Grid-Level Battery Technology: Technology and Policy Considerations in New England
Adriana Ciccone, Dylan Cohen, Sung Kim, Alexander Zavoluk

Abstract
Using grid-level battery storage is a technology and policy solution to several relevant electricity generation and demand issues. Many types of renewable energy sources require energy storage to be feasible as their supply is highly intermittent. Failure to effectively balance electricity generation to forecasted demand can result in capacity problems leading to inefficient use of generators, brown-outs and total loss of service to customers. Batteries providing an energy buffer could lead to improved generator efficiency and increased adoption of renewable technologies. We model such an implementation in the New England region of the United States and analyze the impact on marginal greenhouse gas emissions and recommend policy instruments to incentivize adoption. We conclude that while significant up-front costs are required to implement this project, in many cases the benefit of reduced greenhouse gasses outweigh the costs. With the right policies in place, grid-level batteries can be a successful support of state’s renewable portfolio standards targets and can function as an effective buffer between electricity production and demand.

Introduction
To generate electricity in the United States requires an enormous amount of cooperation among multiple organizations and technologies. Electricity is produced by many generating organizations and sold to distributors through clearinghouses which also manage the electrical grid. To complicate this process, electricity must be produced at the same time it is required, necessitating extremely accurate forecasting and responsive generation capability\(^1\).

The US electrical grid is divided into regional grids with specified interchanges between each. In this analysis we focus exclusively on the New England region, managed by the New England ISO (Independent Service Operator). This ISO is responsible for monitoring grid function, short and long term forecasting, and reporting energy production and sales to distributors in Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island\(^2\).

Forecasting energy demand is a complicated process. Weather conditions, time, day of the week and season all affect the quantity of electricity demanded. Generation is similarly complex, utilizing several production methods, each with their own cost and reaction time. The New England region uses a mix of fossil fuels, renewables, and other alternative energies, with natural gas and nuclear comprising 42% and 31% of demand, respectively. Renewables meet 13% of the New England demand, with hydropower, waste to energy, and wind power being the largest components\(^3\).

\(^1\) http://www.iso-ne.com/nwsiss/grid_mkts/elec_works/index.html
\(^2\) http://www.iso-ne.com/aboutiso/co_profile/overview/index.html
\(^3\) http://www.iso-ne.com/nwsiss/grid_mkts/energy_srcs/index.html
The NE ISO dispatches requirements to 350 generators in the region and coordinates the wholesale energy market across 500 buyers and sellers of electricity\(^4\). Base load demand typically comes from resources with long ramping lead times, such as nuclear power, allowing more responsive sources, like natural gas generators, to provide instantaneous marginal power\(^5\). While natural gas resources can ramp up generating capacity to meet unexpected demand, there may still be times during which immediate production falls short of demand. In these cases, the New England ISO uses pumped water storage to generate electricity. Later, the ISO can pump this water back up to its storage location when electricity demand has fallen to a lower level and extra electricity is being produced.

Pumped water storage, however, has relatively low energy density and is typically only cost effective in areas with appropriate topography\(^6\). There exists an opportunity to utilize battery storage technology in place or in addition to pumped water storage to improve the region’s ability to respond to changes in demand. Improved storage would allow suppliers to stabilize their production and eliminate the majority of ramping to meet peak demand.

One example of using batteries for large-scale storage already exists in the U.S. The AES Laurel Mountain Plant in West Virginia provides energy storage for a 98 MW wind farm with a 32 MW lithium-ion battery energy storage system\(^7\). The AES battery helps match generation and demand by delivering instantaneous response to power requests by the PJM Interconnection. The storage technology also allows AES to smooth out fluctuations in minute-to-minute output in wind generation. Pilot projects like the AES lithium-ion battery demonstrates that the application of energy storage technologies at the grid level may not be too far off.

In this paper, we examine several suitable battery technologies currently available and perform a cost-benefit analysis of the integration of these technologies into the New England power grid. We limit our analysis to the next ten years, as attempting to forecast both long-range battery cost projections and new technological developments past that time would have very high uncertainty. We model electricity supply and demand using historical data and forecasts developed by the New England ISO to understand the impact of adding batteries to electricity generation. Benefits are calculated by quantifying the reduction in marginal GHG emissions, while costs include best estimates of technology costs and projections about future cost reductions. We also evaluate several policy recommendations for their suitability for incentivizing this project.

**Motivation**

One of the benefits of having a grid-level energy storage technology is that it can reduce inefficiencies in the grid. Currently the grid operates as the ultimate Just-In-Time system. Generation must meet demand to maintain a reliable energy supply. More problematic is that the demand fluctuates widely depending on the time of the day. The accompanying figure summarizes the load statistics in a single day in the New England ISO region.

The figure illustrates the high variability in demand. The load required to meet demand varies hour to

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hour and the projections for the exact amount is subject to high uncertainties. To ensure uninterrupted energy supply to US consumers, be they retail or industrial, the grid has to generate electricity at the upper bound of demand. While forecasts exist to inform generating sources about their production requirements, some uncertainty remains for instantaneous demand. Consequences of operating near or at capacity include inefficient production with higher emissions (as more expensive and more polluting power sources are used), wasted energy, hardware overloads, brown-outs and black-outs. A high-capacity energy storage device can remove such inefficiencies by storing power at off-peak times and supplying them during peak hours.

