Making "Beyond Lithium" a Reality: Fostering Innovation in Long-Duration Grid Storage

BY DAVID M. HART | NOVEMBER 2018

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Renewable energy is on a roll. In 2017, global new investment in renewable power and fuels was twice that in fossil and nuclear power.[1] Lithium-ion (Li-ion) batteries are on a roll, too. Global sales have been growing by more than 50 percent per year this decade. The recent progress of these technologies is remarkable, but it cannot be extrapolated indefinitely. Even as they roll on for another decade or so, their weaknesses—variable generation for renewables and limited duration for Li-ion batteries—will become increasingly apparent. Policymakers should take action now to prevent these limitations from stalling the fight against climate change by nurturing the next wave of energy storage technologies that go "beyond lithium."

The present enthusiasm in the climate and energy community about systems that combine Li-ion batteries with variable renewables is understandable. These batteries can fill in gaps of up to a few hours when the sun is not shining or the wind is not blowing. This capacity allows the share of renewables on a grid to rise well above what would be feasible if cloudy days or calm nights interrupted power supplies.

However, due to inherent technological limitations, it is unlikely Li-ion batteries will ever become good enough or cheap enough to solve the problem of variability for periods of more than a few hours. If renewables are to fully displace carbon-emitting fossil fuels, electricity systems will need technologies that provide affordable, reliable long-duration storage at grid scale.

This report begins by laying out this "baseload challenge" and the importance it holds for mitigating the worst effects of climate change. It then briefly explores some of the most promising technologies that may meet this challenge. It concludes by offering recommendations to federal policymakers in the following areas:

- **Goal-setting:**
  - Adopt simple, high-profile goals for affordable, safe, long-duration grid storage system development.
- **Research and development (R&D):**
  - Set up an innovation hub to pursue a broad field of science and technology other than batteries for long-duration grid storage.
  - Expand investment by the Advanced Research Projects Agency-Energy' (ARPA-E) in long-duration grid storage R&D.
  - Expand investments by the applied energy offices of the Department of Energy (DOE) in grid storage R&D and focus them on long-duration problems.
  - Establish a working group on long-duration grid storage within the National Science and Technology Council (NSTC).
- **International collaboration:**
  - Lead a new challenge on long-duration grid storage within Mission Innovation (MI).
- **Technology demonstration:**
  - Expand DOE funding for long-duration grid storage technology demonstration projects, in partnership with lead users.
  - Sustain Department of Defense (DOD) support of demonstration projects, at its facilities, that are consistent with its mission.
  - Assist leading states that coinvest with lead users in demonstration projects.
  - Ensure pathways from R&D to demonstration involving public and private partners exist for all promising technologies.
- **Private-sector support:**
  - Continue to foster and simplify partnerships between DOE national laboratories and technology development companies.
  - Explore whether loan guarantees would assist long-duration grid storage technologies in achieving commercial viability.
  - Create a tax incentive system that supports emerging technologies for long-duration grid storage.
- **Power-sector planning:**
  - Consider regulatory and market reforms to optimize the value of existing pumped-hydropower storage resources.
  - Implement an expedited process for licensing of closed-loop pumped-hydropower storage systems.
  - Expand the collaborative work of planning for the fully decarbonized grid of the future.

VARIABLE RESOURCES, GRID STORAGE, AND THE ENERGY TRANSITION

The world, including the United States, must significantly reduce carbon emissions from energy consumption. These emissions drive climate change, the consequences of which are bad and getting worse. There are many potential pathways the transition to a low-carbon energy system could follow. None are free of obstacles. Cheaper, better energy storage for the grid would surmount key obstacles on some of the most alluring transition pathways, particularly those that rely very heavily on wind and solar power.

Climate change is happening. Evidence abounds, including melting Arctic sea ice, changes in the geographic ranges of animal and plant species, and more frequent extreme weather events. The rising concentration of carbon dioxide in the atmosphere is the primary cause of climate change, and that is caused mainly by fossil-fuel use. Although there may be a few beneficiaries of climate change in the short run, many more people are suffering losses from it. And, if it is not arrested, our descendants will all be worse off.[2]

Hydropower, nuclear power, and CCS, by contrast, have largely stalled; indeed, nuclear power is already contracting or likely to contract in the near future in major countries such as the United States, Japan, and Germany.

The Paris climate accord set a target of limiting the increase in average global temperature to no more than two degrees Celsius. The target is even more ambitious than it may appear on the surface. There will be more people in the world in 2050 than there were in 2005, and, one hopes, their standard of living will be much higher. Poor people who lack vital energy services such as lighting, cooking, and transportation today deserve the chance to get them in the coming decades. The per capita carbon emissions of the poor will likely grow, requiring the emissions of the more fortunate to decline even more sharply.[3]

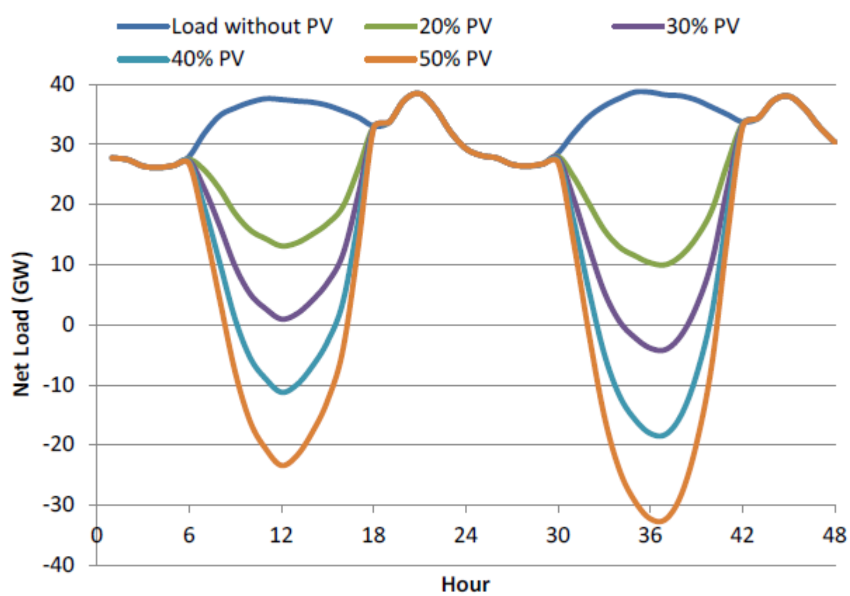
In most Paris-compliant scenarios, the electricity sector is decarbonized by 80 percent or more. Electricity is a highly flexible energy carrier that can be generated relatively cheaply with low-carbon resources. It can substitute for higher-carbon resources in major applications such as heating and ground transportation, where it is not now widely used. Very low emissions from electricity will be needed to offset emissions from sectors such as aviation and heavy industry for which low-carbon solutions are extremely difficult.[4]

Mature technologies for low-carbon electricity generation include hydropower, nuclear fission, wind turbines, and solar photovoltaics (PV); some forms of fossil fuel combustion with carbon capture and sequestration (CCS) have also been demonstrated. Wind and solar PV have grown at an extraordinary pace over the past decade, to the point that they now make a material contribution to electricity supply. Among all Organization for Economic Cooperation and Development (OECD) countries, they accounted for about 8 percent of all generation in 2016; in the United States in 2017, the figure was 7.5 percent. Hydropower, nuclear power, and CCS, by contrast, have largely stalled; indeed, nuclear power is already contracting or likely to contract in the near future in major countries such as the United States, Japan, and Germany.[5]

