



Energy Storage for the Grid: Policy Options for Sustaining Innovation¹

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¹This paper was initially prepared for an expert workshop on energy storage hosted by the MIT Energy Initiative (MITEI) on December 7-8, 2017. The authors thank the participants for their comments during the workshop and on the initial draft of the paper. Thanks also to Martha Broad and Frank O'Sullivan of MITEI for sharing their insights and providing support for the workshop. The workshop did not seek a consensus, and the authors are solely responsible for the content of this paper.

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Executive Summary

The electric power sector must be transformed in the twenty-first century. The threat of climate change, and the difficulty of reducing carbon emissions from other sources, means that power sector emissions must fall to near zero. Grid-scale energy storage has the potential to make this challenging transformation easier, quicker, and cheaper than it would be otherwise.

A wide array of possibilities that could realize this potential have been put forward by the science and technology community. Grid-scale storage has become a major focus for public research and development (R&D) investment around the world. The public sector has also played a crucial role in moving some of these ideas from the laboratory into practice. In the United States, federal investments pushed storage technologies forward in the early 2010s, and state and regional initiatives provided a pull as the federal push slackened in the last few years.

The shift from federal push policies to regional and state pull policies coincided with the consolidation of the grid-scale energy storage market around lithium-ion (Li-ion) batteries. This technology now accounts for more than 90% of the global and domestic markets. It is relatively mature, compared to the battery alternatives, and benefits from large-scale use in electronics and, more recently, electric vehicles (EVs). These qualities have enabled rapid price-cutting for grid-scale applications. Most projections suggest that Li-ion batteries will dominate the grid-scale market as that market grows rapidly in the coming years.

This emerging situation runs the risk of technology “lock-in,” a characteristic pattern in the history of technology in which one “dominant design” drives out alternatives that would perform the same function. Lock-in may be beneficial because it accelerates process innovation and drives down costs for the dominant technology, which in turn expands adoption. In the case of energy storage, Li-ion batteries have begun to break through an older “legacy sector” paradigm that has hindered innovation in the electric power sector. What is needed now, in this interpretation, is to focus innovative effort on the dominant design and use it to transform the entire sector.

An alternative interpretation is that the risks of technology lock-in in grid-scale energy storage outweigh the benefits. One risk is excessive market concentration, which commonly follows the establishment of a dominant design. East Asian producers, notably recent Chinese entrants

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backed by government policies, are the most likely to consolidate control, especially if supply runs ahead of demand for an extended period.

An even more worrisome risk is that innovations that could improve on the dominant design become “stranded” and never fully mature. Li-ion batteries are well-suited to transportation applications, but not necessarily ideal for the grid. Lock-in on Li-ion batteries is already making it difficult for producers of alternative storage technologies to survive, much less continue to innovate and scale up.

Public policy-makers should take action to build on the opportunities and mitigate the risks identified by these two interpretations of the near future of grid-scale energy storage. The objectives of such action should include growing the grid-scale energy storage market overall, creating niches within the market in which a range of technologies have opportunities to establish their cost and value characteristics, and ensuring that R&D continues in order to expand the portfolio of technology options.

The evolving roles of the states, regions, and federal government create new opportunities to realize these objectives, but also complicate policy development and implementation. We argue that the *federal government* should expand funding for R&D, create tax incentives that focus on emerging technologies, support national and international processes that will lead to open standards, and counter unfair international trade practices. Policies that make sense for the *states as well as the federal government* include expanding support for demonstration projects and early deployment and providing financial assistance to help grid-scale energy storage hardware innovators overcome barriers to scaling up.

Important *state* policy options to accelerate grid-scale energy storage innovation include setting smart and ambitious overall targets for deployment while also setting subtargets that are reserved for alternatives to Li-ion batteries. *States along with regional organizations*, including regional transmission organizations (RTOs) as well as groupings of states, should revise their rules so that storage assets can participate fully in electricity markets, implement regulations that allow storage asset owners to receive compensation through multiple value streams, explore the development of market signals that reward the unique performance characteristics of alternatives to Li-ion batteries, oversee integrated resource plans and approve rate designs that encourage storage innovation and deployment, establish regional storage innovation and purchasing consortia, and form expert advisory systems to stay informed about storage technology options.

1. Introduction: Why Grid-Scale Energy Storage Matters

The electricity grid is essential to modern life. The global economy and international security depend on it. Most people in the world rely on it at work and at home, and most of those who still don't have its services want them. It is taken for granted much of the time, but when it breaks down, there is a crisis.

The grid came of age in the developed world in the twentieth century, but it is undergoing a transformation as it expands in the twenty-first. New supply resources, including distributed and

variable wind and solar generation, are rapidly gaining ground on more centralized and less flexible resources, like coal-fired power plants. Digital technologies are lowering the cost of aggregating and integrating such resources; they are also opening up new opportunities to manage demand. Thomas Edison would probably find the grid recognizable today, but he might well be baffled by it a couple of decades hence.

This nascent transformation is essential in light of the threat posed by climate change. If the world and the United States are to hit the target set by the Paris accord of an 80% reduction in greenhouse gas emissions from 2005 levels by 2050, the pace of transformation must be accelerated. In order to accommodate growing emissions from activities that are very hard to decarbonize (such as aviation and heavy industry), electricity generation must be nearly fully decarbonized. That means an even greater emphasis on energy efficiency in the future as well as much deeper penetration of renewables and other low-carbon resources. In addition, the grid worldwide must grow, not only to meet the urgent need for access among the energy poor, but also so that electricity can play a much larger role in providing vital services like transportation and heating than it has in the past.

Grid-scale energy storage matters because it has the potential to make this transformation much easier, quicker, and cheaper than it would be otherwise.² Storage can firm the output of renewables when the sun is shrouded or the wind is still. It can smooth the load curve, thereby avoiding costly investments in peak generation. It may substitute for transmission, again avoiding large costs. It can provide resilience against failures elsewhere in the system.

Nearly any plausible model of the low-carbon electricity grid of the future incorporates a healthy dose of storage to provide these diverse services. The “Two Degree Scenario” of the International Energy Agency (IEA), for instance, which serves as a benchmark for progress in decarbonizing the global energy system, calls for 21 gigawatts (GW) of advanced energy storage capacity to be installed by 2025.³ This target represents a massive expansion of capacity; during calendar year 2015, only half a gigawatt was installed. Yet, IEA’s model now looks conservative; Bloomberg New Energy Finance’s November 2017 forecast is for 125 GW of storage globally by 2030.⁴

In the United States alone, the Energy Storage Association (ESA) has called for “the deployment of more than 35 GW of new, cost-effective advanced energy storage systems” by 2025.⁵ Such a level is ambitious and could be transformative for the way the grid operates. While there are other ways to provide many of the services that storage can provide, such as “super-grids” and large-scale demand response, these alternatives may not be as flexible, responsive, and effective as storage.

² William Braff, Joshua Mueller, and Jessika Trancik, “Value of Storage Technologies for Wind and Solar Energy,” *Nature Climate Change* 6:964-969 (2016).

³ International Energy Agency (IEA), *Tracking Clean Energy Progress 2017* (Paris: IEA 2017), 62. This figure and the term “advanced energy storage” exclude pumped hydro storage, a technology that is well-established but no longer growing in the United States, as we discuss below.

⁴ Bloomberg New Energy Finance (BNEF), “Global Storage Market to Double Six Times by 2030,” November 20, 2017, <https://about.bnef.com/blog/global-storage-market-double-six-times-2030/> .

⁵ Energy Storage Association, “35 x 25: A Vision for Energy Storage,” 2017, 1.

The conclusion that storage will provide vital services to the grid on a large scale assumes that storage technologies continue to develop the way that optimists hope they will. That is not a sure thing. This concern may seem paradoxical, because some forms of grid-scale energy storage have evolved quickly in recent years. However, there is a real prospect that this progress will stall in the near future, because of technology “lock-in.”

Lock-in is a characteristic pattern in the history of industrial technology as one “dominant design” drives out competitors that could perform the same function. It may be beneficial because it accelerates process innovation and drives down costs for the dominant design, which in turn expands adoption. Thanks to this virtuous cycle, the emerging dominant design in energy storage, lithium-ion (Li-ion) batteries, has begun to break through an older “legacy sector” paradigm that has hindered innovation in the electric power sector.

However, technology lock-in also poses two major risks. The most worrisome is that lock-in may cut off promising innovation pathways that have the potential to out-perform the dominant design over the long run. Such “stranded” innovations never have the chance to fully mature. In the context of energy storage, technologies that are better-suited to grid applications may be locked out by Li-ion batteries.

Lock-in is often associated as well with the emergence of excessive market concentration. Competitors that are able to make massive, rapid investments in capacity for producing the dominant design accrue the bulk of the benefits from economies of scale and learning-by-doing. East Asian Li-ion battery producers, notably recent Chinese entrants backed by government policies, have already begun moving down this path and seem likely to continue, especially if supply runs ahead of demand for an extended period.

The energy storage challenge demands action from public policy-makers, and it comes at an interesting moment in this regard in the United States. The federal government, primarily through its network of research and development (R&D) agencies in the Departments of Energy and Defense, has long provided leadership in advanced energy technologies, such as nuclear power, solar photovoltaics, and hydraulic fracturing. The states’ historic role has been regulatory and focused on regional economic development. Regional wholesale electricity markets, which have matured in the past two decades, have focused largely on trying to get prices right.⁶

In the past year, the Trump administration has begun pulling back from energy innovation leadership, although Congress has tempered its most extreme proposals.⁷ At the same time, some states and regions have begun to exert their authority more aggressively to accelerate the implementation of grid-scale energy storage. If the momentum of the energy transformation is to be sustained, it appears that states and regions will need to play an even larger role in the future. If the federal government is moving away from its “top down” role, could a “bottom up” strategy led by states and regions (along with local governments and industry) provide an offset? Grid-scale storage may provide a critical case study to assess this “bottom up” model.

⁶ Richard K. Lester and David M. Hart, *Unlocking Energy Innovation* (Cambridge: MIT Press, 2012).

⁷ Laura Diaz Anadon, Kelly Simms Gallagher and John P. Holdren, “Rescue US Energy Innovation,” *Nature Energy* 2:760–763 (2017), <https://www.nature.com/articles/s41560-017-0012-0>.

In the next section, we briefly review the status of energy storage technologies. We then trace the progress of the grid-scale storage market. Section 4 provides the framework for understanding Li-ion batteries as a dominant design. We explore the benefits and risks of this situation moving forward in sections 5 and 6 before laying out a menu of potential policies for consideration by state, regional, and federal policy-makers in the concluding section.

2. Energy Storage Technologies

The electric power industry has grappled with the problem of how to store excess energy and release it when needed since the invention of the grid. As the grid evolves in the coming years and incorporates new generation resources and consumption patterns, various combinations of capacity, power, reliability, and cost effectiveness in storage technologies might prove useful. Many areas of resource use have long utilized storage to manage supply and demand, from food preservation technologies, silos, and warehouses to dams for water reservoirs. Technologies for storing electrons are only now developing at a scale where they could affect markets. Storage technologists continue to develop a wide variety of potential options to respond to these demands, including kinetic, electrochemical, and thermal technologies. Each of these three categories is in commercial use today and presents possible solutions at grid-scale in the future.

2.1 Kinetic Energy Technologies

By far the largest commercial grid-scale energy storage technology today is pumped hydropower storage (“pumped hydro”). Pumped hydro uses excess electricity generated during off-peak times to pump water from a lower reservoir to a higher reservoir. This water can then be transformed into electricity using traditional hydropower turbines when demand rises. Pumped hydro comprises the vast majority of installed storage capacity in the United States and globally.⁸ While pumped hydro is a highly useful, cost effective, and proven technology, its further expansion has been limited by its geographical requirements, environmental concerns, and high capital costs.