Another chief benefit of energy storage devices is renewable integration. All New England states have Renewable Portfolio Standards (RPS). The figure below summarizes the RPS targets by 2020:

<table>
<thead>
<tr>
<th>State</th>
<th>Classes</th>
<th>RPS Target by 2020 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maine</td>
<td>“Existing”</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>New Capacity</td>
<td>10% of capacity by 2017</td>
</tr>
<tr>
<td></td>
<td>EE Goal*</td>
<td>30*</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>I New</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>II Solar</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>III Existing biomass</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>IV Existing small hydro</td>
<td>1.0</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>New</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Existing I and II</td>
<td>3.6, 3.5</td>
</tr>
<tr>
<td></td>
<td>EE/DR Goal*</td>
<td>25*</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>Existing</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>New</td>
<td>14</td>
</tr>
<tr>
<td>Connecticut</td>
<td>I New</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>II Existing</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>III CHP and EE</td>
<td>4</td>
</tr>
<tr>
<td>Vermont</td>
<td>[has no formal RPS]</td>
<td>goal of 20% by 2017</td>
</tr>
<tr>
<td></td>
<td>SPEED Program</td>
<td>all energy growth above 2005</td>
</tr>
</tbody>
</table>

A considerable proportion of power is scheduled to be obtained by renewable resources. However, due to the nature of intermittent supply of renewable resources such as wind and solar, a proper mechanism for efficiently smoothing supply is needed. A large energy storage capacity can help fulfill that role. Therefore, we will assess the feasibility of the New England ISO implementing grid-level batteries.

**Overview of US Electricity Industry**

The US electricity industry is comprised of many stakeholders. These stakeholders include private investors, consumers, and several regulatory agencies at different levels. The utilities can be split into the following three categories: investor owned utilities, consumer owned utilities, and vertically integrated utilities. Investor owned utilities serve 75% of US consumers. These utilities are privately owned and are mostly subject to state regulation. Only if the utilities are involved in the wholesale market or inter-state transmission are they subject to federal regulation. 25% of US consumers are served by consumer owned utilities. These include city owned utilities, public utilities, and non-profit cooperatives. Vertically integrated utilities are a subcategory of utilities that control all of generation, transmission, and distribution to retail consumers. They do not necessarily own the facilities required for each process but can exert control through contracts with other entities that do own the facilities.

The electricity industry is regulated by multiple agencies at different levels. At the federal level, the Federal Energy Regulatory Commission (FERC) is responsible for overseeing wholesale power sales and interstate transmission. At the state level, commissions are responsible for setting standards for construction of retail distribution facilities. These commissions also mandate quality of service standards and determine retail power prices. Despite the powers state commissions have and with the exception of Texas, Alaska, and Hawaii, all utilities in other states are ultimately under federal jurisdiction and thus have to comply by FERC orders.

The elements of what we commonly call a Grid are: generation, transmission, and distribution. Electricity generated from different generation sources, such as power plants, is linked to three transmission networks called

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synchronous interconnections (or Interconnects). These are the Western Interconnect, the Eastern Interconnect, and the Electric Reliability Council of Texas (ERCOT). Because not many energy storage technologies are deployed, currently electricity is consumed at the same time it is generated. To ensure the reliable distribution of power to consumers, the transmission networks are further subdivided into regions managed by various reliability councils. There are eight reliability councils in the United States under the oversight of the North American Electricity Reliability Council (NERC).

Within each NERC region, numerous entities manage the minute to minute coordination of electricity supply and demand. These entities are split into Regional Transmission Organizations and Independent System Operators (RTOs/ISOs) and control areas. RTOs/ISOs are similar organizations, often considered interchangeable. RTO/ISOs are volunteer organizations established to meet FERC standards. Their chief purpose is to ensure competitive neutrality in the wholesale market and regional power reliability. It is important to note that these organizations are not under the jurisdiction of the state commissions, but rather, are under the jurisdiction of FERC. Control Areas are smaller areas within the NERC region that are not managed by either RTOs or ISOs. These regions are, for the most part, managed by investor owned individual utilities. Due to their smaller scale these areas must coordinate with other entities to ensure reliable supply of electricity and are not under federal jurisdiction. Because they do not participate in competitive wholesale markets, various entities coordinate with each other by bilateral contracts.9

State commissions are responsible for determining the utility revenue requirement, and in turn, establishing retail prices for each class of consumers. State commissions also fulfill other roles such as: managing portfolio standards, integrated resource planning, construction authorization, energy efficiency, and security issuance.

