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Energy Storage: Technology for a More Efficient Grid

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Chapter 1: Introduction

The modern electric grid is an enormously complex system which requires constant forecasting, modeling, monitoring and adjustment in order to match electricity generation with demand. Though changes in demand follow some hourly and seasonal patterns, they are not always predictable to the degree necessary to plan for adequate generation ahead of time. If the electricity supplied to the grid exceeds demand it will cause quality problems and possibly damage grid infrastructure unless it is dumped (wasted).[1] Similarly, if there is insufficient electricity to meet demand, quality problems will arise and either result in a brown or blackout.[2]

As intermittent renewable energy sources begin to supply a larger percentage of load this complexity will multiply. Though wind turbines and photovoltaic solar panels are becoming more efficient, efficiency gains do not make up for the fact that they only produce power when the wind is blowing or the sun is shining. This intermittency creates a further challenge for grid operators who must now anticipate demand and fluctuating renewable output while ensuring resources can come online quickly if either of these variables differs from their projections. Moreover, without reliable supply, renewables

[1] Johannes Rittershausen and Mariko McDonagh, *Moving Energy Storage from Concept to Reality: Southern California Edison's Approach to Evaluating Energy Storage* (Rosemead, CA: Southern California Edison, 2011), 20.
[2] Richard Baxter, *Energy Storage: A Nontechnical Guide* (Tulsa, OK: PennWell, 2006), 20.

are undervalued, making it even harder for them to compete with fossil and nuclear energy sources.[3]

Currently, utilities and grid operators employ a wide array of strategies to ensure they are able to provide sufficient supply. On the demand side, these strategies include interruptible contracts with large customers, differential pricing for periods of high demand, and rebate programs for efficient appliances. Since these strategies are not always sufficient, utilities must also maintain spinning reserve plants which are ready to be put online on very short notice.[4] Spinning reserve plants are run without producing electricity, thus wasting fuel and energy.

Utilities and grid operators must go to these lengths to ensure reliability because electricity is an instantaneous resource. Though *energy* can be stored in a variety of forms, *electricity* must be used as it is generated (and accordingly generated as it is demanded). While the strategies discussed above are effective, they require large investments in power plants and transmission and distribution (T&D) capacity that go unused most of the time.[5] For the consumer, these inefficiencies are reflected in the higher rates required to pay for this additional, under-utilized infrastructure.

An alternative to these strategies that would avoid such unnecessary expenditures would be to store electric energy in other forms at times of low demand for use at times of high demand. This could be accomplished in a number of ways and would effectively increase the profitability of existing power plants, reduce the need to add more capacity,

[3] Nicola Armaroli and Vincenzo Balzani, "Towards an Electricity-Powered World," *Energy and Environmental Science* 4 (2011): 3203.
[4] Ibid., 3195.
[5] Zhenguo Yang et al., "Electrochemical Energy Storage for Green Grid," *Chemical Reviews* 111 (2011): 3579.

help integrate renewables into the grid, and more evenly distribute supply and demand. Fortunately, most of the technologies necessary for such storage are rapidly becoming a reality while others have been in limited use since the late nineteenth century. As renewables start to make up a larger portion of power portfolios, energy storage will become even more advantageous.[6]

That being said, the current market undervalues energy storage since its benefits are diffused across multiple parties and there is no defined method of accounting for it in rate structures.[7] While some states have enacted legislation to facilitate the grid's incorporation of storage, similar efforts at the federal level have stalled.[8] Even as the cost of energy storage technologies falls, these regulations will still be necessary to ensure they are viewed as a viable alternative.

This paper will discuss the need for energy storage to increase the efficiency of current grid assets, defer the need for additional infrastructure, and provide system reliability. It will then provide an overview of utility scale and distributed energy storage technologies. Finally, it will examine legislation dealing with energy storage and make suggestions for future policy.

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[6] Armaroli and Balzani, 3203.

[7] Ethan N. Elkind, *The Power of Energy Storage: How to Increase Deployment in California to Reduce Greenhouse Gas Emissions* (UC Berkeley School of Law's Center for Law, Energy & the Environment and UCLA School of Law's Environmental Law Center & Emmett Center on Climate Change and the Environment, July 2010), 14.

[8] "H.R. 3776: Energy Storage Technology Advancement Act of 2007," GovTrack.us, http://www.govtrack.us/congress/bill.xpd?bill=h110-3776 (accessed November 21, 2011); "S. 1091: STORAGE Act of 2009," GovTrack.us, http://www.govtrack.us/congress/bill.xpd?bill=s111-1091 (accessed November 21, 2011).

Chapter 2: The Need for Energy Storage

The Current Energy Market

In order to understand the importance of energy storage for utility-scale applications it is necessary to first discuss the nature of the electric grid. Electricity presents unique and interesting challenges since—with current technology—it must be produced as it is consumed (just-in-time generation), and demand is highly variable both throughout the day and seasonally.[9] Further complications result from the physical and regulatory constraints of different types of generators on the grid. Nuclear generators, for instance, cannot ramp down their production easily.[10] Wind farms, on the other hand, cannot control when they produce but are often given priority grid access by regulatory authorities.[11] The supply of electricity is also limited by the capacity of the transmission and distribution infrastructure that exists between generators and the end-users. These complications have led to the creation of intricate and sometimes inefficient solutions aimed at matching a reliable, high-quality supply with demand.

Electricity generation can largely be defined by three categories: base load, intermediate, and peaking. Base load power is designed to run around the clock, providing a large percentage of overall demand. These plants typically make up 30–50% of a grid's installed capacity and have lower operating costs than intermediate and

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[9] Kristien Clement-Nyns, Edwin Haesen, and Johan Driesen, "The Impact of Vehicle-to-Grid on the Distribution Grid," *Electric Power Systems Research* 81 (2011): 185.
[10] Chi-Jen Yang and Eric Williams, "Energy Storage for Low-carbon Electricity," *Climate Change Policy Partnership Technology Policy Brief Series* (January 2009): 5.
[11] Porter Bennett, Jozef Lieskovsky, and Brannin McBee, "Impacts of Intermittent Generation," in *Large Energy Storage Systems Handbook*, ed. Frank S. Barnes and Jonah G. Levine (Boca Raton, FL: CRC Press, 2011), 18.

peaking plants.[12] Since running base load plants is preferable to using more expensive sources, base load generation makes up about 60–70% of overall generation.[13] Base load generators—often nuclear or coal—must be highly reliable because they provide such a large percentage of power to the grid.

Due to their high capital cost, it is economically important to run these plants at, or close to, their maximum capacity as much as possible. However, that is not always feasible since demand drops dramatically at night and on weekends. Coal plants, in particular, are affected by this drop in demand as it is easier to shut them down: "coal-fired units do not enjoy the must-run status of nuclear units, leaving the fleet average of all coal units around 70%, whereas nuclear units have been able to increase their levels well above 90%."[14] With 30% of their capacity unused, coal-fired power plants are missing out on significant potential revenue streams.

Energy storage has the potential to significantly increase the utilization of these power plants.[15] By charging during off-peak hours, energy storage facilities could create demand for base load power around the clock. This would have large economic implications for base load plants because "increasing the utilization of these facilities would lower average operating costs—not only increasing overall revenue, but also the profitability of these facilities."[16] The reduction in operating costs results from the higher fuel efficiencies achieved when these plants operate at their optimum levels. Higher

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[12] Nicola Armaroli and Vincenzo Balzani, "Towards an Electricity-Powered World," *Energy and Environmental Science* 4 (2011): 3195.
[13] Jack Casazza and Frank Delea, *Understanding Electric Power Systems: An Overview of the Technology and the Marketplace* (Hoboken, NJ: John Wiley & Sons, 2003), 66.
[14] Richard Baxter, *Energy Storage: A Nontechnical Guide* (Tulsa, OK: PennWell, 2006), 7.
[15] Goran Krajačić et al., "Feed-in Tariffs for Promotion of Energy Storage Technologies," *Energy Policy* 39 (2011): 1423.
[16] Baxter, 7.

efficiency would also lead to lower emissions of greenhouse gases and other pollutants per kilowatt-hour.

Intermediate, or mid-merit, plants are generally smaller than base load plants, with lower capital costs and lower efficiencies. Intermediate plants are designed to be flexible with the ability to cycle as needed "to respond to the variations in customer demand which occur during the day" at around "30-50% of the maximum hourly load for a typical system."[17] Nonetheless, cycling still inflicts a large toll on these plants, since:

> the resulting number of warm or even cold starts is far more than first envisioned for these units … the wear and tear is accelerating, resulting in higher operation and maintenance (O&M) costs, longer and more frequent forced outages, higher heat rates, and shorter life expectancies for critical plant components.[18]

As with base load plants, the increased heat rates (decreased efficiency) caused by cycling effectively increases the plant's emissions.

To decrease both the economic and environmental costs of cycling intermediate plants, energy storage can be used to smooth the variations in demand, allowing for more stable generation.[19] As Baxter describes, storage facilities could respond more quickly to demand—providing enough power to allow intermediate facilities "to ramp along their optimal design path rather than what the market demands."[20] Additionally, by providing demand at times when these plants would typically shut down entirely, energy storage could reduce the amount of cold and warm starts necessary.[21] In this way, energy storage

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[17] Casazza and Delea, 67.
[18] Baxter, 9.
[19] Easan Drury, Paul Denholm, and Ramteen Sioshansi, "The Value of Compressed Air Energy Storage in Energy and Reserve Markets," *Energy* 36 (2011): 4959.
[20] Baxter, 9.
[21] Ibid.

can extend the life of intermediate plants while allowing them to generate much more efficiently.