These trends diverge from the least-cost pathways identified by most models of the future low-carbon energy system. On those pathways, nuclear power and CCS play larger roles than they will play in 2050 if today's trends continue, while wind and solar PV play smaller roles. One key reason for this finding is that wind and solar PV are variable resources. The amount of power they can generate differs greatly from winter to summer, noon to night, and even minute to minute as breezes shift or clouds pass over the sun. The expected cost in 2050 of smoothing these variations well enough to supply power whenever customers demand it is expected to be much higher if the share of variable resources rises very high than it would be if a sizable portion of that demand were met with resources such as nuclear power and fossil with CCS that can dispatch power at virtually any time.[6]

The larger the share of variable resources on a grid, the more acute the challenge of matching supply with demand at all times becomes. California's "duck curve," which traces solar PV's peak production at midday to its rapid disappearance at sunset, provides an illustration. As the share of solar power in the state's generation mix rises toward 50 percent in simulations (from about 15 percent today, which is twice its share in 2014), the daily variation in output could become greater than the total load. For example, on the two spring days modeled in figure 1, the load with no solar power at noon (blue line, hours 12 and 36) is about 40 gigawatts (GW). If solar PV were to provide 50 percent of California's power (orange line), it would be producing 60 or 70 GW at noon, which would result in the net load of 20 to 30 GW having to be curtailed (that is, discarded).[7] At night, however, the entire load would have to be met with other resources. In wind-heavy regions, the shape of the "duck" is different; the wind tends to blow more strongly at night and does not wane as quickly as the sun does when it sets. But the problem of variability is fundamentally similar.

Figure 1: Modeled load profiles for California during two days in the spring[8]



If a grid operator can blend these two forms of variable generation, their variations may offset one another. Texas, with rich solar and wind resources, for example, may benefit from the complementarity of a daytime solar peak and a nighttime wind peak.[9] This Texas example illustrates a more general pattern: Larger grids with more diverse resources are better able to manage variability. The odds the sun will be shining some place when the wind is not blowing in another are higher the more places there are in the mix.

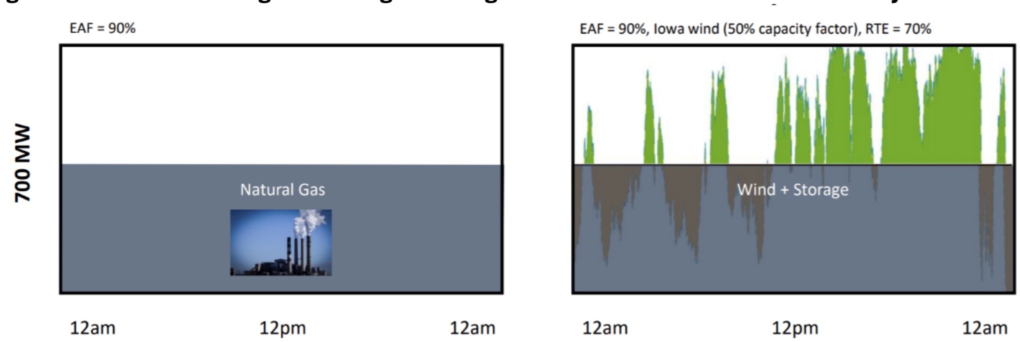
Stronger interconnections across regional grids would therefore complement the growth of wind and solar. The proposed expansion of California's Independent System Operator (CAISO), for instance, is intended to give the state access to a more diverse mix of energy resources. A network of high-voltage, direct-current (HVDC) transmission lines could perform a similar function nationwide at a cost of $1–10 million per mile. [10]

The ability to vary demand rapidly and on a large scale provides another vital tool for balancing variable supply. Industrial and commercial facilities have long been on call to curtail their demand when grids have very high loads. Demand response aggregators, who pay a wide variety of electricity customers to curtail consumption under specific conditions, are increasingly able to participate in wholesale markets in the United States.[11]

But even a more diverse and flexible grid would not fully address the challenge. Electricity is essential to many facets of daily life. Any substantial outage harms the economy and threatens public health. As a result, grid operators are required to meet stringent reliability standards set by the North American Energy Reliability Corporation (NERC). If they are to continue to meet these standards as variable generation rises to a very high share of total capacity, electricity system operators would most likely have to build much more wind and solar capacity than they usually need, and maintain a significant fleet of dispatchable power plants to back it up.[12]

Energy storage could ease these constraints considerably. Figure 2 shows how a stylized storage system can allow a variable renewable resource to match the steady supply of a dispatchable power plant. The green-shaded area in the right panel shows when the storage system is discharging, while the offsetting orange-shaded area within the gray block shows when it is charging.

Figure 2: Wind and storage matching natural gas baseload over the course of a day[13]



This figure focuses on a daily time scale, but the same principle applies on a minute-to-minute or seasonal basis. However, because the size and speed of these fluctuations vary so much across these time scales, the storage technologies that work across these scales also vary greatly.

The two most common technologies used for grid storage today demonstrate this point. Li-ion batteries, akin to those used in cell phones, can discharge a lot of energy very quickly. Their first major use on the grid in the United States was to respond almost instantaneously to variations in the frequency of alternating current (AC), which must stay within a narrow range for the grid to function well. The PJM Interconnection, which oversees wholesale electricity markets for a large portion of the mid-Atlantic and north-central United States, established a market for fast frequency-regulation services in 2012. Li-ion batteries are very well-suited to this application, and some 300 MW of them were installed in response over the following half-decade.[14]

Pumped-hydropower storage ("pumped-hydro"), by contrast, usually operates on a far longer time scale. As the name suggests, pumped-hydro systems store energy by using electricity to pump water from a lower-elevation reservoir to a higher-elevation reservoir. This energy is transformed back into electricity just as the energy in water behind any other dam would be: by running through turbines. Pumped-hydro systems generally cannot respond to fluctuations in the grid as quickly as Li-ion batteries can, but they can store far more energy and discharge it in much greater volumes for much longer durations. The average pumped storage facility in the United States can produce 500 megawatts (MW) of power, roughly the same as a medium-sized power plant, and an order of magnitude or two larger than most grid-scale Li-ion battery systems. Pumped-hydro systems often run for several hours or more at a time, absorbing excess electricity when the price is low and discharging when prices rise.[15]

The trend toward renewables will stall if storage systems that allow such grids of the future to perform at least as well and as affordably as today's do not become available.

If the trend toward grids that rely more and more heavily on wind and solar PV continues, energy storage will become increasingly important on all time scales. Indeed, the trend toward renewables will stall if storage systems that allow such grids of the future to perform at least as well and as affordably as today's do not become available. And, if that trend stalls and alternatives such as nuclear power and CCS are not revived, the low-carbon energy transition as a whole will falter.

LITHIUM-ION BATTERIES: THE RISK OF PREMATURE TRIUMPHALISM

There is good news about grid energy storage: Systems that use Li-ion batteries have been getting cheaper and better very quickly. The technology is diffusing rapidly from frequency regulation into other grid applications on longer time scales, including some that alleviate intermittency from variable resources. But there is also not-so-good news: Li-ion batteries are highly unlikely to become cheap enough and good enough to support long-duration applications that would allow grids with very high renewable penetration to perform as well as today's fossil-fuel-dependent grids. It is premature to declare victory over the energy storage challenge.[16]