A commission’s approved conditions, terms, and prices are published in a document called the power tariff. Utilities wishing to file a rate increase must go through a formal regulatory procedure called the tariff proceedings. In the tariff proceedings the revenue requirement of each utility is calculated. Since not all state commissions have the same consumer sector classifications, retail prices are determined in proportion to each consumer class’s peak demand, energy consumption, and share of total utility revenue from the starting point of the revenue requirement. The revenue requirement is the total amount of revenue the utility would need to provide a reasonable opportunity to earn a fair rate of return. A general formula for calculating the revenue requirement is as follows:

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\text{Revenue Requirement} = \text{Rate base investment} \times \text{Rate of Return} + \text{Operating Expenses}
\]

In the tariff proceedings rate base investment, rate of return and operating expenses are carefully examined based on a historical year’s costs and revenues of the utility, or an estimated year’s calculations. After the revenue requirement is calculated, the actual retail prices are determined by allocating the revenue requirement into different consumer sectors.

**Barriers to Energy Storage**

One regulatory barrier to energy storage deployment lies in procedural issues, namely, administrative delays in implementing new regulations that may help deployment of these technologies.10 For example, FERC Order 755, also called Pay for Performance, requires ISO/RTOs to meet standards in compensation mechanisms in regards to frequency regulation services. The order is of particular importance because one of the chief functions of energy storage technologies is to provide frequency regulation services. Electricity is consumed at the same time it is generated so frequency regulation services are needed to maintain the balance between generation and load in real time. Energy storage technologies are particularly efficient in providing frequency regulation services. However, most RTO/ISOs do not compensate service providers based on performance or efficiency. FERC Order 755 requires ISO/RTOs to compensate

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service providers based on actual service provided, proportional to frequency regulation quantity. Nevertheless, numerous ISO/RTOs have not adopted Pay for Performance, partly due to numerous stakeholders involved with various interests and the complexity of the regulatory climate.

Another regulatory barrier is in the classification of energy storage technologies.\textsuperscript{11} Energy storage technologies are capable of providing multiple services ranging from generation, transmission, and distribution to ancillary services. However, under the current framework, providers are not able to obtain proper compensation from a resource providing services in multiple classifications. For instance, a battery technology that provides distribution relief services and ancillary services cannot obtain revenue for both services. Such limitations prevent energy storage providers from obtaining just compensation.

Furthermore, if an energy storage provider were to try to obtain compensation for both services, the provider is required to obtain FERC and state commission approval. This imposes additional legal costs on providers for presenting a case before the commission, and even if the provider were to do so, the outcome of the ruling is uncertain. FERC and ERCOT both handle such cases on a case-by-case basis and do not consider analogous cases as precedents. When American Electric Power filed a case for its Sodium Sulfur Battery to be considered as a transmission asset, ERCOT approved the suit but specified that the case would not be considered a precedent for other energy storage technologies. Uncertainty in such rulings also poses as a barrier for energy storage providers. FERC approved a pumped storage project in Nevada to recover costs for transmission services, but in an analogous case declined to consider Sodium Sulfur batteries by the Western Grid as providing transmission services.

A third regulatory barrier stems from discrepancies in rules across different markets\textsuperscript{12}. Providers wishing to maximize revenue potential by operating across different markets face a further challenge. Different markets have different classification systems, and therefore, different compensation mechanisms. This variety adds a further burden to energy storage providers because they have to make separate business cases for each market. For example, cooling skid are required to maintain specific temperature of storage technologies while charging. In ERCOT, cooling skids are defined as auxiliary loads and therefore are not considered as necessary components of the energy conversion process. Providers are charged retail rates instead of wholesale rates for cooling skids. However, in other markets cooling skids are considered necessary components and therefore providers for those markets charge wholesale rates for cooling skids. The varying classifications and corresponding differences in price complicate the situation for both energy providers operating within ERCOT and those operating in the other interconnects.

Receiving proper revenue compensation for energy storage providers is problematic, especially in regards to providing ancillary services.\textsuperscript{13} In ISO/RTO regions, where wholesale power sales are regulated under FERC, ancillary service compensation is based on the opportunity cost of generation. Traditional generators that provide ancillary services do so by withholding power from basic services to direct to ancillary services. Thus, the price of providing such services is determined by the opportunity cost of withholding from providing basic services. This market structure is problematic for energy storage providers because storage technologies are often designed to only provide ancillary services. For these technologies, no market price exists because they do not provide basic services. Therefore, it is difficult for ISO/RTO regions to effectively compensate energy storage providers.

Even for frequency regulation, which has mandatory compensation based on actual services for providers due to the ruling of FERC in order 755, the current framework is incomplete at best. Order 755 only mandates that ISO/RTOs meet certain standards in compensation mechanisms and does not dictate specific rules. Therefore, different ISO/RTOs


\textsuperscript{13} Ibid.
have different compensation mechanisms, many of which are far from providing just compensation to providers. Certain technologies are much faster in responding to frequency regulation needs than others. For example, fly-wheels have a much faster response rate than Compressed Air Energy Storage (CAES), and CAES technologies are much faster than coal power plants. However, many districts only have a two part system where they classify response rates as slow or dynamic. This system does not effectively delineate among the differences in performance of different technologies and impedes proper compensation.