When base load and intermediate generation is insufficient to meet demand, peaking plants provide the extra capacity needed—making up roughly 5% of total peak generation.[22] They are typically fueled by natural gas, although fuel oil and hydroelectric power can also be used, and are relatively expensive to operate.[23] Peaking plants must be able to come online very quickly in order to meet spikes in demand. Nonetheless, as their name suggests, they are only used to meet peak demand, thus they spend most of their time offline.[24] Conventional peaking plants could be largely replaced by energy storage facilities that would be charged by base load and intermediate plants during periods of low demand. This capacity would then be available for peak demand. As an added benefit, since the power provided from storage facilities was originally generated by much more efficient plants than typical peaking plants, this peak power would produce far fewer emissions and likely be much cheaper.[25]

In addition to these three categories of generation, power plants can sell ancillary services, such as reserve capacity, to the grid. Reserve capacity is essentially a backup—a generator ready to come online on very short notice for unforeseen spikes in demand or drops in scheduled generation. Since reserves must be able to ramp up generation very quickly, some capacity must be composed of spinning reserve where a plant runs without

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[22] Casazza and Delea, 67.
[23] "Types of Power Plants: Peaking Plants," Oglethorpe Power, http://www.opc.com/PoweringGeorgia/TypesofPowerPlants/PeakingPlants/index.htm (accessed November 19, 2011); Armaroli and Balzani, 3202.
[24] Armaroli and Balzani, 3202.
[25] Yang and Williams, 5–6. This, of course, depends on the roundtrip conversion efficiency of the storage device.

operating its turbines. These spinning reserve plants are often natural gas turbines which must waste fuel in order to keep running. According to Southern California Edison, the California Independent System Operator "currently procures 7% [split 50-50 between spin and non spin] of any given hour's load in operating reserves."[26] Therefore, an amount of energy equivalent to 3.5% of load is wasted as spinning reserve capacity at any given time, adding non-productive greenhouse gases to the atmosphere.

Once again, energy storage technologies such as flow batteries could replace spin and non-spin reserve since they are capable of generating electricity within milliseconds if operated on standby.[27] Not only would this eliminate rarely used, inefficient peaking plants, it may defer the need to invest in additional generation infrastructure to meet rising demand. Since energy storage facilities essentially make better use of existing generation capacity, they could—temporarily at least—eliminate the need to install more capacity.

After generation, a grid operator must also account for the transmission and distribution of electricity on the grid.[28] Since power lines have limited capacity, operators must acquire adequate T&D capacity in addition to generation. Failure to do so may result in congestion charges, or inability to access scheduled generation.

Symptomatically,

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[26] Rittershausen and McDonagh, 18.
[27] Zhenguo Yang et al., "Electrochemical Energy Storage for Green Grid," *Chemical Reviews* 111 (2011): 3584.
[28] Though T&D are distinct in many ways, this paper will discuss them together for the sake of simplicity. Much of the evidence cited here deals specifically with transmission; however, as noted by Richard Baxter, "congestion issues also extend into the distribution market. The previously mentioned underinvestment grows as one moves down in transmission size, leaving the system stressed during peak demand." For the purposes of this paper, there is no need to go into more detail about the distinctions between transmission and distribution. Baxter, 16.

> with an emphasis on reliability rather than efficiency, the system was built out to ensure sufficient capacity during peak demand periods—leaving much of the system largely unused during off-peak times and producing an average system utilization that rarely surpasses 60%. The $100 billion and $250 billion worth of assets in the transmission and distribution markets, respectively, make it apparent why it is necessary to improve their capability and cost effectiveness.[29]

As in generation, with peaking plants and spinning reserve, transmission and distribution requires investment in infrastructure far beyond what is needed on average, providing much lower marginal returns.[30] Moreover, when power lines can no longer support peak demands they are "upgraded significantly to postpone the next required upgrade, ensuring that the average utilization of the power line will remain low."[31] Due to the need to provide for peak periods the current transmission and distribution system must be inefficient by design.

The inherent waste in this system has made it, in all likelihood, unsustainable in current market conditions. As Casazza and Delea explain:

> Transmission systems are aging and growing less adequate … Capital expenditure reductions, reduced maintenance expenditures, increased transmission outages, lack of time to maintain and reinforce the system are all occurring. Needed new transmission lines have not been added in recent years … This trend is creating the potential for a national disaster.[32]

While this analysis may be overly cynical, it should be no surprise that a system that relies so heavily on inefficient overinvestment could be on the brink of failure. It is apparent that the conventional strategies to meet peak loads through heavy investment in

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[29] Baxter, 12.
[30] Yang et al., 3579.
[31] Baxter, 17.
[32] Casazza and Delea, 126.

T&D capacity cannot continue; however, without this investment it will be impossible to meet peak demand with current technology.

Instead of guaranteeing transmission capacity for relatively rare instances of peak demand, grid operators could meet these peaks with localized energy storage facilities.[33] Energy could be "transported" from power plants to demand centers "downstream of the transmission line" during off-peak hours and stored for peak-periods.[34] Since these facilities would be near demand centers, additional transmission capacity would not be necessary and congestion fees would be avoided.

In addition to deferring the need for power line upgrades, energy storage could provide a source of in-basin generation—generation that takes place in the area (basin) being served—a necessity for grid reliability. As a Southern California Edison (SCE) white paper describes, 40% of SCE's generation must be sourced locally: "This poses a particular challenge for SCE, given the stringent air quality requirements in urban areas and difficultly of building new conventional power plants."[35] Since most storage technologies produce no emissions, they would make a cheap, clean proxy for in-basin generation during peak hours.

Finally, having discussed generation and transmission and distribution, it is worth mentioning the impact energy storage can have on ratepayers. In addition to the benefits of utility-scale storage systems discussed above (which can have impacts on customers through overall cost of energy and reliability), some customers may benefit from

[33] Yang and Williams, 7.
[34] Rittershausen and McDonagh, 21.
[35] Ibid., 20.

purchasing smaller storage systems to shift their loads to less costly hours and ensure reliability of electricity supply and quality.

For large commercial and industrial customers, electricity can be very costly—especially if their demand coincides with peak demand and, thus, peak prices. Utilities often offer programs for such customers where they are charged differentially by time-of-use, or are otherwise encouraged to reduce their demand during peak periods. In some cases, large customers can have interruptible rate contracts, receiving lower rates in return for the possibility of losing power during peak periods. As Southern California Edison explains, "while participation in these programs is strong, it is limited by customers' willingness to be inconvenienced by DR [demand response]/ TOU [time-of-use] rate program requirements and costs (e.g. customers must agree to not use an air conditioner during a hot summer day with a high system peak)."[36] This inconvenience may deter customers who might otherwise find large economic benefits in subscribing to these special rates.

With small-scale (distributed) electricity storage devices, commercial and industrial customers could take advantage of lower rates without any such inconvenience. SCE continues, "the customer could take advantage of a DR program or TOU rates without changing their behavior. The system would see the load drop off as required, but the customer would in fact be temporarily serving his/her own load, using a charged energy storage device, rather than system generation."[37] Utilities may also find it beneficial to offer incentives to residential customers to invest in energy storage systems,

[36] Ibid., 23.
[37] Ibid.

as they currently do with rebates for efficient appliances, to further shift load off peak hours. One example of such an energy storage system is thermal energy storage for heating, ventilation and air conditioning (HVAC) systems. These systems create large blocks of ice at night using off-peak, low-cost energy for use in cooling during the day. This benefits customers through lower energy bills, and the utility by shifting demand off peak hours.

Another use for demand-side energy storage lies with ensuring power quality and maintaining an uninterrupted supply. Industrial customers, for whom any deviations in frequency can be disastrous (e.g. computer chip manufacturing), can use storage devices such as flywheels or batteries to maintain frequency with higher precision than the grid can currently provide.[38] Similarly, power interruptions can be extremely costly for information technology companies and some manufacturing applications. Energy storage can both act as bridge power until back-up generators are able to come online or— with sufficient capacity—act as standalone back-up generation. According to Southern California Edison, energy storage devices are already in wide use for these applications.[39]

In order to efficiently and economically supply the grid with power, the entire energy industry must be revolutionized. In essence, a paradigm shift is necessary to take electricity from an instantaneous service to a storable, dispatchable product. Energy storage technologies, both existing and experimental, can make this a reality by converting electricity into chemical, potential, thermal or kinetic energy. Without the constraints of in-time generation, power plant utilization can be improved, capital

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[38] Baxter, 130.
[39] Rittershausen and McDonagh, 23.

investments for generation and T&D can be deferred, congestion fees can be avoided, and higher quality electricity can be provided. This energy storage revolution will address the current inefficiencies in the grid while facilitating the transition to a modern system supplied by renewable energy.