Compressed air energy storage (CAES) is similar to pumped hydro in that it relies on filling a physical reservoir by using excess electricity. As the name suggests, the reservoir, such as an underground cavern, is filled with compressed air that is later released to drive turbines. In the limited commercial applications of CAES to date, stored air is released and mixed with natural gas to generate electricity. Researchers are working on CAES without the addition of hydrocarbons, and with more efficient heating and pressurization systems, but this approach has not yet been commercialized.⁹

Flywheels use excess energy to drive the motion of a wheel suspended on bearings or magnets. The flywheel can then be slowed to produce energy. Flywheels have been in use for hundreds of years in various forms due to their simplicity, reliability, and responsiveness. They are most

⁸ U.S. Department of Energy (DOE), “Global Energy Storage Database,” accessed October 9, 2017, http://www.energystorageexchange.org/projects/data_visualization

⁹ Xing Luo, *et al.*, “Overview of Current Development in Compressed Air Energy Storage Technology,” *Energy Procedia* 62:603-611 (2014), <https://www.sciencedirect.com/science/article/pii/S1876610214034547>

commonly used today for industrial and commercial applications which require high discharge power, although a few grid-scale installations have been built.¹⁰

2.2 Electrochemical Technologies

The most familiar storage technology to most observers of the contemporary energy storage market is the Li-ion battery. Its lithium compound electrode and electrolyte structure recalls similar alkaline batteries that have been used to power consumer electronics for decades. The key difference is that Li-ion batteries are lighter and significantly more energy-dense than their alkaline counterparts.¹¹

Lead acid batteries are also familiar, due to their use in gasoline-powered-EV vehicles. They consist of two lead electrodes submerged in a liquid sulfuric acid electrolyte. Early grid-scale applications composed of stacked lead acid cells were plagued by safety issues.¹² Recent improvements to this 150-year-old technology include incorporating a gel or solid absorbed glass mat electrolyte instead of the standard liquid to improve safety, and the addition of ultra-capacitors to improve performance.¹³

Nickel-based batteries are similar to lithium-based batteries in their construction, but the use of nickel allows for different charging properties which suit distinct applications. Nickel cadmium, and the newer, less toxic, nickel metal hydride (NiMH) batteries provide improved energy and power compared to lead acid batteries and operate in a wider variety of temperature conditions and levels of discharge, but they have not been used much in grid-scale projects.

Electrochemical flow batteries, a relatively recent invention, dispense with the electrode and electrolyte system in favor of two circulating electrolyte fluids which exchange electrons directly across a shared membrane. These batteries are well-suited to grid-scale storage due to their relatively low energy density and power output. While some power is required for the operation of mechanical components, the battery itself has a low self-discharge rate and can increase scale simply by adding electrolyte volume. Significant investments in space and equipment are required to operate these batteries. While commercial flow battery projects within the United States are rare, the international market is rapidly expanding.¹⁴

¹⁰ Sandia National Laboratory, “Beacon Power. 20 MW Flywheel Energy Storage Plant Presentation Slides,” 2014, accessed October 9, 2017.

http://www.sandia.gov/ess/docs/pr_conferences/2014/Thursday/Session7/02_Areseneaux_Jim_20MW_Flywheel_Energy_Storage_Plant_140918.pdf; Diane Cardwell and Andrew Roberts, “The Biggest, Strangest ‘Batteries,’” *New York Times*, June 3, 2017, <https://www.nytimes.com/2017/06/03/business/energy-environment/biggest-batteries.html>

¹¹ Aristides E. Kiprakis and Markus Mueller, “A Numerical and Graphical Review of Energy Storage Technologies,” Institute for Energy Systems (IES), University of Edinburgh, 2015, <http://www.mdpi.com/1996-1073/8/1/172/pdf>

¹² Eric Wesoff, “Battery Room Fire at Kahuku Wind-Energy Storage Farm,” *Greentech Media*, August 3, 2012, <https://www.greentechmedia.com/articles/read/battery-room-fire-at-kahuku-wind-energy-storage-farm#gs.2wEwIkA>

¹³ Commonwealth Scientific and Industrial Research Organisation (CSIRO), “Case Study: Ultrabatteries,” accessed September 20, 2017, <https://www.csiro.au/en/Research/EF/Areas/Energy-storage/UltraBattery>

¹⁴ Vanadium Corporation, “Flow Battery Developer to Build World's Largest Battery Storage System,” press release, June 2016, <http://www.vanadiumcorp.com/news/grid-storage/414-flow-battery-developer-to-build-world-s-largest-battery-storage-system>; Jason Deign, “German Utility EWE Plans a Flow Battery Big Enough to Power

Liquid metal batteries combine the capacity and discharge of electrochemical cells with the stability of thermal salts. These batteries substitute liquid metallic electrodes and electrolytes for the traditional solid metal electrode lattice and electrolyte solution to create a more stable, higher energy density electrical cell. Similar to Li-ion batteries, liquid metal cells can be stacked into systems to provide various amounts of energy storage and high on-demand power supply. While total system heat generation can be prodigious, because the liquid metal reforms for each reaction, liquid metal batteries could significantly improve upon many of the reliability and safety concerns of standard electrochemical batteries.¹⁵

2.3 Thermal Storage

Thermal storage technologies employ cold or heat as an energy reservoir. Thermal salts, which are commonly associated with concentrating solar power (CSP) plants, use excess energy to heat a molten salt solution. The energy in this solution can be turned into electricity by heating steam, which drives a conventional turbine. No company has yet been able to disaggregate thermal salt storage from CSP due to the inefficiency of energy transfer, although new entrants continue to try.¹⁶

Thermal batteries store excess or passive solar energy as ice or heat which is then used to regulate temperatures for building cooling or heating. The wide-scale adoption of thermal batteries could act as a peak shaving or seasonal grid resource, although these sorts of solutions are rarely considered in the same category as other energy storage technologies.¹⁷

2.4 Energy Storage R&D

The full range of technological possibilities for energy storage has hardly been exhausted. The IEA's 2014 *Energy Storage Roadmap* called for continued public investment across the entire innovation chain from basic research to demonstration. Precise global funding data are not available, but it is notable that all members of the 2015 Mission Innovation initiative, which committed the world's leading R&D countries to double their investment, included energy storage in their portfolios. Breakthrough Energy Ventures, which was set up by an international group of deep-pocketed investors in parallel with Mission Innovation, identified grid-scale storage as one of its initial areas of focus as well.¹⁸

Berlin for an Hour," *Greentech Media*, July 20, 2017, <https://www.greentechmedia.com/articles/read/german-utility-plans-a-flow-battery-big-enough-to-power-berlin>

¹⁵ Donald R. Sadoway et al., "Liquid Metal Batteries: Past, Present, and Future," *Chemical Reviews*, November 27, 2012, http://sadoway.mit.edu/wordpress/wp-content/uploads/2011/10/Sadoway_Resume/145.pdf

¹⁶ ARPA-E, "Project Summary: Halotechnics Molten Glass For Thermal Storage," accessed September 20, 2017; <https://arpa-e.energy.gov/?q=slick-sheet-project/molten-glass-thermal-storage>; Raj B. Apte, "Malta: Pumped Hydro Without the Mountain," presentation to ARPA-E Long Duration Storage Workshop, December 8, 2017, <https://arpa-e.energy.gov/?q=workshop/long-duration-stationary-energy-storage>, accessed March 15, 2018.

¹⁷ Drake Landing Solar Community, "Borehole Thermal Energy Storage (BTES)," accessed September 17, 2017, <https://www.dlsc.ca/borehole.htm>

¹⁸ IEA, *Technology Roadmap: Energy Storage* (IEA: Paris, 2014); IEA, "Tracking," 87. The latter document includes a chart of public R&D spending with a category for "hydrogen/storage" on 72, but does not provide more specific data; Breakthrough Energy, "Initial Areas of Focus," accessed January 28, 2018, <http://www.b-t.energy/ventures/areas-of-focus/>.

In the United States, federal funding for energy storage R&D is spread across a number of agencies. Basic research in this field is supported by U.S. Department of Energy’s (DOE) Basic Energy Sciences Program within the Office of Science (including the Joint Center for Energy Storage Research (JCESR), a DOE energy innovation hub) as well as by the National Science Foundation (NSF). Several components within DOE’s applied energy offices support projects in this field as well, including the Energy Storage Program within the Office of Electricity Delivery and Energy Reliability (OE), which focuses on grid-scale applications. The Advanced Research Projects Agency – Energy (ARPA-E), an independent unit within DOE, has put about \$150 – 200 million into energy storage since it began operation in 2009, and it continues to emphasize this field. Finally, the Department of Defense supports an array of storage R&D programs across all of the military services, and it also supports demonstration projects at a number of its facilities.¹⁹

2.5 Comparing Storage Solutions

No storage solution is perfectly-suited for every potential application. Three sets of characteristics provide the basis for matching technology to need. The first is energy and power. At grid-scale, kilowatt-hours (kWh) measure the total available stored energy, while the power with which stored energy is supplied is denoted in kilowatts (kW). For example, a storage device rated at 5 megawatt-hour (MWh) and 10 megawatts (MW) would supply a half-hour of power at peak output. Such a device could be well-suited to smoothing variable renewables, but would not be well-matched to longer-duration or seasonal fluctuations in supply.²⁰

The second basis for comparison is reliability and durability. Many kinetic and thermal systems can operate indefinitely with routine maintenance, while electrochemical cells typically become depleted over time, necessitating replacement. Various cell system designs can improve the durability and longevity of electrochemical batteries at a cost, or systems can be replaced as they age. Storage technologies also vary in their short-term reliability and safety.²¹

¹⁹ No single public source documents all of the federal government’s energy storage R&D programs. The Office of Management and Budget carried out a “crosscut” in this area, the results of which were reported in graphical form in “Government-Wide Funding For Clean Energy Technology,” June 2015,

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiz8IPmhunXAhWGIOAKHXDPFAQFggpMAA&url=https%3A%2F%2Fobamawhitehouse.archives.gov%2Fsites%2Fdefault%2Ffiles%2Fomb%2Fbudget%2Ffy2016%2Fassets%2Ffact_sheets%2Fgovernment-wide-funding-for-clean-energy-technology.pdf&usq=A0vVaw3bGBEjkhHRzEPEt3923cBF. Approximately \$300 million was spent in this area in fiscal 2015. An August 2012 report from the Government Accountability Office (“Batteries and Energy Storage: Federal Initiatives Supported Similar Technologies and Goals but Had Key Differences,” <http://www.gao.gov/products/GAO-12-842>) found 39 initiatives in this field across six federal agencies, including NASA, EPA, and NIST as well as DOE, DOE, and NSF. On ARPA-E, see David M. Hart and Michael Kearney, “ARPA-E: Versatile Catalyst of U.S. Energy Innovation,” Information Technology and Innovation Foundation, November 2017, <https://itif.org/publications/2017/11/15/arpa-e-versatile-catalyst-us-energy-innovation>.

²⁰ On the economic advantages of longer-duration storage, see Fernando J. de Sisternes, Jesse D. Jenkins, and Audun Botterud, “The Value of Energy Storage in Decarbonizing the Electricity Sector,” *Applied Energy* 175:368–379 (2016). Presentations made at ARPA-E’s December 8, 2017, workshop on long-duration storage provide an overview of potential approaches to this challenge, accessed March 15, 2018, <https://arpa-e.energy.gov/?q=workshop/long-duration-stationary-energy-storage>.

²¹ Kandler Smith, *et al.* “Life Prediction Model for Grid Connected Li-ion Battery Energy Storage System,” paper presented at the 2017 American Control Conference, <https://www.nrel.gov/docs/fy17osti/67102.pdf>

Finally, cost efficiency and value generation are critical factors. Increasing effort has been devoted recently to computing the “levelized cost of storage” (LCOS) of various technologies.²² However, LCOS calculations rely on many simplifying assumptions, and project-specific factors will usually determine which, if any, storage solution makes sense. Figure 1 provides a more comprehensive overview of these factors, while Appendix A provides a detailed breakdown.