Market barriers are not only an issue for ISO/RTO regions. The lack of price signals for ancillary services also poses problems for energy storage providers wishing to operate in non-ISO/RTO regions. In non-ISO/RTO regions, coordination among different entities is carried out by bilateral contracts. However, in the absence of prices for ancillary services, it is often difficult to evaluate a provider’s proposal that includes energy storage systems. Parties cannot look to other wholesale markets to estimate revenue streams.

Another concern for energy storage providers is the uncertainty and risks of battery technologies. Advancements in the technology could make one battery economically feasible or render another obsolete. Implementing energy storage technology is unattractive when the product might be non-optimal by the time it begins operation. Even if the energy storage technology used is economically feasible, there is no guarantee that the energy service providers would be compensated appropriately for its usage. As was mentioned earlier, ancillary service pricing varies from region to region and there is still debate over whether or not energy storage would be included under ancillary service pricing in the first place. Energy storage cannot be implemented if the payout from it is uncertain. The uncertainty in this situation is compounded by the difficulty of correctly modeling energy usage and the impact energy storage might have. There is no standardized model so each energy provider would have to develop their own, which runs the risks of the model being faulty and of each company using different models, so they might not act in concert. Finally, there is the uncertainty inherent in the regulatory landscape. Additionally, regulations may change and there is no telling if those changes would be to the benefit or detriment of energy storage technology and implementation.

Lastly, we would like to end the analysis with a brief note on capital costs. While the barriers discussed above are all important impediments to future deployment of energy storage technologies, still the foremost reason stakeholders give for not undertaking these technologies is cost. For most, the high technology costs of energy storage technologies render them un-economical compared to other technologies available on market. Moreover, the costs tend to be up front and in lump sums while the benefits accrue over time, further discouraging entry into the field of energy storage. However, this is an area where continued research and development is leading to breakthroughs in cost-effectiveness, and thus we can expect lower prices and faster returns in the future.

Battery Technologies

In this section, we investigate various chemistries and designs for their suitability in grid-level storage. Batteries must meet certain criteria in order to be considered for such an application, including reasonable energy density, lifespan over charging cycles, charge and discharge rates, low self-discharge rates, and low price per kilowatt hour. Our initial research indicated that the following technologies may be suitable for grid-level applications but before the details of the batteries are discussed it is necessary to explain exactly what a battery is.

At its most basic, a battery is an electrochemical cell. Charging a battery moves electrons from the anode to the cathode, creating a chemical potential. However, it is not enough to simply move the electrons; the defining feature of a

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14 Ibid.
battery is that the electrons remain at the anode and the cathode, that is, in the charged position, until the energy is needed. When the battery is discharged the electrons flow back from the cathode to the anode, creating electrical energy from the chemical potential energy of the battery. Though the different designs discussed below have different specifications driven by their unique chemistry, each follows this same basic structure.17

<table>
<thead>
<tr>
<th></th>
<th>Specific Energy (Wh/Kg)</th>
<th>Charge/Discharge Efficiency (% of total)</th>
<th>Self-discharge rate (%/month)</th>
<th>Cycle Durability (Cycles)</th>
<th>Price ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanadium Redox</td>
<td>25-35</td>
<td>70-75</td>
<td>NA</td>
<td>5000-7000</td>
<td>380-600</td>
</tr>
<tr>
<td>Lithium-Ion</td>
<td>70-200</td>
<td>96</td>
<td>5-10</td>
<td>400-1200</td>
<td>1100</td>
</tr>
<tr>
<td>Sodium-Sulfur</td>
<td>50-200</td>
<td>89-92</td>
<td>NA</td>
<td>1500-4500</td>
<td>140</td>
</tr>
<tr>
<td>Nickel-Cadmium</td>
<td>30-37</td>
<td>70-90</td>
<td>25</td>
<td>1000-2000</td>
<td>300-600</td>
</tr>
</tbody>
</table>

**Vanadium Redox Battery**

A vanadium redox battery is comprised of two containers each with a solution of vanadium sulfate and some quantity of inert connector between them, which serve as anode and cathode, respectively.18 The battery can be made to charge or discharge by switching which container is undergoing which reaction. Maximum wattage is dependent on the quantity of vanadium sulfate in each container, which allows for the battery to be scaled easily in both size and energy density.

Vanadium sulfate is non-toxic so the battery can therefore be stored for long periods of time without concern for environmental contamination. As both the anode and cathode are made of the same material, cross contamination within the battery is also avoided.19

The safety and stability of vanadium-redox batteries is unfortunately offset by its relatively low energy densities; between 25-35 Wh/kg. Producing a single megawatt of power would require a minimum of 35000 kilograms of vanadium redox solution. Mechanical constraints are also considerable. This technology requires relatively complex machinery, such as pumps, for the solution to function properly. Moving parts within the battery increase the likelihood of a breakdown. Finally, the price per kilowatt hour is high enough to potentially be a detriment when compared with other forms of energy storage.

**Lithium Ion Battery**

In a lithium-ion battery the electrodes are naturally comprised of lithium. Due to the unstable nature of lithium in its basic form, batteries are constructed of various forms of lithium ions. The precise nature of these ions varies from

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battery to battery and can affect the properties of the battery within certain ranges. Charge in lithium-ion batteries comes from the electrochemical properties of the metal.