Renewable Integration

Moving forward, renewable energy sources like wind and solar will contribute a growing portion of electricity to the grid. Though renewables come with numerous environmental, health, and safety benefits,[40] they also present significant challenges to grid operators.[41] Since wind and solar resources are intermittent, they cannot be relied upon for consistent generation and they cannot be called upon like a traditional generation resource when additional supply is needed.[42] Furthermore, the peak production of wind farms in particular does not coincide with peak demand.[43] With renewable portfolio standards or goals in 33 states as of 2009, these challenges will multiply, presenting serious grid stability and reliability issues.[44]

Whereas traditional fossil or nuclear power sources can provide consistent, dependable power to the grid, solar and wind can only generate when the sun is shining

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[40] "Benefits of Renewable Energy Use," Union of Concerned Scientists, http://www.ucsusa.org/clean_energy/technology_and_impacts/impacts/public-benefits-of-renewable.html (accessed November 19, 2011).
[41] Matthew Deal, Susannah Churchill, Larry Chaset, and Christopher Villarreal, *Electric Energy Storage: An Assessment of Potential Barriers and Opportunities* (California Public Utilities Commission, July 2010), 1.
[42] Yang and Williams, 5.
[43] Deal et al., 1–2.
[44] "Renewable Portolio Standards Fact Sheet," United States Environmental Protection Agency, http://www.epa.gov/chp/state-policy/renewable_fs.html (accessed November 19, 2011); Jarno D. Dogger, Bart Roossien, and Frans D. J. Nieuwenhout, "Characterization of Li-Ion Batteries for Intelligent Management of Distributed Grid-Connected Storage," *IEEE Transactions on Energy Conversion* 26, no. 1 (March 2011): 256.

and the wind is blowing, respectively. Grid operators must then accommodate their intermittent production while ensuring intermediate plants and reserves can meet demand if they go offline.[45] Furthermore, wind and solar are not dispatchable—their production cannot be brought online as needed and cannot be increased without a corresponding increase in wind speed or sunlight. Thus, from a scheduling perspective, operators must rely on estimates and forecasts, once again requiring adequate reserve capacity if renewable generation falls short. As Richard Baxter explains, "in the broader wholesale power market, system operators account for their additional balancing cost in part through a reduction in capacity payment to wind developers—often by 80%."[46] Essentially, owners of wind and solar farms are being paid less for the same capacity since they cannot guarantee its availability.

Additionally, the variability of renewable output inflicts costs on the conventional plants, which must firm renewable output by cycling. This cycling stresses "the flexibility limits of fossil fuel generation sources to the point where some exhibit severe inefficiencies … The more wind and solar power used, the more inefficient coal facilities become."[47] The intermittency of these renewable sources combined with the inefficiency that arises from cycling coal plants has the ironic effect of increasing the emissions of greenhouse gases and other pollutants as more renewables are installed with the desired effect of limiting these same emissions. Furthermore, as discussed previously, cycling decreases the lifespan and profitability of coal facilities, imposing additional costs on utilities and accordingly on ratepayers.

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[45] Yang et al., 3578.
[46] Baxter, 219.
[47] Bennett, Lieskovsky, and McBee, 18.

Regarding wind power in particular, a further complication arises from its non-coincident peak. “It simply does not blow the hardest at the best times to produce electricity. For many sites, upward of 67% of the total wind power resource can be outside of the peak demand period (i.e., 9 a.m. to 5 p.m. Monday through Friday).”[48] Instead, wind is most abundant in the early morning and in the evening when electricity demand is significantly lower. Wind is also non-coincident with demand seasonally, “with maximum winds occurring (for most locations) in winter and spring, and minimum winds in summer and autumn.”[49] Due to the need for air conditioning, summer represents the peak of seasonal demand for most areas. Consequently, relying heavily on wind power would require investing in additional generation for summer demand that would go unused when wind production picked up in winter and spring. Wind farms would also miss out on high peak summer electricity prices, making them less profitable investments than other plants of similar capacity.

Strategies to increase the adoption of renewable energy have thus far depended on reaching price parity with coal and natural gas generation. As the cost of renewable generation drops due to technological and production advancements, it should become apparent that price parity alone is insufficient to make renewables competitive. Even with ambitious renewable portfolio standards, subsidies, investment, and public support, renewables will continue to struggle against more conventional power sources as long as their energy is not dispatchable and dependable. In short, “being competitive on price does not mean that wind [or solar] is as useful an energy resource to the system

[48] Baxter, 218.
[49] Ibid.

administrator."[50] To make wind and solar useful alternatives to coal and natural gas, a new strategy must be implemented to make their energy available when needed. This can only occur by coupling renewable generators with utility-scale or distributed energy storage devices.

Facilitating the integration of renewable energy sources is one of the most important uses for energy storage technology. The first benefit of storage comes with the ability to firm renewable output. A storage component can be charged in periods of excess production and discharged when production falls, thus allowing the facility as a whole to provide reliable, constant output and eliminating the need for fossil-fuel reserve plants.[51] A solar plant, for instance, could rely on a coupled storage component—for instance, a battery or a physical storage medium such as compressed air—to supply the grid on a partly cloudy day when solar generation is temporarily interrupted.[52]

The same concept could also work without being directly coupled to a renewable generator. Instead, storage could be distributed across the grid in smaller amounts. For example, plug-in electric vehicle batteries that are not in use would stop charging and begin to supply electricity back to the grid when generation decreases.[53] Owners could program their vehicles to charge only when electricity prices are low and discharge when prices are high (with a minimum charge level to guarantee sufficient range at any given time). This form of storage would accommodate the variable production of wind and

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[50] Ibid., 233.

[51] Rodica Loisel et al., "Valuation Framework for Large Scale Electricity Storage in a Case with Wind Curtailment," *Energy Policy* 38 (2010): 7323–7324.

[52] Sergio Vazquez et al., "Energy Storage Systems for Transport and Grid Applications," *IEEE Transactions on Industrial Electronics* 57, no. 12 (December 2010): 3885.

[53] Kristien Clement-Nyns, Edwin Haesen, and Johan Driesen, "The Impact of Vehicle-to-Grid on the Distribution Grid," *Electric Power Systems Research* 81 (2011): 185.

solar generators while providing further economic incentive for electric vehicle ownership.[54]

With storage capacity in the grid, renewable generators can also produce electricity when wind or solar resources are available without risking price penalties at times of low demand. Currently, wind farms in Texas must often "sell electricity at negative prices—owners are paying ERCOT [Electric Reliability Council of Texas] to take the energy—in order to qualify for a production tax credit that is based on megawatt-hours produced."[55] In essence, a market distortion caused by the tax credit has incentivized the production of worthless energy. In other cases, renewable generation is curtailed if there is not enough demand for its energy, letting the potential capacity of these facilities go wasted.[56] Instead, that energy could be stored and sold at periods of peak demand when prices are most advantageous. This sort of storage would also provide grid operators with dependable energy sources to call upon during peak demand and decrease the need for reserve capacity.

Wind and solar have been fighting to gain acceptance in a market that is essentially stacked against them. Conventional wisdom in electricity generation, transmission, and distribution does not easily incorporate intermittent, unwieldy sources of energy because the industry is accustomed to dealing with a just-in-time generation framework. Even as renewables reach price parity with fossil and nuclear generation, they are at an inherent disadvantage.

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[54] Mehdi Ferdowsi, "Vehicle Fleet as a Distributed Energy Storage System for the Power Grid" (paper presented at the IEEE Power & Energy Society General Meeting, Calgary, AB, July 26, 2009).
[55] Robert Peltier, "Energy Storage Enables Just-in-Time Generation," *Powermag.com,* April 1, 2011, under "It's Complicated," http://www.powermag.com/business/3556.html (accessed November 19, 2011).
[56] Loisel et al., 7323–7324.

Energy storage has the potential to change this paradigm. By decoupling supply and demand, there is no longer the need to fit the whims of the weather into neat schedules and forecasts. Wind and solar production can then be valuable regardless of when and in what quantity they occur. Storage also reduces the cycling pressure on coal and natural gas plants that normally firm renewable output. As storage technologies become a reality, so too will wide-scale renewable generation.

Natural Gas Storage

Though changing the model for electricity generation in such a substantial way may seem like an insurmountable task, such a change is not unheard of. Starting as early as 1916 in the United States natural gas was stored to make up for seasonal variations in demand.[57] Using depleted oil and gas reservoirs, salt caverns, and aquifers suppliers were able to store natural gas during the summer for use in heating during the winter.

The ability to store natural gas allowed more even utilization of associated reservoirs and pipelines. In turn, more even utilization reduced the need to add costly excess capacity for high-demand periods (in this case, winter) since some portion of demand could be met with localized, stored reserves. In contrast to the current electric transmission and distribution system, which achieves only about 60% utilization, natural gas storage allowed "the average utilization of the system to remain more than 90%" while "avoiding 50% of the required transmission upgrades."[58] Not only does this storage limit the need for upgrades and make existing infrastructure more economical, it also

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[57] Kent F. Perry, "Natural Gas Storage," in *Large Energy Storage Systems Handbook*, ed. Frank S. Barnes and Jonah G. Levine (Boca Raton, FL: CRC Press, 2011), 218.
[58] Baxter, 48. Baxter does mention some restructuring already taking place by the late 1980s, but 1992 is the first specific mention of a regulatory act (FERC Order 636).

prevents shortages that might otherwise occur in cold winters that spur exceptionally high demand.