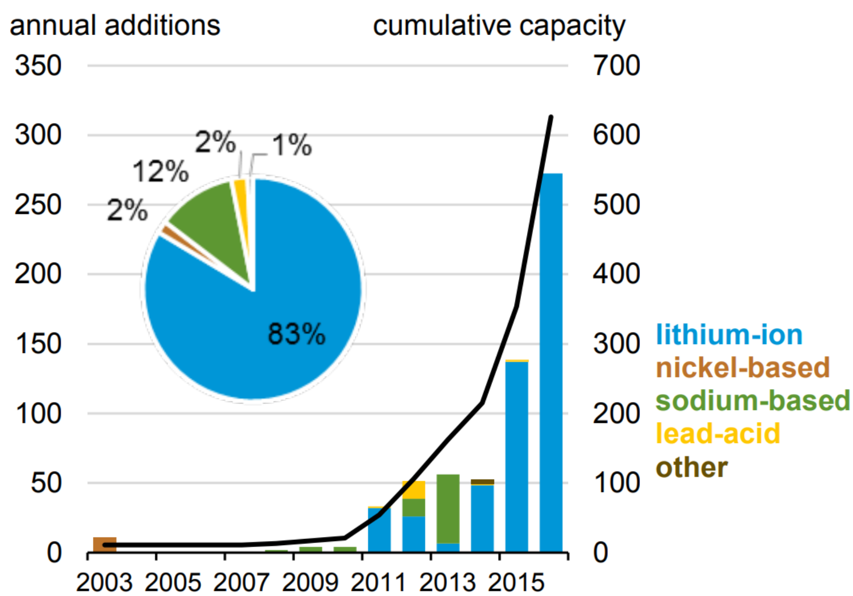
Li-ion batteries were first commercialized by Sony for use in consumer electronics in 1991, building on basic research that had been carried out across several countries, including the United States. Over the next quarter-century, the Japanese government played a leading role in fostering the development of this technology, encouraging its use in electric vehicles

(EVs) and on the grid. These efforts began to pay big dividends in the 2010s. In 2018, EVs overtook electronics as the largest end use, accounting for more than 50 percent of Li-ion battery demand for the first time. Demand for Li-ion batteries for grid storage applications is growing even more rapidly than for EVs, although the grid segment remains much smaller in absolute terms.[17]

Rapid market growth has contributed to rapidly declining prices. The experience curve is a standardized way to relate these two variables. For utility-scale Li-ion battery systems, each doubling of cumulative production has meant a price decline of 9 to 15 percent, according to recent work by Oliver Schmidt and his colleagues. With the market growing at 50 percent or more annually, system prices have been more than halved already in this decade. As these systems have only been on the market for a few years, this estimate should be treated with care. In 2017, for instance, the International Energy Agency reported that prices fell by 22 percent.[18] (Costs are further reduced in the United States by accelerated depreciation and, for storage systems that are charged by power from solar PV, the investment tax credit.)

Dropping prices have allowed Li-ion batteries to enter applications in the U.S. grid that require longer-duration service than frequency regulation. In California, for instance, a growing number of Li-ion battery facilities are firming the output of variable resources, absorbing their excess generation, and shaving the grid's peak load, among other things. While these deployments have frequently been mandated, rather than driven by market-based compensation, such mandates are far easier for policymakers to impose when the cost of compliance is declining at such a pace. Not surprisingly, a half-dozen states have followed California's lead by imposing storage mandates on or setting storage targets for their utilities. Li-ion batteries dominate new U.S. grid storage installations, holding a 98.8 percent market share at the end of 2017 (figure 3).[19]

Figure 3: U.S. grid-scale battery storage capacity by chemistry in megawatt-hours[20]



Market incentives and conventional rate-making are expected to supplant mandates in sustaining the rapid growth of Li-ion battery deployment in the United States moving forward. The Federal Energy Regulatory Commission has ordered regional grid operators to revise their rules such that they treat storage more fairly in electricity wholesale markets. Integrated resource plans by regulated utilities in states as diverse as Florida, New Mexico, and Indiana now incorporate energy-storage resources. Contracts recently offered in Nevada for combined solar-plus-storage facilities that would open in 2021 and operate for at least 10 years from that date have priced the output at less than 3 cents per kilowatt-hour (kWh), which is below the average wholesale price of electricity in the United States today.[21]

The prospect of future market growth across all end uses is stimulating the construction of ever-larger Li-ion battery factories, such as Tesla's "giga-factory" in Nevada (figure 4). Such factories will test how far economies of scale in production can be stretched—and will also yield innovations in production processes. Perhaps more important, a variety of companies, including hot start-ups such as Sila Nanotechnologies and Ionic Materials, are pursuing product innovations that could substantially improve Li-ion battery performance. Such innovations are, as Daniel Kammen and his colleagues at the University of California at Berkeley have shown, essential to sustaining the pace of cost reduction.[22]

Figure 4: Tesla's "giga-factory" outside Reno, Nevada[23]

The virtuous cycle of scale, innovation, and cost reduction of the recent past has led many analysts to project it to continue far into the future. The widely-cited *2018 New Energy Outlook* from Bloomberg New Energy Finance (BNEF), for instance, anticipates Li-ion battery systems for the grid will cost just $70 per kWh in 2030, down 67 percent from 2018. Such prices would permit renewables-plus-storage systems to displace natural-gas-fired "peaker" plants that supply electricity when demand is strong and prices are high in many locations today. In California and Texas, systems with Li-ion battery arrays that supply power to the grid for up to four hours are already being planned for operation within three years. Analyst Shayle Kann of Energy Impact Partners has stated that he "can't see a reason why we should ever build a gas peaker again in the U.S. after, say, 2025."[24]

Such projections are subject to much uncertainty, as previously noted. Prices could drop more rapidly than anticipated, driving even faster deployment. For instance, if electric vehicle (EV) demand does not grow rapidly enough to absorb the vast quantities of Li-ion batteries that will be produced by the 45 "giga-factories" currently operating or under construction globally, the excess might be dumped onto the grid market, temporarily driving down prices. The growth of a market for "second life" EV batteries that are no longer powerful enough for transportation but will still work for grid applications could also amplify price reductions.[25]

Alternatively, price declines might decelerate. Writing about Li-ion batteries in *Nature* in July 2018, Georgia Tech's Kostiantyn Turcheniuk and his colleagues argued that the "pace of advance is slowing." Continued reliance on scarce and expensive materials, such as cobalt and nickel, they argue, puts a floor on future cost reduction. Future product innovation could be disrupted, as my colleagues and I have argued in prior work, if below-cost dumping by Chinese or other manufacturers drives innovators out of business before they are able to test their advances fairly in the market. Innovations driven by the requirements of EVs, which increasingly drive Li-ion battery production, might also diverge from those that would be most cost-effective for grid applications.[26]

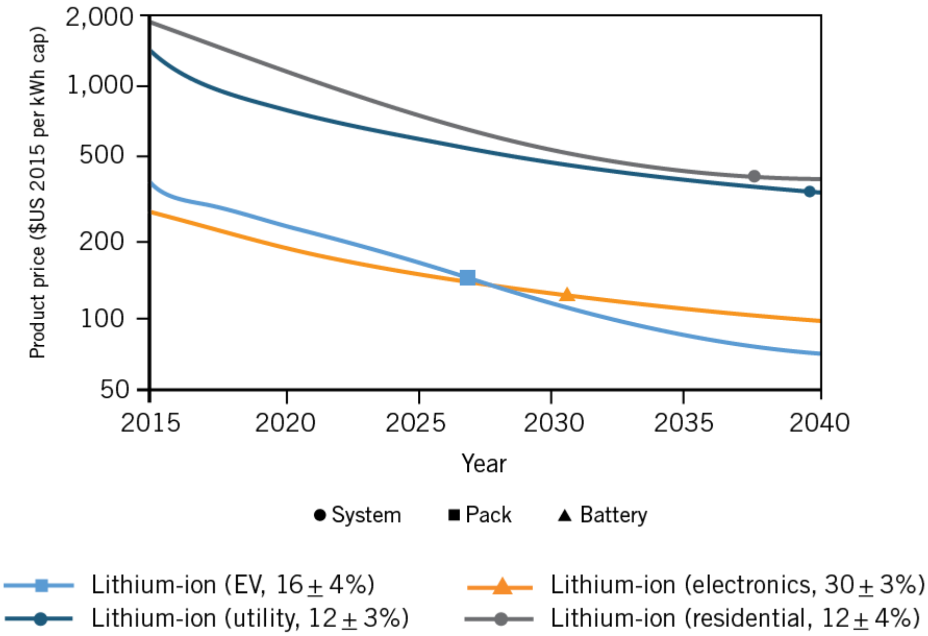
Li-ion batteries will confront fundamental barriers that make it unlikely for renewables-plus-storage systems that use them to match the price and performance of today's baseload systems in places that are not blessed with outstanding solar or wind resources.

