.[114] DOE's EGS Collab program, which focuses on testing and validation modeling activities, is another flagship effort.

Increased support for geothermal R&D, especially in the critically important demonstration phase, and improved collaboration among relevant industries would accelerate progress.

Innovation Challenges

Innovation Challenge #1: Develop enhanced subsurface characterization tools, better drilling technologies, and other assets to reduce the costs of geothermal development.

A major challenge in geothermal development is accurate characterization of subsurface resources. Exploratory drilling, which is typically required in order to find viable resources, is time consuming, expensive, and leads to full-scale projects less than a third of the time.[115] If subsurface characterization could be done without in situ measurements, geothermal project developers would be able to finance and site many more projects.

Drilling is another major cost driver for geothermal projects, and will become even more important as EGS projects endeavor to reach higher temperatures and greater depths. Improved drilling technologies and practices can cut these costs and raise efficiencies. The oil and gas industry has experience in drilling and other aspects of subsurface exploration and development, although it has not faced the specific technical challenges of EGS resource development.

- **Recommendation:** DOE should reestablish a Subsurface Energy Technologies Program that combines expertise from geothermal and related fields such as oil and gas and carbon sequestration. The program could tackle common challenges and leverage ideas across these fields. A collaboration among these research communities and industrial experts could advance subsurface characterization, drilling technologies, and other areas of geothermal development. It would be able to build on prior work by the Subsurface Technology and Engineering Research, Development, and Demonstration (SubTER) Tech Team.

Innovation Challenge #2: Develop tools and techniques to engineer sustainable EGS reservoirs in the hot, high-pressure EGS environment.
EGS development at great depths and high temperatures calls for new technologies and techniques in drilling, casing, fracturing, mapping, monitoring, and other aspects of reservoir development. In addition, unlike unconventional oil and gas extraction, in which projects are built and exhausted within a few years, EGS developers must engineer underground fracture networks that can continue to harness energy sustainably for decades.

The geothermal industry has had few opportunities to test new ideas in the field. DOE has only a small portfolio of EGS demonstration projects, and there are few opportunities outside the United States. A larger EGS demonstration and testing program is required to validate modeling and smaller-scale R&D, as well as to develop tools. DOE's $140 million FORGE initiative is an important step in the right direction, but even it will likely only have enough funding to drill two or three wells over its planned five years of operation. No similar projects are on the horizon.

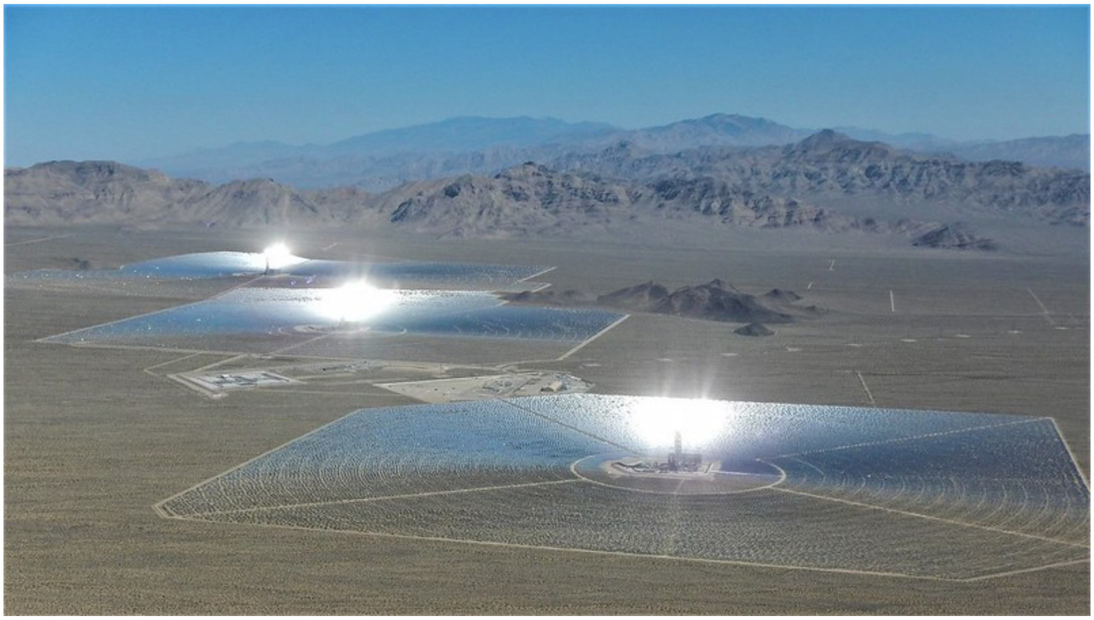
- **Recommendation:** Congress should provide additional funding to the FORGE initiative to allow the Utah site to continue operating beyond its current five-year timeline. Such funding would allow researchers to drill more wells, test more methods of stimulation and fracture control, and better understand the long-term stability of the engineered reservoir. Devoting more funding to FORGE, rather than additional sites, would provide continuity and shorten the timeline to advance the field.
- **Recommendation:** DOE should enter cost-share agreements with private companies to build commercial EGS demonstration projects. Such demonstration projects would build confidence in the technology and help disseminate successful approaches to reservoir development. Because the processes to develop EGS resources will vary in different geologies, DOE's demonstration portfolio should target projects in various subsurface conditions and diverse geographic locations.
- **Recommendation:** Congress should support the development of a high-temperature laboratory facility that can hold large-enough rock samples to enable advances in super hot rock EGS without the need for deep wells to access extreme temperatures in the field. Super-hot-rock EGS could offer enormous efficiency gains, but the technologies and practices that will function at temperatures over 400°C are not yet well-understood.