As the natural gas market developed (the industry was restructured in 1992) the benefits of storage expanded.[59] A white paper by the Energy Storage Council explains, "gas storage has grown to become a critical "dimension" in making gas markets efficient. Without it, trading, reliability, and tailored services would all be far more expensive—and in the worst case not available at all" (9). With energy storage, the same could easily be true for electricity markets. Incidentally, energy storage could also benefit natural gas storage since currently, peaking plants are competing with storage facilities for gas during the summer when electricity loads peak.[60]

Similarities can also be drawn between the natural gas market and renewable generation. When oil wells produce natural gas as well, this gas is harvested regardless of current gas prices as a byproduct of the oil drilling process. In other words, "natural gas produced in association with oil production is a function of oil market decisions that may not coincide with natural gas demand or available pipeline capacity to transport the gas to end-use markets."[61] This production is essentially no different from wind generation that occurs regardless of current demand or transmission availability, substituting the volatility of the weather for the effect of oil prices. To deal with this natural gas byproduct "some underground storage facilities are located in production areas at the beginning of the pipeline corridor and, in contrast to storage near consuming markets, can

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[59] Ibid., 40.
[60] Baxter, 44.
[61] Perry, 222.

store gas that may not be marketable at the time of production."[62] In much the same way, electricity storage coupled with wind farms could ensure that electricity generated is sold at optimum prices and when transmission is accessible. For this application, energy storage may actually be much more valuable since wind generation is often given "must-take" priority[63], whereas natural gas can always be flared (burned as waste). By storing the wind energy, operators can comply with its must-take status while avoiding issues of cost and transmission capacity.

Given the similarities between these two forms of storage, it is worth discussing the factors that led to the implementation of widespread natural gas storage. Though facilities existed earlier, storage became much more common in the U.S. after World War II. As the economy grew, the demand for natural gas grew along with it—expanding long-distance pipelines into new regions. With this expansion:

> The industry recognized that new storage would be needed to serve these regions with weather-sensitive loads. Without new storage capabilities, the pipeline sizes would exceed the abilities of the steel industry of the 1950s to manufacture them. The alternative of laying numerous small lines was determined to be cost prohibitive.[64]

Thus, one of the main factors in the development of storage in the natural gas market was the technological limitations of transmission at the time. As discussed earlier, overbuilding electrical transmission capacity has similarly become "cost prohibitive" due to its inherent inefficiencies. Now that utility-scale energy storage is becoming a technological reality, it could eliminate the need to upgrade transmission capacity any further just as natural gas storage did before it.

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[62] Ibid.
[63] Bennett, Lieskovsky, and McBee, 18.
[64] Perry, 214.

Chapter 3: Energy Storage Technologies

There are a wide variety of potential and current energy storage technologies. Some have been in use for over one hundred years, while many more are still being developed and tested.[65] It is worth noting that as new technologies become available, they will not necessarily be competing with existing energy storage technologies. Since there are a wide variety of storage applications, it is more likely that there will be a diverse array of storage options each tailored to specific grid services. The relevant characteristics that determine the suitability of a given technology to a grid service application include the energy-to-power ratio, ability to cycle, charge/discharge efficiency and costs of operation and maintenance.

The energy-to-power ratio is dependent on both the overall and instantaneous capacity of the facility.[66] The overall capacity is defined by the energy rating of a storage device, measured in kilowatt-hours (kWh). As Baxter explains, "the energy rating (kWh) is sometimes thought of as the *volume* or scale of the facility and is usually the prime determinant in how long a unit can operate."[67] Accordingly, the power rating—measured in kilowatts (kW)—is "the rate at which it can absorb and discharge energy."[68] According to Southern California Edison, a high energy-to-power ratio would be desirable for shifting renewable generation from off-peak to on-peak hours, whereas a low ratio would

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[65] Richard Baxter, *Energy Storage: A Nontechnical Guide* (Tulsa, OK: PennWell, 2006), 61.
[66] Johannes Rittershausen and Mariko McDonagh, *Moving Energy Storage from Concept to Reality: Southern California Edison's Approach to Evaluating Energy Storage* (Rosemead, CA: Southern California Edison, 2011), 35.
[67] Baxter, 169.
[68] Ibid.

be preferred for smoothing intermittent generation.[69] Since shifting energy to on-peak hours requires a high volume of storage, a high ratio is necessary. Smoothing generation, on the other hand, requires the ability to output large amounts of power for short periods of time and thus a low energy-to-power ratio is more appropriate.

As with conventional generation, the ability to cycle frequently is necessary for storage applications such as smoothing the intermittent output of renewables.[70] Whereas some energy storage technologies (like batteries) have very limited "cycle lives"—they can only cycle a few hundred to a few thousand times during their lifespan—storage technologies such as flywheels and super capacitors are optimized for this sort of frequent charging and discharging and have lives on the order of hundreds of thousands of cycles.[71] Along the same lines, it is important to consider the speed with which storage devices can switch from a charging to a discharging state. This is particularly important for regulating the frequency and overall output of the grid. Since "slower-ramping resources cannot switch direction quickly, they sometimes provide regulation in a counterproductive direction and, as a result, actually add to the ACE [area control error], requiring the dispatch of other resources to counteract it."[72] Thus, for grid regulation, storage devices must be evaluated both on their ability to cycle quickly and frequently. Baxter also mentions "depth of discharge" as an important cycling consideration as "the cycle life of many of these chemical-battery systems deteriorates

[69] Rittershausen and McDonagh, 36–40.
[70] Ibid.
[71] Ibid., 43; Baxter, 170.
[72] *Energy Storage—a Cheaper Faster, & Cleaner Alternative to Conventional Frequency Regulation* (Berkeley, CA: California Energy Storage Alliance), 3. This report defines the Area Control Error as "the deviation from the ideal frequency and output" on the grid which requires either up or down regulation.

dramatically" when discharged below 80%.[73] The same is not true for technologies like flywheels and capacitors.

Finally, the efficiencies and maintenance needs of each technology affect its overall cost-effectiveness and, thus, its suitability to different applications. For instance, when storage is used to shift off-peak production to on-peak hours, one of the primary purposes is to take advantage of the price difference between the two periods (price arbitrage).[74] The efficiency of the energy conversion must be sufficient to preserve profitability in this case.

Similarly, the operational and maintenance needs of a device must be taken into account. In addition to the cost of each, if a device needs frequent maintenance or continual monitoring it will also be inapplicable for distribution and end-use settings where such inconveniences would be undesirable. A manufacturer that installs a device for frequency regulation would expect relatively low upkeep in order to make the purchase worthwhile. In contrast, for energy storage devices that are coupled with renewable generation, maintenance needs would be a less significant drawback "due to the co-location of the storage device with generation, and the likely availability of maintenance staff at that site."[75] Thus, even technologies with relatively high upkeep and operational costs can be desirable for certain applications.

These characteristics are just some of the factors that go into evaluating the applicability of a particular technology to a specific grid service; however, they should be sufficient to demonstrate the wide array of niches for storage technologies with certain

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[73] Baxter, 171.
[74] Rittershausen and McDonagh, 36.
[75] Ibid., 40.

capabilities and limitations. With that in mind, the future of energy storage—and the grid—will revolve not around one, but many technologies providing the services they are each best suited for. This section will introduce many of the technologies being developed and currently in use, and discuss their capabilities and limitations.

Pumped Hydroelectric Energy Storage

Pumped hydroelectric energy storage (pumped hydro) is the oldest and most common form of utility-scale energy storage, originating in late 19th century Europe.[76] In essence the technology consists of an upper reservoir (also called a forebay), a lower reservoir (afterbay), and a pump/turbine.[77] Simply, electric energy is used to pump water from the lower reservoir to the higher reservoir and stored as gravitational potential energy. To supply energy the pump is reversed (now being used as a turbine) and power is produced from the downward flow of water much as in a conventional hydroelectric facility.[78] The greater the height differential between the two reservoirs (referred to as the hydraulic head height), and the greater the flow rate of the water, the more energy produced by the facility.[79] Overall, pumped hydro facilities range widely from "10–100

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76 Baxter, 61; D. Connolly, H. Lund, P. Finn, B.V. Mathiesen, M. Leahy, "Practical Operation Strategies for Pumped Hydroelectric Energy Storage (PHES) Utilising Electricity Price Arbitrage," *Energy Policy* 39 (2011): 4189.

77 Jonah G. Levine, "Pumped Hydroelectric Energy Storage," in *Large Energy Storage Systems Handbook*, ed. Frank S. Barnes and Jonah G. Levine (Boca Raton, FL: CRC Press, 2011), 52.

78 Paul Denholm and Gerald L. Kulcinski, "Life Cycle Energy Requirements and Greenhouse Gas Emissions from Large Scale Energy Storage Systems," *Energy Conversion and Management* 45 (2004): 2156.

