Deployment of Grid-Scale Batteries in the United States

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Executive Summary

This study describes the deployment of grid-scale batteries in the U.S. using data from the DOE Global Energy Storage Database and provides an interpretation of the patterns revealed in these data. This technology has followed a diffusion pathway that is characteristic of rapidly-growing industries. In the 1990s and early 2000s unique projects were undertaken, and there was no evident trend in battery chemistry or application. 2009-2014 can be seen as a period of ferment, in which diverse chemistries were tried out in diverse applications, often with risk-sharing support from government agencies and incentives from regulators. The end of this period saw a shakeout. Lithium-ion chemistry for frequency regulation ascended in prominence, and by 2015, it had become dominant, even as the market grew exponentially. Looking forward, however, limits to this trajectory are apparent, and another period of ferment may be required to bring other chemistries to maturity to serve other applications.

Key Takeaways

1. Before 2009, the cost/risk/benefit profile of grid-scale battery projects deterred all but the most motivated buyers:
   - There are only 9 projects in the database from this period.
   - Early projects used well-established technologies from incumbent suppliers for unique applications, such as
     - A remote and environmentally-sensitive National Park Service installation at Lake Powell, Utah, and
     - A remote community on the Alaska Panhandle.
   - Later projects all used sulfur-sodium batteries produced by NGK.
     - Four projects developed by AEP sought to establish that firm's leadership position,
     - But the cost of this technology did not decline in subsequent years, nor was its value demonstrated as a result of these projects.

2. Public investment was an important enabler of the period of ferment from 2009 to 2014, facilitating risk-taking by project developers.
   - 124 projects were commissioned in this period, employing a wide variety of chemistries and ownership structures, across many regions and applications.
     - The American Recovery and Reinvestment Act (ARRA) is the most commonly-identified funding source for projects in this period.
     - State R&D and commercialization programs, such as those in New York and California, also supported many projects.

3. Lithium-ion chemistry emerged as a dominant design for frequency regulation and renewables integration through a combination of regulatory innovation and cost reduction.
   - In 2015, the market for grid-scale batteries was four times larger than any prior year, lithium-ion batteries made up 95% of deployed capacity, and 80% of this capacity was located in PJM territory.
     - PJM interpreted FERC's 2011 order to "pay for performance" for grid services so as to create a promising market for frequency regulation.
     - Lithium-ion batteries are well-suited for this short duration application.
     - Price reductions for lithium-ion batteres were driven largely by R&D for other sectors, such as electric vehicles.
     - Private investors appear to have funded most of these projects.

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1. Introduction: The Tantalizing Prospect of Grid-Scale Batteries

This study describes the deployment of grid-scale batteries in the U.S. and provides an interpretation of the patterns revealed in these data. This section sets the broad context for the study. Grid-scale batteries hold the promise of making the difficult task of balancing electricity supply and demand much easier and supplying ancillary services needed to stabilize the grid as well. If batteries can perform these functions at a reasonable cost, the U.S. and other nations will more easily be able to integrate renewables into their power systems on a large scale, which in turn will accelerate the energy transition needed to meet the challenge of climate change. The section concludes with a roadmap of the rest of the paper.

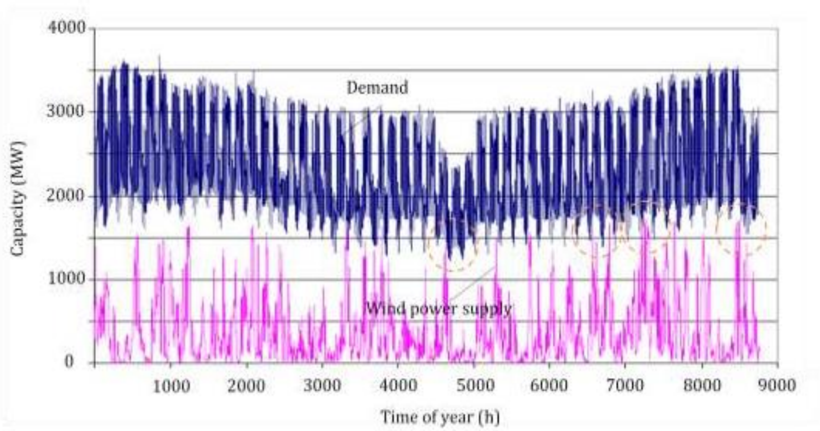
Electricity is an extraordinarily versatile energy carrier. It rapidly transformed daily life in industrial societies after it was first harnessed in the 19th century, and it does so in this century as it reaches remote villages. New uses for electricity are still emerging, notably in recent years for transportation. If the climate policy goals set in Paris in December 2015 are to be achieved, both trends – increasing penetration and diversification of electricity use – will need to continue, if not accelerate.

Of course, penetration and diversification are insufficient in themselves to achieve climate policy goals; they must be accompanied by a dramatic change in the mix of fuels used to generate electricity. The 2 Degree Scenario of the International Energy Agency, for instance, foresees renewables accounting for 63% of global generation in 2050.[1] In the United States, the National Renewable Energy Laboratory explores scenarios for renewable generation ranging up to 90% in 2050 in a large-scale 2012 study.[2]

Shifting the generation mix to this extent on this timescale presents a wide range of challenges, ranging from the cost of new power technologies and the stranding of old assets to the reconfiguration and modernization of the transmission and distribution system. Yet, throughout the transition and in the long-term, low-carbon future itself, the electricity system must continue to be reliable. The lights must go on when the switch is flipped.

Reliable power requires that supply and demand to be matched at all times; it is a physical requirement of the power system. Yet, most renewable generation technologies are intermittent; they produce power when the wind blows or the sun shines and not when they don't. Their production does not necessarily match demand, either; the customer is usually indifferent to the weather and is often far away from the site of generation. (See Figure 1.)

Figure 2: *Example of the demand and supply of wind power in Denmark in 2001*



Source: P. Sørensen, 2004.

Figure 1: Supply of Wind-Generated Electricity and Electricity Demand in Denmark over the Course of a Year[3]

The challenge of intermittency is deepened by the decentralization of the power system that is accompanying the transition in the fuel mix. Many renewable systems are small-scale and installed on customer premises, yet interconnected to the grid through net metering arrangements which allow these small generators export power. Electricity customers (and third party energy managers working for them) are also increasingly able to vary demand, and this flexibility will grow as "smart" end use technology improves and diffuses. In short, balancing electricity systems is a hard task that is likely to keep getting harder.

There are three major strategies for addressing this challenge.[4] One is to expand and diversify interconnections among grid resources. A big, diverse grid is more likely than a small, homogeneous one to have supply and demand effects that counteract one another. Bad weather in Boston may be balanced by a balmy day in Detroit. The second strategy is to make the grid smarter. Sensors and analytics can predict and pinpoint real-time balancing concerns and opportunities, while new equipment allows for more flexible responses.

"Super" grids and smart grids complement one another, and both are complementary with the third strategy, grid-scale storage. If adopted on a widespread basis, grid-scale storage would create new options for managing the electricity system in an era of decentralized and intermittent supply and demand – low-carbon alternatives to the gas peaking plants that provide most of these options today. Grid-scale storage would be able to balance changes in customer behavior and respond to weather events that affect renewable generation and other supply disruptions. It would also supply ancillary services that enhance grid functioning, such as frequency regulation and provision of spinning reserves, and allow existing resources to be used more effectively, deferring capital investment.

Some grid-scale storage technologies are already mature and have provided some of these services for many years. Pumped hydroelectric storage and compressed air energy storage (CAES), for instance, are excellent for providing large amounts of power over long durations. These technologies are therefore found at the right side of figures 2 and 3 below. (They are also constrained by geography and geology.) Grid-scale batteries, the focus of this paper, are, in general, more versatile and flexible than pumped hydro or CAES, as suggested by the bars of diverse widths and locations in figure 2, but they are also generally less mature and thus appear to the middle and left in figure 3. Some battery chemistries, such as those based on zinc, promise to nearly match pumped hydro in scale and duration, but have not yet been deployed at scale, appearing on the right of figure 2 and the left of figure 3. Lithium-ion batteries, by contrast, as we describe in more detail below, have begun to be deployed on a large scale, as suggested by their placement in the middle of figure 3. They can be dispatched much more quickly than alternative storage technologies, but for shorter durations, as implied by their placement at the left of figure 2.

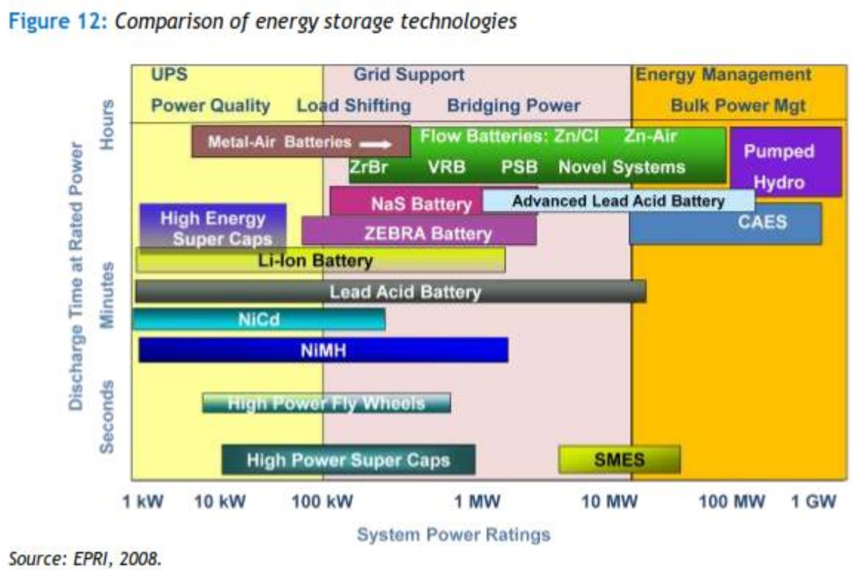


Figure 2: Comparison of Energy Storage Technologies[5]

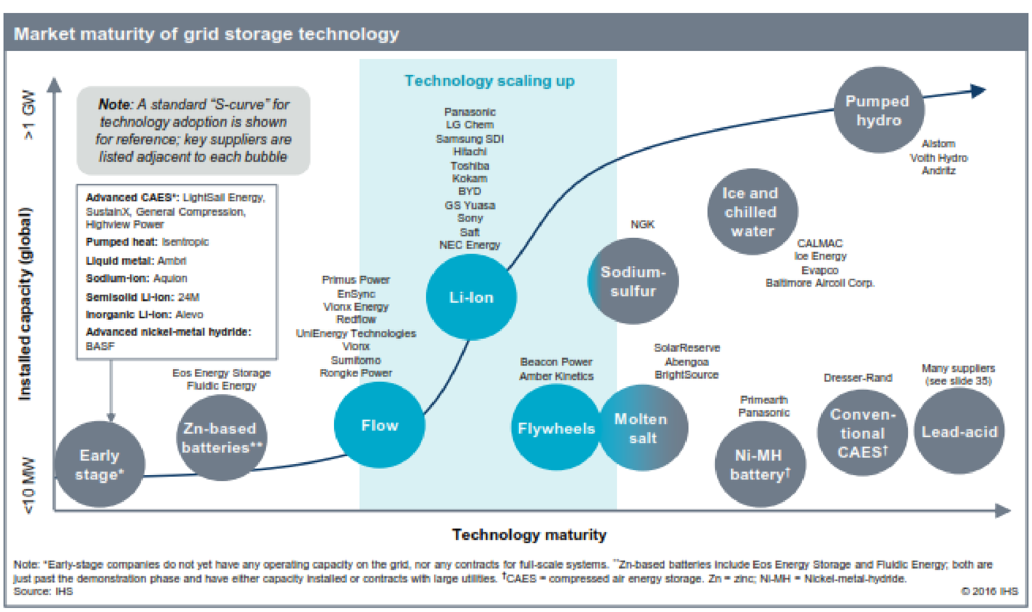


Figure 3: Market Maturity of Grid Storage Technology[6]

Grid-scale batteries' potential to provide a wide range of new options for grid management makes them a tantalizing prospect that is attracting significant interest from utilities, governments, and technology developers around the world. This paper assesses the progress that has been made to date in the U.S. in putting such systems in the field. In the next section, we describe our data. We then cover the deployment process over three time periods. Before 2009, high costs, high risks, and modest benefits limited deployment to a few isolated cases. From 2009 to 2014, public investment and regulatory incentives helped to precipitate an "era of ferment" in which a variety of alternative chemistries were tried out in practice in diverse applications. This process of real-world experimentation and demonstration helped establish lithium-ion batteries as a viable grid-scale storage option for the application of frequency regulation. In the past year, this option has come to maturity, attracting large-scale private investment. The paper concludes by looking forward, when new challenges will emerge as this application is saturated and policy-makers pursue others.