Concentrating Solar Power

CSP technologies capture thermal energy by using mirrors to focus sunlight onto a thermal medium, such as salt. That medium is then used to generate steam, which drives a turbine to produce electricity. Most CSP systems incorporate thermal storage so that they can continue to raise steam and make electricity even when there is cloud cover or at night. As a result, CSP functions as firm power.

CSP plants use a variety of configurations. The largest systems, which hold the most promise for utility-scale generation, are "power towers." They use concentric rows of flat mirrors (called heliostats) to direct light toward a central tower. The Ivanpah Solar Electric Generating System in the Mojave Desert (figure 8) has three power tower configurations that generate 392 MW with 173,500 heliostats.[116] CSP can also be colocated with industrial facilities to provide process heat, built at small scale to provide distributed generation, or paired with fossil fuel facilities to help reduce emissions.

Figure 8: The Ivanpah Solar Electric Generating System in the Mojave Desert produces 392 MW power. Image courtesy of the U.S. Department of Energy.[117]



The Case for Innovation in Concentrating Solar Power

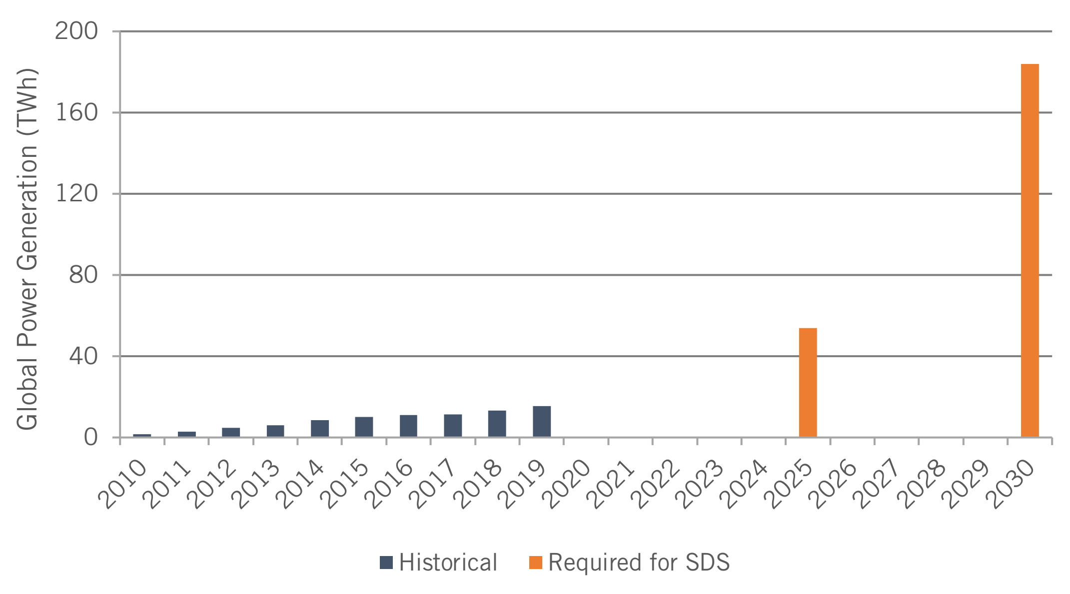
It is unlikely that CSP will be able to compete with solar PV on a levelized cost of electricity basis any time soon. Like geothermal power, CSP's value proposition lies in its dispatchability. It can make the grid more reliable because its storage capabilities allow it to complement the generation profiles of variable renewables, especially solar PV.[118]

There are only a few CSP plants operating either within or outside of the United States. Nine sites, predominantly in the Southwest, operate domestically with a total capacity of approximately 2 GW; and an additional 4 GW are deployed in the rest of the world.[119]