79 Levine, 54, 61.

hours of output energy, at several hundred MWs of rated power"[80] with an efficiency of 70–85%.[81]

Conventional pumped hydro designs make use of stream valleys or hilltops—typically creating artificial reservoirs. For instance, a reservoir can be "created by an impoundment constructed across a stream valley such that it fills the valley behind the impoundment."[82] Alternatively, "a hilltop reservoir is constructed by building an embankment around a hilltop and storing water inside the embanked hilltop."[83] Examples of stream valley pumped hydro projects are numerous, including Cabin Creek in Georgetown, Colorado and Castaic Lake in Southern California.[84] An example of a hilltop reservoir is the Raccoon Mountain pumped storage project in Tennessee.[85]

While these are the most straightforward methods for creating reservoirs, several alternative methods exist. A Berkeley and UCLA report explains that "the technology can also work with other water storage methods, such as with contained seawater as the lower reservoir, underground caverns, and even floating sea walls that create a sealed interior to pump water in and out."[86] The first pumped hydro project to use seawater was constructed in Okinawa, Japan in 1999.[87] Furthermore, storage capabilities can even be incorporated into existing hydroelectric power plants by "adding a pump station and

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[80] Rittershausen and McDonagh, 33.
[81] Cesar Pasten and J. Carlos Santamarina, "Energy Geo-Storage – Analysis and Geomechanical Implications," *KSCE Journal of Civil Engineering* 15, no. 4 (2011): 658.
[82] Levine, 63.
[83] Ibid.
[84] Ibid.; Ethan N. Elkind, *The Power of Energy Storage: How to Increase Deployment in California to Reduce Greenhouse Gas Emissions* (UC Berkeley School of Law's Center for Law, Energy & the Environment and UCLA School of Law's Environmental Law Center & Emmett Center on Climate Change and the Environment, July 2010), 5.
[85] Levine, 63.
[86] Elkind, 5.
[87] Baxter, 65.

pumping penstock."[88] These alternative methods are interesting because they decrease the geographical limitations of pumped hydro technology, a subject that will be discussed in more detail later in this section.

Not surprisingly, the original reasons for developing pumped hydro storage were not much different from the reasons for renewed interest now: "the concept of pumped hydro as a means of leveling the diurnal load variations experienced by the utilities was first proposed in Germany in 1910.[89] By 1930 there were several pumped-hydro units in Europe and a single 25 MW unit in the United States." This was by no means the end of pumped hydro's development in the U.S. In fact, construction peaked fairly recently—between the 1960s and 1980s.[90] Moreover, since their inception, the uses of pumped hydro facilities have expanded to include ancillary services like reserve generation (providing an emission-free alternative to natural gas plants). Ultimately, pumped hydro storage made up about three percent of all power provided in the U.S. in 2000, making it a worthwhile model for energy storage overall.[91]

From the experience of the past hundred years, pumped hydroelectric storage has proved to be a valuable part of the grid; however, more recently, few new projects have been possible because conventional facilities are limited by cost, regulation, and geographical constraints. First, conventional pumped hydro suffers from "high construction costs, long construction times, and the requirement of large amounts of

[88] Goran Krajačić et al., "Feed-in Tariffs for Promotion of Energy Storage Technologies," *Energy Policy* 39 (2011): 1413.
[89] W.V. Hassenzahl, ed., *Mechanical, Thermal, and Chemical Storage of Energy* (Stoudsburg, PA: Hutchinson Ross Publishing Company, 1981), 29.
[90] Baxter, 61.
[91] Elkind, 6.

land" making any such projects very capital intensive.[92] Second, as Southern California Edison explains, facilities in many regions are subject to "strict water and environmental regulations" that add further costs and challenges.[93]

But, perhaps the most important factor in the decline of new construction is that "most of the technically attractive sites for pumped hydro in the United States have already been used."[94] W.V. Hassenzahl cites three necessities for a conventional pumped hydro project: "sufficient water, terrain and rock structure adequate for both upper and lower reservoirs, and proximity to either the load or the generating plant."[95] These rather specific requirements leave very few possible sites, most of which have already been developed. With these limitations in mind, conventional pumped hydroelectric energy storage will probably have little influence on future expansions of energy storage capacity (barring retrofits of existing facilities to increase energy or power capacity). According to Baxter, "although many U.S. utilities have expressed a wistful desire for more of these facilities, the current focus for development of this technology in countries like the United States is to upgrade existing PHS facilities."[96] Clearly, though the opportunities for new conventional pumped hydro projects are severely limited, the technology itself is far from irrelevant.

Fortunately, newer, alternative designs can make use of the same storage principle—gravitational potential energy—without the same limitations. Of particular interest is the concept of underground pumped hydroelectric storage, of which there are

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[92] *Energy Storage: The Missing Link in the Electricity Value Chain* (Energy Storage Council, May 2002), 16.
[93] Rittershausen and McDonagh, 33.
[94] Hassenzahl, 29.
[95] Ibid., 28.
[96] Baxter, 67.

two main varieties. The first uses an underground cavern as the lower reservoir, pumping water vertically up to an upper reservoir that can have a relatively small footprint.[97] Since this design moves water vertically, it achieves "a greater energy-per-unit volume than a natural system—which must pump the water up at an angle and is limited by geography to a maximum vertical distance."[98] Furthermore, the small area of the upper reservoir helps to avoid many of the environmental concerns of conventional designs.[99] The concept for this form of pumped storage is credited to Harza Engineering Company in 1960.[100] Such a design was planned and licensed for Mt. Hope, New Jersey in 1992, but failure to proceed with construction led to the cancellation of the license.[101]

A newer variety of underground pumped hydro goes one step further, eliminating the need for underground caverns to create lower reservoirs. Instead:

> construction begins with a large borehole drilled straight down into the ground, perhaps thousands of feet for a utility-scale system. At the bottom of the shaft is a large concrete piston fitted to the shaft, called the "weight stack." Also bored into the ground is a parallel but smaller-diameter "return pipe" that is connected to the main shaft at the top and bottom. Finally, the entire volume is filled with water and tightly sealed—air is compressible and its presence reduces the system effectiveness.[102]

To store energy, water is pumped from the return pipe into the bottom of the main borehole, raising the weight stack and, thus, the gravitation potential. The facility

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97 Hassenzahl, 29.
98 Baxter, 67.
99 Hassenzahl, 30.
100 William S. Mitchell, "Underground Pumped Hydro Storage," *Energy Storage: User Needs and Technology Applications* (1976): 247, repr. in W.V. Hassenzahl, *Mechanical, Thermal, and Chemical Storage of Energy* (Stoudsburg, PA: Hutchinson Ross Publishing Company, 1981), 63.
101 "Mount Hope Pumped Storage," Hydropower Reform Coalition. http://www.hydroreform.org/projects/mount-hope-pumped-storage-p-9401 (accessed November 19, 2011).
102 Robert Peltier, "Energy Storage Enables Just-in-Time Generation," *Powermag.com,* April 1, 2011, under "Underground Pumped Storage," http://www.powermag.com/business/3556.html (accessed November 19, 2011).

generates electricity by allowing the weight stack to fall, thereby pushing water back up the return pipe and through a turbine. Once again, this technology requires a relatively small footprint relative to conventional pumped hydro designs: "a 7-acre site can accommodate more than 2 GW of installed power storage, depending on the depth and diameter of the storage shaft" with an efficiency of 75–80%. Gravity Power, LLC, is already operating a test facility in Santa Barbara, California, and projects a full utility-scale unit in 2013.[103]

Underground pumped hydro does requires sites with certain geologic conditions;[104] however, these conditions are not as restrictive as those required for conventional pumped hydro facilities. Thus, this newer form of the technology presents many more opportunities for large-scale energy storage. Moreover, most—if not all—of the sites that are suitable for underground pumped hydro have not yet been exploited. For now, Gravity Power projects higher per kWh costs than conventional designs; however, costs should come down as the technology becomes more common. Furthermore, the clear desire for more pumped storage among utilities may make cost a less significant factor.

Compressed Air Energy Storage

Around the same time that the construction of pumped hydro plants in the U.S. peaked, Compressed Air Energy Storage (CAES) was introduced as a novel way to store energy. CAES makes use of cheap, off-peak electricity to compress air in underground

[103] Ibid.
[104] Ibid.

aquifers, depleted oil and gas fields, and porous rock formations.[105] Air can also be compressed in storage tanks above ground or even in underwater inflatable bags anchored to the ocean floor.[106] At times of high demand, this compressed air is fed into natural gas turbines where it is heated by the combustion of natural gas, driving a turbine as it expands. In essence, CAES uses two forms of stored energy—compressed air and natural gas. For this reason, CAES is sometimes referred to as a "hybrid generation/storage system."[107]

This technology originated with a 290 MW facility in Huntorf, Germany in 1978.[108] In 1991, another facility was constructed in McIntosh, Alabama.[109] While interest in CAES declined for some time after its inception due to lower energy prices and the decline of the nuclear power industry, the possibility of coupling compressed air storage with wind farms has brought renewed attention to the technology.[110] One project that will take advantage of this possibility is the Iowa Stored Energy Project, near Des Moines, Iowa. The project, slated for completion in 2015, will combine an 84 MW wind farm with a 200 MW compressed air facility that makes use of an underground aquifer to store both compressed air and natural gas.[111] Initially the project is intended to provide intermediate power, though it eventually may be expanded to provide baseload power.