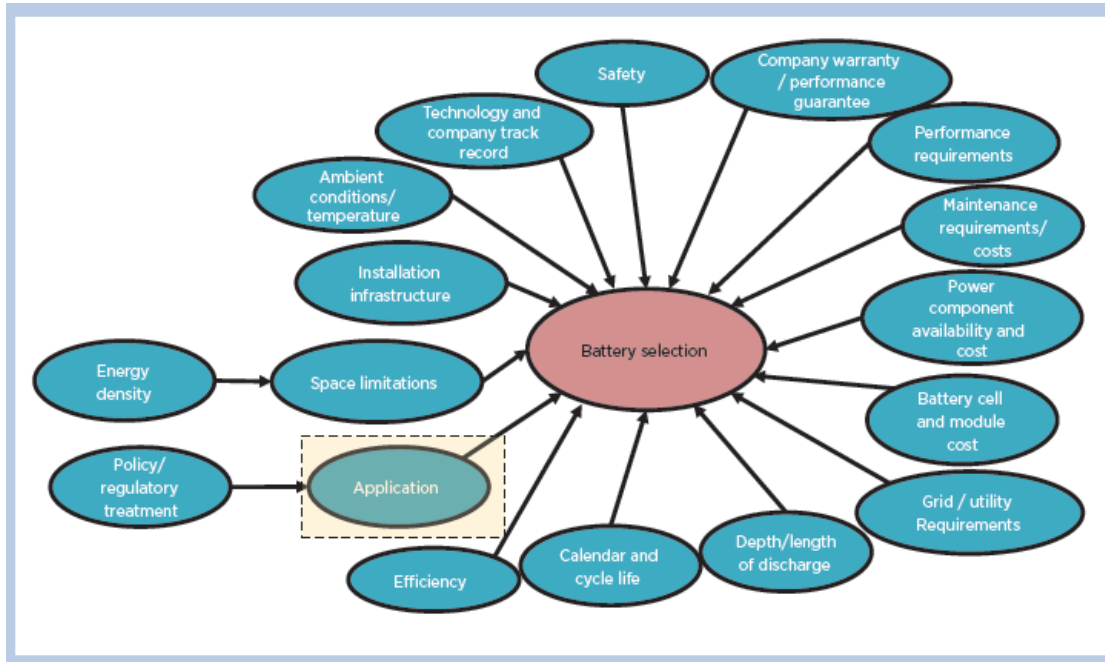


Figure 1: Important Considerations for Storage Technology Selection²³

3.0 The Nascent Grid-Scale Energy Storage Market and the Rise of Lithium-Ion Batteries

As recently as the 2000’s, the grid-scale storage market was made up of small one-off projects that used a diversity of technologies. Over the last five years, this market has grown rapidly in the United States and the rest of the world and has come to be dominated by Li-ion batteries. This growth was initially driven in the United States by short-duration applications in restructured wholesale markets. More recently, state procurement mandates have begun to drive larger-scale applications. Signs of interest have also appeared as well in states with vertically-integrated electric power markets. The driving forces globally are disparate, depending on local factors, but some form of public policy has been critical in most places. Japan and Germany, for instance, have subsidized behind-the-meter systems, often to complement renewables, whereas the United Kingdom has emphasized grid-scale applications.²⁴ The growth of the market and emerging dominance of Li-ion batteries can be seen in global and national data in figures 2 and

²² E.g., Lazard, “Lazard’s Levelized Cost of Storage Analysis Version 3.0,” November 2017, accessed March 15, 2018, <https://www.lazard.com/perspective/levelized-cost-of-storage-2017/>.

²³ International Renewable Energy Agency (IRENA), “Battery Storage for Renewables: Market Status and Technology Outlook,” January 2015, 9.

²⁴ IRENA, “Battery Storage,” 34-35.

3. Li-ion batteries have led the U.S. market since the end of 2013 and held a 98.8 percent market share in the fourth quarter of 2017.²⁵

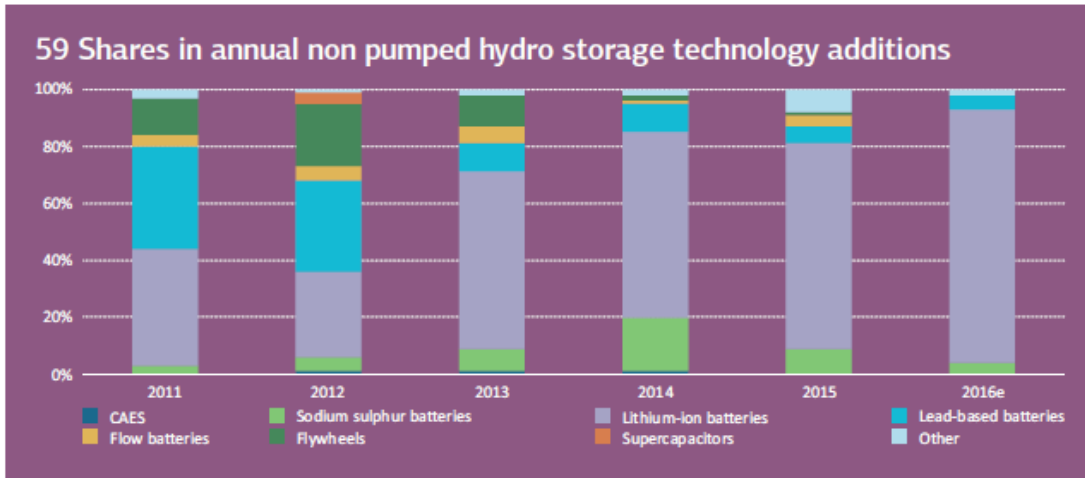


Figure 2: Shares in Global Non Pumped Hydro Storage Technology Additions, 2011-2016²⁶

²⁵ Mike Munsell, "US Energy Storage Market Tops the 1 GWh Milestone in 2017," *Greentech Media*, March 6, 2018 accessed, March 15, 2018, <https://www.greentechmedia.com/articles/read/us-energy-storage-market-tops-the-gwh-milestone-in-2017> .

²⁶ IEA, "Tracking," 63.

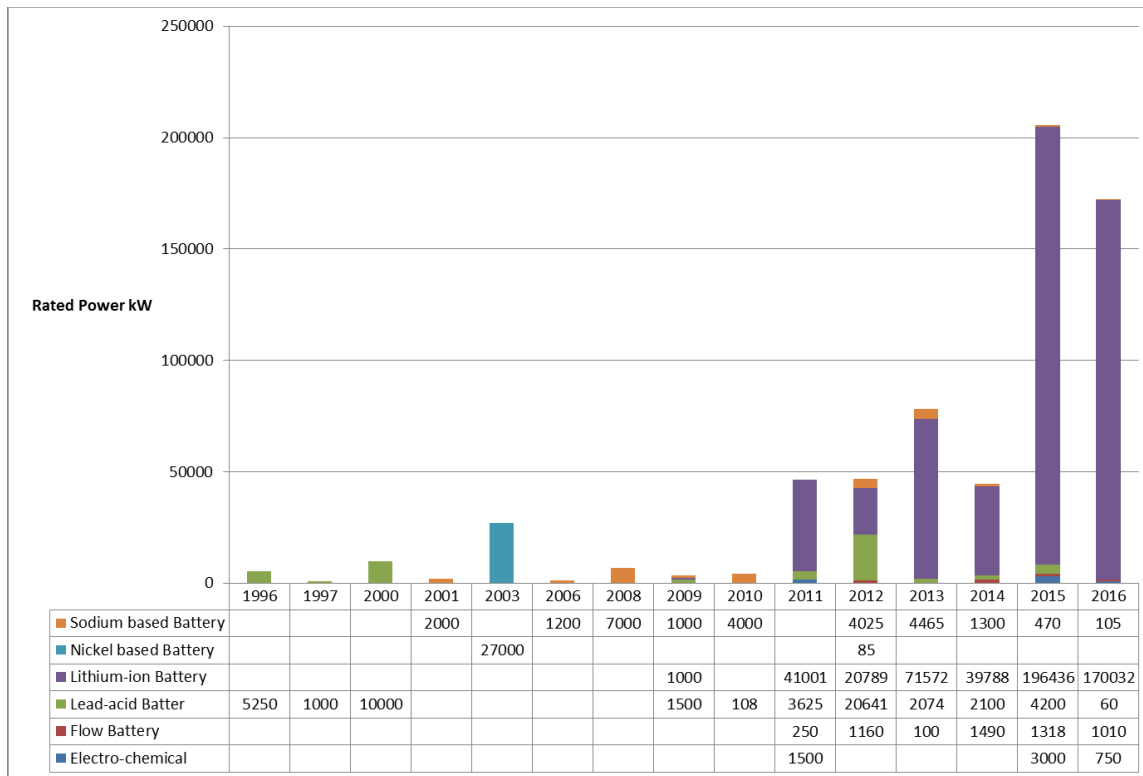


Figure 3: U.S. Battery Project Additions by Technology, 1996-2016²⁷

3.1 The Market to 2010

Pumped hydro storage was virtually the only technological option for grid-scale storage before this decade. Nearly 150 GW of pumped hydro was installed globally as of 2010, of which approximately 20 GW was in the United States. The first pumped hydro facilities were built in the 1930s, but no new capacity has been added in the United States in more than a decade.²⁸

Alternatives to pumped hydro before 2010 were confined largely to one-off projects in remote locations with unique requirements. For instance, one of the earliest large battery projects in the United States, which was completed in 1997, serves the Metlakatla community at the southern tip of the Alaska Panhandle.²⁹ Off-grid storage applications, which are typically paired with renewable generation as an alternative to diesel generators, remain important in islands and microgrids around the world.³⁰

²⁷ DOE, “Storage Database.”

²⁸ IEA, “Tracking,” 63; Federal Energy Regulatory Commission, “Pumped Storage Projects,” accessed November 18, 2017, <https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp> FERC has issued licenses for three proposed pumped storage projects since the beginning of 2014.

²⁹ Srinivas Bharadwaj, “Clean Energy Storage for Grid Load Leveling - The Metlakatla Battery Energy Storage System - Twelve Years Of Success,” in International Renewable Energy Agency Workshop on Assessment of Grid Stability for Increased Renewable Energy Integration in the Pacific, Port Vila, Vanuatu, 2012 <http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=30&CatID=79&SubcatID=200> accessed September 14, 2017.

³⁰ IRENA, “Battery Storage,” 12-14.

3.2 Federal Push, Regional Pull

Grid-connected energy storage began to grow toward more significant levels around 2010. The rising penetration of wind and solar power, along with the constraints on building more pumped hydro capacity, heightened interest in developing new options. “Green growth” initiatives funded by stimulus packages enacted in response to the global recession provided financial support to pursue many of these options. Energy storage systems were a major focus of South Korea’s green growth strategy, for instance.³¹

In the United States, DOE funded sixteen energy storage demonstration projects under the American Recovery and Reinvestment Act (ARRA) stimulus program. This program encompassed several technology classes including compressed air, flywheels, and a variety of battery chemistries. DOE’s Loan Program Office also provided a guarantee for a large flywheel storage system. IHS Research estimated in 2011 that about one-quarter of utility-scale battery projects, as measured by capacity, received ARRA funding.³²

State R&D and commercialization programs, such those in California and New York, also provided funding for storage demonstration projects as well as R&D in this period. California, for instance, funded twenty energy storage RD&D projects between 2010 and 2013, such as the Camp Pendleton Intelligent Microgrid Project.³³ New York seeded the New York Battery and Energy Storage Consortium (NY-BEST) in 2010 with \$25.5 million for R&D, testing, and characterization activities.³⁴

As the “push” of stimulus funding wound down, regulatory incentives “pulled” private investment into the energy storage market. In October 2011, the Federal Energy Regulatory Commission (FERC) issued order 755, which required Regional Transmission Organizations (RTOs) to change the way that their markets compensated fast-responding frequency regulation resources. FERC Order 784 reinforced this change two years later.³⁵

The PJM Interconnection, which runs the nation’s largest wholesale electricity market, took a particularly assertive approach to the implementation of these orders. By 2014, about 84 MW of large-scale, independently-owned battery storage capacity was participating in the short-duration PJM frequency regulation market, a figure that more than doubled in 2015.³⁶ (In February 2018,

³¹ Global Green Growth Institute, *Korea’s Green Growth Experience: Process, Outcomes and Lessons Learned* (GGGI: Seoul, 2015), 176.