The benefits from this type of battery are fairly straightforward. Lithium-ion batteries provide a very high energy density, several times that of other possible grid level batteries. In addition, lithium-ion batteries are very energy efficient while charging and discharging, so little of the energy the battery can provide is lost in the transfer process. Unfortunately, the benefits of lithium-ion batteries come with several very significant drawbacks. Lithium ions can be harmful to the other components of the battery, requiring considerable insulation. Additionally, lithium has a relatively low melting point, 180 degrees Celsius, and if it begins to melt that can disrupt the workings of the battery and potentially lead to a chemical reaction. Water reacts with lithium and creates hydrogen which can raise the pressure in the battery to unsafe levels, potentially causing explosions.\(^{20}\) At the grid level the most problematic feature is lithium’s reaction to heat. A lithium-ion grid level battery would be composed of multiple cells and each cell of a battery produces heat. If the cells are not carefully managed and arranged the temperature threshold of 180 degrees that would be far more dangerous for a large battery than overheating would be in the more common smaller lithium-ion batteries.

Lithium batteries will discharge over time and the higher the temperature of the battery, the larger the self-discharge. This feature, as well as the aforementioned heat threshold necessitate that the batteries have some form of cooling system. Such a system would naturally be expensive both financially and in terms of energy, reducing the benefit gained from lithium-ions high energy density. Finally, lithium itself is a very expensive and a large lithium-ion battery could be prohibitively expensive.

**Sodium Sulfur Battery**

Sodium sulfur batteries are known as molten salt batteries\(^ {21}\). The temperature of this battery type is around 350 degrees Celsius, high enough for the anode and cathode to be in a liquid form and for the electrolyte to operate at peak efficiency. Excluding the higher operating temperature, this battery is similar to other battery types. While discharging electrons are taken from the sodium at the anode and flow to the sulfur at the cathode, creating sodium polysulfide. To recharge the battery the process is simply reversed, sodium polysulfide is broken down and electrons return to the sodium from which they originated.

Sodium sulfur batteries have several significant benefits. They have a high energy density and an energy efficiency of around 90%. Sodium and sulfur are both common materials so the price per kilowatt hour of sodium sulfur batteries is very low, around $140/kWh which is comparable with currently widespread systems of energy storage such as pumped water storage. That price might drop even further if sodium sulfur batteries were to enter mass production. Finally, the battery does not discharge over time and can undergo a large number of cycles without breaking down.

The specifications of the sodium sulfur battery are very promising for grid-level applications, though there are still costs associated with this technology. The most notable cost of this battery is the high temperature at which it must operate. Naturally, heating and maintaining the battery at the high temperature carries an energy cost making the battery slightly less efficient overall than it would be if it functioned at room temperature. In addition, the high temperature increases the risk associated with the anode and the cathode coming into contact. Such an event would result in the instantaneous release of large amounts of chemical energy. However it would also include the release of materials at extremely high temperatures and sodium, which burns when placed in contact with the atmosphere\(^ {22}\). In short, a malfunction of this battery type could be exceedingly dangerous. The problem is compounded by the fact that the tests


needed to detect the warning signs of such a meltdown are likely to give false positives, which could lead to a sodium sulfur battery being shut down far more than is optimal.

Nickel Cadmium Battery

Much like the lithium-ion battery, the nickel cadmium battery is also a straightforward electrochemical cell. In this case cadmium is used as the anode and nickel hydroxide is used as the cathode. Potassium hydroxide is generally also present as the electrolyte for the battery. The nickel cadmium battery was invented over 100 years ago and is a very well understood form of technology. Currently the largest battery in the world, located in Fairbanks Alaska, is a 40 MW nickel cadmium battery demonstrably capable of being used at a grid level\(^{23}\). The battery is also fairly consistent in its output. Variation in temperature does not damage it and it can be deeply discharged without damage as well.

Nickel cadmium batteries have small costs proportional to the small benefits they provide. Cadmium is a heavy metal and as such slightly dangerous to living creatures\(^{24}\). However, the technology exists to render its usage in nickel cadmium batteries safe and affordable. Nickel cadmium batteries also experience a memory effect. If they are discharged to the same point a large number of times the battery begins to experience a drop in voltage at that point. This effect can be repaired by fully charging and discharging the battery several times and is in any case unlikely to be a problem for a grid level storage battery.

Battery Selection

In terms of pure numbers the only battery type that stands out is the sodium sulfur battery. Lithium-ion has the shortest life cycle and the highest price to along with the highest specific energy and energy efficiency. Vanadium redox and nickel cadmium both have lower specific energies, efficiencies, and costs. Only sodium sulfur has a low cost and high specific energy as well as a reasonably high efficiency and life cycle duration.

Expanding the comparison to include the properties of each battery changes the analysis slightly. From a safety perspective vanadium redox batteries appear more attractive due to their stability while lithium-ion and sodium sulfur appear less attractive due to the dangerous chemicals they contain. Nickel Cadmium stays about the same because while it is reliable and well understood it also suffers from a memory effect, decreasing its overall value.

The discussion above naturally represents the current state of battery technology. Advancement will certainly be made but such advancements will not necessarily be equally distributed between the battery types.