Yet, even if the optimists are right, potential bottlenecks are avoided, and the experience curve steepens over the next decade, Li-ion batteries will confront fundamental barriers that make it unlikely for renewables-plus-storage systems that use them to match the price and performance of today's baseload systems in places that are not blessed with outstanding solar or wind resources.

Meeting the "baseload challenge," as Marco Ferrara and his colleagues at MIT put it, will require storage costs to fall at least 50 percent below BNEF's 2030 projection, even as the duration of service lengthens considerably and charge-discharge cycles become less frequent, reducing revenues. Ferrara et al. call for systems that provide one hundred or more hours of service at a cost of less than $20 per kilowatt-hour. ARPA-E long-duration storage program director Paul Albertus provided a range of $5 to $30 per kilowatt-hour for systems with durations of eight to one hundred or more hours. BNEF itself projects gas peaker capacity will actually grow by a factor of almost four globally by 2050 in order to back up renewables.[27]

Figure 5, derived from Schmidt et al., projects experience curves for Li-ion batteries in four different applications. Neither the curve for electronics, where prices fall most quickly for each doubling of production, nor the curve for EVs, where prices fall furthest because production grows the most, comes close to Ferrara et al.'s target in 2040. Materials costs alone, even for advanced Li-ion battery technologies under development today, which would use Earth-abundant materials instead of relatively rare metals such as cobalt, are likely to remain well above the target.[28]

Figure 5: Projected unit costs of storage technologies as extrapolated from experience curves



At some point short of solving the baseload challenge in most locations, Li-ion batteries will hit their limit.

There are also serious questions about how well the enormous Li-ion battery arrays that would be needed to provide long-duration grid storage would perform. The safety risks of massing batteries on this scale could be daunting for a technology that U.S. authorities currently do not allow to fly in airline luggage compartments. Li-ion batteries are not yet durable enough either, particularly when operating under harsh conditions, to meet the baseload challenge. The University of Southern California's Sri Narayan has concluded that to do so, they would need to become "10 times more durable than … today."[29]

The recent trajectory of Li-ion batteries has surprised nearly everyone. Few imagined even a half-decade ago that this technology would become competitive in grid applications that require a duration of four hours, yet it has. Some forecasts anticipate six- and eight-hour duration markets will soon emerge in the United States, and perhaps big arrays or massive distributed networks of Li-ion batteries will dominate these applications as well. Form Energy CEO Ted Wiley went so far as to say, "Thanks to lithium-ion batteries, storing energy for less than a day is a solved problem…"[30]

The accuracy of Wiley's prediction will depend on the continued advance of Li-ion technology and the market constructs in which these assets are deployed—that is, how their owners will be paid. But at some point short of solving the baseload challenge in most locations, Li-ion batteries will hit their limit. As the authors of an editorial in *Nature Energy* concluded, "A consensus has now formed that lithium-ion batteries will not be able to satisfy the energy storage requirements of the long-term future and new battery technologies are urgently needed." Form's Wiley, for his part, continued, "Our goal is to find solutions to store energy for weeks, months, and maybe even across seasons at a fraction of the cost of current technology."[31]

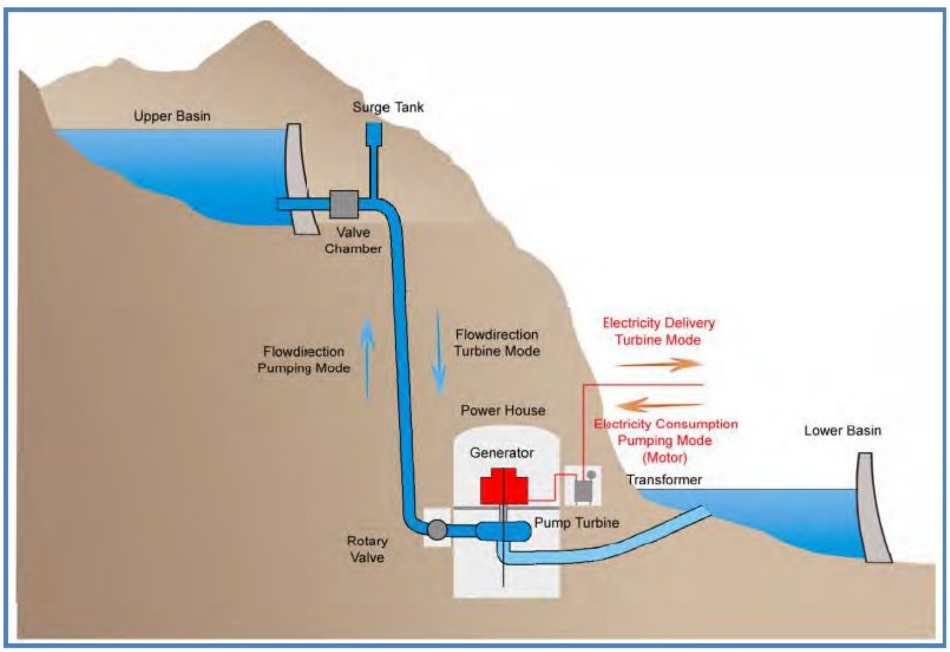
BEYOND LITHIUM: TECHNOLOGICAL ALTERNATIVES

The solutions to which Wiley refers are not entirely hypothetical. Pumped-hydro, in fact, still comprises the vast majority of all grid storage capacity in the United States and globally. It can indeed store energy for months and deliver electricity economically under many circumstances. Further deployment of pumped-hydro systems has halted in recent decades, however, and innovation is required to kick-start it. Other technologies, including flow and liquid metal batteries, thermal storage, compressed air, and hydrogen-based systems, hold the promise of addressing the baseload challenge, but are not yet mature, much less economically proven. A diverse portfolio of alternatives should be explored in the coming decade, so that viable options are available when Li-ion batteries reach their limit.[32]

Pumped-Hydropower

Hydropower is often overlooked in discussions of renewable energy. Unlike wind and solar PV, however, most hydropower projects provide dispatchable capacity. Water in a hydropower reservoir, whether pumped or gathered naturally, stores energy that can be converted to electricity when the facility's owner chooses (figure 6). Reservoirs filled by snowmelt are thus systems for storing energy supplied by nature in the winter that generate electricity for human activities the rest of the year.