2. Grid-Scale Batteries: Definition and Measurement

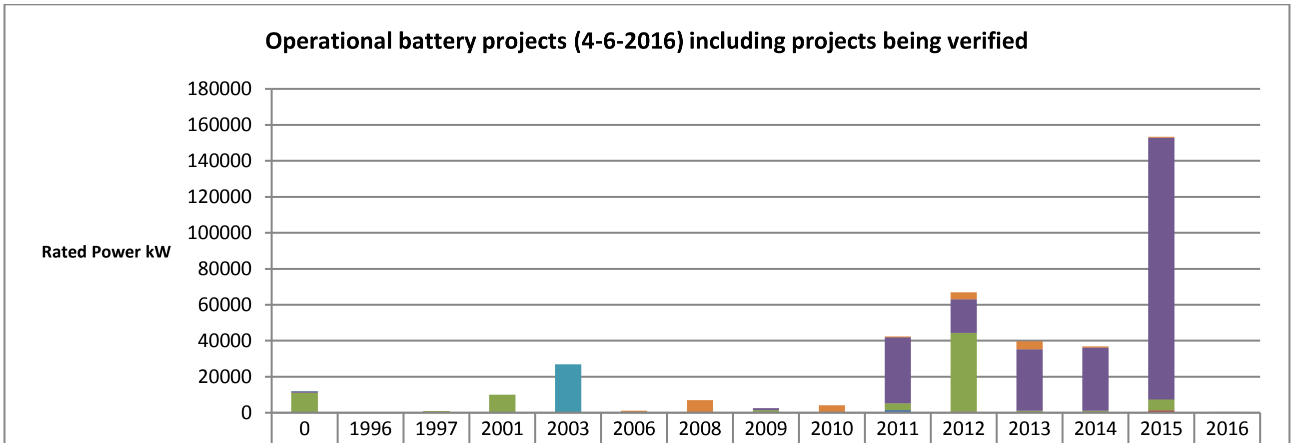
The data that we use in this paper are taken from the DOE Global Energy Storage Database. This section describes why we chose this data source and how we used it. We then lay out the big picture of deployment over time as measured by rated power and number of projects, broken down as well by battery chemistry and location.

The DOE Global Energy Storage Database provides up-to-date information on grid-connected energy storage projects. It is widely used for research and was recommended by the International Renewable Energy Agency as a model for other national energy storage databases.[7] [a] We filtered out non-battery technologies and non-operational systems from the database, yielding a core dataset covering 205 operational battery projects in the U.S.[8] [b]

The total deployed capacity of these 205 projects is about 400 MW. This figure may be compared with approximately 21,500 MW of the more mature pumped hydro technology.[9] Individual projects range in size between 4 kW and 36 MW. Figure 4 depicts the distribution of battery projects over time based on the rated power of each project, while Figure 5 shows the number of projects in each year. The vast majority of the capacity has been deployed in the past five years. Between 2011 and 2014, the total deployment was approximately 186 MW. In 2015, more than 150 MW were deployed.

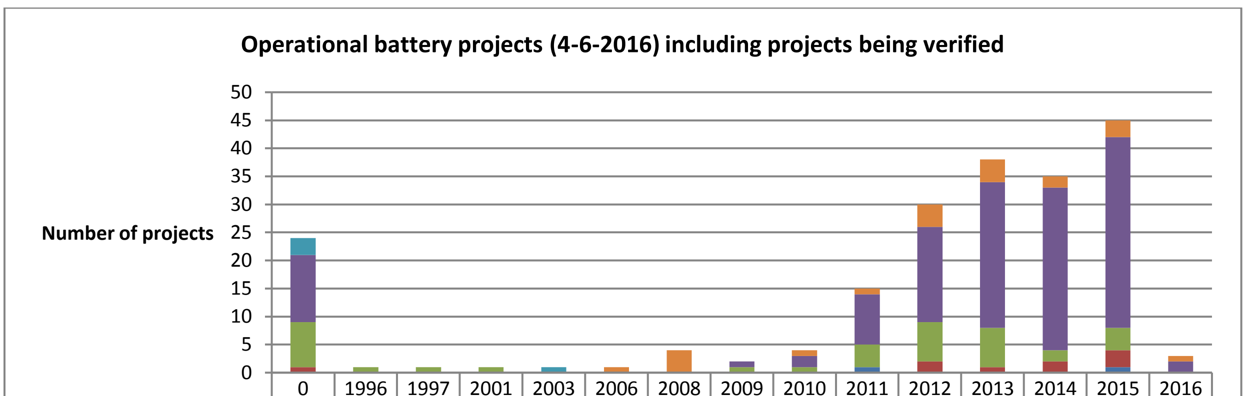
[a] HDR Engineering ("Update to Energy Storage Screening Study for Integrating Variable Energy Resources within the PacifiCorp System," July 2014) cautions, however, that "Data from the Energy Storage Database provides an approximate indication of the battery industry and should not be construed as an accurate predictor of industry / market behavior. The data collected is not all inclusive of all commercialized manufacturers, does not include all of the projects a given manufacturer has completed, and does not include any emerging technologies that are under final stages of research and development."

[b] We downloaded our project dataset on April 6, 2016, using only the country filter (United States) and keeping unverified entries . This search yielded 619 entries. We dropped projects using Thermal Storage, Pumped Hydro Storage, Compressed Air Storage, and Flywheel, ending up with 391 projects, of which 186 are not operational (non-operational statuses include announced, contracted, de-commissioned, offline/under repair, and under construction). DOE vets the projects through a third party verification process. Of the 205 projects in our dataset, 133 were verified and the rest were in the verification process.



	0	1996	1997	2001	2003	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016
Sodium based Battery						1200	7000		4000	402	4025	4365	600	470	25
Nickel based Battery	85				27000										
Lithium-ion Battery	790							1000	100	36800	18665	34131	35016	145470	430
Lead-acid Batter	11008	250	1000	10000				1500	100	3625	43641	1044	1100	6100	
Flow Battery	25										660	100	100	1270	
Electro-chemical										1500				48	

Figure 4: All Projects in Our Database (Rated Power in kW)
[Note: 0 denotes undated projects][c]



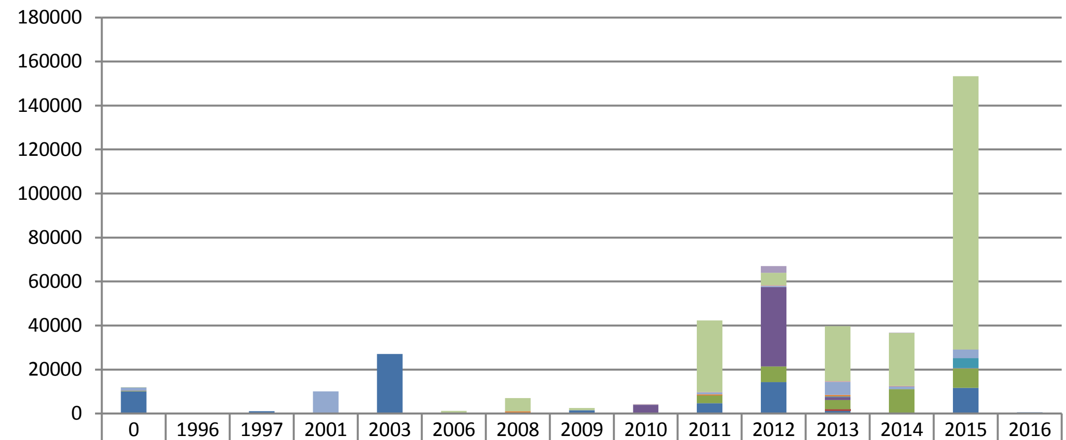
	0	1996	1997	2001	2003	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016
Sodium based Battery						1	4		1	1	4	4	2	3	1
Nickel based Battery	3				1										
Lithium-ion Battery	12							1	2	9	17	26	29	34	2
Lead-acid Batter	8	1	1	1				1	1	4	7	7	2	4	
Flow Battery	1										2	1	2	3	
Electro-chemical										1				1	

Figure 5: All Projects in Our Database (Number of Projects) [d]

[c] Of the 24 undated projects, by far the largest is the 10 MW Kaheawa Wind Power Project II, which is discussed below.
[d] The electro-chemical designation is for only two projects that are in the verification process; hence, we may assume once verified they may be recategorized into one of the other battery chemistries.

[Note: 0 denotes undated projects]

Figures 4 and 5 demonstrate a transformation in preferred battery chemistries over time. In particular, lithium-ion batteries dominate the field after 2010, accounting for more than 270 MW of the approximately 340 MW deployed in that period. In 2015, this technology's share of the grid-scale battery market was nearly 95%. It is worth noting that no new pumped hydro capacity has been added in the U.S. in more than a decade. The shift in battery chemistry over time corresponds with a shift in location and use of projects.   As Figure 6 shows, over 80% of the deployed capacity in 2015 occurred within the territory of the PJM Independent System Operator (ISO), and the predominant use was frequency regulation.



	0	1996	1997	2001	2003	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016
SPP											3000		100		
PJM	35					1200	6000	1000		32600	5676	24880	24150	124248	
NYISO									100	50	225	300	331	20	
N/A	1525	250		10000					100	952	675	5940	1115	3860	30
MISO	113						1000			500		769			
ISO-NE	20									100		250		4500	400
ERCOT									4000		36000	1300		225	
CAISO	210									3500	7105	4298	11120	8875	
BANC												703			
Alaska-Hawaii	10005		1000		27000			1500		4625	14310	1200		11630	25

Figure 6: All Projects in Our Database by Deployment Location and Rated Power
[Note: 0 denotes undated projects]

These observations lead us to divide the rest of the paper into three periods with distinct patterns. Before 2009, projects are sporadic and employ a diverse range of chemistries. 2009 marks the first project using lithium-ion technology, and in the ensuing years, this technology emerges as the dominant one. In addition, the 2009 American Recovery and Reinvestment (ARRA) Act provided unprecedented availability to public financial resources, including an investment of about $97 million in grid-scale battery storage demonstration.[10] Figure 7, which uses data assembled by Bloomberg New Energy Finance, also suggests the increasing diversification of the energy storage market starting around 2008. 2015 tentatively marks another break point in our dataset, with a further sharp increase in lithium-ion batteries deployed for frequency regulation in the PJM territory.