[105] Energy Storage Council, 16; Giuseppe Grazzini and Adriano Milazzo, "Thermodynamic Analysis of CAES/TES Systems for Renewable Energy Plants," *Renewable Energy* 33 (2008): 1998.
[106] Elkind, 6; A. J. Pimm, S. D. Garvey, and R. J. Drew, "Shape and Cost Analysis of Pressurized Fabric Structures for Subsea Compressed Air Energy Storage," *Proceedings of the Institution of Mechanical Engineers: Mechanical Engineering Science* 225, no. 5 (2011): 1027.
[107] Denholm and Kulcinski, 2160.
[108] Energy Storage Council, 16.
[109] Energy Storage Council, 16.
[110] Samir Succar, "Compressed Air Energy Storage," in *Large Energy Storage Systems Handbook*, ed. Frank S. Barnes and Jonah G. Levine (Boca Raton, FL: CRC Press, 2011), 113.
[111] "Frequently Asked Questions," The Iowa Stored Energy Park, http://www.isepa.com/FAQs.asp (accessed November 19, 2011); Baxter, 77.

This project should supply significant benefits over using conventional natural gas turbines to balance the output from wind turbines.

In a conventional natural gas turbine, sixty-five percent of the energy produced is used by the compressors, and is subsequently expelled as waste heat.[112] By replacing the compression process of conventional gas turbines with pre-compressed air, CAES can achieve much higher efficiencies while using significantly less natural gas.[113] Accordingly, "a CAES system provides 25–60% more energy to the power grid than a conventional gas turbine power plant."[114] Additionally, whereas combustion and combined cycle gas turbines are derated—operate at lower power—on hot days or at high elevations because of the extra energy that must be expended by the compressors, no such derating is necessary for CAES plants. This is especially useful on hot days when such plants are essential to meet the demand for air-conditioning. Even though natural gas is used in the generation process, the fact that energy is stored from more efficient, baseload plants, combined with the increased efficiency of CAES itself, leads to much fewer greenhouse gas emissions than a traditional gas peaking plant.

Another benefit of compressed air storage over gas peaking plants is its ability to ramp up generation quickly. As Baxter explains, "with their responsiveness maintained, CAES facilities are able to ramp three times as fast as gas combine cycle facilities."[115] Furthermore, by either turning on or off its compressor, a CAES facility can rapidly increase or decrease electricity demand—a capability that could be harnessed to provide

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[112] Hassenzahl, 82.
[113] Denholm and Kulcinski, 2160; Energy Storage Council, 16.
[114] Tae Sup Yun et al., "Geotechnical Issues Related to Renewable Energy," *KSCE Journal of Civil Engineering* 15, no. 4 (2011): 640.
[115] Baxter, 72.

frequency regulation and other ancillary services.[116] With their ability to ramp quickly and turn compressors on or off, CAES facilities would be an ideal choice for operating reserves, peaking power, and smoothing or shaping the output of renewable sources. Since, they are more efficient than traditional gas peaking plants, running CAES facilities as operating reserves would waste far less natural gas, and emit far fewer greenhouse gases.

Moreover, compressed air technologies can combine very large storage capacities with the ability to provide power for long periods of time. Facilities can "generate up to several hundred MWs and can be discharged over periods ranging from four to twenty-four hours at a time."[117] Given their large capacities, CAES facilities could compete in larger energy markets. According to Richard Baxter, "the real value of CAES is as a mid-merit facility—able to provide this [ramping] capability at low cost over a much larger period of the year instead of only the 1,000 hours of a peaking gas turbine."[118] In this way, compressed air storage could massively increase its return-on-investment, and profitability.

Though the benefits of compressed air energy storage over traditional gas peaking plants are numerous, it is still hard to ignore the technology's own reliance on natural gas. After all, despite its increased efficiency, CAES coupled with renewable generation would still produce greenhouse gases. According to a 2004 study, a CAES facility could still emit almost 288 metric tons of greenhouse gases over its lifespan.[119] This type of

[116] Ibid., 72–73.
[117] Elkind, 6.
[118] Baxter, 72.
[119] Denholm and Kulcinski, 2164.

emissions profile would, in effect, offset one of the main advantages of any renewable energy resource paired with CAES.

One method of avoiding these emissions is to power the wind farm coupled CAES combustion turbines with biofuels instead of natural gas. Basically, this system would use synthetic gas (syngas)—"a mixture of combustible gases including H_2, CO, CH_4, C_2H_4, and other minor constituents"—produced from crops like switchgrass.[120] These energy crops could be grown nearby and then be converted to syngas at the wind farm/CAES site for use in the combustion turbines. By doing so, greenhouse gas emissions would be greatly reduced—the remaining emissions stemming mainly from agricultural energy inputs and transportation.[121] Furthermore, this combined wind-CAES-biofuel system could avoid one of the pitfalls of traditional wind farms, which often have difficulty establishing transmission lines due to not-in-my-backyard attitudes of local landowners. Instead:

> Farmers who agree to transmission line right-of-ways could benefit from long term purchase contracts, which may be necessary to guarantee availability of biomass fuel. This allows the transmission system to be a mechanism for export of farm products, making the farmer a stakeholder in the development and operation of the transmission system…[122]

Finally, it is worth noting that since CAES facilities often have multiple turbines, this type of system could be piloted alongside natural gas turbines in an existing, conventional CAES plant.[123]

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[120] Paul Denholm, "Improving the Technical, Environmental and Social Performance of Wind Energy Systems Using Biomass-Based Energy Storage," *Renewable Energy* 31 (2006): 1361.
[121] Ibid., 1368.
[122] Ibid., 1361.
[123] Ibid., 1368.

Another form of CAES being developed would remove natural gas from the process entirely.[124] Known as adiabatic compressed air energy storage, the technology keeps temperature constant during compression (charging) and expansion (generation) thereby eliminating the need for natural gas.[125] Whereas CAES typically suffers efficiency losses from heat produced in the compression process, adiabatic storage uses a water spray to absorb that heat and keep the compressed air cool. During generation, where CAES typically requires the combustion of natural gas for sufficient heat, the same water is used to keep the expanding air from cooling. Since adiabatic CAES does not require a combustion turbine or natural gas fuel, it can be significantly cheaper than traditional CAES technology. It can also achieve much higher efficiencies by keeping the compressed air at a constant temperature.[126] Finally, by using aboveground storage tanks, the siting of adiabatic CAES is much more flexible. Combined with renewable generation, this technology has the potential to provide truly emission-free energy storage and grid services.

Flywheel Frequency Regulation

Flywheels actually long predate the electric grid. Essentially, the technology consists of large rotors that store energy kinetically (in their rotational motion), and is recognizable in its most basic form, as a potter's wheel. As W.V. Hassenzahl explains, "the earliest potter's wheels, which were made of stone, date back nearly five millennia and were pushed at irregular intervals by the potter or an assistant; the large mass of the

[124] Grazzini and Milazzo, 2006.
[125] Senate Committee on Energy and Natural Resources, *Grid-Scale Energy Storage*, 111th Cong., 1st sess., 2009, 10.
[126] Peltier, under "Electricity as Compressed Air."

wheel allowed the artist to make more delicate and perfect pots."[127] The ability of the wheel's inertia to smooth the potter's energy input is directly analogous to a flywheel's modern day use, regulating variations in electricity frequency and voltage and providing uninterrupted, smooth power. Hassenzahl continues:

> As technology developed during the Middle Ages and the Renaissance and man began using complex gears and other mechanical devices, flywheels occasionally were used to moderate the effects of irregular power generation and energy use. During this period, however, even though they were used in some water pumps, pile drivers, and mills, they were mainly a not-too-well understood curiosity in the form of tops and gyroscopes.[128]

With the advent of electronics that could control the frequency and voltage of power stored and generated in this fashion, flywheels became a realistic option for use in electrical energy storage.[129]

The first such applications were uninterruptible power supply (UPS) systems for electronics manufacturers and other industries for which power interruptions are extremely costly.[130] For example, Deluxe Films—a motion picture film processor in Toronto, Canada—installed a 2.2 MW flywheel system in 2003 to provide uninterrupted power after growing electricity demand in the region caused a decline in the quality and reliability of power provided by the utility. This system saved Deluxe Films millions of dollars in direct costs from equipment shutdowns, and even more by maintaining good customer relationships.[131] In addition to uninterruptible power, flywheels can moderate highly irregular power generation from, for example, metro trains with regenerative

[127] Hassenzahl, 234–235.
[128] Ibid.
[129] Sergio Vazquez et al., "Energy Storage Systems for Transport and Grid Applications," *IEEE Transactions on Industrial Electronics* 57, no. 12 (December 2010): 3884.
[130] Rittershausen and McDonagh, 28,57.
[131] Baxter, 131.

braking. The Lyon France Metro uses a flywheel system (again, installed in 2003) to absorb excess energy produced as trains brake. This energy is then discharged to provide supplemental power to HVAC, lighting, and even station escalators.[132] While intriguing, these applications are relatively small-scale and do not have a real impact beyond a single utility customer. More recently, flywheel technology has been applied to grid-scale energy storage applications to provide regulation services.