1. Nickel cadmium is an old and well understood form of battery; it is unlikely that innovation will drastically improve any aspect of the technology. The benefit of nickel cadmium lies in its current functionality rather than its potential for improvement.

2. Lithium-ion batteries are expensive in part because lithium itself is a rare and valuable material. Mining lithium is expensive and there is no indication that it will become cheaper in the near future so the price of lithium batteries is likely to stay at its current rate. The efficiency of lithium-ion batteries is also unlikely to improve simply because efficiency becomes harder to improve the higher it is and at 96% the efficiency of lithium-ion batteries is already very high. Similarly, improving the specific energy of lithium ion would be difficult because it


is already very high and the danger of the battery increases as the specific energy is raised. Minor improvements could improve its level of safety. However, the materials in this battery are fundamentally dangerous and any improvements are likely to be only incremental.

3. Vanadium redox batteries are a fairly new battery type and may well see improvement. In particular one research group claims that they have managed to increase the specific energy of vanadium redox batteries to levels comparable with lithium-ion batteries. This technology is only in the prototype phase and currently being researched with an eye toward electric car batteries rather than grid storage. However if successful, such an advancement could overcome the greatest detriment to vanadium redox batteries. In addition, as this battery is used more often, better designs that allow for fewer moving parts will presumably be developed.

4. Sodium sulfur batteries may improve most significantly in the area of cost. Currently, sodium sulfur batteries are not being mass produced. If facilities were put in place to mass produce these batteries the already low price would drop further. Pumped hydro storage is one of the most widely used forms of grid storage with a price of approximately $100/kWh. With mass production and its higher energy efficiency sodium sulfur batteries might pass pumped hydro storage to become a feasible form of grid level energy storage. That said, this battery will still contain dangerous materials at high temperatures. Better methods of detecting breakdowns may be developed but the risk inherent in the design of this battery is unlikely to be completely alleviated. Siting of battery storage in an area with low population density would be an important requirement for successful implementation of this technology.

Final Thoughts on Technology

Each of the battery types considered has significant benefits and costs. Despite the dangers sodium sulfur batteries stand out as the optimal first choice for a grid level storage battery. Vanadium redox batteries represent a possible avenue for fruitful further research and development. With a few advances vanadium redox could become a major contender for grid storage batteries. Nickel cadmium batteries currently represent the largest grid storage battery. However, the limits of that technology are fast approaching and it is unlikely that this form of battery will persist at the grid level. Finally, lithium-ion, while excellent in energy density, is far too expensive to be worth developing considering the dangers of this battery type.

The Model

As discussed elsewhere, increasing energy storage capacity on the grid level allows for three major benefits: increased renewable usage, reduced ramp-up time for conventional power plants, and decreased use of inefficient conventional power plants. Here we propose a model for distributing instantaneous power supply among renewable sources, conventional sources, nuclear power, and stored energy. The essential idea is that stored energy will be used to cover some fixed fraction of the variance of energy demand away from its mean. Specifically, we considered

$$C(t) = D_T + (1 - f_T)(D(t) - D_T) - N(t)$$

Where:

- $C(t)$ is energy supplied by conventional sources (such as natural gas) at time $t$;
- $D_T$ is the average demand over a long time period $T$;
- $f_T$ is the fraction of variance in demand allocated to batteries over time period $T$ (the rest of the variance is covered by conventional sources);
- $D(t)$ is demand at time $t$;
R(t) is renewable energy generated at time t;  
N(t) is nuclear energy generated at time t  
Note that the capital T refers to a long time period (a year), and the lower case to a short one (an hour).

**The Data and Assumptions**

We obtained hourly forecasted and actual demand from the New England ISO. We collected one week’s worth of hourly data for each month of the year to ensure seasonal changes were captured, in addition to capturing hourly and weekly variability. We then applied linear transformations to capture the increase in demand forecasted by the ISO over the next 10 years as part of their strategic planning assessment\(^\text{25}\). To estimate the renewable parameter\(^\text{26,27}\), we used their projections for renewable energy production, again over ten years\(^\text{28}\). They also supplied numbers for the marginal output of carbon based on electricity production\(^\text{29}\). Combining this information allowed us to express the conventional supply as a function of only that fraction. It also allowed us to keep track of the “demand gap” or difference between production and demand; by finding the maximum cumulative demand gap, we determined our necessary storage capacity.

We used estimates for the social cost of carbon from the federal government’s Interagency Working Group on Social Cost of Carbon\(^\text{30}\). That allowed us to calculate the benefit of reduced greenhouse gas emissions due to less conventional power source usage. We did likewise for NOx emissions by finding an estimate for the relative impact of these two greenhouse gases on the environment. We took into account the effect on renewables by assuming that the New England ISO would hit its renewable projections.

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\(^{28}\) Ibid

\(^{29}\) Ibid

program written in python. Its construction allows for the precision of the estimate for each of these fractions, as well as any of the value of the above parameters, to be easily modified, so different sets of assumptions can be tested with only slight modifications. The program, in addition to calculating optimal fractions for each time period, also calculates the actual net benefit in each year and the overall benefit. Results are shown above for three scenarios (battery types).