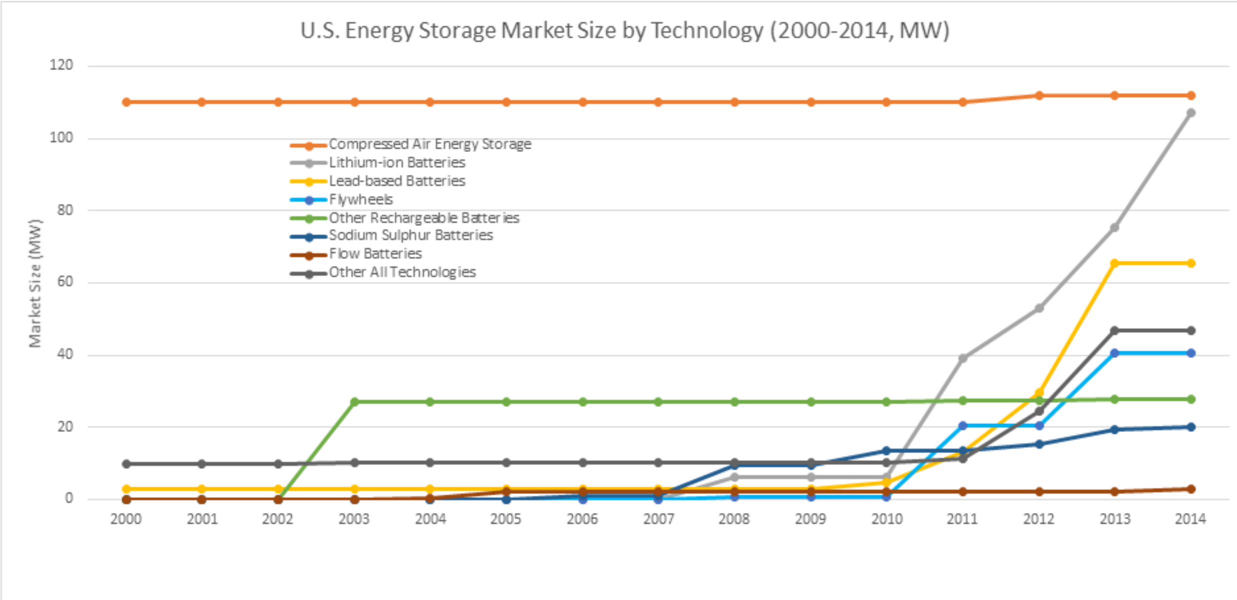


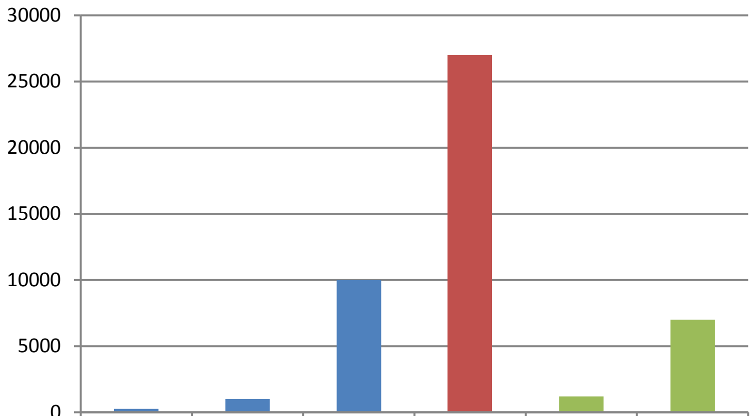
Figure 7: U.S. Energy Storage Market Size by Technology (2000-2014)[11]

3. Grid-Scale Battery Deployment Before 2009

We begin this section by describing the deployment pattern, or lack thereof, from the oldest project in our database, which was commissioned in 1996, through 2008. There are so few projects in this period that we can explore them individually. This exploration places them in two groups. The earliest projects were idiosyncratic solutions to unusual problems using established technologies; the later projects were efforts to demonstrate that untested technologies could solve more general problems. The overall paucity of deployment in this period is overdetermined; grid-scale batteries were high cost and high risk and offered modest benefits.

As shown in figures 5 and 6 above, the period before 2009 in our database is distinguished from later periods by the sporadic completion of projects. Unlike the years from 2009 on, the period before 2009 contains several years during which no projects were completed. The fallow periods include one stretch of three years (1998-2000) and another of two years (2004-2005). In addition, there is no obvious pattern to the time trend in total deployed capacity. It does not rise steadily. Indeed, a single large project completed in 2003 accounts for well over half of the capacity added in the entire period from 1996 to 2008.

With respect to battery chemistry, this period stands out in another way. There is no year before 2009 in which multiple projects were completed that used different chemistries, whereas this is true of every year from 2009 on. As we noted above, the period is also striking due to the complete absence of projects using lithium-ion chemistries. Figure 8 provides an overview of the period, while Table 1 lists the nine projects that we discuss below.



	1996	1997	2001	2003	2006	2008
Sodium based Battery					1200	7000
Nickel based Battery				27000		
Lead-acid Batter	250	1000	10000			

Figure 8: Projects Before 2009 (Rated Power in kW)

Project Name	Rated Power (in kW)	Technology	Commissioning Date	Service Use Case	State
Dangling Rope Marina Hybrid Power System	250	Lead-acid Battery	1996	Renewables Capacity Firming; Onsite Renewable Generation Shifting; Electric Supply Capacity	UT
Metlakatla BESS	1000	Lead-acid Battery	1997	Electric Supply Reserve Capacity - Spinning; Frequency Regulation; Voltage Support	AK
STMicroelectronics UBS System	10000	Lead-acid Battery	2001	Grid-Connected Commercial (Reliability & Quality)	AZ
GVEA Battery Energy Storage System (BESS)	27000	Nickel based Battery	2003	Electric Supply Reserve Capacity - Spinning; Grid-Connected Residential (Reliability); Grid-Connected Commercial (Reliability & Quality)	AK
AEP Charleston NaS Energy Storage Project	1200	Sodium based Battery	2006	Electric Energy Time Shift; Transportable Transmission/Distribution Upgrade Deferral	WV
XCEL MinnWind Wind-to-Battery Project	1000	Sodium based Battery	2008	Renewables Energy Time Shift; Ramping; Voltage Support; Frequency Regulation	MN
Milton NaS Battery Energy Storage System	2000	Sodium based Battery	2008	Transportable Transmission/Distribution Upgrade Deferral; Electric Energy Time Shift; Electric Supply Reserve Capacity - Spinning; Grid-Connected Residential (Reliability)	WV
AEP Churubusco NaS Battery Energy Storage System	2000	Sodium based Battery	2008	Transportable Transmission/Distribution Upgrade Deferral; Electric Energy Time Shift; Electric Supply Reserve Capacity - Spinning	IN
AEP Bluffton NaS Energy Storage System	2000	Sodium based Battery	2008	Transportable Transmission/Distribution Upgrade Deferral; Electric Energy Time Shift; Electric Supply Reserve Capacity - Spinning	OH

Table 1: Project Profiles Before 2009

The first three projects in Table 1 use lead-acid batteries. This technology is the most mature of those used for grid-scale batteries; in fact, these projects used off-the-shelf technology manufactured by well-established companies. Each of these three projects solved a different and unique problem. The first was paired with a PV system operated by the U.S. National Park Service at the remote and environmentally-sensitive Lake Powell in Utah to replace a diesel generator in 1996.[12] The second, completed in 1997, also serves a remote location, the Metlakatla community at the southern tip of the Alaska Panhandle. This battery was paired with a diesel generator to replace rain-fed hydro units that faced recurring brown-outs, overvoltage, and frequency fluctuation in response to demand.[13] The third shields the entire semiconductor wafer fab operation of STMicroelectronics in Phoenix, Arizona, from power disturbances. "Producing complex computer chips is an extremely delicate process that blends microelectronics with chemical and mechanical systems, requiring tolerances in microns. The process can take 30 to 50 days to complete and can be totally ruined in a blink of an eye." When it was completed in 2001, this 10 MW unit, which uses Delco 1150 truck batteries, was the world's largest battery-based uninterruptible power supply operating at medium voltage.[14]

The fourth project in Table 1 was by far the largest of this period at 27 MW, and it was the only one to use nickel-based batteries. Completed in 2003, it is owned by the Golden Valley Electric Association (GVEA), a cooperative which serves about 100,000 customers in central Alaska. The battery system's main purpose was to improve the reliability of GVEA's electric service, which hit a peak load of 223 MW in December 2007.[15] For remote customers of this cooperative, one presumes that outages in the middle of the Alaskan winter present risks that justified the system's $35 million installation cost.

The five projects completed from 2006 to 2008 all use sodium sulfur (NaS) battery technology and were intended to prove the viability of this technology in various applications. The 2006 American Electric Power (AEP) Charleston Project uses an NaS system developed by NGK in collaboration with Tokyo Electric Power Company (TEPCO). This 1.2 MW system was the first deployment of this technology at this scale outside Japan. Its primary purposes were peak-shaving and transmission upgrade deferral. The system is mobile, which expands its usefulness for deferring transmission upgrades.[16] AEP's success in Charleston led it to install three 2 MW NaS battery systems in 2008. These later systems also provide back-up power to islanded customers.[17] The final project was a 1 MW demonstration carried out by Xcel Energy to evaluate the effectiveness of NGK's NaS battery technology in the grid-integration of wind energy. The battery performed successfully in all modes tested.[18]

For analytical purposes, battery systems deployed before 2009 can be divided into two groups. The first four are one-off projects that use well-established technology provided by large incumbent providers, albeit in some cases in new configurations. The project at Lake Powell, Utah, and the two projects in Alaska solved difficult problems in remote locations. STMicroelectronics' Phoenix project solved a standard industry problem by collaborating closely with its utility partner to create a larger-scale solution than had previously been deployed.

The second group of projects, comprising the four owned by AEP and the one by Xcel, use a more innovative technology. These projects were intended to advance the state-of-the-art and strengthen operational knowledge. Unlike the problems solved by the first group of projects, the problems that this group of projects sought to solve will be increasingly common as the grid becomes more distributed and generation more intermittent in the future. AEP's effort was supported in part by the U.S. Department of Energy and thus may be seen as a precursor to the smart grid demonstration projects that were funded in later years. ""AEP realizes that deployment of distributed energy storage is currently costing the company more than some alternative, conventional solutions; however, AEP regards the marginally higher cost as a "premium" that it is willing to pay to advance the company's grid performance and enhance AEP's future in the electric power industry."[19]

Xcel's project was funded by the utility's own renewable energy fund, again like many later storage projects. All of these projects relied on NGK, suggesting that this company may have made a marketing push in this period. However, the cost of the NaS technology did not decline very rapidly in subsequent years, and its characteristics are not well-suited for many applications, limiting its later diffusion.[20]

There were many barrier to deployment in this period. One was certainly high capital costs; lithium-ion batteries in 2007 cost more than $1000/kWh.[21] In addition, it is likely that the high risk and unproven nature of the technology deterred interest in it. Finally, the benefits of deployment were typically both uncertain and modest. In short, the risk/benefit/cost tradeoff was not favorable to grid-scale batteries before 2009.