³² Alex Klein and Thomas Maslin, “US Utility-Scale Battery Storage Market Surges Forward,” IHS Research, September 28, 2011, 7. Reports on ARRA-funded DOE demonstration projects are available at https://www.smartgrid.gov/recovery_act/program_impacts/energy_storage_technology_performance_reports.html.

³³ California Energy Commission, *Public Interest Energy Research Annual Report 2013*, March 2014, 30-35, <http://www.energy.ca.gov/2014publications/CEC-500-2014-035/CEC-500-2014-035-CMF.pdf>

³⁴ NASEO, “The New York Battery and Energy Storage Technology (NY-BEST) Consortium,” July, 2013, <https://www.naseo.org/data/sites/1/documents/publications/NASEO-Case-Study--NY-BEST.pdf>

³⁵ Peter Behr, “FERC Rulings Open Opportunities for Storage Technologies,” *E&E News*, December 9, 2013, <https://www.eenews.net/stories/1059991463>

³⁶ DOE, “Storage Database.”

FERC issued order 841, requiring that RTOs make it easier for storage resources to participate in all energy, capacity, and ancillary services markets.³⁷⁾

3.3 The Emergence of State Storage Demonstration and Deployment Policy

State procurement mandates, especially California's, drove the U.S. grid-scale energy storage market in 2016 and 2017. California bill AB 2514, which was enacted in 2010, required the state's investor-owned utilities to procure 1,325 MW of storage by 2020 under the supervision of the California Public Utility Commission (CPUC).³⁸ The program was given further impetus by the failure of a gas storage facility at Aliso Canyon in southern California in October 2015. The situation prompted an expedited procurement of 84.5 MW of energy storage in May 2016. These projects were completed in early 2017, demonstrating that large battery facilities could be built quickly. All are 4-hour duration, much longer than usually employed in PJM, and use Li-ion batteries.³⁹ Governor Brown recently added another 500 MW to the mandate.⁴⁰

Following California's lead, Massachusetts conducted a comprehensive review of energy storage opportunities in 2016 and set an aspirational target of having 200 MWh installed by 2020.⁴¹ New York announced a target in January 2018 of 1500 MW installed by 2025.⁴² In all, the Interstate Renewable Energy Council (IREC) found that twenty states across all regions of the country had taken one or more actions to accelerate deployment of energy storage, as shown in Figure 4. The group includes states with vertically-integrated power markets, such as North Carolina and Minnesota, as well as those that have restructured these markets, like California, Massachusetts, and New York.

³⁷ The Brattle Group's early estimate is that order 841 could catalyze the installation of 7 GW of energy storage capacity. See Roger Lueken, *et al.* "Getting to 50 GW? The Role of FERC Order 841, RTOs, States, and Utilities in Unlocking Storage's Potential," Brattle Group, February 22, 2018.

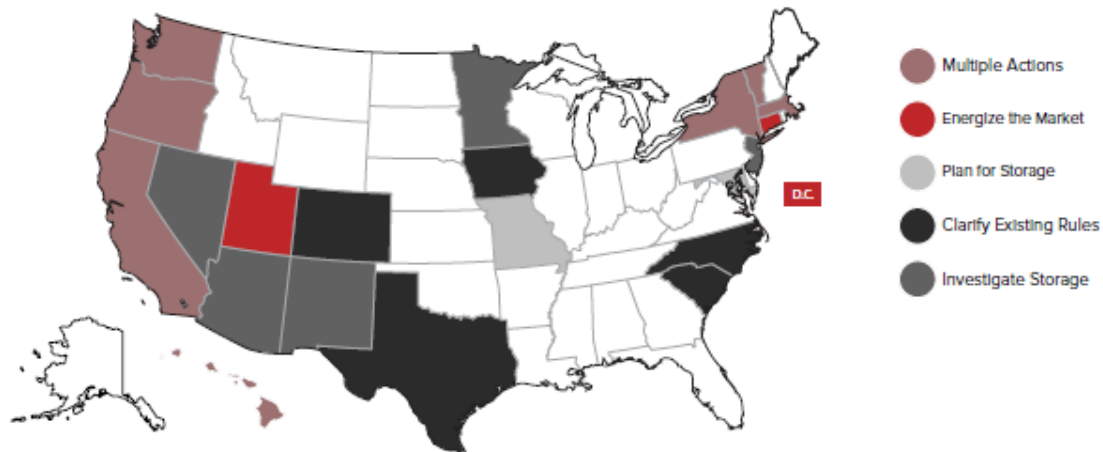
³⁸ Interstate Renewable Energy Council, "Charging Ahead: An Energy Storage Guide for Policymakers," April 2017, 23.

³⁹ GTM Research, "U.S. Energy Storage Monitor: Q4 2016 Full Report," December 2016, 35-41.

⁴⁰ Andy Colthorp, "'Global Leader' California's Main Utilities Given Additional 500MW Energy Storage Procurement Target." *Energy Storage News*, May 4, 2017, <https://www.energy-storage.news/news/global-leader-californias-main-utilities-given-additional-500mw-energy-stor>

⁴¹ Julian Spector, "The Long-Awaited Massachusetts Storage Target Has Finally Arrived," *Greentech Media*, June 30, 2017, <https://www.greentechmedia.com/articles/read/the-massachusetts-energy-storage-target-has-finally-arrived> ; Judith Judson, MITEI storage workshop presentation, December 8, 2017.

⁴² New York Governor's Office, "Governor Cuomo Unveils 20th Proposal of 2018 State of the State: New York's Clean Energy Jobs and Climate Agenda," January 2, 2018, <https://www.governor.ny.gov/news/governor-cuomo-unveils-20th-proposal-2018-state-state-new-yorks-clean-energy-jobs-and-climate> accessed January 28, 2018; Alicia Barton, MITEI storage workshop presentation, December 8, 2017.



Note: Map is not reflective of all state activities on energy storage. Certain early stage policy/regulatory efforts, grant programs and/or pilot projects may not be reflected herein.

Figure 4: Map of State Policy Actions on Energy Storage⁴³

3.4 2016: A Turning Point?

These developments prompted some observers to label 2016 a “turning point” for the grid-scale storage market.⁴⁴ Figure 4 above, which runs from 1996 to 2016, includes a cumulative total of just over 650 MW of storage capacity that was deployed during that period. About 500 MW more came on-line in 2017, virtually all of it Li-ion batteries.⁴⁵

Globally, the pattern is similar. Energy storage is one of the few technologies that the International Energy Agency reports as being “on track” to meet its 2 Degree Scenario by 2025, with Li-ion batteries accounting for approximately 90% of today’s market. IHS Markit estimated in April 2017 that the global pipeline for grid-scale energy storage was 3,400 MW, representing a doubling over the previous year.⁴⁶

4.0 The Future of Lithium-Ion Batteries

Lithium-ion battery technology is relatively mature, it is flexible, and it has large-scale applications outside the still-modest grid-scale storage market. These features have enabled rapid price-cutting in recent years that have allowed the technology to build market share. Looking ahead, many observers believe that continued falling costs will fuel an explosion of privately-financed growth in the use of Li-ion batteries for grid-scale energy storage, which would entrench it as the dominant design in this market.

⁴³ IREC, “Charging,” 17.

⁴⁴ Herman K. Trabish, “Is Battery Energy Storage at a Turning Point for U.S. Utilities?,” *Utility Dive*, April 11, 2017, <http://www.utilitydive.com/news/is-battery-energy-storage-at-a-turning-point-for-us-utilities/440055/>

⁴⁵ ESA, “35 x 25,” 1; ESA and GTM Research, “U.S. Energy Storage Monitor: Q2 2017 Executive Summary,” 6.

⁴⁶ Sam Wilkinson, “Global Battery Energy Storage Pipeline Reaches 3.4 GW in Q1 2017,” IHS Markit, April 4, 2017, <https://technology.ihs.com/590967/global-battery-energy-storage-pipeline-reaches-34-gw-in-q1-2017>

Li-ion batteries derived a considerable first mover advantage from large-scale use since the early 1990s in consumer electronics, a sector it now dominates. The expectation of rapid growth in the deployment of electric vehicles (EVs) has been the primary driver of improvements in Li-ion batteries recently, and this emerging market will continue to provide an advantage over alternative technologies in the near future.⁴⁷ Lithium's relatively light weight and high power density, unmatched by alternative energy storage technologies, are even more significant advantages in vehicle applications than in consumer electronics.

The EV market is likely to sustain the virtuous cycle between scale and innovation that has benefited Li-ion battery technology in the recent past.⁴⁸ Increasing scale has been provided by massive investments by companies around the world. According to *The Economist*, "The top five manufacturers...are ramping up capital expenditure with a view to almost tripling capacity by 2020."⁴⁹ The vast majority of this growth is expected to be in Asia, particularly China.⁵⁰ Government commitments to the transition to EVs are accumulating quickly as well, adding further momentum to the scale-up of the Li-ion battery industry. China, India, France, and the United Kingdom, among others, announced timelines for the elimination of internal combustion vehicle sales during 2017. California was said to be considering joining this list.⁵¹

Larger scale production of Li-ion batteries should trigger further manufacturing process innovation. In order to achieve cost efficiencies, innovators in the United States and elsewhere are testing modifications to the traditional production line, in which a metal film is coated with electrode materials and run through a series of special purpose ovens.⁵² MIT researchers propose instead to use a gelled electrode and streamlined assembly process to achieve similar results at a fraction of the cost of current facilities.⁵³

Product innovation is also accelerating. The redesign process generally focuses on varying the chemistry of the cell's electrodes. Substituting manganese for cobalt, for example, would make the battery more chemically stable at the cost of some energy capacity. Replacing graphite with silicon in anodes would significantly improve energy density. Changing the lattice structure of

⁴⁷ Gert Berckmans *et al.*, "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," *Energies* 10, 1314 (2017), <http://www.mdpi.com/1996-1073/10/9/1314/pdf>

⁴⁸ Noah Kittner, Felix Lill, and Daniel M. Kammen, "Energy Storage Deployment and Innovation for the Clean Energy Transition," *Nature Energy* 2, art. no. 17125 (2017) <https://www.nature.com/articles/nenergy2017125>

⁴⁹ *The Economist*, "After Electric Cars, What More Will It Take for Batteries To Change the Face of Energy?," August 12, 2017, <https://www.economist.com/news/briefing/21726069-no-need-subsidies-higher-volumes-and-better-chemistry-are-causing-costs-plummet-after>

⁵⁰ M. Steen *et al.*, *EU Competitiveness in Advanced Lithium-Ion Batteries for E-Mobility and Stationary Storage Applications: Opportunities and Action*, (JRC Science Hub, 2017).

⁵¹ Ryan Beene and John Lippert, "California Mulls Following China with Combustion Engine Car Ban," September 26, 2017, accessed January 28, 2018, <https://www.bloomberg.com/news/articles/2017-09-26/california-mulls-following-china-with-combustion-engine-car-ban> .