Concentrating Solar Power in IEA's SDS

CSP deployment is not on track, according to IEA's SDS. The SDS calls for 183.8 TWh of annual CSP generation by 2030, or a tenfold increase in CSP generation from 2019, which was 15.6 TWh. CSP generation increased by a strong 34 percent last year (600 MW), but average annual capacity additions in the preceding years were far short of the pace needed to meet the SDS goal.[120]

Figure 9: Concentrating Solar Power in IEA's Sustainable Development Scenario[121]



Despite its modest presence today, CSP has the potential to grow to a significant level. DOE models project that CSP capacity could grow to between 25 and 158 GW by 2050 if the agency's 2030 cost target is achieved. While CSP is most likely to become viable in places with high-quality solar resources, such as the southwestern United States, its footprint could extend across Texas, the Southeast, and the Midwest, if costs are low enough.[122] As the penetration of variable renewable energy increases in the grid and storage capacity becomes more valuable, CSP's value will rise as well.[123]

CSP faces two broad challenges. First, it's too expensive. The unsubsidized, levelized cost of energy from CSP with on-site storage is between $126 and $156 per MWh—several times the cost of utility-scale solar PV or wind.[124] CSP costs are falling quickly, by 46 percent since 2010, according to IRENA, and is approaching parity with offshore wind.[125]

Second, many existing plants, especially in the United States, have been plagued by technical and financing problems that have stunted performance and hurt investor confidence. For instance, Crescent Dunes, a 110 MW project in Nevada that received a loan guarantee from DOE, closed in 2020 because of leaks in a molten salt tank and mismanagement of its economic capacity.[126] Ivanpah, which DOE also backed with a loan guarantee, failed to meet its contractually obligated power production during its first few years of operation and has faced public opposition because of plant operations leading to the death of birds.[127]

An NREL study found that more than half of the technical problems encountered at CSP projects had nothing to do with CSP-specific technologies, but instead were generic powerplant issues. The researchers concluded that many such issues are caused by tight project timelines and a lack of experience among builders and operators.[128] Nonetheless, the industry's struggles have lowered investor's appetite for CSP projects. Only two major CSP developers (along with a few companies focused on process heat) are active in the United States at the moment.[129] IEA expects most new CSP capacity to be built in international markets, such as China, Morocco, and South Africa.[130]

DOE Portfolio in Brief

DOE's SETO aims to lower the costs and improve the efficiency and reliability of CSP. Its CSP program focuses on component-level R&D for solar collectors, receivers, heat-transfer fluids, power conversion, and thermal energy storage, along with the integration of subcomponents into CSP systems.[131] DOE's 2030 cost target is \$50/MWh for a CSP baseload power plant with a minimum of 12 hours storage, or \$100/MWh for a peaker plant with 6 hours of storage. At these levels, CSP systems would be competitive with other dispatchable generators.[132] ARPA-E also supports a project aimed at enhancing advanced thermal storage systems that might be used in CSP.[133]

This portfolio could be fortified to further accelerate progress.

Innovation Challenges

Innovation Challenge #1: Develop higher-temperature, higher-efficiency CSP systems.

One way to improve the efficiency of CSP systems is to build systems that operate at higher temperatures. The most advanced CSP systems today use molten salt to store energy at 565°C, or are conventional steam-Rankine power systems. A more efficient CSP system could operate at over 700°C and pair with a supercritical CO_2 Brayton cycle. Such a system would convert heat to electricity more efficiently while using lower-cost equipment.[134]

CSP researchers are exploring three storage media that might be integrated into higher-temperature systems: molten salt, falling particle, and gas phase.[135] SETO's "Gen 3" program has made a number of awards to test these technology pathways: by first advancing specific components, then designing a full system, and finally building a test facility.[136]

- **Recommendation:** DOE should continue to support research on storage media for higher-temperature systems, and should follow up this work by supporting R&D focused on the integration of CO_2 supercritical cycles in CSP systems. DOE released an RFI last year on this topic.[137]

Innovation Challenge #2: Overcome technical issues associated with scale-up that have depressed plant performance.

Many of the issues plaguing CSP plants in operation have been low-tech in nature, caused by scaling up too quickly or a lack of knowledge about plant construction and maintenance.[138] For power towers in particular, the operational implications of scaling up and the diurnal cycling of the plants has led to significant underperformance.[139]

- **Recommendation:** In 2010, DOE and the Bureau of Land Management established a Solar Demonstration Zone to serve as a test bed for advanced solar technologies including

CSP.[140] DOE should revitalize this program and incentivize developers to test and iteratively upscale new CSP designs. DOE should also ensure best practices for implementing new CSP technologies are widely disseminated to the industry.