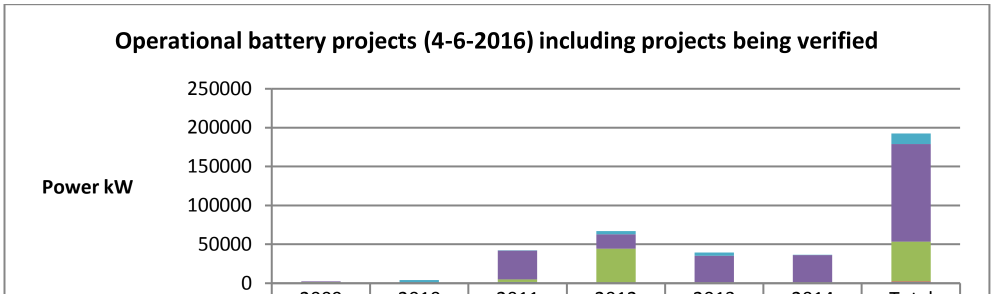
4. Grid-Scale Battery Deployment, 2009-2014

2009 marks a turning point in grid-scale battery deployment in the U.S. Although the number of projects completed in that year was small, the passage of ARRA opened up a large new source of financing. In addition, the diffusion process from 2009 to 2014 is characterized by greater diversity in terms of chemistries pursued, locations served, and services provided than the years before or after. We place 2015 into a different period because lithium-ion technology providing frequency regulation service in the PJM territory grew so much in that year, dramatically extending its dominance of the market.

In this section, we first describe the deployment pattern in this period by year, chemistry, and location. We then dig deeper into the services that these projects provide, which show the important pull of renewables integration on grid-scale battery deployment, and look at the more limited information available on project funding, which points to the importance of public risk- and cost-sharing as a facilitator of deployment. Regulatory incentives also played a crucial role in encouraging deployment. We conclude by characterizing the period as an "era of ferment" in which project developers sought to legitimate specific chemistries for specific applications, and lithium-ion emerged as a "dominant design" for frequency regulation and perhaps for other applications as well.

124 grid-scale battery projects with a rated power of about 192 MW were completed in this six year period, compared with only 9 totalling about 46 MW in the previous 13 years. Figure 9 shows the deployment process by year and battery chemistry in terms of rated power. Lithium-ion takes off in 2011, hitting its peak for the period in that year, although later years (2013-2014) are nearly as high. However, in 2012, it is displaced from first place among battery chemistries

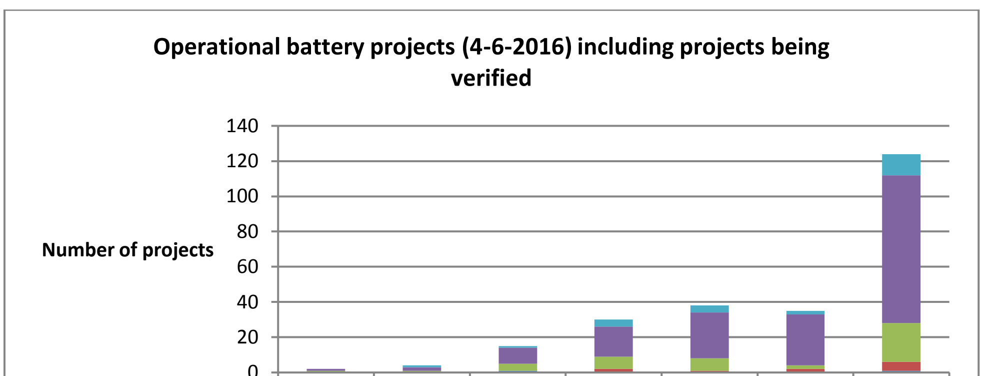
by lead-acid, thanks to two very large projects, which are discussed further below. 2012 is also the year with the largest total aggregate growth, with about 67 MW of capacity added.



	2009	2010	2011	2012	2013	2014	Total
Sodium based Battery		4000	402	4025	4365	600	13392
Lithium-ion Battery	1000	100	36800	18665	34131	35016	125712
Lead-acid Battery	1500	100	3625	43641	1044	1100	51010
Flow Battery				660	100	100	860
Electro-chemical			1500				1500

Figure 9: Projects by Chemistry and Year, 2009-14 (Rated Power in kW)

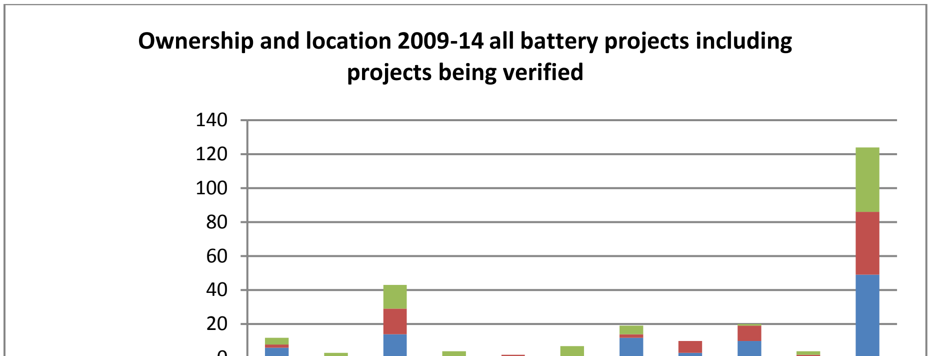
Figure 10 displays the number of projects in the period. The striking trend in this figure is the steady rise of lithium-ion projects throughout the period, as contrasted with the rise and fall of lead-acid and sodium-based batteries. No nickel-based battery projects were completed in this period, while flow batteries, a promising but immature technology, appear for the first time in these data in 2012. 84 of the 124 projects in this period, however, use lithium-ion technology. 29 of these projects were completed in the last year of the period, 2014, making up more than 80% of the 35 projects of all types completed in that year.



	2009	2010	2011	2012	2013	2014	Total
Sodium based Battery		1	1	4	4	2	12
Lithium-ion Battery	1	2	9	17	26	29	84
Lead-acid Battery	1	1	4	7	7	2	22
Flow Battery				2	1	2	5
Electro-chemical			1				1

Figure 10: Projects by Chemistry and Year, 2009-14 (Number of Projects)

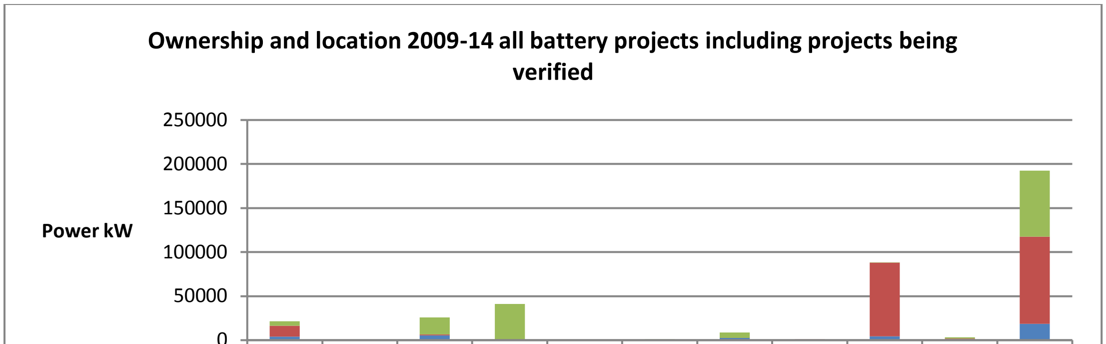
Figure 11 depicts the project portfolio for the entire period broken down by RTO/ISO location and ownership structure. The portfolio as a whole is almost evenly distributed among projects owned by customers, utilities, and third parties. California (CAISO), where the largest number of projects (about one-third of the total) is located, shows a similar distribution. That is not the case in other regions. In the MISO territory, for instance, all of the projects are all utility-owned, whereas in New York (NYISO), none of them are.



	Alaska-Ha	BANC	CAISO	ERCOT	ISO-NE	MISO	N/A	NYISO	PJM	SPP	Total
Utility-Owned	4	2	14	3	0	7	5	0	1	2	38
Third-Party-Owned	2	0	15	0	1	0	2	7	9	1	37
Customer-Owned	6	1	14	1	1	0	12	3	10	1	49

Figure 11: Projects by RTO/ISO and Ownership, 2009-14 (Number of Projects)

Figure 12 displays the same data based on the rated power of the projects. Not surprisingly, customer-owned projects are much smaller on average (about 376 kw) than those in the other two categories (about 2.3 MW). Projects located in PJM territory are indicative in this regard. The 9 third-party-owned projects in this group average 9.3 MW, while the 10 customer-owned projects average 440 kw. In Texas (ERCOT), the 3 utility-owned projects average 14 MW, compared to the single 300 kw customer-owned project. The large projects in these two territories leads them to take first and second place respectively when deployment is measured by total rated power, ahead of California, which has many more projects. California's projects are smaller than the national average across all three ownership categories.



	Alaska - Hawaii	BANC	CAISO	ERCOT	ISO-NE	MISO	N/A	NYISO	PJM	SPP	Total
Utility-Owned	5250	653	19456	41000		1269	6202		100	1100	75030
Third-Party-Owned	12500		1173		100		60	431	83750	1000	99014
Customer-Owned	3885	50	5394	300	250		2520	575	4456	1000	18430

Figure 12: Projects by RTO/ISO and Ownership (Rated Power in kW)

The variation displayed in Figures 11 and 12 point to the importance of RTO/ISO rules in explaining the size and ownership of these projects as well as their location across the four largest groupings. PJM operates a wholesale market in which independent power producers play the dominant role and has created a similar market for ancillary services. This market was stimulated by FERC Order 755 (2011), which requires RTO/ISOs to "pay for performance" for frequency regulation services. ERCOT is not subject to FERC, but created a pilot program in 2013 that created an ancillary service market for the utility-owned Notrees project discussed below. [22]

California, long the leader among the states in tackling climate and energy policy challenges, had a more varied policy in this period, which helps to account for the diversity of project sizes and ownership in the state. The California Public Utility Commission's Self-Generation Incentive Program (SGIP) began allowing stand-alone energy storage projects on customer sites to qualify in starting in 2011. California was also the site of several major ARRA-funded projects, such as the 8 MW Tehachapi project installed by Southern California Edison.[23] Hawaii's unique location, encompassing isolation, high electricity costs, and a rich renewable resource, give its policies a unique cast. Power Purchase Agreements (PPAs) provide revenue security to system owners by guaranteeing that the system output will be purchased at a set price. PPAs helped to drive several large storage projects associated with renewables integration in Hawaii in the 2009-2014 period.[24]

The DOE Global Energy Storage Database records the services (up to 29) that each project is intended to provide, which provide further insight. Figure 13 depicts the frequency with which all of the services appear in our database. The four services that appear most frequently are:

- Renewables capacity firming
- Electric energy time shift
- Frequency regulation

- Electric bill management

It is also worth noting that four services directly related to deployment of renewable energy systems (renewables capacity firming; onsite renewable generation shifting; renewables energy time shift; and electric bill management with renewables) appear first, fifth, sixth and seventh in these rankings. Other services, such as electric energy time shift, may also be tied to renewables. Renewables are clearly important in pulling energy storage deployment in this period.