**Discussion**

**Reliability of Results**

As with any model, ours runs the risk of oversimplification. Other factors could affect the cost-benefit analysis (see below) which were not taken into account. Perhaps there is an alternative method for distributing the power supply among renewable energy, conventional sources, and energy stored in batteries which is more efficient. Our model took into account very little information; it ignores, for instance, the ability of the New England ISO to fairly accurately predict electricity demand ahead of time. One might construct a more complicated model which allows the fraction of variation corresponding to conventional sources to vary more, perhaps to better adapt to fluctuations in renewable energy supply.

Our demand data, sampling the first week in every month for a year over time periods of one hour, should be reliable. The sample is large, and includes all times of year. New England experiences significant weather changes across seasons, so our results may be extended to a variety of climates. Based on historical yearly data and future projections, it appears that overall electricity consumption in 2013 was not exceptionally high or low.\[31\]

The results are highly dependent on the values of the parameters. For example, we relied on an outside source for the social cost of carbon, so any uncertainty in those estimates would lead to uncertainty in our model. We also had to estimate the cost of battery technologies which are still in the research phase, as well as the rate at which their price might decline. All of these estimates have their own uncertainty; however, while the overall uncertainty might seem large, some of the values should be overestimated and some underestimated so the final result should be more accurate than the individual parameters.

**Additional Costs and Benefits**

In this preliminary research, it was not feasible to quantify and include all possible costs and benefits in our analysis. Since batteries that could be used for grid-level storage are still mostly in the research phase, possible legal barriers and the costs to overcome them are currently unspecified. Similarly, because some of these technologies have not been tested at the scale necessary for grid-level implementation, the potential risks to health, safety, and the environment are not fully understood. In addition, a more complete cost-benefit analysis should take into account the opportunity cost of implementing grid-level battery storage. In some places, pumped water storage already does part of the job that we intend batteries to do, making investment in battery technology in place of, or in addition to pumped water storage, less worthwhile.

On the other hand, we only considered already existing and in-use sources of renewable energy. Perhaps there are renewable sources of energy which have been considered, but dismissed or limited in use due to the unreliability of their production. Battery storage could allow for increased use of these forms of renewable energy, if they exist, but the benefits of such an unspecified category would be difficult to quantify. We also do not consider the benefit of simplified

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production on generators and forecasters in the region. While continued monitoring of the grid will remain in place, batteries allow for a more substantial buffer between supply and demand, reducing grid administration requirements. The fact that they can respond to a change in demand instantly and can be spread out (putting small installations of batteries in many places) might also allow for faster, more precise response to periods of extreme demand or reduced supply, such as during natural disasters.

Policy implications

The policy implications of this research can be split into three broad categories: policies that affect the battery technology directly, policies that affect the role of batteries in the larger context of energy generation and storage, and policies that alter the current policy landscape. Within the first category, we can further focus on battery-specific policy. According to our analysis a battery with a $200/kWh would have a net benefit the first year of operation, which would furthermore increase in magnitude over time. At $140/kWh the sodium sulfur battery has already crossed that threshold. The technology does not need to improve drastically but it does need to be made safe. Guidelines as to the safe operation of sodium sulfur batteries need to be determined and put into place and a regulatory body. We recommend that before this battery technology is implemented, a subcommittee of FERC should be put into place to ensure appropriate guidelines are created and followed. In addition, laws may need to be put in place governing where a sodium sulfur battery can be constructed. Energy loses relatively little during transmission over long distances so it makes no sense to construct a potentially dangerous battery in a crowded area.

The other type of batteries that has policy implications is vanadium redox. While promising, this technology requires additional study to determine if it will be suitable for implementation in a grid-level storage system. According to our model a price per kilowatt of $400/kWh would have a net benefit over ten years, which is within the price range of a vanadium redox battery. However, given the variability in vanadium redox pricing and the uncertainty in our model, government policies should be designed to encourage further research and trial applications. These policies could take the form of grants for further research on vanadium redox batteries. Another possibility is that a lump sum could be offered as a prize to the first group to build a prototype vanadium redox battery that reliably crosses the $400/kWh without sacrificing the other advantages of the battery.

Beyond the specifics of the battery technology our research has policy implications in the larger realm of energy storage. Our model suggests that even at the current level of technology further investment in grid level battery storage would be a net positive. However, the upfront cost is large, possibly prohibitively so, and the payout is largely in the form of reduced GHG emissions. It would therefore make sense for the government to encourage the adoption of battery storage. However, the situation is not so simple. As was discussed in the overview of the electrical industry, there is a tangled mess of public and private agencies each responsible for different parts of the whole. Thus, we recommend three types of policy measures: demonstration projects, timely compliance of existing measures, and incentive programs.

There are already a number of demonstration projects aimed at informing the general public and various stakeholders of the benefits and capabilities of energy storage systems. The lithium-ion battery at the AES Laurel Mountain Plant is one example, and the Tomamae Wind Villa’s Vanadium Redox battery in Japan is another. Grid-level demonstration of Vanadium Redox in the US would be a good way to inform stakeholders of the feasibility of the technology in US. The project would also help assuage uncertainties in application of Vanadium Redox as well.