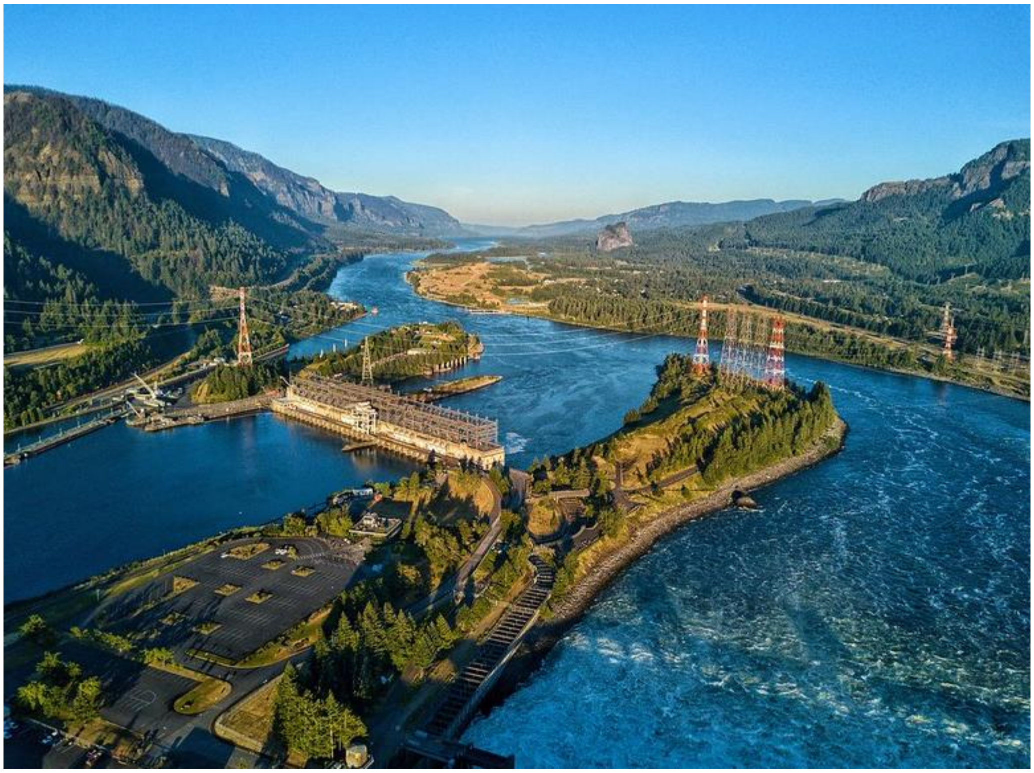
Innovation Challenge #3: Improve integration of CSP with other infrastructures such as industrial processes.
DOE's CSP program focuses primarily on components and systems. It has not looked as much into using CSP to provide process heat, an opportunity that may mature as industries that need high-temperature heat seek to reduce their carbon emissions.

- **Recommendation:** DOE should establish an RD&D program that seeks to use CSP to provide process heat. State-of-the-art CSP systems today can produce temperatures sufficient for ammonia synthesis, methanol production, and paper and pulp manufacturing—and even higher-temperature systems could feed into processes such as steam methane reformation or steel production.[141]

Hydropower

Hydropower facilities use the kinetic energy of water moving downhill to spin a turbine and produce electricity. Hydropower facilities follow three basic designs: impoundment, in which water is stored in a reservoir and undergoes controlled releases; diversion, in which a portion of a river is channeled through a power plant, typically without a dam; and pumped-storage hydropower (PSH), in which water is pumped uphill to a reservoir and released for electricity generation as needed.[142]

Figure 10: The Bonneville Dam in Washington, first opened in 1937, can provide over 1.2 GW of power.[143] Image courtesy of the U.S. Department of Energy.[144]



The Case for Innovation in Hydropower

Hydropower systems are well-proven, mature technologies. They provide flexibility, resiliency, and reliability benefits to the grid.[145] Hydropower can be developed alongside other water management projects, such as the diversion or impoundment of water for use in agriculture or drinking.