Figure 6: Typical pumped-hydro configuration[33]



While building more reservoirs of any kind may therefore be seen as an expansion of long-duration grid storage, pumped-hydro is a more flexible form of storage than conventional hydro, because it can take electricity off the grid as well as put it on. The first pumped-hydro facility in the United States opened in 1929, and about 21 GW of capacity are currently operating in the country. Although this figure dwarfs the 1 GW of grid-scale battery capacity deployed to date, geographical limitations and environmental opposition have stalled growth of pumped-hydro for many years.[34]

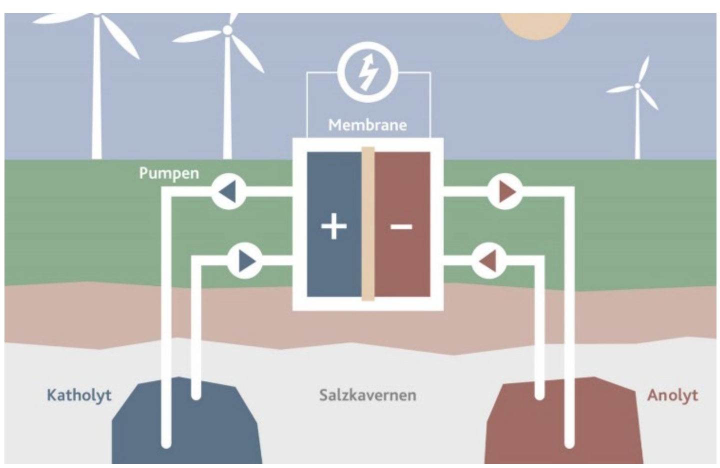
DOE's 2016 *Hydropower Vision* report estimated that more than 35 GW of new pumped-hydro capacity could theoretically be installed by 2050 if innovations in technology, market design, and regulation are realized and risks to wildlife habitat, water quality, and other environmental and cultural assets are mitigated. Undersea and underground designs, for instance, could radically expand the range of pumped-hydro locations while reducing environmental damage. Quidnet Energy, a start-up that is developing technology to store energy in pressurized water underground, and has received support from Breakthrough Energy Ventures and the Advanced Research Projects Agency – Energy (ARPA-E) in the past year, is one firm that is pursuing such innovation.[35]

Flow Batteries

Flow batteries differ fundamentally from lead-acid or Li-ion batteries. They store energy in two separated tanks of fluid and generate electricity by pumping the fluids together into "stacks," rather than integrating storage and generation in cells, such as with Li-ion batteries. This design allows the amount of energy stored to be independent of the amount of electricity generated at any one time. System capacity is determined by the size of the tanks, while instantaneous power depends on the size of the stacks. Tanks and stacks become cheaper to build on a unit basis as they get larger, unlike conventional battery systems in which unit costs are largely fixed by the cost of cells, regardless of how many cells are used in a system.[36]

Flow systems are being developed on a variety of scales. Avalon Battery supplies 25 kWh units that are integrated into each row of solar panels in NEXTracker's large-scale PV systems. The German utility EWE Gasspeicher has announced plans to build a flow system with a capacity of 700 megawatt-hours (MWh), 28,000 times larger. (Each tank would fill an underground cavern with the volume of a cube that is 50 yards on each side.) EWE's proposed system (figure 7) could power the city of Berlin for an hour, but such a system could use fewer stacks to provide less power for many hours or even days.[37]

Figure 7: EWE Gasspeicher's proposed flow battery[38]



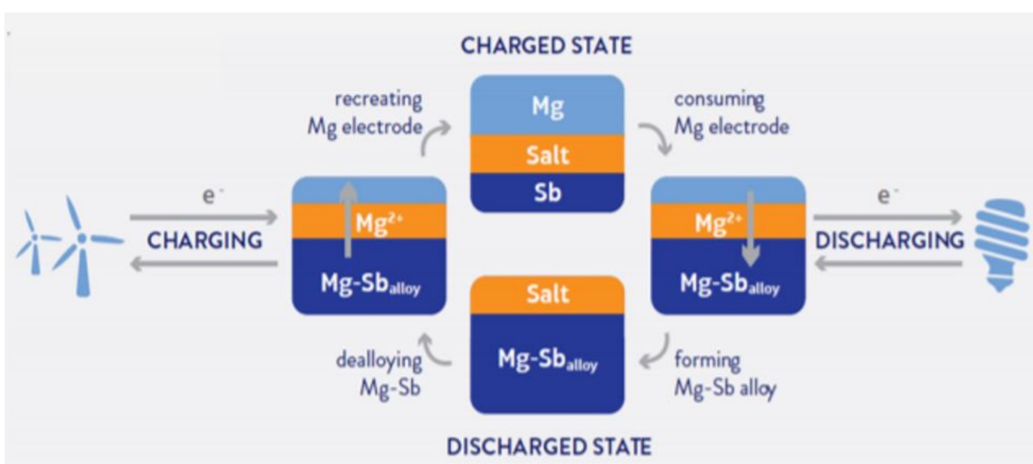
Most companies in the flow battery business presently target a sweet spot of five to ten hours' duration. At the low end of this range, their products face growing competition from Li-ion-based systems; the high-end falls far short of meeting the baseload challenge, although it could fill an important intermediate niche. To extend the duration as well as lower costs and improve performance, researchers are exploring a wide range of materials and designs. For instance, Wiley's company, Form Energy, is developing flow batteries that may use sulfur dissolved in water for the anode and "breathe" oxygen from the air in the cathode. "The battery's total chemical cost," according to an MIT press release, "is about 1/30th the cost of competing batteries, such as lithium-ion batteries. Scaled-up systems could be used to store electricity from wind or solar power, for multiple days to entire seasons, for about $20 to $30 per kilowatt-hour."[39]

Liquid Metal Batteries

Liquid metal batteries take their name from the materials used in their electrodes; most other batteries, including Li-ion cells in production today, use solid electrodes. Molten salt serves as the electrolyte. The cathode, electrolyte, and anode liquid layers in the battery cell have different densities and therefore "self segregate, kind of like oil and vinegar," as inventor Donald Sadoway put it. As the battery's state changes by charging and discharging, the three layers grow and shrink accordingly, reforming with each cycle. In order to keep its metal components liquid, the battery must operate at a temperature of several hundred degrees Celsius.[40]

Liquid metal batteries can be built on a large scale for grid storage applications of up to twelve hours' duration. They use Earth-abundant, low-cost materials. Their simple design creates the potential for products that are more intrinsically safe, efficient, reliable, and far more durable than Li-ion batteries. Sadoway reported that Ambri, the company he cofounded to commercialize the technology, has run test cells for over 5,000 cycles with 100 percent depth of discharge that retain more than 99 percent of their capacity (figure 8).[41]

Figure 8: Schematic of Ambri's liquid metal battery[42]



Test cells, of course, are not commercial systems, and Ambri has encountered many challenges in building full-scale systems that can compete with Li-ion batteries, despite benefiting from more than $10 million in research grants and more than $50 million in equity investment. As Li-ion battery prices have plummeted, Ambri has had to reformulate its cell chemistry to try to keep up. High-temperature operation poses difficult system-engineering problems that have delayed full-scale manufacturing. If Ambri is unable to field a viable product within a few years, liquid-metal battery technology may fall by the wayside.[43]

Thermal Storage

Pumped-hydro stores energy kinetically, with gravity doing the work to turn it into electricity. Batteries store energy chemically and recoup it through reactions. Thermal storage typically uses a heat reservoir, the energy from which can be released by heating a working fluid that drives a turbine. [44] A common thermal storage design uses tanks of molten salt, which is inexpensive, stable, and relatively easy to handle, as the reservoir, and steam as the working fluid, as in conventional power plants.