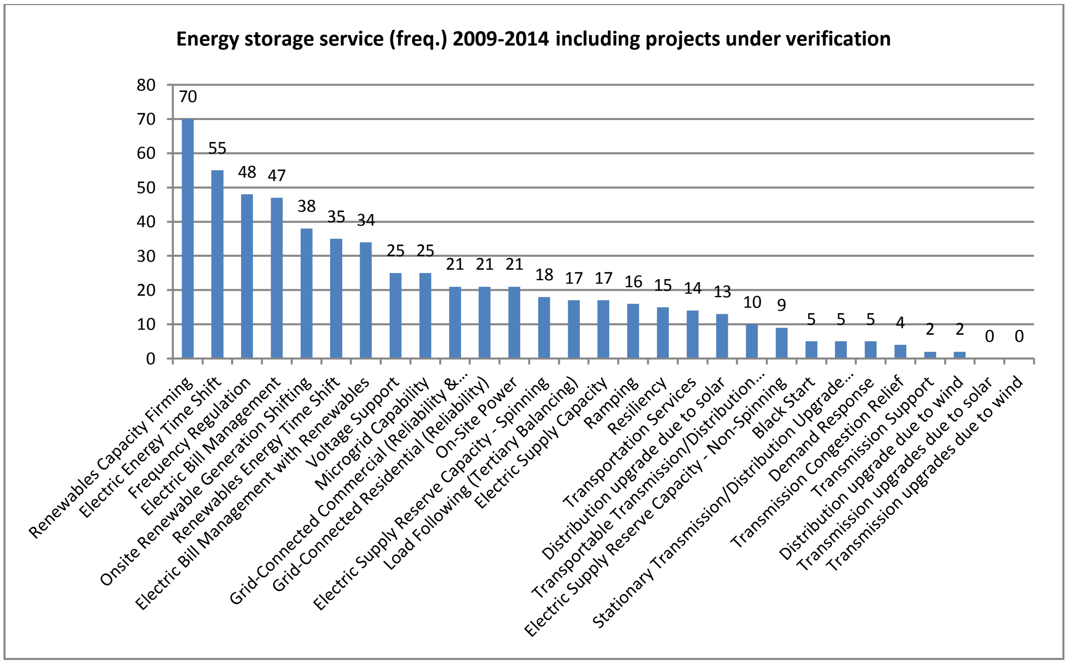


Figure 13: Energy Storage Services by Project, 2009-2014 (Number of Appearances in Database)

A closer look at some of the larger projects provides further insight. The largest project in all three of the most frequently listed services is Duke Energy's 36 MW advanced lead-acid Notrees Wind Storage Demonstration Project in Goldsmith, Texas. As the name suggests, this project's main purpose is to optimize energy delivery from an adjacent 153 MW wind farm. In addition to capacity firming and time shifting, Notrees also provides frequency regulation services to the ERCOT market.[25] The AES Laurel Mountain Project in Elkins, West Virginia is similar to Notrees. Initially rated at 32 MW, this lithium-ion storage array is sited with a 98 MW wind farm. It also bids into the PJM market, providing frequency regulation and ramping services.[26]

Although the DOE Global Energy Storage Database does not include a date for it,[e] the 10 MW Kaheawa Wind II project went into operation in July, 2012, according to the developers,

[e] Another relatively large project that lacks a date in the database is the NEDO Los Alamos Smart Grid Demonstration project, which was funded by ARRA and deployed a 1.8 MW sodium-sulfur battery that went

primarily to firm capacity from a 71 MW wind farm as well as provide ancillary services to the grid on the island of Oahu. The database indicates that the project uses lead-acid technology, although media reports suggest it uses a proprietary dry cell technology. The system ensures that output remains within the parameters of the project's PPA.[27]

The technology used at Kaheawa apparently did not prove to be reliable, and the vendor, Xtreme Power, went bankrupt in 2014. The Notrees project is scheduled to be converted to lithium-ion batteries in 2016. This conversion, of what is by far the largest lead-acid battery project in the database, suggests that this period can be seen as one of technological experimentation, with lithium-ion chemistry proving to be superior for this type of configuration.

The Salem (Oregon) Smart Power Center is one of the largest battery projects that provides time shifting service that was completed between 2009 and 2014. It is owned by Pacific Gas & Electric and rated at 5 MW. The Center was built as a component of the 5-state Battelle Pacific Northwest Smart Grid Demonstration project. It aims to increase distribution system reliability and decrease peak-price risk as well as aiding with integration of renewable resources.[28]

The largest project in the "electric bill management" service category is at the Santa Rita Jail in Dublin, California. This project has a lithium-ion battery system rated at 2 MW that provides power to the jail's microgrid in island mode in case of a service disruption as well as arbitraging time of use rates during normal operation. It is the first project of its type and scale that uses Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid protocol, which is intended to reduce the cost and improve the functionality of microgrids.[29]

Both the Salem Smart Power Center and the Santa Rita Jail project, as well as the Notrees project, were supported in part by the Department of Energy's Smart Grid Demonstration Program, which was funded under ARRA.[f] In fact, of the projects that list funding sources, ARRA is by far the most commonly mentioned.[g] State R&D and commercialization programs, especially those in California and New York, also provided funding for many projects in this period.

Private funding appears to have been less significant in this period, especially for large projects, although the AES Laurel Mountain project is a pioneering commercial venture.[h] AES Energy Storage, wrote Klein and Maslin (2011) "has established an early-mover position as an

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operational in 2012. Ucilian Wang, "Japan-U.S. Smart Grid Project Now Live in New Mexico," *GigaOm*, September 20, 2012, (https://gigaom.com/2012/09/20/japan-u-s-smart-grid-project-now-live-in-new-mexico/ accessed May 2, 2016).

[f] Reports on projects funded by the energy storage projects funded by the Smart Grid Demonstration Program can be found at https://www.smartgrid.gov/recovery_act/program_impacts/energy_storage_technology_performance_reports.html.

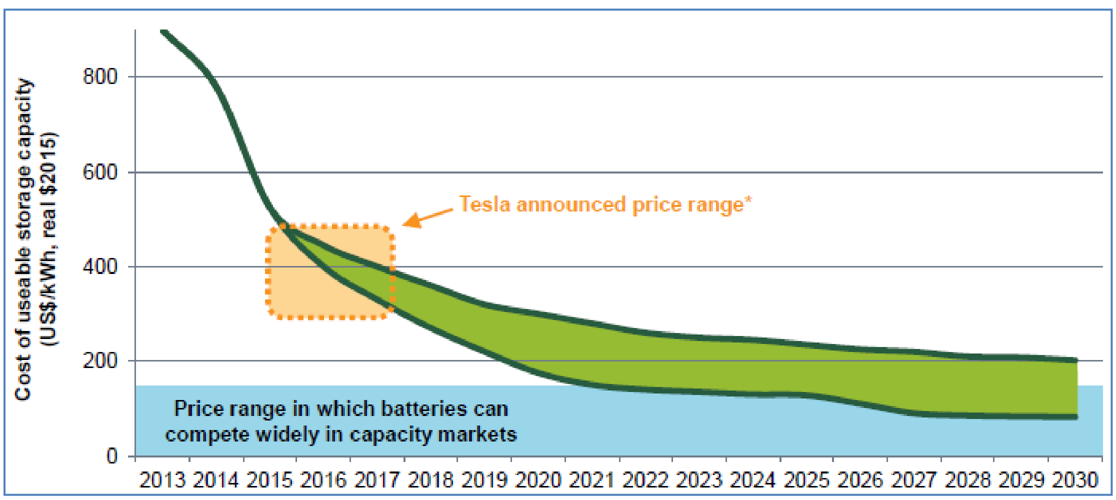
[g] IHS Research estimated in 2011 that about one-quarter of utility-scale battery projects, as measured by capacity, received ARRA funding. See Alex Klein and Thomas Maslin, "US Utility-Scale Battery Storage Market Surges Forward," IHS Research, September 28, 2011, p. 7

[h] Eric Wesoff "Slideshow: DOE Energy Storage Project Portfolio Funded by ARRA," *Greentech Media*, June 4, 2012 (http://www.greentechmedia.com/articles/read/Slideshow-DOE-Energy-Storage-Project-Portfolio-Funded-by-ARRA accessed April 29, 2016) states that this project received support from ARRA, but it does not appear on the project list of the Smart Grid and Energy Storage Demonstration Program. The project did receive an ARRA grant-in-lieu-of-tax-credit for the wind power portion.

independent storage services provider, tapping its global footprint for scaling a battery-focused storage portfolio." They also note, though, that the firm received a Federal loan guarantee for a utility-scale lithium-ion project in Johnson City, New York.[i] Smaller behind-the-meter projects, such as those provided by Stem and Green Charge and aimed at reducing electricity costs, also seem more likely to be primarily privately funded, although in California these systems receive subsidies through SGIP.[30]

To sum up, the 2009-2014 period may be seen as a "period of ferment"[31] in the evolution of grid-scale battery technology. The number of projects completed rose rapidly as did the diversity of chemistries and uses. Many projects aimed at legitimating specific applications, that is, showing to potential adopters that specific chemistries used for specific purposes would be safe and economical. Chief among these applications are those associated with renewable electricity generation along with ancillary services, such as frequency regulation. Public funding played an important role in fostering this phase of technological evolution by sharing the risk of certain projects and encouraging information about them to be widely shared.

In addition, regulatory incentives "pulled" private investment into the market, especially the PJM frequency regulation market.[j] In fact, by the end of this period, lithium-ion batteries emerged as a standard or "dominant design" for this application and possibly for others. Although deployments at grid-scale in this period strengthened the power sector's confidence in the reliability and profitability of this technology for this purpose, cost reductions were "driven largely by R&D in other sectors" (such as automobiles). The rapid price reduction that occurred in this period and continued into 2015 can be seen in Figure 14.[32]



[i] Klein and Maslin, p. 3, state that the project is 12 MW. DOE's announcement puts the rating at 20 MW, while the DOE Global Energy Storage Database includes it at 8 MW. See energy.gov, "DOE Completes $17 Million Loan Guarantee for New York Energy Storage System with Recovery Act Funds," December 23, 2010 (http://energy.gov/articles/doe-completes-17-million-loan-guarantee-new-york-energy-storage-system-recovery-act-funds, accessed April 29, 2016).
[j] "The industry participants concur that frequency regulation ancillary service currently represents an economically viable market for grid connected energy storage." Bender *et al.*, p. 59. See also Andy Lubershane and Alex Klein, "2014: A Turning Point for the U.S. Grid-Connected Battery Market?" IHS Research, January 23, 2014, p. 12.

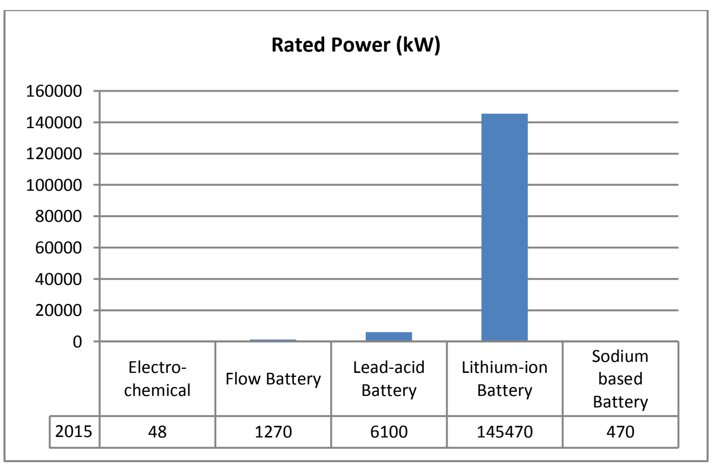
Figure 14: IHS Benchmark Battery Module Price Forecast in 2015 (US$/kWh)[33] [k]

5. Grid-Scale Battery Deployment, 2015[l]

We tentatively identify 2015 as the beginning of a new period in the deployment of grid-scale batteries. This periodization will need to be confirmed as new data comes in. We have two main reasons for making this claim. The first is the large scale of deployment. 145 MW of lithium-ion projects came on line in 2015; that is about four times as much rated power from this technology as in any prior year and more than the entire 2009-2014 period as a whole. The second reason is the expansion of private financing. Most projects funded by ARRA were completed before 2015. The PJM frequency regulation market was well enough established by 2015 to drive private project investment.