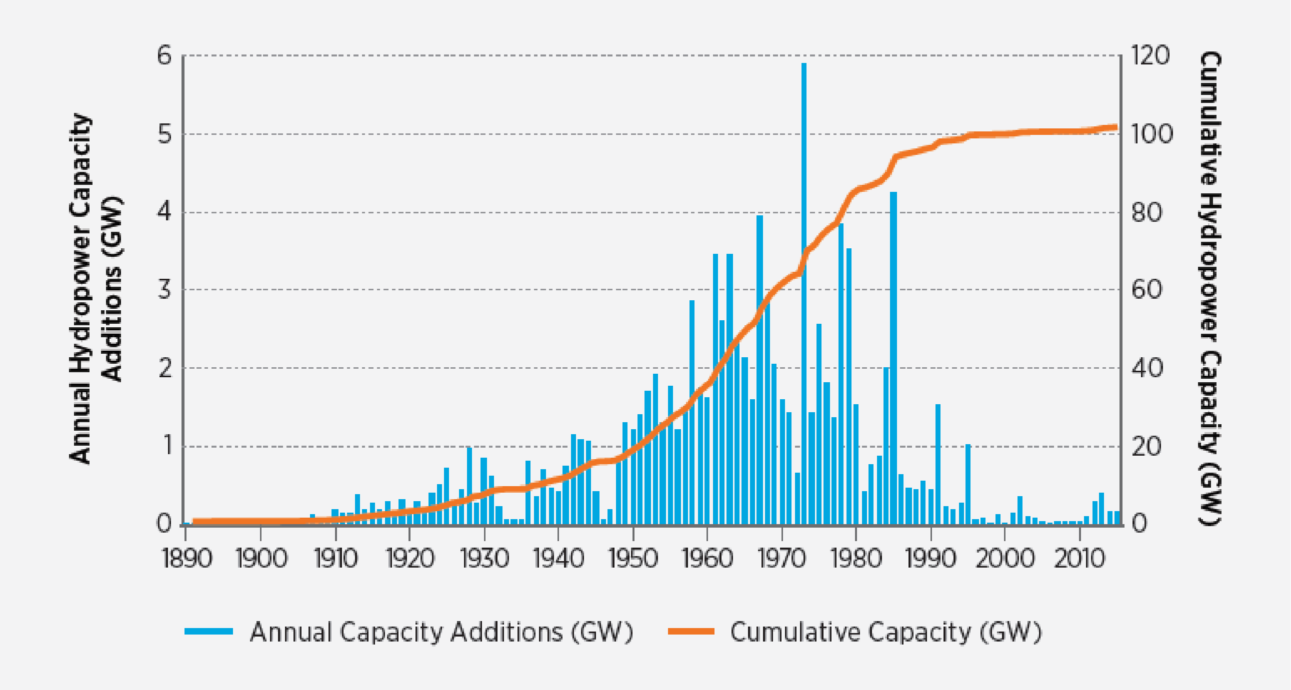
As of 2015, the U.S. hydropower generation fleet included 2,198 active power plants with a capacity of 79.6 GW. Hydropower plants supplied 6.6 percent of U.S. electricity generation in 2019.[146] The PSH fleet, made up of 42 plants totaling 21.6 GW, provides 95 percent of the U.S. energy storage.[147] About half of all U.S. hydropower assets are owned by the federal government, a quarter are under other forms of public ownership, and the remaining quarter are privately owned. [148] Globally, hydropower represents 16 percent of all electricity production.[149]

While few new hydropower resources are likely to be developed in the United States, technological innovation, combined with low-cost financing and other improvements, could unlock much more value from the existing fleet. DOE estimates that the potential for expansion by 2050 to be 12.8 GW of generation capacity and 35.5 GW of storage capacity. The main pathways for growth are modernization of existing infrastructure, conversion of non-powered dams to generate electricity, and sustainably developing new stream-reaches for diversion. New technologies in this context operate mainly as force multipliers for financial and other forms of innovation, accounting for only a small fraction of capacity expansion directly.[150]

Hydropower capacity growth on this scale in the future would be a break from the past. Growth in recent years has slowed to a crawl (see figure 11), and few additions are currently on the drawing board.[151] Hydropower has suffered from economic competition with lower-cost renewables, and has been omitted from the Renewable Portfolio Standards that have helped drive those competitors forward.[152]

Environmental opposition has been a crucial challenge for hydropower development. Dams and other hydropower facilities can harm fish and other aquatic populations by altering the dissolved oxygen content in water, contributing to sediment build-up, and blocking passages.[153] Environmental regulation sparked by public opposition has added costs for hydropower developers and operators. For example, Bonneville Power Administration, a federal agency that manages a fleet of projects in the Pacific Northwest (see figure 10), is currently facing financial troubles in part due to the cost of rehabilitating disrupted salmon populations.[154]