If the heat reservoir is sufficiently large and adequately insulated, thermal storage can provide long-duration grid storage. At Crescent Dunes in Nevada, for instance, a molten salt/steam system provides 10 hours of storage for a 110 MW concentrating solar power (CSP) plant, enough to supply 75,000 homes. (CSP plants operate on a different principle than solar PV plants. They generate electricity by using mirrors to focus the sun's energy to create heat within a working fluid that drives a turbine.) Newer thermal storage designs use solids or other liquids for the heat reservoir; heat pumps, heat engines, and thermovoltaic panels in place of or in addition to turbines; and carbon dioxide as the working fluid.[45]

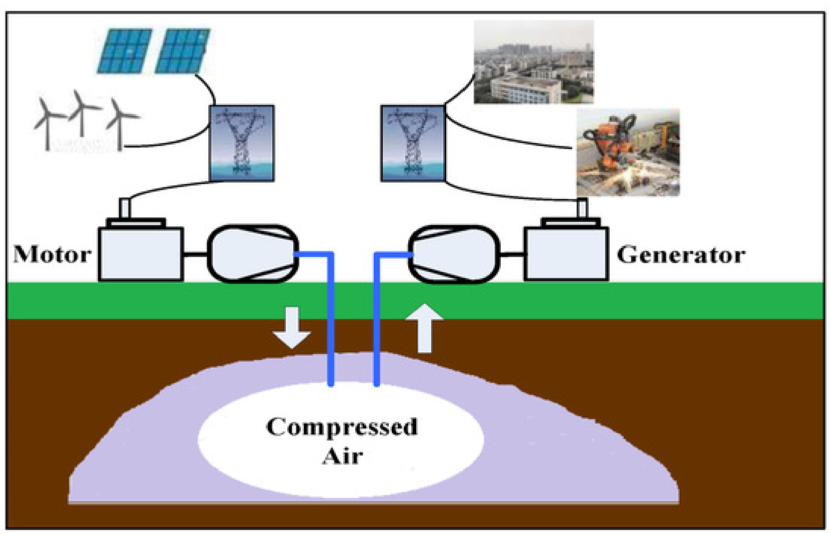
Crescent Dunes, a first-of-its-kind plant that benefited from a federal loan guarantee, sells power for about twice the price of natural-gas-fired plants, and suffered an eight-month shutdown for repairs during its first two years of operation (figure 9). The plant's owner, SolarReserve, has proposed a project that would be 10 times as big and sell power for at least a third less, $90 per kWh. Such a plant would represent continued progress toward meeting the baseload challenge, but much further innovation is required to drop this price by another 50 percent or more and, more importantly, to decouple thermal storage from CSP so it can be sited independently. Raj Apte of Google X's thermal storage project Malta, for instance, identified high-temperature materials, new designs for components such as tanks and heat exchangers, and novel manufacturing methods as important areas for future work in a December 2017 presentation.[46]

Figure 9: Crescent Dunes concentrating solar power and storage plant[47]

Compressed Air

Compressed air energy storage (CAES) uses electricity to run compressors that pack air into a confined space (figure 10). The energy is recovered by releasing the pressurized air into turbines to generate electricity. The two commercial grid-scale CAES facilities operating today, in McIntosh, Alabama, and Huntorf, Germany, burn natural gas to add more power in the recovery phase. The compression phase of CAES generates a lot of heat. Venting this heat reduces efficiency considerably. Advanced CAES designs therefore include thermal storage to retain the energy within this heat and supercritical heat transfer, although no such design has yet been built on a commercial scale.[48]

Figure 10: Simple compressed air energy storage[49]



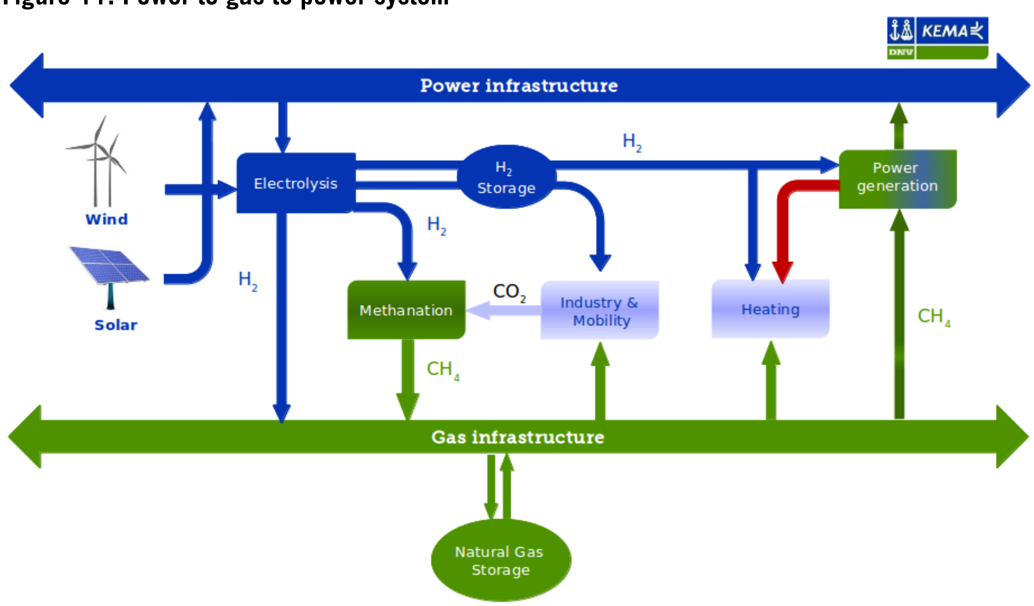
The duration of services CAES facilities can provide depends primarily on their physical features. The McIntosh and Huntorf plants both use salt-dome caverns; McIntosh is capable of supplying 110 MW to the grid for 26 hours, whereas Huntorf typically discharges for 2 hours at a time. In addition to caverns, CAES could be sited in abandoned mines, oil wells, aquifers, and even underwater. A number of start-ups have also sought to build CAES tanks that would free the technology from dependence on geology and geography.[50]

No CAES start-up has yet come close to commercial success in the United States. General Compression, which sought to marry wind power with storage in a cavern and raised $86 million from investors, has gone under. So has Lightsail, which developed a system using carbon-fiber tanks and ran through $53 million of venture funding. At least three major demonstration projects in the United States have been cancelled in recent years because they were not financially viable, despite receiving federal support. Site-dependent costs and revenues, efficient integration of thermal storage, and the cost and durability of tanks for above-ground systems remain significant challenges for this technology.[51]

Hydrogen

Hydrogen, the most abundant element in the universe, is a remarkably versatile energy carrier. In addition to serving as a fuel for electricity generation in turbines and fuel cells, it can power vehicles, heat buildings, and feed industrial processes without generating greenhouse gases at the point of use. Hydrogen can be extracted by splitting water molecules with an electric current (a process known as electrolysis) and stored in bulk as a gas or further processed into another form of fuel. If the electricity used to make hydrogen comes from renewables or other low-carbon energy resources, the entire cycle of production, storage, and use avoids fossil-fuel consumption. These attractive features have led many to call for the eventual creation of a "hydrogen economy."[52]

Figure 11: Power to gas to power system[53]



Hydrogen is now used on a large scale in the petroleum refining and fertilizer industries. Underground storage in salt caverns and depleted oil wells is a well-established practice. Industrial hydrogen is mostly made by processing natural gas, coal, or petroleum; only 1 percent of production employs electrolysis, although a tripling of global capacity has been announced. A few planned electrolysis projects are multi-megawatt in size, comparable to a utility-scale battery array, and use renewable energy. But such "power-to-gas-to-power" (P2G2P) systems are intended for demonstration purposes and are far from commercial viability (figure 11).[54]

For hydrogen to become a significant resource for long-duration grid storage, round-trip efficiency must rise well above the 30 to 50 percent level of today's P2G2P systems. As with CAES, strong, cheap, large tanks would free hydrogen storage from locational constraints. Even though some existing natural gas infrastructure, such as pipelines and power plants, could be used in P2G2P systems, the capital costs of electrolyzing equipment and other facets of infrastructure would need to decline sharply to meet the baseload challenge.[55]

The federal government, led by DOE and in collaboration with other federal agencies, states, and international partners, should build on this legacy of leadership to fill the innovation pipeline for long-duration grid storage.