⁵² George E. Blomgren, "The Development and Future of Lithium Ion Batteries," *Journal of the Electrochemical Society* vol. 164, iss. 1, 2017, <http://jes.ecsdl.org/content/164/1/A5019.full>

⁵³ Steve Levine, "The Story of the Invention That Could Revolutionize Batteries—And Maybe American Manufacturing as Well," *Quartz*, June 22, 2015, <https://qz.com/433131/the-story-of-the-invention-that-could-revolutionize-batteries-and-maybe-american-manufacturing-as-well/>

the electrode may provide more reaction surface and thus more energy capacity. Substituting one electrode for atmospheric air might drastically improve the energy density of the battery.⁵⁴

The virtuous circle of scale and innovation is moving this technology rapidly down the experience curve, which correlates cumulative production with falling cost and price.⁵⁵ In some applications, some forecasters anticipate battery pack prices as low as \$100/kWh as early as 2020. (See Figure 5 below.) This price level would make it difficult for alternative storage technologies to Li-ion to compete. In Lazard's recent assessment of the levelized cost of storage, Li-ion batteries dominated all current use cases. GTM Research anticipates that four-hour Li-ion systems will be competitive with gas combustion plants for new peaking capacity in the United States by 2022 and dominate this segment by 2027. IHS Markit forecasts that Li-ion batteries will be the standard storage technology for at least the next ten years.⁵⁶

However, predictions about future prices vary significantly.⁵⁷ Figure 5, compiled by researchers at the National Renewable Energy Laboratory in 2016, shows a range of projected prices for Li-ion battery packs from 2015 through 2030. Outlying analysts differed by a factor of five in 2020 and three in 2030.

⁵⁴ Hitoshi Maruyama et al., "Improving Battery Safety by Reducing the Formation of Li Dendrites with the Use of Amorphous Silicon Polymer Anodes," *Scientific Reports* 5: 13219 (07 Aug 2015); Sa Li et al., "High-rate Aluminium Yolk-Shell Nanoparticle Anode for Li-Ion Battery with Long Cycle Life and Ultrahigh Capacity," *Nature Communications* 6:7872 (05 Aug 2015); Francois Ozanam and Michel Rosso, "Silicon as Anode Material for Li-ion Batteries," *Materials Science and Engineering B* 213:2-11 (2013).

⁵⁵ Peter Fairley, "2017 Is the Make-or-Break Year for Tesla's Gigafactory," *IEEE Spectrum*, December 30, 2016, <https://spectrum.ieee.org/transportation/advanced-cars/2017-is-the-makeorbreak-year-for-teslas-gigafactory>; Elizabeth Woyke, "24M's Batteries Could Better Harness Wind and Solar Power," *Technology Review*, June 21, 2016, <https://www.technologyreview.com/s/601500/24ms-batteries-could-better-harness-wind-and-solar-power/>; David Feldman, et al., "Exploring the Potential Competitiveness of Utility Scale Photovoltaics plus Batteries with Concentrating Solar Power, 2015–2030," National Renewable Energy Laboratory, August 2016, <https://www.nrel.gov/docs/fy16osti/66592.pdf>

⁵⁶ Vincent Sprenkle, MITEI storage workshop presentation, December 8, 2017; Lazard, "Lazard's Levelized Cost of Storage Analysis Version 3.0," November 2017; Ravi Manghani, "Will Energy Storage Replace Peaker Plants," GTM Research webinar, March 1, 2018; IHS Markit, "Global Grid-Connected Energy Storage Capacity to Double in 2016, IHS Markit Says," July 28, 2016 <https://technology.ihs.com/582088/global-grid-connected-energy-storage-capacity-to-double-in-2016-ihs-markit-says>

⁵⁷ Oliver Schmidt, et al., "The Future Cost of Electrical Energy Storage Based on Experience Rates," *Nature Energy* 2, art no. 17110 (2017), <https://www.nature.com/articles/nenergy2017110>

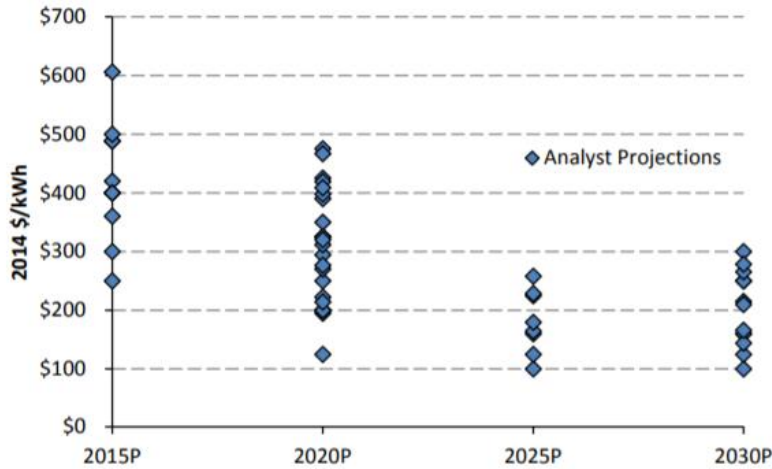


Figure 17. Price estimates for Li-ion battery pack, 2015–2030

Sources: BNEF 2015b; Gandolfi et al. 2015; Lee et al. 2015; Nykvist and Nilson 2015

Figure 5: Price Estimates for Li-ion Battery Pack, 2015-2030⁵⁸

5.0 Lithium-Ion Batteries as a Dominant Design: A Beneficial Process?

Of the rich range and still-evolving array of grid-scale energy storage technology options, then, one stands out as uniquely-positioned. Li-ion batteries are rapidly approaching technological and price readiness for mass adoption. Innovation scholars describe this situation as having the potential for technology “lock-in.” Lock-in is a characteristic pattern industrial history in which one “dominant design” drives out competing technologies that could perform the same function.⁵⁹ The successful design’s advantages become self-reinforcing over time, while the alternatives are relegated to small niches or eliminated.

Lock-in may be beneficial because it accelerates innovation within the dominant design paradigm and drives down costs. In doing so, it may break through the barriers that have kept a prior legacy paradigm in place. One interpretation of the contemporary situation in energy storage is that it should be celebrated for this reason. Li-ion batteries have just begun to enter the electric power sector in force, and continued price declines and market growth lie ahead. Now is the time to accelerate the invasion and use this bridgehead to transform the sector.

5.1 Beneficial Lock-In: Theory

A dominant design emerges over time out of a set of technological options from which users may choose. Dominance may be the result of objective price and performance characteristics as well

⁵⁸ Feldman, *et al.*, “Exploring,” 18. Workshop participants expressed widely divergent views about the expected future cost of Li-ion battery systems for grid applications.

⁵⁹ James M. Utterback and William J. Abernathy, “A Dynamic Model of Process and Product Innovation,” *Omega* 3:639-656 (1975); James M. Utterback, *Mastering the Dynamics of Innovation* (Cambridge, MA: Harvard Business School Press 1994).

as perceived potential that form a rational basis for users' adoption decisions. (We explore cases in which user decisions are less rational in the next section.) These decisions may be the result of open competition within a well-functioning market. They might also be determined by non-market processes that are run by objective experts, for instance, within standards organizations or in regulatory settings.

Social processes complement the economic and technological forces that drive adoption of the dominant design in such cases. For instance, users gain confidence in the dominant design's quality and performance, and workers are trained to use it effectively. "Network" effects emerge, in which rising usage increases the value and utility of the new technology to each user. Policy-makers may contribute to a design's dominance by providing government support for it.

When a dominant design is superior in price, performance, and potential, there is little to be gained from pursuing alternatives. Society benefits from focusing resources on it, deepening its techno-economic strengths. In particular, process innovation accelerates and prices decline in this phase of the technology lifecycle, because key product parameters are taken for granted by producers and users. This phase is also associated with a shakeout of producers; process innovation typically involves rapid increases in the scale of production, which squeezes out less competitive and financially weak producers.⁶⁰

These insights helped to form the basis of Clayton Christensen's work on disruptive innovation, in which new technologies create the opportunity for new entrants to create new markets.⁶¹ Entrants, writes Christensen, "gain a foothold by delivering more-suitable functionality— frequently at a lower price....When mainstream customers start adopting the entrants' offerings in volume, disruption has occurred."⁶² If the virtuous circle of scale-up, innovation, and cost declines that we described above continues, Li-ion batteries (along with other distributed resources) could disrupt the electric power sector.

5.2 Lithium-ion Batteries and the Challenges of Innovation in a Legacy Sector

Electric power is a legacy sector that is highly resistant to the entry of disruptive innovations. Legacy sectors are very different from frontier sectors, like information technology and biotechnology, which are more open to innovation. Utilities, which are the key players in the power sector, tend to be conservative and risk-averse, inclinations that are usually reinforced by regulators and legislators who shape their decision-making. The established paradigm in this sector evolves slowly through incremental advances in existing technologies and the cautious deployment of complementary new technologies that sustain the dominant design.⁶³

⁶⁰ Utterback, *Mastering the Dynamics*.

⁶¹ Clayton M. Christensen, Fernando F. Suárez, and James M. Utterback, "Strategies for Survival in Fast-Changing Industries," *Management Science* 44:S207-S220 (1998).

⁶² Clayton M. Christensen, Michael E. Raynor, and Rory McDonald. "What Is Disruptive Innovation?," *Harvard Business Review*, December 2015, <https://hbr.org/2015/12/what-is-disruptive-innovation>.

⁶³ William B. Bonvillian and Charles Weiss, *Technological Innovation in Legacy Sectors* (MIT Press: Cambridge, MA, 2015), 15-17, 33-38, 58-60.

This pattern is evident in the sector's recent history. Utilities tend to be technologically conservative, a frame of mind that is strongly reinforced by regulators.⁶⁴ Vendors who supply equipment to the power sector are well aware of their customers' conservatism and take it into account in their own product strategies. Digital technologies, which have fully penetrated many other economic sectors, have made slow progress in this one. "Many utilities," write McKinsey's power sector consulting team, "see the digital revolution as a threat to their business model."⁶⁵ Even the apparently revolutionary technology of hydraulic fracturing ("fracking"), which has unlocked vast reserves of shale gas, was long resisted by the incumbent energy industry, even though it is largely compatible with the existing paradigm.⁶⁶

The barriers that must be overcome before energy storage can take off are far more daunting than those that confronted fracking. For example, the grid is designed primarily for one-way flows from generators to customers, but storage, along with other distributed assets, depends on two-way flows that require additional investments in complementary infrastructure. Laws and regulations may classify storage devices as generation assets and arbitrarily limit the services that they can provide and who may own them. Market designs and rate regulators typically fail to fully value the services that storage can provide and make it difficult for storage asset owners to earn adequate compensation, inhibiting the introduction of new business and financial models. Incumbent providers may exercise their leverage with legislators and regulators to block or slow changes that would lower these barriers.⁶⁷

Li-ion batteries are beginning to break through such barriers.⁶⁸ Along with sustained drops in the technology's cost and improvements in its performance, significant effort will need to be exerted to remake the social, political, and institutional context for its widespread adoption. The number of states, for instance, that have aggressive storage policies can be counted on the fingers of one hand. Few utilities have yet incorporated storage into their planning processes⁶⁹. "Value-stacking," compensation of storage assets for multiple services, which is held by many analysts

⁶⁴ Lester and Hart, *Unlocking*.

⁶⁵ Adrian Booth, Niko Mohr, and Peter Peters, "The Digital Utility: New Opportunities and Challenges," May 2016, <https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/the-digital-utility-new-opportunities-and-challenges> accessed January 28, 2018.