Modern, utility-scale units follow the same principles as their earlier counterparts, substituting advanced composite materials for stone, cast-iron, and steel.[133] Flywheels use an electrical motor to accelerate the rotor and subsequently maintain "its rotational speed (and level of energy) with a small but constant additional energy input."[134] This additional energy input is minimized by housing the rotors in a vacuum, and using low-friction magnetic bearings and lightweight composite materials. During discharge, the electric motor is used as a generator—decelerating the rotor.[135] Since the energy stored in a flywheel is exponentially proportional to its rotational speed, high power can be achieved with relatively small, lightweight designs. Furthermore, they are capable of reacting to demand quickly[136] with a "virtually infinite number of charge-discharge cycles,"[137] and—in contrast to many battery technologies—can be discharged deeply

[132] Ibid., 132.
[133] Hassenzahl, 234–236; John D. Boyes and Nancy H. Clark, "Technologies for Energy Storage: Flywheels and Super Conducting Magnetic Energy Storage," (paper presented at the Power Engineering Society Summer Meeting, Seattle, WA, July 16, 2000).
[134] Baxter, 127.
[135] Boyes and Clark.
[136] Rittershausen and McDonagh, 32.
[137] Vazquez et al., 3884.

without suffering capacity or efficiency losses.[138] These capabilities make modern flywheels ideal for grid-scale voltage and frequency control.

According to a Senate hearing on grid-scale energy storage, flywheel pilot projects in the U.S. have proven the technology's usefulness for grid regulation.[139] Subsequently, in 2011 Beacon Power "reached the technical milestone of building the world's first grid-scale flywheel-based storage plant."[140] The plant, which is located in New York, is composed of 200 high-speed flywheels, providing five megawatt hours (MWh) of frequency regulation services. This translates to 20 MW of regulation—up or down—for fifteen minutes, with an efficiency of 85%.[141] Unfortunately, not long after beginning operation, Beacon Power declared bankruptcy in late October, 2011.[142] Whether this development spells the end for grid-scale flywheel systems remains to be seen. Despite the bankruptcy, Beacon's plant is still operational, and may see increased revenues when a decision by the Federal Energy Regulatory Commission "to force the nation's grid operators to pay more for 'fast' response power than slow, fossil-fueled power" takes effect.[143] As will be discussed later, this and other regulatory changes could make the difference for technologies like flywheel energy storage.

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[138] Baxter, 127.
[139] Senate Committee, *Grid-Scale*, 16.
[140] Sonal Patel, "Milestones for Flywheel, Lithium Battery Grid-Scale Projects," Powermag.com, August 1, 2011, under "World's First Grid-Scale Flywheel Storage Plant," http://www.powermag.com/issues/departments/global_monitor/3871.html (accessed November 21, 2011).
[141] Ibid.
[142] Tom Hals and Roberta Rampton, "Beacon Power Bankrupt; had U.S. Backing Like Solyndra," *Reuters*, October 31, 2011, http://www.reuters.com/article/2011/10/31/us-beaconpower-bankruptcy-idUSTRE79T39320111031 (accessed November 21, 2011).
[143] Jeff St. John, "Beacon Power's Bankruptcy Autopsy," *GreenTechMedia.com*, October 31, 2011, under "Regulations Could Double Revenues?," http://www.greentechmedia.com/articles/read/beacon-powers-bankruptcy-autopsy/ (accessed November 21, 2011).

Battery Energy Storage

Batteries—probably the most familiar type of energy storage—store energy in chemical bonds. When those bonds are broken, free electrons travel across an ion gradient, creating an electric current and releasing energy. Rechargeable battery technology has garnered considerable attention recently because of the popularity of hybrid-electric and plug-in electric vehicles; however, battery technology also has significant potential for grid-scale energy storage. Designs being considered for this application include lithium-ion, lead-acid, sodium sulfur, and flow batteries. Each of these designs has multiple variants, but this paper will not delve into them significantly. Furthermore, there are many other battery designs that may ultimately prove useful that will not be discussed in this paper. Instead, since battery designs are incredibly complex and diverse, and are constantly being innovated, this section will only provide an overview of some battery technologies that may be used for energy storage and their possible applications.

Lead-Acid Batteries

Lead-acid batteries were developed in the mid-nineteenth century by Gaston Plante; by the 1920s, utilities began using them to "provide load leveling and to average out the demand peaks. Since then, numerous stationary systems up to multi-MW/MWh … were installed, which demonstrated the value of the lead acid batteries in the grid."[144] Their basic design consists of a lead dioxide positive electrode and a lead negative

[144] Zhenguo Yang et al., "Electrochemical Energy Storage for Green Grid," *Chemical Reviews* 111 (2011): 3602.

electrode surrounded by sulfuric acid, which facilitates the chemical reaction.[145] Lead-acid batteries "can respond within milliseconds and provide full power instantaneously."[146] They also tend to be the cheapest type of energy storage, with the ability to cycle up to one thousand times at about 75% efficiency.[147]

While these characteristics make them well suited for providing frequency and voltage regulation, "demonstration projects showed that larger MW-scale facilities can have operational difficulty."[148] Lead-acid batteries are limited by their ability to discharge deeply, and by their lengthy charge times—"it takes about 5 times as long to recharge a lead-acid battery to the same charge capacity as it does to discharge."[149] Charging or discharging outside of their optimal range can damage these batteries and decrease their lifespan. For example, a 20-MW, 14-MWh lead-acid storage facility that provided spinning reserve and grid regulation in Puerto Rico was closed only five years after its installation due to the declining capacity of the batteries. Though the plant was successful during its tenure, the potential for such decreases in lifespan may deter future investment in this technology. New, "advanced" lead-acid designs are being developed to counter these weaknesses, but at this time there is insufficient information to evaluate them.[150]

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145 Isaac Scott and Se-Hee Lee, "Battery Energy Storage," in *Large Energy Storage Systems Handbook*, ed. Frank S. Barnes and Jonah G. Levine (Boca Raton, FL: CRC Press, 2011), 156.
146 Baxter, 112.
147 Yang et al., 3602.
148 Baxter, 112.
149 Yang et al., 3602.
150 Ibid., 3605; Rittershausen and McDonagh, 31.

Sodium Sulfur Batteries

Sodium Sulfur (NaS) batteries originated in the 1960s from research by Ford Motor Company into electric vehicles.[151] NaS batteries are composed of molten sulfur (the positive electrode) and molten sodium (the negative electrode). The electrodes must be maintained at very high temperatures—570^{o} Fahrenheit—and are "separated by a solid, ceramic electrolyte that conducts sodium ions."[152] Due to the high temperatures involved, NaS cells must be tightly sealed and well maintained.[153]

NaS batteries are particularly well suited for peak shaving and power quality applications,[154] but may also be applied to load shifting, renewable integration, and in-basin generation. Individual modules can be tailored to either power quality or peak shaving uses. These modules can then "be combined to provide up to 20 MW for PS [peak shaving] and up to 100 MW for PQ [power quality] applications. PS modules are optimized to deliver long discharges with modest voltage drop, whereas PQ modules are designed to deliver short pulses of power."[155] As compared to lead-acid batteries, NaS units can have up to five times higher energy density, longer life spans and cycle-lives, deeper discharge capability and lower maintenance and operation costs.[156] Furthermore, they can achieve an efficiency of 89%.

One disadvantage of NaS batteries is that there is only one company capable of producing them—NGK—limiting the production of NaS units significantly. Such

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[151] Yang et al., 3591.
[152] Ken Wicker, "Big Batteries Blooming," *Powermag.com*, February 15, 2005, under "Sodium-sulfur: A Hot New Battery," http://www.powermag.com/environmental/Big-batteries-blooming_1042.html (accessed November 21, 2011).
[153] Scott and Lee, 159.
[154] Wicker, under "Sodium-sulfur"; Vazquez et al., 3883.
[155] Wicker, under "Sodium-sulfur"
[156] Senate Committee, *Grid-Scale*, 66; Wicker, under "Sodium-sulfur" ;Baxter, 106.

limitations are made especially clear by a 1,000 MW sodium sulfur battery storage project proposed for Baja California, which could potentially "take up that company's entire production capacity for nearly the next decade."[157] Nonetheless, NGK has plans to expand production capability,[158] and as the technology becomes more common it is likely that other companies will gain the technical know-how to compete with NGK. Other issues with NaS batteries include the safety and reliability concerns, along with the need for cost reductions.[159]

Sodium sulfur systems are still a relatively new technology. While NaS facilities were constructed in Japan much earlier, the first unit in America came online in 2002.[160] This unit, located in Gahanna, Ohio, is owned by American Electric Power Co. (AEP) and is used to provide power quality and peak shaving on a relatively small scale.[161] AEP installed another unit in 2006 in Charleston, West Virginia to provide peak shaving on a larger scale (1.2-MW, 7.2-MWh) while allowing the company to defer upgrading its Charleston substation.[162] NaS batteries are also capable of truly, grid-scale energy storage, as demonstrated by a 34-MW, 238-MWh facility in Japan that will shift off-peak production of the Rokkasho wind farm, making the resource dispatchable.[163] As costs decline and production ramps up, NaS batteries should enjoy increasing popularity for similar grid-scale applications.