As in the previous section, we begin this section by describing our data in terms of capacity installed, chemistry, location, and ownership. We then consider the services provided by the projects, showing that renewables integration and frequency regulation continue to drive deployment of grid-scale batteries in this period. We argue that this latter service has reached maturity in the PJM market; it is predominantly privately funded and overwhelmingly uses lithium-ion technology.

Figure 15 displays the rated power of projects completed in 2015, and Figure 16 depicts the number of projects. Lithium-ion battery projects make up about 95% of the total capacity. Although chemistries other than lithium-ion made up a larger proportion of projects than capacity (about a quarter), these projects were roughly 1/6 the size of lithium-ion projects on average, about 700 kw. The lithium-ion projects averaged over 4 MW, which was about four times as large as projects using this chemistry in the three prior years.[m] According to Bloomberg New Energy Finance, lithium-ion has become the technology of choice globally for projects of all sizes and applications of up to four hours duration.[34]



[k] This forecast excludes inverter, balance of system, or installation costs.

[l] As of April 6, 2016, only three projects had been added to the DOE Global Energy Storage Database in 2016, so we have confined our analysis in this period to 2015.

[m] The average rated power for lithium-ion projects was about the same in 2011 as in 2015, because it included the very large (32 MW) Laurel Mountain project.

Figure 15: Projects by Chemistry, 2015 (Rated Power in kW)

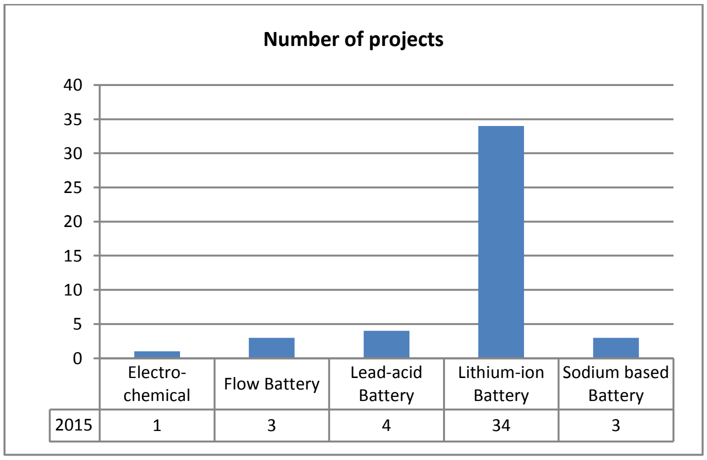


Figure 16: Projects by Chemistry, 2015 (Number of Projects)

Figure 17 shows the 2015 portfolio of projects by RTO/ISO and ownership. The pattern is similar to the previous period; for example, projects are distributed across ownership categories fairly evenly, with just a few more customer-owned projects than utility- or third party-owned projects. However, in terms of rated power, which is displayed in Figure 18, third-party owned projects dominate to a much greater extent. As in the previous period, the PJM market design is the key explanation for this pattern.

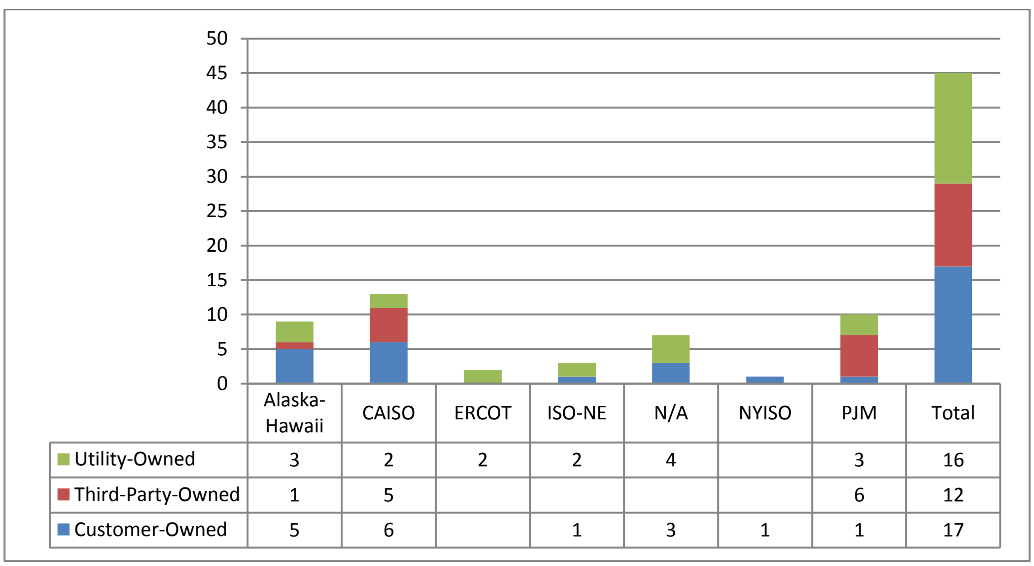
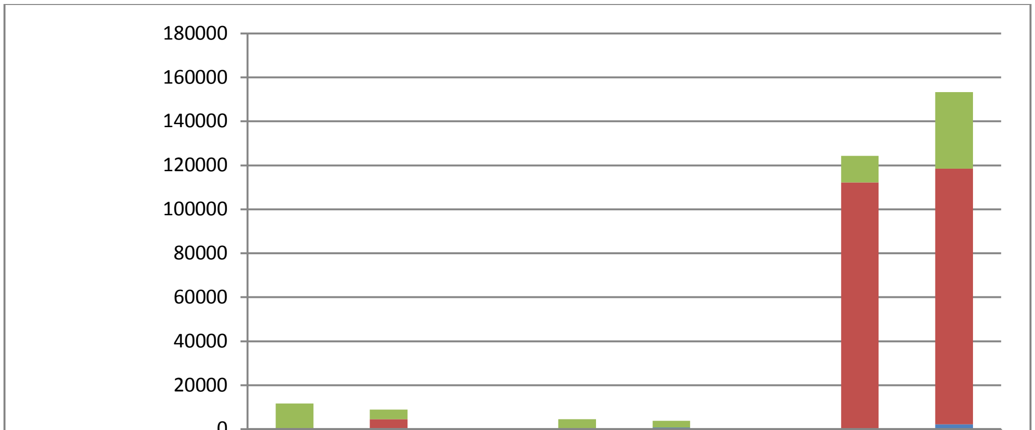


Figure 17: Projects by RTO/ISO and Ownership, 2015 (Number of Projects)



	Alaska-Hawaii	CAISO	ERCOT	ISO-NE	N/A	NYISO	PJM	Total
Utility-Owned	11100	4400	225	4000	3050		12048	34823
Third-Party-Owned	36	4064					112200	116300
Customer-Owned	494	411		500	810	20	0	2235

Figure 18: Projects by RTO/ISO and ownership, 2015 (Rated Power in kW)

Figure 19 depicts the services provided by the 2015 projects. Compared with the 2009-14 period we see some change in this ranking. "Microgrid capability" is the second most frequently mentioned use with 14 mentions.[n] In the prior period, which lasted 6 years, it was only mentioned 25 times, ranking ninth among all services. Resiliency also climbed significantly in the rankings, indicating greater attention to reliability-related issues in this period. However, renewables integration and frequency regulation clearly continue to drive many projects as well; "renewable capacity firming" and "frequency regulation" are among the top three uses in 2015, just as they were in 2009-2014.

[n] Omar Sadeh, "U.S. Microgrid Market Update Q2 2016," GTM Research, May 2016, p. 9, reports that in the wake of Superstorm Sandy and other weather-related events that northeastern states have committed almost $500 million to microgrid projects, including several with significant storage components. However (p. 16), most microgrids in operation today are powered by fossil fuels.

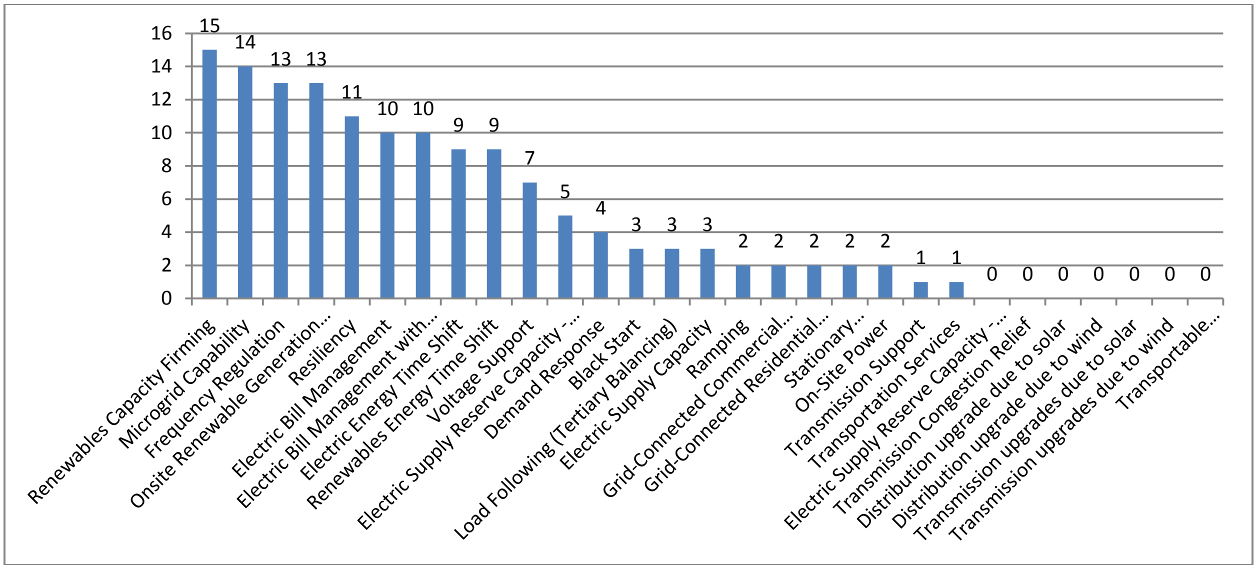


Figure 19: Energy Storage Services by Project, 2015 (Number of Appearances in Database)

As might be expected from the distribution in Figure 15, the largest projects in each of the four most frequently mentioned service categories all used lithium-ion batteries. Two 31.5 MW projects, at Beech Ridge, West Virginia, and Grand Ridge, Illinois, respectively, are associated with wind farms and provide frequency regulation services to the PJM market. [35] A 6 MW system was installed alongside a large solar farm on Kauai, Hawaii, that provides 20% of the island's daytime demand; the batteries primarily provide ancillary services during the day, although they can also provide capacity after the sun goes down. [36] The largest microgrid project, rated at 2 MW, was installed for the Kotzebue Electric Association (KEA) in Kotzebue, Alaska. It uses a lithium-ion system designed for extreme cold environments.[37]