⁶⁶ Michael Shellenberger et al., "Where the Shale Gas Revolution Came From: Government's Role in the Development of Hydraulic Fracturing in Shale" (Breakthrough Institute, May 2012), http://thebreakthrough.org/archive/shale_gas_fracking_history_and; Loren King et al., "Lessons from the Shale Revolution: A Report on the Conference Proceedings" (Breakthrough Institute, April 2015), http://thebreakthrough.org/archive/shale_gas_fracking_history_and.

⁶⁷ Garrett Fitzgerald, James Mandel, Jesse Morris, and Hervé Touati, "The Economics of Battery Energy Storage," Rocky Mountain Institute, September 2015, http://www.rmi.org/electricity_battery_value; Ryan Hledik, Roger Lueken, Colin McIntyre, and Heidi Bishop, "Stacked Benefits: Comprehensively Valuing Battery Storage in California," Brattle Group, September 2017, http://www.brattle.com/system/publications/pdfs/000/005/494/original/Stacked_Benefits_-_Final_Report.pdf?1505226490; Gridwise Alliance, "Advancing Batteries to Enhance the Electric Grid Chapter One: Front-of-Meter Applications," July 2017.

⁶⁸ As one workshop participant put it, "no one ever got fired for buying a diesel generator."

⁶⁹ Will Driscoll, "Making the Case for Energy Storage in Integrated Resource Planning," *Greentech Media*, December 1, 2016, <https://www.greentechmedia.com/articles/read/making-a-case-for-energy-storage-in-integrated-resource-planning#gs.yflahCY>; Julian Spector, "Arizona Regulators Freeze New Gas Plants, Demand More Clean Energy Planning From Utilities," *Greentech Media*, March 16, 2018, <https://www.greentechmedia.com/articles/read/arizona-regulators-freeze-new-gas-plants-renewables-planning>

to be the key to sustainable deployment, is largely a theoretical construct, rarely realized in practice. As the Gridwise Alliance put it in a 2017 report, “Although batteries have the potential to offer numerous value streams to enhance the electric grid’s efficiency and operations, existing laws, regulations, and market treatment...artificially restrict batteries from leveraging and maximizing their multiple capabilities, resulting in missed opportunities and substantial lost value.”⁷⁰

It might reasonably be argued that any worry about lock-in within the storage sector obscures the larger and far-from-achieved objective of breaking legacy barriers within the electric power sector writ large. The imperative from this perspective is to accelerate the process of storage technology diffusion, and consolidation on a dominant design may be the best way to do that. Commodification of Li-ion batteries and accelerated process innovation could shift the target of product innovation to the system level, including thermal and power controls, management software, and interfaces with the rest of the power system, which might yield great benefits for users.

6.0 Risks of Lock-In

An alternative interpretation of today’s energy storage market suggests that the risks of lock-in outweigh the likely benefits. One major risk is market dominance, as the shake out that follows the entrenchment of a dominant design reduces competition among producers. A second and even more worrisome risk is “stranded innovation,” in which promising innovation pathways with the potential to out-perform the dominant design over the long run are shut down.

A premise for this argument is that the dominant design is not the result of intrinsically superior price, performance, and potential, but rather contingent managerial, political, and social processes. Historians have found that such contingencies can account for the dominance of particular designs in key energy technologies of the past, including the internal combustion engine, light water nuclear reactor, ethanol-based biofuels, and silicon-crystalline solar panels. As energy analyst Varun Sivaram puts it: “Dominant designs can emerge for a variety of reasons unrelated to technological merits.”⁷¹

The risks and benefits of lock-in in the case of Li-ion batteries must be judged with particular care because of the duration and importance of the climate challenge. The transition to a low-carbon energy system is different than other technology challenges that the United States has faced: it will take much longer. The Manhattan Project lasted four years, and the Apollo moonshot, nine. In contrast, the development of low-carbon energy technologies will take at least several decades.⁷² The stakes in this case warrant leaning in favor of keeping alternatives to the

⁷⁰ Gridwise Alliance, “Advancing Batteries,” iii-iv.

⁷¹ Varun Sivaram, “Unlocking Clean Energy,” *Issues in Science and Technology*, Winter 2017, <http://issues.org/33-2/unlocking-clean-energy/>.

⁷² IEA, *Energy and Climate Change – World Energy Outlook Special Report*, June 2015, 105-130, <http://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf>

dominant design as healthy as possible, if for no other reason than as an insurance policy in case the price and performance trajectory of Li-ion batteries should plateau unexpectedly.

6.1 The Risk of Market Dominance

There are some indications that a shake-out has begun in the energy storage industry. A small number of large firms, backed by governments, especially in East Asia, are the largest suppliers of Li-ion cells and components. They have committed significant resources to scaling up production and controlling upstream inputs. Market analysts anticipate further vertical integration in this sector.

LG Chem, Samsung and Panasonic are the longest-established major Li-ion battery producers, serving as the primary suppliers for Nissan, Tesla, and Chevrolet electric vehicles, among others. Although they are now diversifying their factory locations, the strength of these firms have allowed Japan and Korea to run very large trade surpluses in Li-ion cells.⁷³ Chinese firms have entered the industry at very large scale in recent years, serving both home and export markets, and like their Asian counterparts, beginning to establish overseas production platforms.⁷⁴ (See Figure 6 below.) BYD is the largest of these new entrants, and it is also the world's largest maker of electric vehicles.⁷⁵ CATL, which was founded in 2011 in Ningde in Fujian province, has grown rapidly into the third largest producer and may soon leapfrog into first.⁷⁶ A 2017 report from the Yano Research Institute in Tokyo found that Chinese firms were rapidly consolidating their control over global markets for key components and materials.⁷⁷

Figure 6: Planned and Existing Battery Cell Production Capacity⁷⁸

⁷³ Steen, *EU Competitiveness*, 9.

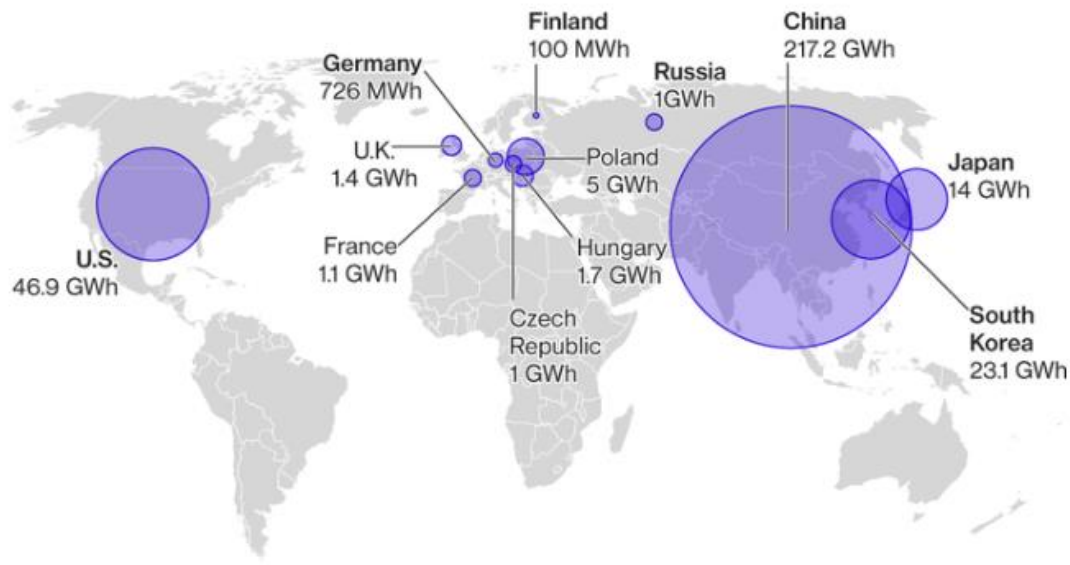
⁷⁴ Joe Ryan, "China Is About to Bury Elon Musk in Batteries," *Bloomberg*, June 28, 2017, <https://www.bloomberg.com/news/articles/2017-06-28/china-is-about-to-bury-elon-musk-in-batteries>; Henry Sanderson, Tom Hancock and Leo Lewis, "Electric Cars: China's Battle for the Battery Market," *Financial Times*, March 5, 2017, <https://www.ft.com/content/8c94a2f6-fdcd-11e6-8d8e-a5e3738f9ae4>

⁷⁵ Matthew Klippenstein, "Tesla Is Playing Catch-Up with China's BYD in Nearly Every Business Category," *Greentech Media*, August 9, 2017, <https://www.greentechmedia.com/articles/read/tesla-is-playing-catch-up-with-chinas-byd#gs.A1dppTw.xY1IsSU>.

⁷⁶ Reuters, "China Battery Giant CATL Plans \$2 Billion IPO To Fund Expansion," November 14, 2017, <https://www.reuters.com/article/us-china-catl-batteries/china-battery-giant-catl-plans-2-billion-ipo-to-fund-expansion-idUSKBN1DE0I4>; Jie Ma, *et al.*, "The Breakneck Rise of China's Colossus of Electric-Car Batteries," *Bloomberg BusinessWeek*, February 1, 2018, <https://www.bloomberg.com/news/features/2018-02-01/the-breakneck-rise-of-china-s-colossus-of-electric-car-batteries>

⁷⁷ James Ayre, "China Has 75% Of Electrolyte Solution Market & 75% Of Anode Materials Market," *CleanTechnica*, September 2017, <https://cleantechnica.com/2017/09/20/china-75-electrolyte-solution-market-75-anode-materials-market-key-lithium-ion-battery-components/>

⁷⁸ Ma *et al.*, "Breakneck Rise."



Source: Bloomberg New Energy Finance, CATL IPO prospectus

Bloomberg

Asian battery manufacturers have benefited from concerted government efforts on their behalf. The Korean government, for example, has set a target of controlling 30% of the global market in 2020, while cutting costs by half.⁷⁹ China’s central government published its first national plan for the battery industry in October 2017, setting the goal of becoming an “technologically independent storage superpower” and reinforcing its effort to create a massive electric vehicle market.⁸⁰ Domestic battery producers receive preference under these policies; for instance, only electric vehicles powered by BYD and CATL batteries were allowed to receive subsidies under guidance issued in 2016.⁸¹ A Bloomberg analyst states, “This is about industrial policy. The Chinese government sees Li-ion batteries as a hugely important industry in the 2020s and beyond.”⁸²

⁷⁹ APEC Energy Working Group, “Research on Energy Storage Technologies to Build Sustainable Energy Systems in the APEC Region,” June 2017, 28. Korean firms LG and Samsung top Navigant’s Q1 2018 Leaderboard for grid-tied energy storage, <https://www.navigantresearch.com/research/navigant-research-leaderboard-lithium-ion-batteries-for-grid-storage>

⁸⁰ Jonas Nahm, MITEI storage workshop presentation, December 8, 2017; China Energy Storage Association, “China Releases First National Level Policy Document Guiding Storage Industry Development,” October 24, 2017, <http://en.cnesa.org/featured-stories/2017/10/24/china-releases-first-national-level-policy-document-guiding-storage-industry-development>

⁸¹ Steen, *EU Competitiveness*, 15; Sanderson, Hancock, and Lewis, “Electric Cars;” Mark L. Clifford, “Chinese Government Subsidies Play Major Part In Electric Car Maker BYD’s Rise,” *Forbes*, July 26, 2016, <https://www.forbes.com/sites/mclifford/2016/07/26/with-a-little-help-from-its-friends-lavish-chinese-government-help-for-top-electric-car-maker-byd/2/#4c9a1fb123a5> ; Ma, *et al.*, “Breakneck Rise.”