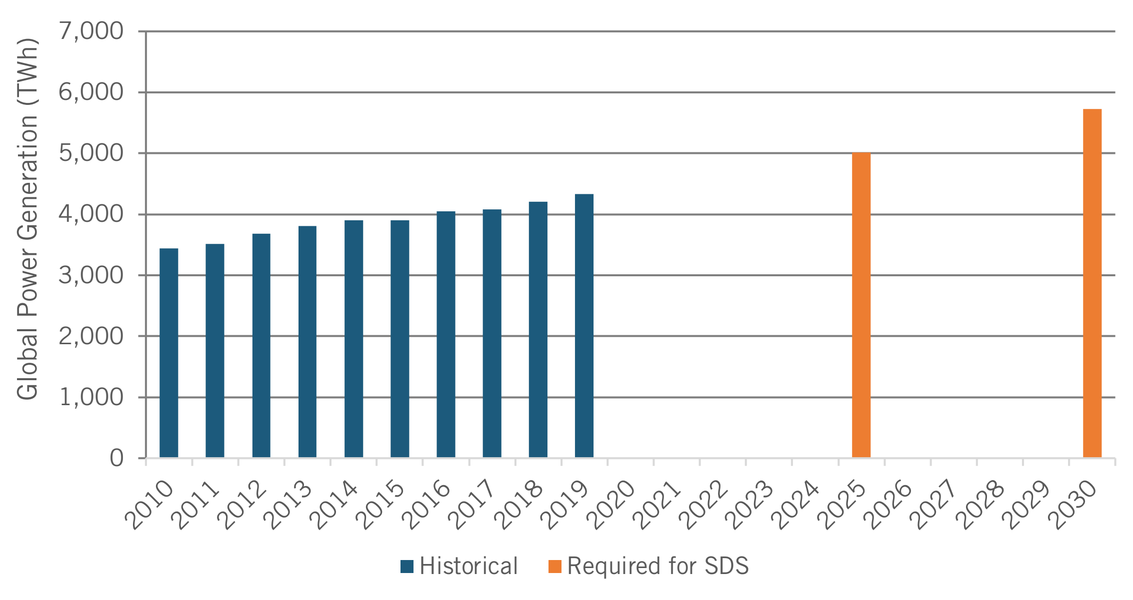
Figure 11: U.S. hydropower development has slowed in recent decades. Image courtesy of DOE.[155]



Hydropower in IEA's SDS

Globally, hydropower growth is not on track with IEA's SDS, which calls for 2.5 percent capacity additions per year through 2030. Capacity additions in recent years have been led by China, Brazil, and the European Union.[156]

Figure 12: Hydropower in IEA's Sustainable Development Scenario[157]



DOE Portfolio in Brief

DOE's Water Power Technologies Office (WPTO) manages the department's hydropower R&D portfolio. WPTO's priorities include reducing the costs and environmental impacts of infrastructure, optimizing existing hydropower performance, and developing new pumped-storage designs. WPTO's HydroWIRES (Hydropower and Water Innovation for a Resilient Electricity System) initiative seeks to improve the contribution of existing hydropower infrastructure to the grid. The office is currently developing an RD&D strategy in line with its comprehensive 2016 report, *Hydropower Vision*.

Further investments can amplify the contributions of existing infrastructure and spur new development, especially PSH.

Innovation Challenges

Innovation Challenge #1: Improve existing plant and fleet performance (efficiency, longevity, flexibility, etc.).

U.S. hydropower infrastructure is in poor shape, earning a D in the American Society of Civil Engineers' 2017 Infrastructure Report Card.[158] The average age of the nation's 80,000 dams is 56 years. Less than 3 percent of them produce power today.[159] Upgrades to dams, locks, irrigation canals, and other infrastructure could shore up existing generation and add hydropower to non-generating infrastructure.[160] Given the size of the U.S. hydropower fleet, relatively small increases in hydropower capacity would translate into significantly more clean power generation, accounting for the majority of the 12.8 GW of new capacity additions in DOE's models for 2050.

R&D to improve hydropower infrastructure can focus on reducing operation and maintenance costs; developing more durable, cheaper materials for components; improving manufacturing processes; and developing standardized components.[161] R&D to improve fleet performance can build on the work of DOE's HydroWIRES program by enabling hydropower to provide better grid services (e.g., storage, resilience, reliability), increase plant availability and capacity, and develop analytical tools to better support resource management.[162]

- **Recommendation:** DOE should establish a modeling and computational program to better understand key issues such as the integration of new components into infrastructure; component degradation over time; use of the existing fleet to provide more generation and offer flexibility to complement variable renewables; adaptation to changing water availability due to climate change; and reduction of the expected environmental impacts of new stream-reach development.
- **Recommendation:** DOE should establish partnerships with hydropower facilities around the country to test the integration of new components and tools to improve hydropower plant performance and limit environmental impacts, building on successful initiatives in California, Colorado, and Maryland.[163]

Innovation Challenge #2: Develop technologies and techniques to enable new, sustainable hydropower development.

New hydropower development in the United States is an innovation and sustainability challenge. New stream-reaches are the most expensive and environmentally challenging class of hydropower to build, with only a modest potential of 1.7 GW by 2050, according to DOE's modeling.[164]

Developing technologies that can be exported to parts of the world where there are more promising opportunities may be a better strategy to emphasize.