The largest non-lithium-ion project in this period is also located in Alaska. Younicos, which acquired the assets of Xtreme Power in 2014,completed a 3 MW system in Kodiak in June 2015. This project is likely a legacy of the prior period, rather than indicating a technological trend of the future. According to a 2014 media report, the company's "most recent projects use lithium-ion batteries… not its own chemistry."[38]

While a variety of Federal and state programs are mentioned in the database as funders for projects completed in 2015 (including programs in the U.S. Departments of Agriculture, Defense, and Energy), private funding is much more common than it was in prior years. Private funders included utilities, independent power producers, vendors, and other investors. [39] The Beech Ridge and Grand Ridge projects, which were mentioned above, for example, make up the largest part of over 100 MW of storage owned by Invenergy to provide frequency regulation services to the PJM market.[40]

These investments suggest that lithium-ion technology for the provision of frequency regulation services and associated with renewables integration reached maturity in 2015. FERC order 755 had created a market, and public subsidies had helped companies respond to this initially risky opportunity before 2015. In 2015, however, both the technology and market were reliable enough, and sufficiently remunerative, for the private sector to bear the full risk of investment. This "dominant design" appears likely to continue to foster exponential growth in 2016. At least 360 MW of additional privately-owned storage capacity is planned to serve this market, and vigorous competition among vendors (in part an extension of competition in the electric vehicle market) continues.[41]

6. Grid-Scale Battery Deployment in 2016: Looking Back and Looking Forward

Grid-scale batteries in the U.S. have followed a diffusion pattern that is characteristic of rapidly-growing industries. In the 1990s and early 2000s unique projects were undertaken, and there was no evident trend in technology or application. 2009-2014 can be seen as a period of ferment, in which diverse technologies were tried out in diverse applications, often with risk-sharing support from government agencies. The end of this period saw a shakeout. Lithium-ion technology for frequency regulation associated with renewables integration ascended in prominence, and in 2015, it established dominance, even as the market grew exponentially. A 2013 report by Sandia National Laboratories stated: "The benefits and costs of energy storage technologies beyond pumped storage hydro are not well understood in real deployment environments, leading to limited action promoting their further use..."[42] In 2016, this statement is no longer accurate for this particular application.

Looking forward, however, limits to this trajectory are apparent. Vertically integrated utilities like Duke Energy, which have recently expressed enthusiasm for deploying storage systems, and other RTO/ISOs, like MISO, which have begun to follow PJM, may provide it with some further momentum.[43] On the other hand, the PJM frequency regulation market may soon be saturated, and in other wholesale markets, technologies other than batteries may be more cost-effective for providing ancillary services.[44] FERC recently opened a proceeding to explore barriers to greater participation of energy storage in wholesale markets.[45] But the slow pace with which its 2011 orders have been implemented suggests that its leverage may be limited.

In any case, IHS estimates the total U.S. market opportunity for storage systems that would participate in frequency regulation markets to be only about 3% of a total potential U.S. grid-scale battery market of over 100 GW in 2030. Already, less than 10% of planned or contracted utility battery capacity is solely dedicated to regulation. Major applications in the future include transmission and distribution services that reduce the need for other capital investment, renewables integration, and peak shaving/demand management.[46]

Most of these other applications are not yet cost-effective, although specific projects in specific locations, such as at the distribution level in dense urban areas, may be. Stacking multiple services on a single storage system may also bring more projects within reach at today's battery prices.[47] But the "levelized cost of storage," to use the terms of Lazard's recent analysis, is generally higher than the alternative in every use case. [48] Similarly, Hittinger and Lueken argue that falling natural gas prices have adversely affected the revenues of U.S. energy storage projects since 2009, because they must compete with gas turbines for peak shifting purposes.[49] Figure 20 displays Lazard's comparison of various battery chemistries (blue horizontal bars, ranging from $221/MWh to $1247/MWh) to gas peakers (gray vertical bar, ranging from $165/MWh to $218/MWh).

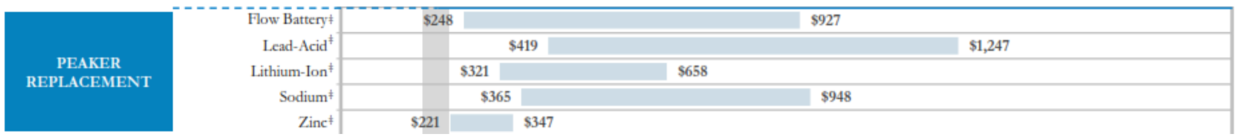


Figure 20: Unsubsidized Levelized Cost ($/MWh) of Storage Comparison (Peaker Replacement)[50]

The biggest drivers of the next phase of grid-scale battery deployment are likely to be state mandates, rather than markets. Most notably, California utilities are required to procure 1.3 GW of storage by 2020 (none of which is yet recorded in the DOE Global Storage Database), provide incentives for customer-sited storage resources, and include storage among preferred resources for distributed generation and demand management. Arizona, Hawaii, Massachusetts, New Jersey, New York, and Washington are among the other states that are mandating or subsidizing electricity storage on a reasonably large scale.[51] (See Figure 21.) Given the difficulties of siting pumped hydro and CAES as well as the growing experience with batteries, it seems highly likely that such mandates will led to growth in the grid-scale battery market.

State incentive programs for energy storage

Region	Program	Form of Subsidy	Activity thus far
FERC-regulated wholesale markets	Frequency and voltage regulation ancillary services	Improved compensation for "fast response" resources like batteries.	PJM and NY have ~104 MW and 28 MW of battery & flywheel storage, respectively. PJM, MISO, CAISO, NYISO, ISO-NE and SPP have all complied with Order 755.
Arizona	Contracts, rebates		Tuscon Electric - 10 MW solicitation
			Arizona Public Service: 2 MW of DG solar + storage plus $1 million in rebates
California	Mandate to procure 1,325 MW of storage by 2020	Storage contract with utilities via RFP.	SCE has signed contracts for 325 MW
	SGIP Incentives		SGIP incentives for 6.8 MW of "behind the meter" storage. Reserved funding for another 85.5 MW
New York	Reforming the Energy Vision (REV)	Details being finalized. Broad reform of utility business model.	Plan to add 100 MW of efficiency and storage in NYC to offset congestion and risk of Indian Point nuclear plant shutting down. Incentives at $2,100/kW.
Texas	Ancillary services market rules + utility investment	Rules similar to FERC rules. Utility investment will need changes in Texas regulatory policy for transmission and distribution service providers.	New ancillary market rules under consideration. No legislation yet to support Oncor's storage proposal.
Hawaii	PPAs, tax credits	Contract with utilities for grid storage projects; bills introduced for tax credits for "behind the meter" storage.	11 grid storage pilot projects initiated. Looking to obtain up to 200 MW in Oahu.
Oregon	Storage mandate	Bill to procure at least 5 MW in storage by 2020.	
Maryland	Pilot projects	Bill introduced to require PSC to implement pilot projects.	
Washington	Grants	Four projects received $14.3 million in grants from the state's clean energy fund.	Two 1 MW projects are operational
Illinois	Rate base	Bill to enable Comed to invest $300 million in six micro-grids.	
New Jersey	Grants	Storage projects paired with renewable plants.	$2.9 million for 13 projects totaling 8.75 MW

Sources: US Department of Energy Global Energy Storage Database; Greentech Media; Environment & Energy (E&E) Publishing

Figure 21: State Incentive Programs for Energy Storage[52]

Lithium-ion chemistries may well prove to be the best technological choice for applications other than frequency regulation. The relatively rapid cost reduction of the past few years is expected to continue, aided by massive manufacturing investments being made by vehicle manufacturers, such as Tesla and BYD.[53] Yet, as with solar photovoltaic generating systems, the cost of the balance of the system becomes more important as the cost of the core technology (in this case lithium-ion batteries) declines. In addition, for longer duration applications, other chemistries that are currently less mature may prove to be more effective. Some venture investors, at least, seem to think so, as does the International Energy Agency, which calls for continued public support for battery R&D and demonstration projects.[54] Federal investments in R&D and risk-sharing in demonstration projects would hasten the next era of ferment in these respects.

Coherent market development for energy storage services is probably a more important priority for Federal and state regulators and policy-makers than technology development. As both a generator and a load, both in front of and behind the meter, and operating at all scales, storage does not fit easily into established regulatory and policy categories. The business case for grid-scale batteries will depend heavily on regulatory designs that provide a reasonable prospect of adequate revenue and sufficiently low market risk.[55]

Although the unit costs of battery systems are much cheaper on a large scale, some, perhaps many, customers may value self-sufficiency enough to be willing to pay a premium for smaller systems. In the extreme, distributed generation and storage systems have the potential to fragment the grid as loads "defect," leaving a heavy and inequitable burden on customers who remain on the grid. Some current policies, such as the Federal solar investment tax credit and Hawaii self-supply tariff option, may wittingly or unwittingly incentivize load defection and thus grid fragmentation.

If ways can be found for energy storage services to be adequately compensated, including distributed storage resources and stacking of multiple services, the equity and efficiency benefits to society of an unfragmented grid are more likely to be retained, even as grid-scale battery deployment accelerates. As with renewable portfolio standards, state-level experimentation is likely to provide the most important insights into how to solve this complex puzzle. California and New York are furthest along in this regard. A key Federal role will be to enable such experiments and facilitate evaluation and information sharing about them. FERC's policies for wholesale markets and transmission must also play a vital supporting role, along with Federal smart grid programs. The evolution of electric vehicles and the market for them will shape the future deployment pattern as well, both through technological spillovers to battery technology and potentially through electricity consumption and even vehicle-based storage. A sustained and coordinated effort that remains flexible to technological opportunities and policy learning is required to realize the tantalizing prospect referred to at the opening of this paper.

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[1] International Energy Agency, *Energy Technology Perspectives 2015,* 38.

[2] T. Mai, *et al.*, *Renewable Electricity Futures Study: Executive Summary*, National Renewable Energy Laboratory. NREL/TP-6A20-52409-ES, 2012.

[3] Shin-Ichi Inage, *Prospects for Large-Scale Energy Storage in Decarbonized Power Grids* (IEA, 2008), p. 8.

[4] Anthony Patt, *Transforming Energy: Solving Climate Change with Technology Policy* (Cambridge University Press, 2015).

[5] Inage, *op. cit.*, p. 19.

[6] Andy Lubershane, "Following the Grid Storage Current," IHS Energy, April 8, 2016, p. 6.

[7] International Renewable Energy Agency, "Renewables and Electricity Storage- A Technology Roadmap for REmap 2030," June 2015 https://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_Electricity_Storage_2015.pdf.

[8] US Department of Energy. *DOE Global Energy Storage Database*. 2016 http://www.energystorageexchange.org/

[9] Lubershane, *op. cit.*, p. 33. Non-battery storage technologies are described briefly in Eric Wesoff, "First Grid-Scale Rail Energy Storage Project Gets Environmental Approval From BLM," *Greentech Media*, April 18, 2016.