⁸² Colin McKerracher, Bloomberg New Energy Finance, quoted by Ryan, “China.” See also: *Wall Street Journal*, China’s Road to Electric Car Domination is Driven in Part by Batteries, Oct. 21, 2017, <https://www.wsj.com/articles/chinas-road-to-electric-car-domination-is-driven-in-part-by-batteries-1508587203>; Thomas J. Duesterberg, “5G: China’s Dream to Dominate World Technology,” *The Globalist*, December 19, 2017, <https://www.theglobalist.com/china-united-states-europe-technology-internet>

In the United States, Tesla has been developing synergies between solar power, electric vehicles, and energy storage, both in front of and behind the meter. Tesla's electric vehicles and solar panels are currently assembled in two "gigafactories," taking advantage of the potential for joint learning effects, infrastructure, and economies of scale in the supply chain. Although Tesla is projected to have the world's second largest Li-ion battery manufacturing capacity in 2030, it remains dependent on its suppliers, especially Panasonic, for cells and is unlikely to develop a wholly independent production line in the near future.⁸³

The risk of market dominance is raised by the prospect that the supply of batteries, particularly from China, will outstrip demand for them. The consulting firm Wood McKenzie projects that production capacity in 2020 will be two and a half times larger than demand; demand will not catch up until 2028.⁸⁴ Although the Chinese central government has begun to develop policies that would increase domestic demand for grid-scale storage, provincial and local governments have stronger incentives to support production than consumption.⁸⁵ The imbalance between domestic supply and demand may lead to dumping of Li-ion batteries on the world market, repeating the experience of the solar panel market of the early 2010s. Foreign competition was decimated in that episode, leaving Chinese producers with 65% of global production in solar panels in 2016.⁸⁶

6.2. The Risk of "Stranded Innovation"

The prospect of a rerun in batteries of the recent history of solar industry points to the second major risk of lock-in: "stranded innovation." The flood of cheap imported crystalline-silicon solar panels from China in the past decade helped to undermine the commercial prospects for next generation solar technologies. The rate of new company formation and venture capital support for innovative solar manufacturing plummeted. Although basic and applied research has continued in academic and government settings, the industry itself is "laser-focused on cutting costs," in the words of Varun Sivaram. "This approach looks set to fuel continued growth in the coming years," he continues, "but it is not at all conducive to the innovation the industry needs to pursue to brighten solar's long-term prospects."⁸⁷

⁸³ Himanshu Goenka, "Tesla Chooses Samsung Over Panasonic For World's Largest Battery In Australia." *International Business Times*, October 1, 2017, <http://www.ibtimes.com/tesla-chooses-samsung-over-panasonic-worlds-largest-battery-australia-2595988>; Clair Curry, "Lithium Ion Battery Costs," *Bloomberg New Energy Finance*, July, 20, 2017, 5, <https://about.bnef.com/blog/lithium-ion-battery-costs-squeezed-margins-new-business-models/>; See also Jason Deign, "Bosch Abandons EV Battery Making as Asian Firms Dominate," *Greentech Media*, March 6, 2018, <https://www.greentechmedia.com/articles/read/bosch-abandons-ev-battery-manufacturing>

⁸⁴ Wood McKenzie, "The Rise of the Electric Car: How Will it Impact Oil Power and Metals," GTM Research, December 2017, <https://www.greentechmedia.com/research/report/the-rise-of-the-electric-car-how-will-it-impact-oil-power-and-metals>; Emma F. Merchant, "3 Charts that Illustrate the Impact of EVs on Batter Supply, the Electric Grid and Oil Supply," *Greentech Media*, December 14, 2017, <https://www.greentechmedia.com/articles/read/three-hockey-stick-charts-that-illustrate-the-coming-impact-of-evs>

⁸⁵ Jonas Nahm, MITEI storage workshop presentation, December 8, 2017.

⁸⁶ U.S. International Trade Commission, *Crystalline Silicon Photovoltaic Cells*, publication 4739, November 2017, p. IV-7.

⁸⁷ Matthew Stepp and Robert D. Atkinson, "Green Mercantilism: Threat to the Clean Energy Economy," Information Technology and Innovation Foundation, June 2012; Sivaram, "Unlocking Clean Energy;" Varun Sivaram, *Taming the Sun: Innovations to Harness Solar Energy and Power the Planet* (MIT Press, 2018), 29. Analysts have long noted that when a technology locks-in and production shifts abroad, innovation in the technology at home gets curtailed. Erica R.H. Fuchs, On the Relationship between Manufacturing and Innovation: Why Not All

Stranded innovation seemed unlikely to industry observers just a couple of years ago. A 2015 Deloitte study, for instance, projected that flow batteries would dominate grid-scale storage by 2030, with hydrogen-based storage emerging thereafter to a leading position.⁸⁸ Alternative storage technologies could improve upon the dominant design in a variety of ways. Although the technology may improve, Li-ion battery cells today are prone to over-heating and are limited in their durability, cycle life, depth of discharge, charging time, and other metrics which negatively impact their performance, particularly in grid applications. Materials requirements alone may set a floor on cost reductions.⁸⁹ Long-duration storage, which will be critical for deep penetration of variable renewable generation, is a particular challenge for Li-ion battery systems.⁹⁰

To these concerns must be added uncertainty about material supply chains for the current generation of batteries. Although lithium itself is relatively abundant, other key inputs, especially cobalt, are supply constrained and sourced from unstable locations, such as the Democratic Republic of the Congo.⁹¹ While these weaknesses are being addressed and may be overcome through innovations in battery chemistry and cell construction, they bear consideration in the context of increasing global demand. A 2016 editorial in *Nature Energy* concluded that “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.”⁹²

Many alternative technologies have been demonstrated with some promising results. A number of experts believe that vanadium redox flow batteries, for instance, could become cost-competitive with Li-ion batteries for grid applications, while lasting far longer.⁹³ Makers of liquid metal batteries are working toward storage solutions they state will be less expensive,

Technologies Are Created Equal,” October 8, 2012, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2103827; Chia-Hsuan Yang, Rebecca Nugent, and Erica R.H. Fuchs, “Gains from Others’ Losses: Technology Trajectories and the Global Division of Firms,” Carnegie-Mellon University, August 2014,

<http://repository.cmu.edu/cgi/viewcontent.cgi?article=1157&context=epp>

⁸⁸Deloitte Development LLC, “Energy Storage: Tracking the Technologies That Will Transform the Power Sector,” 2015, 12, <https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-er-energy-storage-tracking-technologies-transform-power-sector.pdf>

⁸⁹ Craig Irwin and David Bradwell, MITEI storage workshop presentations, December 8, 2017.

⁹⁰ Sisternes *et al.*, “Value of Energy Storage.” See also presentations by Paul Albertus and Marco Ferrara at ARPA-E’s December 8, 2017, workshop on long-duration storage, accessed March 15, 2018, <https://arpa-e.energy.gov/?q=workshop/long-duration-stationary-energy-storage> .

⁹¹ Daniel H. Doughty and E. Peter Roth. “A General Discussion of Li Ion Battery Safety,” *Electrochem. Soc. Interface* vol. 21, iss. 2, Summer 2012, 37-44, <http://interface.ecsdl.org/content/21/2/37.short> ; Diego Lisbona and Timothy Snee, “A Review of Hazards Associated with Primary Lithium and Lithium-ion Batteries,” *Process Safety and Environmental Protection* 89:434-442 (2011),

<http://www.sciencedirect.com/science/article/pii/S095758201100067X> ; Rahul Verma, *et al.* “Battery Materials Value Chains Demand, Capacity and Challenges” Center For Energy Economics, April 2016,

http://www.beg.utexas.edu/energyecon/thinkcorner/CEE_Research_Note-Battery_Materials_Value_Chain-Apr16.pdf ; Mark Burton, “How Batteries Sparked a Cobalt Frenzy and What Could Happen Next,” Bloomberg New Energy Finance, December 18, 2017, <https://about.bnef.com/blog/how-batteries-sparked-a-cobalt-frenzy-and-what-could-happen-next/>

⁹² “Foundations for the Future,” *Nature Energy*, vol. 1, art. 16147, <https://www.nature.com/articles/nenergy2016147>

⁹³ Z. Gary Yang, “It’s Big and Long-Lived, and It Won’t Catch Fire: The Vanadium Redox Flow Battery,” *IEEE Spectrum*, Oct. 26, 2017, <https://spectrum.ieee.org/green-tech/fuel-cells/its-big-and-longlived-and-it-wont-catch-fire-the-vanadium-redoxflow-battery> ; Sprengle presentation.

safer, and more reliable than Li-ion batteries for grid-scale applications.⁹⁴ Passive thermal storage could reduce the demand for energy in heating and cooling systems, while active thermal storage systems might provide long-duration, dispatchable power resources.⁹⁵

Whether these alternative technologies have the chance to supplant Li-ion batteries at grid-level will depend on their ability to serve market niches in direct competition with the emerging dominant design. That, in turn, will depend not only on the needs of utilities, independent power providers, and other grid-scale customers, but also on policy and market design decisions. It was the creation of a more robust market for ancillary services by PJM under a mandate from FERC, for example, that kick-started the grid-scale storage market in 2011. Policies that place value on particular applications for which alternatives are best-suited or directly preserve market share for them could send reassuring signals to investors in alternative storage technologies in the face of intense cost pressure from glutted global markets.

At the moment, however, alternative technologies face the threat of a vicious cycle that parallels the virtuous cycle that is fueling improvements in Li-ion batteries. The companies that build the alternatives are under-capitalized, buyers have difficulty financing projects that use them, and public policy-makers neglect them. Even when these companies are able to get a foothold in the market, they have difficulty scaling up production due to the high capital requirements and long lead times required. The shift of production to the lowest-cost sites undermines innovation investment in more research-intensive locations like the United States.⁹⁶

The sharp decline in venture capital (VC) funding for “hard” technologies, such as battery manufacturing, over the past few years is an indication of that this cycle may be taking hold.⁹⁷ VC-funded start-up businesses, often building on breakthroughs generated with federally-funded R&D, have played a central role in translating innovative technologies into market-ready products across a variety of industrial sectors, such as software and biotechnology. However, hard technology companies have different attributes than software or biotechnology start-ups and lack a well-defined VC model.

The “cleantech” VC boom and bust of the late 2000s and early 2010s demonstrates the point. A variety of factors made the sector appear promising for investment: high oil prices, growing environmental awareness, and an economy that had seen steady growth in the years after the dot-com bubble. But these factors were not sustained, and cleantech VC investors suffered major losses as a result.⁹⁸ The bust fell disproportionately on energy hard technology firms. In 2006,

⁹⁴ Bradwell presentation.

⁹⁵ ARPA-E, workshop on long-duration storage, December 8, 2017, <https://arpa-e.energy.gov/?q=workshop/long-duration-stationary-energy-storage>, accessed March 15, 2018. Priorities for longer-range research were articulated in DOE, Office of Science, Basic Energy Sciences Program, *Next Generation Electrical Energy Storage*, December 2017, which reports on a March 2017 workshop.

⁹⁶ William B. Bonvillian and Peter L. Singer, *Advanced Manufacturing – The New American Innovation Policies* (Cambridge, MA: MIT Press, 2017), 57-58.

⁹⁷ Peter S. Singer and William B. Bonvillian, “Innovation Orchards: Helping Tech Startups Scale,” Information Technology and Innovation Foundation, March 2017, 1-17, <http://www2.itif.org/2017-innovation-orchards.pdf>

⁹⁸ Benjamin Gaddy, Varun Sivaram, and Francis O’Sullivan, *Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation* (working paper, MIT Energy Initiative, Cambridge, MA, July 2016), <http://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf>.

such firms received many more investments and much more funding than energy-related software firms, but a decade later this pattern was reversed, establishing a new normal for this sector.⁹⁹

Traditional financing channels, including VC and corporate funding, may not be sufficient to sustain alternative storage technology manufacturers in the United States. While federally-funded basic research remains essential for the creation of new technologies, the processes of commercializing and scaling up these capital-intensive technologies may require new solutions. “Green banks,” “innovation orchards,” and similar public-private partnerships¹⁰⁰ may be able to help bridge these gaps, but they require strong local commitment and funding. It is worth noting that foreign firms have been active in acquiring failing U.S. energy storage start-ups, which may exacerbate these issues.¹⁰¹

Putting all of these components together yields a worrisome scenario. Rising concentration, oversupply for an extended period, foreign government support, and the demise of entrants championing alternative technologies could be a perfect storm for lock-in that strands innovation in this vital field.