FEDERAL LEADERSHIP TO FILL THE LONG-DURATION GRID STORAGE INNOVATION PIPELINE

The United States has been and remains a global leader in energy storage science, technology, and innovation. American scientist John Goodenough, now at the University of Texas, made seminal contributions to the invention of the Li-ion battery; researchers at Argonne National Laboratory provided insights that made it practical for use in EVs; and the PJM Interconnection pioneered market frameworks that enabled it to be used at grid scale. The National Aeronautics and Space Administration (NASA) developed flow batteries, MIT researchers invented liquid-metal batteries, and Oak Ridge National Laboratory pioneered thermal storage with molten salt. The federal government, led by DOE and in collaboration with other federal agencies, states, and international partners, should build on this legacy of leadership to fill the innovation pipeline for long-duration grid storage.[56]

Set Cost and Performance Goals to Meet the Baseload Challenge

DOE regularly sets cost and performance goals for key energy technologies. These goals focus the thinking of the relevant scientific, technical, and business communities and provide output benchmarks for federal research, development, and demonstration investments. A famous example is the SunShot Initiative's 2020 goal of an average price of 6 cents per kWh for electricity generated by solar PV, which was achieved ahead of schedule in 2017.[57]

DOE's current goals for long-duration grid storage vary by technology. DOE's Office of Energy Efficiency and Renewable Energy (EERE) has adopted a 2030 goal for CSP with a minimum of 12 hours of storage of a levelized cost of energy of 5 cents per kWh. The goal of the Energy Storage Program, which lies within DOE's Office of Electricity Delivery and Energy Reliability (OE), is $100 per kWh of installed capacity (i.e., unit capital cost) by 2025 for a four-hour flow battery system.[58]

Long-duration grid storage system development would be aided by the adoption across DOE of simple, high-profile goals modeled on SunShot. (In fact, the CSP goal is part of the SunShot 2030 initiative.) These goals should meet the baseload challenge across all major geographical zones in the United States by 2040. Technology-specific milestones, such as OE's 2025 goal, could be incorporated into roadmaps by the appropriate units.

Invest More in Research and Development and Coordinate Better

The technologies reviewed in the previous section are at different stages of maturity, but all—even mature technologies like pumped-hydro—would benefit from continued use-inspired knowledge creation and experimentation. Scientific researchers may also make discoveries that expand today's portfolio of technologies for long-duration grid storage. (John Goodenough, for instance, 95 years young, continues to push the envelope in battery science.[59]) Federal investment is crucial to sustain scientific research that can underpin such advances, and federal coinvestment is needed to encourage private investors to fund ventures and projects in this field that would otherwise be too risky for them to take on.

Relevant science is supported by several federal agencies, including DOE's Basic Energy Sciences program within the Office of Science (SC), the National Science Foundation, NASA, and DOD. A March 2017 workshop convened by SC identified five priority research directions for next-generation electrical energy storage. Battery scientists express excitement at the prospect of applying machine learning and other artificial intelligence techniques to the study of materials, components, and systems. New legislation creates an electricity storage research initiative that will involve several SC units as well as EERE.[60]

The Joint Center for Energy Storage Research (JCESR), an energy innovation hub supported by SC and headquartered at Argonne, was recently renewed for another five years of federal funding at $24 million per year. Its integration of battery science, product design, prototyping, and manufacturing-process development in a single organization represents a model that should be replicated. JCESR R&D has led to three battery and component start-ups, and informs the ongoing work of numerous affiliated battery makers and users. **SC should set up a second hub on the JCESR model to pursue another broad technology field related to long-duration grid storage.**[61]

ARPA-E funds high-risk, high-impact applied research, with an emphasis on proof of concept. It seeks out science and technology "white spaces" that have been neglected by other organizations. A National Academies evaluation found that ARPA-E's funding of energy storage R&D had been "highly productive with respect to accelerating commercialization" and led to the formation of at least six new companies in the field. The agency recently announced ten awards totaling about $28 million for long-duration grid storage. **ARPA's long-duration grid storage investment should be continued and expanded.**[62]

The solar technology, water power, and hydrogen and fuel cell offices within EERE, as well as OE's Energy Storage Program, support R&D related to long-duration grid storage. A portion of the $25 million annual hydropower R&D budget, for instance, is devoted to closed-loop pumped-hydro designs. The Energy Storage Program, which concentrates on grid storage, won increases from Congress in fiscal 2018 and 2019, bringing its budget to $46 million. Such figures are modest relative the baseload challenge. **Investments in grid storage R&D by DOE's applied office investments should be expanded and focused on long-duration problems.**[63]

The wide range of federal agencies that support R&D relevant to long-duration grid storage mirrors the diversity of potential technological solutions to the baseload challenge, as well as agency missions. However, this pluralistic funding system, particularly if it were to expand, would benefit from stronger horizontal linkages for information exchange and coordination, both within DOE, where the Grid Modernization Initiative provides a framework, and beyond it. **NSTC should establish an interagency working group on long-duration grid storage to perform this function.**[64]

Lead International Collaboration in Research and Development

The baseload challenge is not confined to the United States. Many countries are pursuing strategies that rely heavily on variable resources to comply with the Paris accord. Germany, for instance, plans to phase out nuclear power and has no large-scale CCS facility at present. Denmark seeks to supply all of its electricity with renewables by 2030.[65]

The United States does not have a monopoly on long-duration grid storage technologies—far from it.

The United States does not have a monopoly on long-duration grid storage technologies—far from it. For example, the first liquid-air (a form of CAES) storage facility opened this year in the United Kingdom. China is constructing the world's largest flow battery, and designing a 100 MW CAES plant.[66] International collaboration on long-duration grid storage R&D would allow countries to contribute to and take advantage of a global pool of knowledge for mutual benefit.

Mission Innovation (MI), a parallel initiative to the Paris accord that commits major governments to doubling their investments in clean energy R&D by 2020, provides a framework for such collaboration. MI has identified eight innovation challenges, "global calls to action … in technology areas where MI members believe increased international attention would make a significant impact in our shared fight against climate change." The United States is not leading any of the eight.[67] **It should propose and take leadership of a new innovation challenge on long-duration grid storage.**

Catalyze Demonstration Projects by DOE, DOD, and the States

R&D is necessary, but not sufficient, for long-duration grid storage technologies to be deployed at scale. These technologies are capital-intensive and long-lived; good performance in a laboratory does not typically provide their potential owners with confidence that investments in them will yield an adequate return. Demonstration projects in real-world settings generate valuable information for investors about costs, revenues, and performance. These projects also allow problems at scale to be identified and solved, thus lowering costs in later installations.

DOE support for grid storage demonstration projects dates back to the George W. Bush administration, when it coinvested with two utilities in sodium-sulfur batteries for renewables integration. The 2009 American Recovery and Reinvestment Act (ARRA) dramatically expanded this effort with an investment of about $97 million. ARRA funded 16 energy storage demonstration projects spanning several types of batteries, CAES, and flywheels. In addition, DOE's Loan Program Office guaranteed the financing for the Crescent Dunes CSP-with-integrated-storage power plant. DOE has continued to provide technical assistance and financial support for grid storage demonstrations in the post-ARRA period, albeit at a reduced level.[68] **DOE should expand its long-duration grid storage technology demonstration program in partnership with lead users.**

DOD installations are among the lead users of grid storage systems. Some defense installations place a premium on risk reduction and resilience, and have therefore been willing to pay the relatively high costs of serving as proving grounds for storage technologies. DOD's Environmental Security Technology Certification Program (ESTCP) funded about two dozen demonstrations of advanced microgrid and energy storage technologies on military bases. ESTCP support laid the groundwork for Primus Power's first deployment of a flow battery system at Marine Corps Air Station Miramar in 2015.[69] **DOD should sustain support of long-duration grid storage technology demonstration projects, at its facilities, that are consistent with its mission.**

State governments have also been key players in the advancement of energy storage technology. While they rarely fund R&D, states such as California, New York, and Massachusetts have supported many energy storage demonstration projects in recent years. These projects have often been intended to facilitate the integration of renewables as penetration has risen under the pressure of ever-higher state renewable portfolio standards.[70] **DOE should assist leading states that coinvest in long-duration grid storage demonstration projects.**