[10] Calculated from Ralph Masiello, *et al.* "Energy Storage Activities in the United States Electricity Grid," May 2011, (http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/FINAL_DOE_Report-Storage_Activities_5-1-11.pdf), pp. 6-9, accessed May 10, 2016; Executive Office of the President, *A Retrospective Assessment of Clean Energy Investments in the Recovery Act*, February 2016. U.S. Department of Energy, *Grid Energy Storage*, December 2013, p. 61, (http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf) puts the amount spent by the Federal government on all large-scale storage energy demonstration projects at $185 million. The same report (p. 62) estimates total Federal R&D spending on energy storage from fiscal 2009 to fiscal 2012 at just over $1.3 billion. A fuller accounting of the program can be found in Donald Bender, Raymond Byrne, and Daniel Borneo, "ARRA Energy Storage Demonstration Projects: Lessons Learned and Recommendations," Sandia National Laboratories (SAND2015-5242), June 2015.

[11] Received from DOE EPSA 50: "2016 02 22 BNEF Storage Market Size by Technology US only_redacted"

[12] National Renewable Energy Lab, "Image Gallery #1163" (http://images.nrel.gov/viewphoto.php?imageId=6321534&albumId=207405, accessed April 17, 2016); Andrew L. Rosenthal, et al., *Economics and Performance of PV Hybrid Power Systems: Three Case Studies*, Sandia National Labs, SAND--98-1743C, 1998 .

[13] 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 May 2, 2016); Nicholas W. Miller, *et al.* , "A VRLA Battery Energy Storage System for Metlakatla, Alaska" in *IEEE Battery Conference on Applications and Advances,1996*, pp. 241–48 (http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=485002)

[14] "Semiconductor Wafer FAB Plant Gets Premium Utility Power," *Energy User News*, January 2001, 29-30, quote from 29 (http://www.sandc.com/edocs_pdfs/EDOC_001729.pdf, accessed April 25, 2016).

[15] Golden Valley Electric Association, "About GVEA" (http://www.gvea.com/inside/about, accessed April 25, 2016), and "Battery Energy Storage System" (http://www.gvea.com/energy/bess, accessed April 17, 2016).

[16] DOE Global Energy Storage Database, "Charleston NaS Energy Storage Project," (http://www.energystorageexchange.org/projects/182, accessed April 17, 2016).

[17] DOE Global Energy Storage Database, "Milton NaS Battery Energy Storage System," (http://www.energystorageexchange.org/projects/268, accessed April 17, 2016).

[18] J. Himelic and F. Novachek, "Sodium Sulfur Battery Energy Storage and Its Potential to Enable Further Integration of Wind," Xcel Energy, 2011. (https://www.xcelenergy.com/staticfiles/xe/Corporate/Renewable%20Energy%20Grants/Milestone%206%20Final%20Report%20PUBLIC.pdf accessed April 17, 2016).

[19] International Energy Agency, "Technology Roadmap – Energy Storage," 2014

[20] Lubershane, *op. cit.* p. 36; David Lindley, "The Energy Storage Problem," *Nature* 463:18-20 (7 January 2010).

[21] Bjorn Nykvist and Mans Nilsson, "Rapidly Falling Costs of Battery Packs for Electric Vehicles," *Nature Climate Change* 5:329-332 (23 March 2015).

[22] Michael Kintner-Meyer, "Regulatory Policy and Markets for Energy Storage in North America," *IEEE Proceedings* 102:1065-1071 (2014)

[23] Itron, *2013 SGIP Impact Evaluation*, April 2015; Masiello, *op. cit.*

[24] Hawaii Clean Energy Initiative, *HCEI Road Map, 2011 Edition*, August 2011.

[25] DOE Global Energy Storage Database, "Duke Energy - Notrees Wind Storage Demonstration Project - (Goldsmith,Texas)" (http://www.energystorageexchange.org/projects/11, accessed April 24, 2016).

[26] DOE Global Energy Storage Database, "AES Laurel Mountain" (http://www.energystorageexchange.org/projects/164, accessed April 24, 2016); AES Energy Storage, "Deployments," (http://aesenergystorage.com/deployments/, accessed April 29, 2016). The AES website states that the rated power of this system is 64 MW.

[27] DOE Global Energy Storage Database, "Kaheawa Wind Power Project II -(Maalaea, Hawaii, United States)" (http://www.energystorageexchange.org/projects/137 accessed April 29, 2016); Energy Storage Association, "Earning Revenue via Multiple Value Streams: Kaheawa Windfarm Dynamic Power Resource (DPR®) Energy Storage," (http://energystorage.org/energy-storage/case-studies/earning-revenue-multiple-value-streams-kaheawa-windfarm-dynamic-power accessed April 29, 2016); Eric Wesoff, "Xtreme Blends 15 MW of Energy Storage With Wind," *Greentech Media*, March 24, 2011 (http://www.greentechmedia.com/articles/read/xtreme-power-on-hawaii accessed April 29, 2016); Business Wire, "First Wind Announces Completion of Kaheawa Wind II Project and Start of Commercial Operations," July 5, 2012; Klein and Maslin, p. 2 and p. 12. See also Eric Wesoff, "Battery Room Fire at Kahuku Wind-Energy Storage Farm," *Greentech Media*, August 3, 2012, (http://www.greentechmedia.com/articles/read/Battery-Room-Fire-at-Kahuku-Wind-Energy-Storage-Farm) and Jeff St. John, "The Risks of Novel Batteries Wearing Out Before Their Time," *Greentech* Media, July 8, 2015, (http://www.greentechmedia.com/articles/read/the-risks-of-novel-batteries-wearing-out-before-their-time), both accessed April 29, 2016.

[28] DOE Global Energy Storage Database, "Battelle Memorial Institute Pacific Northwest Smart Grid Demonstration-(Salem, Oregon, United States)" (http://www.energystorageexchange.org/projects/40, accessed April 24, 2016); smartgrid.gov, "Battelle Memorial Institute Pacific Northwest Division Smart Grid Demonstration Project," (https://www.smartgrid.gov/project/battelle_memorial_institute_pacific_northwest_division_smart_grid_demonstration_project.html, accessed April 29, 2016).

[29] DOE Global Energy Storage Database, "Alameda County RDSI CERTS Microgrid Demonstration Santa Rita Jail Smart Grid-(Dublin, California, United States)" (http://www.energystorageexchange.org/projects/91, accessed April 24, 2016); Chevron Energy Solutions Company, "CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewables at Santa Rita Jail," Final Project Report, May 2014.

[30] "The Next Wave of Energy Storage Financing: Green Charge Closes $50M Non-Recourse Debt Funding | Greentech Media." Accessed April 25, 2016. http://www.greentechmedia.com/articles/read/the-next-wave-of-energy-storage-financing-green-charge-closes-50m-non-recou.

[31] Philip Anderson and Michael Tushman, "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change," *Administrative Science Quarterly* 35:604-633 (1990).
[32] Lubershane and Klein, p. 17.
[33] Alex Klein and Andy Lubershane, "Battery Surge?," IHS Research, June 4, 2015, p. 6.
[34] Bloomberg New Energy Finance, *2016 Sustainable Energy in America Factbook*, p. 107.
[35] DOE Global Energy Storage Database, "Beech Ridge Wind Storage 31.5 MW" (http://www.energystorageexchange.org/projects/1745, accessed April 27, 2016) and "Grand Ridge Energy Storage 31.5 MW" (http://www.energystorageexchange.org/projects/1746, accessed May 1, 2016).
[36] Christian Roselund, "REC Puts Online Hawaii's Largest Solar Plant," *pv-magazine*, November 2, 2015 (http://www.pv-magazine.com/news/details/beitrag/rec-puts-online-hawaiis-largest-solar-plant_100021823/#axzz3qQI5jmIC, accessed April 27, 2016).
[37] DOE Global Energy Storage Database. "2 MW / 950 kWh - Kotzebue - Saft". (http://www.energystorageexchange.org/projects/1964, accessed April 27, 2016).
[38] Jeff St. John, "Bankrupt Grid Battery Alert: Xtreme Power Bought by Germany's Younicos," *Greentech Media*, April 15, 2014 (http://www.greentechmedia.com/articles/read/bankrupt-grid-battery-alert-xtreme-power-bought-by-germanys-younicos accessed May 1, 2016).
[39] Posi-Fen Solar Solutions, "New Orleans Solar Startup Partners with City of New Orleans to Help Power a Resilient City Hall" (http://www.prnewswire.com/news-releases/new-orleans-solar-startup-partners-with-city-of-new-orleans-to-help-power-a-resilient-city-hall-300133595.html, accessed April 29, 2016).
[40] Herman K. Trabish, "Invenergy Adds 31.5 MW Battery to Booming PJM Frequency Regulation Market," *Utility Dive*, November 4, 2016 (http://www.utilitydive.com/news/invenergy-adds-315-mw-battery-to-booming-pjm-frequency-regulation-market/408558/ accessed May 2, 2016).
[41] Trabish, *op. cit.*
[42] Dhruv Bhatnagar, *et al.*, *Market and Policy Barriers to Energy Storage Deployment*, Sandia National Laboratory, SAND2013-7606, September 2013.
[43] GTM Research, "U.S. Energy Storage Monitor: 2015 Year in Review Executive Summary," March 2016; Robert Walton, "Beyond Pilots: Duke Energy Looks to Install Storage in Regulated Market," *Utility Dive*, April 28, 2016 (http://www.utilitydive.com/news/beyond-pilots-duke-energy-looks-to-install-storage-in-regulated-market/418265/ accessed May 2, 2016).
[44] Kintner-Meyer, *op. cit.*; Lubershane, 2016, p. 9 and p. 19.
[45] Peter Maloney, "FERC Seeks Input from ISOs on Possible Market Barriers to Energy Storage," *Utility Dive*, April 19, 2016 (http://www.utilitydive.com/news/ferc-seeks-input-from-isos-on-possible-market-barriers-to-energy-storage/417629/ accessed May 2, 2016).
[46] Lubershane, *op. cit.*, p. 9; Bloomberg New Energy Finance, *op. cit.*, p. 106
[47] Lubershane, *op. cit.*, p. 26. On stacking services for behind-the-meter systems, see Garrett Fitzgerald, *et al.*, "The Economics of Battery Energy Storage," Rocky Mountain Institute, September 2015.
[48] Lazard, "Levelized Cost of Storage Analysis 1.0," November 2015 (https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf accessed May 1, 2016). See also Lubershane, *op. cit.*, pp. 18-31; and Moody's Investor Service, "Batteries Charge Up For the Electric Grid," September 24, 2015.
[49] Eric Hittinger and Roger Lueken. "Is Inexpensive Natural Gas Hindering the Grid Energy Storage Industry?" *Energy Policy* 87:140-152 (2015).
[50] Lazard, *op. cit.*, p. 9.
[51] Lubershane, *op. cit.*, p. 8; Bloomberg New Energy Finance, *op. cit*, pp. 104; GTM Research 2016, *op. cit.*, pp. 6-9.
[52] Moody's Investor Service, *op. cit.*, p. 14.
[53] Nykvist and Nilsson, *op. cit.*; Andy Colthorpe, "Lux Research: BYD's 'Rival Gigafactory Plans' Facing Same Challenges As Tesla," *Energy Storage News*, March 25, 2015 (http://www.energy-storage.news/news/lux-research-byds-rival-gigafactory-plans-present-similar-challenges-to-tes accessed May 2, 2016).
[54] BNEF, *op. cit.*, p. 108; International Energy Agency, "Energy Storage Roadmap 2014."
[55] Bhatnagar, *et al.*, *op. cit.*, pp. 22-24.