R&D for new sustainable hydropower development could focus on more standardized designs that are less project-specific and easier to install, as well as designs that will not require dams or resettlement of populations. Improved methods, technologies, and materials can also reduce construction costs, which can make up 70 percent of total project costs.[165]

- **Recommendation:** DOE should support demonstrations of innovative, environmentally sustainable hydropower designs. It should seek to build linkages between U.S. companies and international partners in order to capture export opportunities.
- **Recommendation:** DOE should establish a hydropower R&D test facility to demonstrate new environmental protection technologies, such as fish protection mechanisms that are currently the object of a DOE's prize competition.[166]

Innovation Challenge #3: Develop innovative approaches that enable PSH in new environments.
DOE's *Hydropower Vision* study suggests that the largest opportunity for new domestic hydropower is PSH. The 35.5 GW of new capacity it estimates is possible by 2050 would more than double the current amount.[167] New closed-loop designs promise to overcome the geographical limitations that have confined PSH to mountainous regions and reduce its environmental footprint. For example, the company Quidnet Energy is developing a long-duration storage system that uses wells rather than reservoirs.[168] PSH systems can also be hybridized with variable renewables to create more reliable and flexible grid assets. Modular PSH units on the order of 50–100 MW each may expand the range of applications.

- **Recommendation:** DOE should demonstrate new PSH designs—especially those that may be built modularly—that have minimal environmental impacts on local watersheds and are less dependent on mountainous geographies.

Marine Power

Marine power technologies capture hydrokinetic energy with a diverse array of designs.[169] For instance, buoys can tap into the up-and-down motion of waves, while turbines fixed to the ocean floor or the bottom of a barge can draw on currents and tides. This diversity stems in part from the diversity of applications and operating conditions, and in part from the fact that marine power technologies are immature and have not yet been standardized.

The biggest challenge in this field is systems must be built to withstand the harsh marine environment, including corrosive seawater and the threat of collisions with large objects, while having a minimal environmental impact.[170]

Figure 13: A wave-power buoy device operates near the Marine Corps Base Hawaii. Photo courtesy of the U.S. Marine Corps.[171]

The Case for Innovation in Marine Power

Marine power technologies are further away from being a mainstream resource than other technologies covered in this report. U.S. marine power capacity was only 531 MW as of the end of 2019.[172] Still, this opportunity for future energy production should not be ignored. Marine resources are enormous, theoretically amounting to 90 percent of current electricity consumption. [173] These resources (predominantly waves and tides) are located conveniently close to large load centers, since more than half of the U.S. population resides close to a coastline.[174]

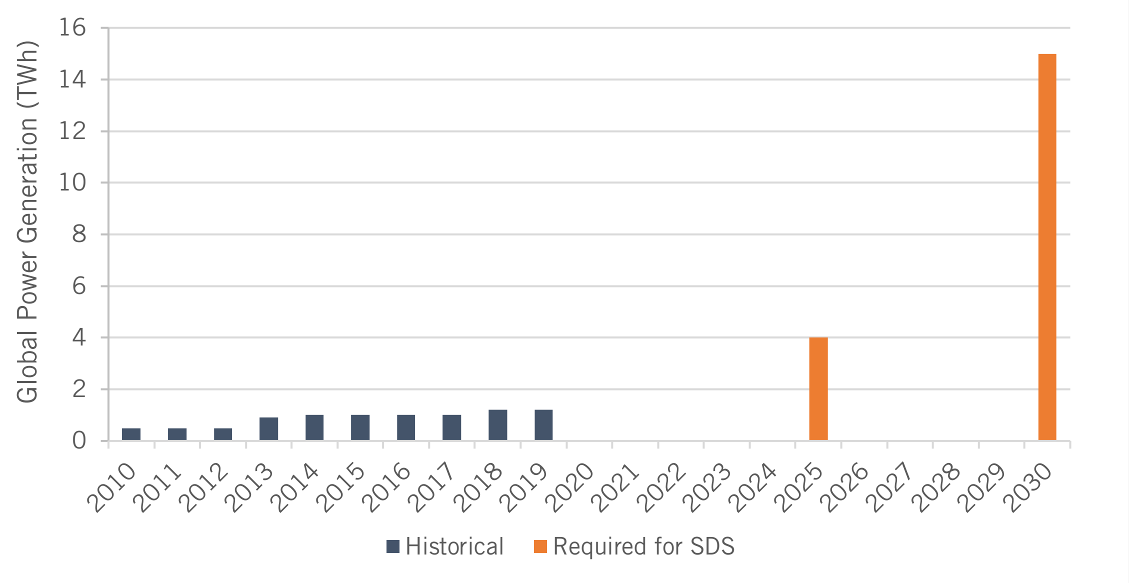
Marine energy resources are highly predictable and reliable, making marine power well-suited for large-scale industrial applications such as clean hydrogen production and water desalination. In the near term, marine power could make initial inroads into the “blue economy,” ocean-related sectors, and activities such as marine transport and port electrification. The blue economy was worth $1.5 trillion globally in 2016, a figure expected to double by 2030.[175] Marine power might be developed effectively in tandem with offshore wind power, with which it could share vessels and a highly skilled workforce.[176]