The demonstration phase of long-duration grid storage innovation involves both backward linkages to R&D as well as forward linkages to storage-asset owners. Primus Power, for instance, received funding from ARPA-E before it won the Marine Corps contract—a project that also involved the state of California, DOE's National Renewable Energy Laboratory, and Raytheon. As a recent report from the Union of Concerned Scientists pointed out, strengthening the connections among these players would help to prevent promising technologies from slipping into the "commercialization valley of death." **NSTC should work with DOE, DOD, key states, and private partners to develop pathways from R&D to demonstration for promising long-duration grid storage systems.**[71]

Support Private-Sector Technology Development and Deployment

Long-duration grid storage technology has been pursued by both established companies and start-ups. Navigant Research's 2017 Leaderboard for Non-Lithium Ion Batteries for Grid Storage, for instance, included Japanese multinational Sumitomo; Italian multinational FIAMM; Vionx, a spinoff from U.S. multinational United Technologies; UniEnergy Technologies (UET), a spinoff from DOE's Pacific Northwest National Laboratory (PNNL); and Silicon Valley-based, venture-capital-funded Primus Power, among others. The value propositions of these efforts remain highly uncertain, due to intense competitive pressure from rapidly improving Li-ion batteries for shorter-duration applications and weak revenue streams from longer-duration applications, as well as technological uncertainty. The spring 2018 failure of ViZn Energy, which had topped Navigant's list just months earlier, highlights the risks being taken by investors in these technologies and companies.[72]

In addition to having a high risk tolerance, such investors must be patient. An early wave of venture capital investment in energy storage in the 2000s yielded meager returns and led to widespread disillusionment with "cleantech VC." Strategic investors, particularly multinationals in related industries such as chemicals and oil and gas, who can be more patient, have been more prominent in this sector during this decade. Breakthrough Energy Ventures, which was set up by an international group of deep-pocketed investors to carry forward promising projects growing out of MI, has begun to focus some of its patient capital on long-duration grid storage as well. It is worth bearing in mind that fuel-cell manufacturer Bloom Energy had to raise more than $1 billion over 17 years before being able to make an initial public offering of its stock in July of 2018.[73]

It is worth bearing in mind that fuel-cell manufacturer Bloom Energy had to raise more than $1 billion over 17 years before being able to make an initial public offering of its stock in July of 2018.

DOE's national labs have the potential to support private-sector development of long-duration grid storage technology in a variety of ways. Spinoffs from PNNL, Argonne, and other national labs, for instance, may license federally-owned intellectual property and sustain collaborative relationships with lab research groups. DOE's Lab Embedded Entrepreneur Programs, such as Argonne's Chain Reaction Innovations, provide promising start-ups that originate elsewhere with access to lab experts and equipment. The national labs have a growing set of mechanisms for carrying out work on behalf of or in cooperation with private partners.[74] **DOE should continue to foster and simplify lab-company partnerships, including for long-duration grid storage.**

Loan guarantees are another tool the federal government can use to reduce risk and induce investment in first-of-a-kind commercial-scale facilities, as it did in the case of Crescent Dunes. The Energy Futures Initiative has reported that the authority to guarantee $3.6 billion of investment in energy efficiency and renewable energy projects remains unused.[75] **DOE should explore whether loan guarantees would assist "beyond lithium" long-duration grid storage technologies to achieve commercial viability in the next few years.**

Tax incentives for the purchase or use of new technologies could help them progress down the experience curve as they mature beyond R&D and demonstration. Deployment of renewable energy in the United States has been greatly aided by production and investment tax credits and accelerated depreciation. Storage systems charged by solar PV are now eligible for some of these incentives as well. For instance, a battery system that will draw 80 percent of its power from a solar array on the same site is eligible for a 24 percent investment tax credit. However, stand-alone energy storage systems are not eligible for this incentive.[76]

Congress should rationalize the tax incentive system as it bears on these technologies in two ways. On the one hand, the system should discriminate less by technology type; there is no analytically justifiable reason to systematically incentivize storage technologies differently than, say, generation technologies. On the other hand, it should discriminate more on the basis of technological maturity; as technologies mature, their incentives should sunset. Open-ended incentives can ultimately become a deterrent to innovation by locking in dominant designs.[77] **Congress should create a tax-incentive system that supports emerging technologies for long-duration grid storage, while eventually phasing out incentives for Li-ion batteries and other maturing technologies.**

Plan for Future Power Markets

The baseload challenge is ultimately a market test. The owners of long-duration grid storage assets will have to be able to make money by supplying electricity, and perhaps associated services, at an acceptable price.

The baseload challenge is ultimately a market test. The owners of long-duration grid storage assets will have to be able to make money by supplying electricity, and perhaps associated services, at an acceptable price. The United States currently has two ways of determining what price is acceptable. In about half of the country, wholesale markets managed by regional transmission organizations (RTOs) and regulated by the Federal Energy Regulatory Commission (FERC) set prices. In the other half, state public utility commissions (PUCs) do so. The decisions of these bodies will shape which technologies and business models for long-duration grid storage ultimately succeed.

Pumped-hydro systems participate in both RTO-managed and PUC-regulated markets today. They have historically been treated mainly as generating resources, and undervalued as storage resources. According to Aidan Tuohy of the Electric Power Research Institute (EPRI), most RTOs are moving toward fixing this inequity—for instance, making it easier for pumped-hydro systems to arbitrage wholesale price changes. PUCs, too, as documented by the Energy Storage Association, are becoming more sophisticated in how they value storage, such as in integrated resource plans (IRPs). **EPRI, DOE, and the National Hydropower Association have laid out a series of further steps to optimize existing storage resources that should be considered by FERC, RTOs, and PUCs**.[78]

Properly valuing existing pumped-hydro storage systems, most of which are more than 30 years old, should encourage the development of new facilities, even without further technological progress. Licensing reform might also foster new starts. Securing licenses from FERC and other federal and state environmental, energy, resource, and other agencies can take five years or more, which discourages potential applicants. **In particular, an expedited process for licensing for closed-loop pumped-hydro systems, which pose limited environmental risks, should be implemented.**[79]

The participation of long-duration grid storage technologies other than pumped-hydro in wholesale markets is likely to remain modest for a number of years. Some flow-battery companies have recently reported an increase in demand for six- to eight-hour systems, and have high hopes for the opportunities that will be unlocked in California as it moves toward its goal of 100 percent zero-carbon power. [80] Although the rest of the country trails California in achieved penetration of renewables as well as long-term emissions-reduction aspiration, it is vital that compensation mechanisms that will allow investors to realize value from long-duration storage assets be developed, so that these assets will be built as technologies mature and demand for their services emerges. **DOE should expand its work with FERC, RTOs, and states to plan for the fully decarbonized grid of the future (which will very likely incorporate a significant amount of long-duration storage) including study of and experimentation with new business models, market structures, and emerging technologies.**

CONCLUSION

Renewables and Li-ion batteries are making important contributions to decarbonizing electricity now, and these contributions will grow much larger. But the stakes in mitigating climate change are enormous—too large to warrant putting all of our technological bets on a restricted range of possible solutions. Long-duration grid storage technologies have the potential to unlock a wider range of decarbonization solutions, perhaps making grids that rely only on variable generation feasible. Taking action to explore these opportunities more aggressively today would be worthwhile to diversify the national and global energy technology portfolio against the risk of catastrophic failure tomorrow.

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ABOUT THE AUTHOR

David M. Hart is a senior fellow at ITIF and director of the Center for Science, Technology, and Innovation Policy at George Mason University's Schar School of Policy and Government, where he is professor of public policy. Hart is the author of numerous ITIF reports, academic journal articles, and books, including *Unlocking Energy Innovation* (MIT Press, coauthored with Richard K. Lester).

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