7.0 Policy Options

Technology lock-in, to summarize, brings both opportunities and risks. It has been a beneficial process in many industries, driving mass adoption through standardization and cost reduction. In doing so, however, it has sometimes led to market dominance and stranded innovation by precluding potentially promising alternative technologies from reaching their full potential. Grid-scale energy storage seems to be on the brink of locking-in on Li-ion batteries, if it has not already done so.¹⁰²

As we have argued, lock-in is not always the result of rational user choices based on the intrinsic characteristics of competing technologies. It may be contingent on decisions made by governments, businesses, and other actors for other reasons. Because grid-scale storage is so vital for the transition to a low-carbon energy system, policy-makers should engage stakeholders in a dialogue about policy options that would mitigate the risks of lock-in without undermining the cost trajectory and rapid diffusion of the emerging dominant design.

The objectives of such policies should include:

⁹⁹ Hart and Kearney, “ARPA-E.”

¹⁰⁰ Coalition for Green Capital, “Green Bank 101,” <http://coalitionforgreencapital.com/whats-a-green-bank-html/>; Singer and Bonvillian, “Innovation Orchards.”

¹⁰¹ Joe Napsha, “Aquion Energy Will Move to China, Close Westmoreland Plant at Former Sony Site,” *Trib Live*, September 18, 2017.

¹⁰² For a perspective from two IEA analysts that is congruent with ours, see Simon Bennett and Luis Munuera, “Commentary: Who Wants To Be in Charge?,” [iea.org](https://www.iea.org/newsroom/news/2017/november/commentary-battery-production---who-wants-to-be-in-charge.html), November 21, 2017, <https://www.iea.org/newsroom/news/2017/november/commentary-battery-production---who-wants-to-be-in-charge.html>

- *Sustained growth in the grid-scale energy storage market.* Sustained growth is a fundamental precondition for Li-ion batteries to continue down the experience curve, and it also makes it more likely that there will be a vibrant market if alternative storage technologies can evolve.
- *Diversification of segments and use cases that make up the storage market.* Growth alone may be less important for the prospects for averting lock-in than the emergence of segments and use cases that value features (such as duration and durability) on which the alternative technologies are most likely to out-perform the dominant design.
- *Open standards that allow diverse storage technologies to “plug and play” in any system.* The hardware and software that connect storage devices to the grid should be a platform for competition among evolving technologies, rather than being packaged with the devices in integrated systems that limit technology choice.¹⁰³
- *Complementary public and private investment in research, development, demonstration, and early deployment of emerging storage technologies.* The energy storage innovation system should yield a continual stream of potential alternatives to the dominant design. The public sector should share the risks of storage product and process innovation, but on a declining basis as each technology matures, taking a large share of the risk in the research phase and sunsetting its support when the technology has been a given a chance to establish a foothold in a competitive market.
- *Fair competition among energy storage technology vendors.* Technology choice by customers should not be subverted by government subsidies to vendors or by the exercise of political power to restrict the options available to customers to preferred vendors.

Achieving these objectives is a shared responsibility across all levels of government in the United States. The federal government has historically propelled advanced technology development and remains a significant repository of expertise, but has signaled that it will pull back from this leadership role. States are increasingly adopting forward-leaning energy storage policies and are in position to exercise greater influence in the future. Regions are also likely to play a growing role in shaping the future of the storage industry.

Top priorities for the *federal government* are to:

- *Expand funding for storage R&D.* Although some states, such as California and New York, have made modest investments in R&D, only federal government invests in it on the required scale to move this technology forward. Congress should continue to support storage R&D on a larger scale than in the past.
- *Create tax incentives for energy storage that focus on emerging technologies.* Tax incentives are a good tool for risk sharing with early adopters of new technologies, but, in general, they should not remain in place once technology risks have been eliminated. Congress should

¹⁰³ Doosan GridTech, “Making Utility-Integrated Energy Storage a Used, Useful and Universal Resource,” September 2017, 5.

create a tax incentive system that supports emerging storage technologies and phases out as they mature, excluding the dominant design while encouraging more advanced alternatives.¹⁰⁴

- *Support national and international processes that will lead to open standards.* The private sector typically leads the standard-setting process in the United States; international processes are more likely to include national governments as well as industry. The federal government should make its support of open standards for storage system integration known at both levels and share evidence to back its position.
- *Work with international allies to counter unfair trade practices.* Global trade has the potential to accelerate both innovation and diffusion of storage technologies, but the innovation impact depends on effective rules that limit subsidies and other policies that may tilt the playing field. The administration should collaborate with partners globally to establish and enforce such rules that take into account differences across end uses and the storage value chain.

Key policies that make sense for *the states as well as the federal government* are to:

- *Expand support for storage demonstration projects and early deployment.* Demonstration projects and early deployment are critical for establishing the viability of new segments and use cases. Government agencies should continue to fund, wholly or partially, projects that serve unique system loads (such as health facilities and military bases that have high value and cannot tolerate service interruptions) while also creating knowledge of value to other potential users.
- *Provide financial assistance to help storage hardware innovators overcome barriers to scaling up.* Private institutions in the United States are poorly positioned to finance costly and lengthy manufacturing scale-up. Within the constraints imposed by international trade rules, public institutions like “green banks” should work with private partners to fill this gap.

Uniquely important *state* policy options to accelerate storage innovation in the United States are to:

- *Set smart and ambitious targets for storage deployment.* States have detailed information about the grid at the distribution as well as transmission levels and unique legal authorities. They should use these resources as well as their relationships with stakeholders to devise targets and to set forth pathways that will lead to the targets’ achievement.
- *Establish subtargets that are reserved for alternative storage technologies.* Much as solar carve-outs in renewable portfolio standards aided solar power to compete with wind power, technology-restricted subtargets can create niches that are temporarily sheltered from

¹⁰⁴ Although federal tax credits focused on storage technologies have been proposed, they are not in place now. However, storage currently benefits from accelerated depreciation under the Modified Accelerated Cost Recovery System and from the investment tax credit when paired with a renewable energy systems and charged primarily by those systems. These provisions do not distinguish among the types of storage technology employed.

competition with the dominant design. States should use this mechanism to support long-duration and other grid-scale applications for which the alternative storage technologies have greater long-run potential.

States along with regional organizations, notably RTOs but also issue-specific regional groupings of states, should take action to:

- *Revise rules so that storage assets can participate fully in electricity markets.* The unique attributes of storage technologies are rarely fully utilized and may even be detrimental in current market designs. Products and price formation processes should be designed so that storage can compete on a level playing field with generation and demand response assets. FERC order 841 will help catalyze these revisions.
- *Implement regulations that allow storage asset owners to receive compensation through multiple value streams.* The storage market will grow more quickly if assets are fully compensated for all the services that they can provide. Regulators and grid operators should encourage such compensation, while protecting the system from risks that could emerge if storage assets are expected to provide multiple incompatible services simultaneously.
- *Explore the development of products and market signals that reward the unique performance characteristics of alternative storage technologies.* Such signals could complement or provide an alternative to state-level subtargets in order to establish competitive niches for alternatives to Li-ion batteries, for instance for long-duration or seasonal storage as renewable penetration rates rise.
- *Oversee integrated resource plans and approve rate designs that encourage storage innovation and deployment.* Utilities are increasingly expected to incorporate grid modernization and decarbonization into their long-range plans. They should be encouraged by regulators and other oversight bodies to incorporate storage into these plans and, where functionally appropriate, encourage adoption of non-Li-ion technologies.
- *Establish regional storage innovation and purchasing consortia.* Storage device makers may need to surpass a minimum threshold of orders to remain viable. States (and local governments) should explore working together, and perhaps with other actors as well, to coordinate purchasing for storage projects at state facilities and when contributing to privately owned demonstration projects.
- *Form an expert advisory system to stay informed about storage technology options.* Storage technologies are evolving quickly. States should share resources, including expertise from the national laboratories as well as industry and academia, so that they take the latest high-quality information into account in their decision-making.

We have articulated a complex policy agenda for bridging the innovation gap in energy storage. In addition to spanning levels of government, it involves multiple agencies within each level and requires engagement with the private sector and with international actors as well. Yet, the prize

for working through this agenda is a big one: an easier and cheaper transition to a low-carbon energy future.

Appendix A: Summary of Grid Storage Technologies Comparison Metrics

Metric	Hydro	Flywheel	Lead-acid	NMH	Thermal	Li	Advanced Li (etc)	Flow	Liquid Metal	Compressed Air
Specific Energy (kW/kg)	.3 - 1.33	5-200	30-50	30-90	10-250	90-250	unknown	10-90.0	100-240	3.2-60
Energy Density (kWh/volume)	.5-1.33	.25-424	25-90	38.9-300	25-370	94-500	unknown	5.17-70	150-345	.4-20
Specific Power (W/kg)	.001-.12	400-30,000	25-415	50-1,000	10-30.0	8-2,000	unknown	5.5-166	14.29-260	2.2-24
Cycle life	20-50k	Indefinite	200-2,000	300-10,000	Indefinite	500-10,000	2,000-5,000	10,000+	5,000-10,000+	5,000-20,000+
Useful Life	50-60	20	10-15	5 to 10	20+	5 to 15	unknown	5 to 20	10	25-40
Lifecycle comments	Near universal life with maintenance	Near universal life with maintenance	Useful life varies by depth of discharge and application, variations by chemistry	Allows deeper depth of discharge and more stable storage, variations by chemistry	Thermal salts not yet proven, passive storage varies by technology	Useful life varies by depth of discharge and other applications, variations by chemistry	New chemistries not fully proven	Moving parts require replacement intermittently	Not yet proven	Near universal life with maintenance
Cost per kwh	\$1-291	\$200-150,000	\$50-1,100	\$100-1,000	\$1-137	\$200-4,000	unknown	\$100-2000	\$150-900	\$1-140
Environmental Impact	High/Mixed	Low	High	High/Med	Low	High/Med	High/Med	Medium	Low	Low/Med
Pros	Large power capacity, positive externalities	Very fast response, high specific power, low cost, long life	Mature technology with established value proposition	Deep discharge capacity, reliable, high energy density	Could pair with waste heat generation, scalable, low cost, large scale	Flexible uses, very fast response and high specific power	Unknown comparison to standard Li	Large storage capacity, cheap materials	High capacity, fast response, cheap materials, highly stable, temperature tolerant	Low cost, large scale, mature technology paired with gas turbines
Cons	Geographically limited, expensive construction, low energy density and environmentally damaging	Low energy density	Low lifecycle, toxic materials, flammability risk	Some toxic variations, less specific power than Li, high self-discharge, high memory effect	Not fully commercialized or not electrified	Safety Concerns, Low depth of discharge, Corrosion, self-discharge, and efficiency loss over time	Unknown comparison to standard Li	Space requirements, Economic efficiency in multiple applications	Untested in commercial use, persistent technology issues	Geographically limited, not scalable

¹A Numerical and Graphical Review of Energy Storage Technologies. Siraj Sabihuddin *, Aristides E. Kiprakis and Markus Mueller Institute for Energy Systems (IES), School of Engineering, University of Edinburgh, 2015. <http://www.mdpi.com/1996-1073/8/1/172/pdf>

²The Future of Solar Energy. MIT Energy Initiative. 2015. pg 293. <https://energy.mit.edu/wp-content/uploads/2015/05/MITEI-The-Future-of-Solar-Energy.pdf>