Developers are still figuring out which marine power systems work best. Early tidal energy designs attached very large machines to the seabed, but most were commercially unsuccessful because raising the machines for repairs and maintenance was costly. Newer tidal power companies are exploring designs that are more easily serviced, less capital-intensive, and more flexible, such as hanging turbines under barges or installing arrays of small turbines.[177]

Ocean Power in IEA’s SDS

IEA calls for annual growth of ocean power of 23 percent through 2030, totaling 15 TWh generation by that year. However, development of ocean power is not on track. In 2019, total global generation amounted to only 1.2 TWh, increasing merely 13 percent from the previous year.[178]

Figure 14: Ocean Power in IEA’s Sustainable Development Scenario[179]



DOE Portfolio in Brief

DOE’s WPTO seeks to improve the performance and reduce the cost of marine power technologies. A major prong of the office’s approach targets niche applications through its Powering the Blue Economy program. Marine power could remove constraints and enable new capabilities in activities such as ocean observation and offshore aquaculture, while also serving isolated communities.[180] WPTO’s work in such areas is supplemented by an ARPA-E program that seeks to develop low-cost hydrokinetic turbines.[181]

DOE partners with universities to test marine power technologies through its National Marine Renewable Energy Centers in Oregon, Florida, and Hawaii.[182] It is supporting the development of PacWave, a major testing facility in Oregon that will soon commence construction. DOE and the state of Oregon have put $35 million and $3.8 million, respectively, into this facility, which is expected to come online in 2022 or 2023. PacWave will feature four testing berths seven miles offshore, which will be capable of delivering 20 MW of power in total.[183]

Continued support of marine power R&D, as well as expansion of testing and demonstration facilities, will help bring the most promising technologies to market faster.

Innovation Challenges

Innovation Challenge #1: Reduce the cost and raise the efficiency of marine power systems.
Marine power is expensive today. One of the largest tidal power projects, built by SIMEC Atlantis Energy, provides 6 MW of power to Scotland at a cost of $123 per MWh, which is several times the cost of competing technologies.[184]

Marine power R&D can focus on improving system reliability and cutting maintenance costs. Monitoring and predictive maintenance systems as well as more robust and simple designs would advance these goals. Marine turbines can also be optimized by better understanding the interactions among individual turbines in an array. Other frontiers include the conversion of low-frequency ocean energy into electricity; unmoored designs for wave energy; and systems made with materials lighter than steel. Another key agenda should focus on minimizing environmental impacts.[185]

- **Recommendation:** DOE should continue to support R&D programs that address key barriers to affordable marine energy. Prize competitions are particularly well-suited for this field because of its technological immaturity, uncertainty about the eventual design of optimal systems, and the relatively low barrier to entry, especially for modular systems. New programs could continue to support applications within the Powering the Blue Economy initiative, such as seawater mining or powering isolated communities, which may be important steppingstones on the path to grid-scale marine power. Other efforts could focus on novel approaches to servicing turbines as well as reducing domestic manufacturing costs.

Innovation Challenge #2: Provide testing facilities to validate and refine prototypes.
Despite its academic partnerships and the new PacWave center, DOE's marine power program has gaps. For instance, the European Marine Energy Centre allows prototypes up to 1 MW to be tested in open water. There is no comparable test bed on this scale in the United States.[186]

- **Recommendation:** Congress should increase funding to existing National Marine Renewable Energy Centers and authorize the establishment of new centers in different marine and riverine environments. DOE's 2019 funding competition and its TEAMER program, which links companies more effectively to academic and government laboratories, were positive steps.[187] Additional open-water facilities would accelerate validation and enable system development. Pre-permitted testing would also reduce developers' compliance costs.
- **Recommendation:** DOE should continue to partner with stakeholders on marine power demonstration projects for applications such as remote electricity, desalination, and ocean observations. A 2015 project for a next-generation riverine turbine in a remote Alaskan community, which offset reliance on diesel generators, is a good example.[188] More efforts of this type are needed.

CONCLUSION

By nearly any measure, the global community is moving far too slowly to reach net-zero emissions by mid-century.[189] The United Nations found last year that the world is on track for a temperature rise of over 3°C by the end of the century. The devastation that would be wrought by such a rise is difficult to fathom.[190]

A rapid transition to a low-carbon energy system will only be achieved if clean technologies that can power homes, cars, businesses, factories, and more are able to match the tremendous convenience provided by fossil fuels. While the task is far from easy, renewable energy technologies have already begun to deliver on their great promise to become the foundations of a clean economy.

To maximize the chance of a successful energy transition, governments ought to invest in innovation that will address key challenges and seize opportunities to accelerate innovation in renewables. Federal investment in RD&D should pursue technologies that are cheaper, higher performing, viable in broader geographies, better integrated within the grid, more environmentally sustainable, and a boon to domestic economic growth. There's no time to waste.

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