Another type of policy measure that is needed is timely compliance of existing measures. FERC has already issued a number of orders aimed at addressing compensation issues of energy storage systems such as FERC Order 755 which stipulates energy storage systems to be compensated by actual service provided. FERC Order 784 also attempts to address classification issues of energy storage systems discussed above. The problem is that these measures are not
implemented in a timely fashion, further instigating uncertainty for providers. Reliable implementation on these fronts would ease the way for deployment of energy storage systems.

Third, another effective policy would be incentives. At the federal level, offering funds to states if they were to implement a grid level battery would be an example. This would allow those closest to the situation to make the decision while still encouraging the implementation of grid level battery storage. The Storage Act of 2011 was introduced to congress for this purpose, stipulating the expansion of energy investment credit to include energy storage property connected to the grid. Examples of incentive programs at the state level are those implemented by the California Public Utilities Commission and the California Self-Generation Incentive Program. The California Public Utilities Commission is accepting applications for long-term procurement of energy storage capacity. By this program, South California Edison would be required to procure 50MW in energy storage capacity. The California Self-Generation Incentive Program also provides rebates for qualifying energy systems, including energy storage systems, at $1.8/W. We recommend the promotion of incentive programs like these at both the federal and state level.

Another possibility would be to tie in grid level storage with current laws. It could be included among the avenues a state may take to reduce its greenhouse gas emissions. As a final possibility, our analysis does suggest that there is a niche in the market for a company that updates electrical grids to include battery storage technology. The government then could play a role in paying out to the company the benefits accrued from the reduced emissions sustaining that companies role in the market. Naturally, there are further possible policies that could be put in place to encourage the use of grid level batteries but the options mentioned above cover many of the more prominent policies. Further study is warranted to determine which of the policies, if any, would provide the greatest benefits.

The current state of the electrical energy system is not conducive to innovation. A huge volume of the product, electricity, must be provided constantly across the entire nation. This leaves very little room for error or experimentation. Broad policies to improve the entire system are beyond the scope of this paper but there is a small policy change that could be implemented to encourage the adoption of efficient energy storage technology. A national classification specifically for energy storage technology should be created. Note that this classification would not be limited to battery technology but would include other forms of energy storage such as pumped hydro, compressed air, flywheels and several others with the defining characteristic being the ability to store surplus energy and discharge it the required time. This classification would standardize the compensation an energy provider receives for implementing energy storage options. The creation of a new classification for energy storage would also eliminate the confusion that comes from different regions classifying energy storage under different compensation schemes. Finally, it would end the difficulty of receiving compensation when energy storage performs multiple tasks by folding all of that into the single classification of energy storage. With the rise of renewable energy and the variability inherent therein sources of energy storage will be a necessity and leaving their classification confused will only hinder the development of the US electrical system.

Conclusions

Feasibility

The monetary cost could be a limiting factor for grid-level batteries. A project similar to the one simulated above will cost several billions of dollars to implement, and the cost-benefit analysis is only positive by taking into account large negative externalities. Thus, implementing battery storage, now or in the near future, would require significant investment by institutions which are not required to make a positive return on investment, such as governments, charitable groups, or other non-governmental organizations. State governments could band together in accordance with their respective ISO to offer incentives for grid-level battery research and production, or the federal government could offer similar incentives. Non-government organizations could provide funding for research and/or implementation.

The direct monetary cost of batteries should continue to decrease, but their benefits might decrease as well, for instance if nuclear power becomes more prevalent, though in the wake of Fukushima that appears unlikely. The incentive for batteries also depends on the price of fossil fuels; cheap hydrocarbons make it easier to justify running less efficient power plants and harder to encourage renewable energy sources.

Another potential limiting factor is location. Even if land can be purchased, it is likely that there are environmental or health and safety regulations to overcome. In addition, citizens may oppose the installation of batteries near occupied areas for health and safety reasons and in non-occupied areas for environmental reasons (see the section on battery technology for more detail on safety and battery composition).

None of these factors appear to render grid-level battery storage infeasible. The monetary cost, measured in the billions or tens of billions, is still relatively small compared to the size of the relevant agencies, including multiple state governments or possibly even the U.S. government. The batteries themselves can be located far away from communities, where health and safety should not become issues. It does not appear that there are any barriers to implementing grid-level battery storage that we cannot already overcome.

**Future Work**

Aside from continuing and expanding research into battery technology, the most important next step is to improve and generalize modeling for grid-level battery storage. More models for the distribution of renewable, conventional, and stored energy supply should be investigated, in case more efficient scenarios can be found. More intricate cost-benefit analyses should also be done (see the section on additional cost/benefit variables, above), with additional variables. It might also be useful to attempt to find a general solution for the fraction $f_T$ (in terms of the other parameters such as the social cost of carbon, discount rate, cost of batteries, etc.) for this model, or do likewise for the variable of interest in some other model, so that the effect of changing each of those variables on the results can be seen more quickly and easily.
Bibliography