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[157] Sonal Patel, "Massive Energy Storage Facility Planned for Mexico-U.S. Border," *Powermag.com*, December 1, 2010, http://www.powermag.com/issues/departments/global_monitor/3205.html (accessed November 21, 2011).
[158] Baxter, 107.
[159] Yang et al., 3596.
[160] Wicker, under "Sodium-sulfur."
[161] Ibid.
[162] Brad Roberts, "Shaving Load Peaks from the Substation," *Powermag.com*, October 15, 2006, http://www.powermag.com/business/587.html (accessed November 21, 2011).
[163] Yang et al., 3591.

Lithium-Ion Batteries

As their name suggests, lithium-ion (Li-ion) batteries harness electrical current from the movement of lithium ions from a positive electrode to a negative electrode. Originating in the 1990s, they are now commonly used to power consumer electronics like laptop computers.[164] Multiple variations on the Li-ion design exist, "including but not limited to lithium iron-phosphate, lithium manganese-spinel, and nickel-manganese-cobalt."[165] These variations give Li-ion batteries a flexible range of power-to-energy ratios, which, in turn, make them suitable for a wider array of storage applications. Furthermore, they have relatively low operating and maintenance costs and relatively high energy densities.[166] According to Southern California Edison, there are many Li-ion projects in the U.S testing the technology's capabilities and it is "nearing commercial availability for widespread use on the electric grid."[167]

Unfortunately, lithium-ion batteries are not without drawbacks. They are more costly than other technologies and can suffer capacity losses or even failure when overheated. This is especially problematic since they have "a risk of heat generation, thermal runaway, and fire."[168] Though there are methods of dealing with these overheating limitations, they are often "too costly or significantly alter the weight, size, and durability advantages of Li-ion batteries."[169] Li-ion batteries also have limited cycle-

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164 Scott and Lee, 178.
165 Rittershausen and McDonagh, 30.
166 Ibid.; Jarno D. Dogger, Bart Roossien, and Frans D. J. Nieuwenhout, "Characterization of Li-Ion Batteries for Intelligent Management of Distributed Grid-Connected Storage," *IEEE Transactions on Energy Conversion* 26, no. 1 (March 2011): 256.
167 Rittershausen and McDonagh, 30.
168 Yang et al., 3597.
169 Scott and Lee, 176.

lives, meaning they can only be charged and discharged a discrete number of times, which can be an issue in some energy storage applications.[170] Discharging too deeply or at the wrong rate can also negatively affect a Li-ion battery's cycle life.[171] Despite these disadvantages, Li-ion batteries have been widely used in hybrid and plug-in electric vehicles.[172] While this application has spurred significant development of the technology, lithium is a scarce resource and "its widespread use for vehicle batteries will gradually deplete known resources, leading to increasing raw material costs."[173]

Much like flywheels, lithium ion batteries are well matched for grid regulation services. One such application, has been serving PJM [Pennsylvania-New Jersey-Maryland Interconnection], a regional transmission organization, since 2009. As described in U.S. Senate testimony, "the facility can help PJM quickly balance variations in load to regulate frequency as an alternative to adjusting the output of fossil-fuel generators; it is capable of changing its output in less than one second ... Thirty four MWs of battery storage have been put in the PJM generation queues for 2010."[174] Furthermore, in contrast to traditional generation resources, the battery unit is housed in a trailer, making it able to relocate wherever regulation services are most needed. Another possible application for Li-ion batteries is for distribution level storage—providing better power quality and allowing the deferment of distribution system upgrades.[175]

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170 Ibid., 177.
171 Dogger, Roossien, and Nieuwenhoot, 256.
172 Yang et al., 3597.
173 Vazquez et al., 3882.
174 Senate Committee, *Grid-Scale*, 47.
175 Yang et al., 3601.

<u>Flow Batteries</u>

Finally, flow batteries consist of two electrolyte solutions that flow through electrodes in a “cell stack” to create electricity. This process is similar to that of a fuel cell, except, whereas fuel cells oxidize a fuel (typically hydrogen), flow batteries harness the reversible, electrochemical reactions of electrolytes. In this way, “flow batteries are fuel cells that can be recharged.”[176] When not flowing through the cell stack, the electrolytes are stored in external tanks. Since the energy capacity of a flow battery is related to its volume and concentration of electrolytes, increasing the size of these tanks can upgrade the capacity of a facility at relatively low cost.[177]

Numerous variations of flow battery technology exist, including iron-chromium, vanadium redox, zinc bromine, polysulfide bromide, and cerium zinc. The capabilities of these variations differ, as does the state of research on each; however, since they largely make use of the same principles, it is not necessary—for the purposes of this paper—to make any further distinction between them. Instead, this section will consider the advantages and disadvantage of the technology as a whole.

As mentioned previously, flow batteries have flexible energy capacities since their electrolytes are stored externally. Moreover, they can increase their power capacities through the installation of additional cell stacks: “simplicity in cell and stack structure allows for building large systems based on module design.”[178] Essentially, “the use of solutions to store energy means that system power and storage capacity are independent

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[176] Scott and Lee, 167.
[177] Rittershausen and McDonagh, 31.
[178] Yang et al., 3584.

… allowing them to be tailored for diverse applications."[179] Additionally, they have very long cycle-lives and overall lifespans relative to other batteries, can discharge deeply without capacity losses, and are capable of either providing power over long periods or in "high power pulses" very quickly.[180]

Disadvantages of the technology include high maintenance costs, and high upfront costs.[181] Flow batteries can require frequent maintenance since they have a complex array of pumps, pipes, and other components.[182] Their upfront costs are also significantly higher than other technologies like lead-acid batteries—$350/kWh and $200/kWh respectively.[183] Nonetheless, flow batteries are still a relatively young technology and are largely limited to trial applications.[184] Therefore, it is likely that these costs will fall once commercial production begins. Combined with the technology's long cycle-life, these cost reductions should make flow batteries an attractive, competitive option for energy storage.

Currently, flow batteries are mostly in use in relatively small-scale applications. For example, Detroit Edison ran a two-year trial of two 200-kW, 400-kWh zinc bromine systems for use in peak shaving and grid regulation. Notably, the batteries were mounted on trucks and could, thus, be moved around to "support areas with only seasonal daily peak loads."[185] Another application, in Moab, Utah, has used a vanadium redox battery

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179 Scott and Lee, 169–170.
180 Scott and Lee, 167–169; Anthony Price et al., "A Novel Approach to Utility Scale Energy Storage," *Power Engineering Journal* 13, no. 3 (June 1999): 124; Wicker, under "Flow Batteries' Pros and Cons"; Yang et al., 3584.
181 Yang et al., 3591.
182 Rittershausen and McDonagh, 31.
183 Wicker, under "Flow Batteries' Pros and Cons."
184 Rittershausen and McDonagh, 31.
185 Baxter, 95.

system to provide peak shaving and voltage control since 2004.[186] One large-scale flow battery system does exist at Little Barford Power Station in the U.K.[187] This polysulfide bromide system is rated at 10 MW and can provide 100 MWh of storage.[188] As the technology matures further and costs decrease, it is likely that installations like this one will become more common.

Distributed Battery Storage: Electric Vehicles

As mentioned at the opening of this chapter, batteries have been the focus of considerable attention recently due to renewed interest in plug-in hybrid-electric (PHEV) and plug-in electric vehicles (PEV). In addition to providing potentially emission-free transportation, these vehicles have the potential to create a distributed energy storage network that could provide "backup power for homes and businesses, peak shaving, regulation, reactive power, and transmission stabilization."[189] Since cars are driven somewhat predictably and, on average, they are parked for 90% of the day, there is significant opportunity to leverage the batteries in electric vehicles for grid storage. [190]

Distributed battery storage would provide services to grid, benefitting the utility; in return, customers could be compensated financially for the energy their vehicles provide. These incentives might spur more customers to invest in an electric vehicle over a conventional, internal combustion engine, making up for the current premium on

186 Wicker, under "Perhaps Vanadium Redox."
187 Baxter, 84.
188 Price et al., 126.
189 Mehdi Ferdowsi, "Vehicle Fleet as a Distributed Energy Storage System for the Power Grid" (paper presented at the IEEE Power & Energy Society General Meeting, Calgary, AB, July 26, 2009).
190 Kristien Clement-Nyns, Edwin Haesen, and Johan Driesen, "The Impact of Vehicle-to-Grid on the Distribution Grid," *Electric Power Systems Research* 81 (2011): 185.

PHEVs.[191] At the same time, there is concern that the constant charging and discharging caused by providing grid services could diminish battery lives and inconvenience drivers. For these reasons, smart meters would be necessary to coordinate charge and discharge cycles to optimize for battery life and each customer's preferred minimum charge levels.[192] Furthermore, this technology will not be realistic until electric vehicle market penetration is much higher.

Thermal Energy Storage

Energy can also be stored as heat or, in some cases, lack thereof. Thermal energy storage, or TES as it is often referred to, can be designed for both utility-scale, and commercial or residential applications. On the utility side, the most available technology is thermal storage coupled with concentrated solar power plants. Additionally, a relatively new form of utility-scale thermal storage called "Pumped Heat Electricity Storage" uses large heat differentials to drive a heat engine.[193] Pumped heat plants do not necessarily need to be coupled with generation. Finally, thermal storage can be used to store energy on the demand side, shifting load to off-peak hours. In this case, instead of storing heat, storage systems create large blocks of ice at night. This ice is then used as a heat sink for air conditioning units during the day.

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[191] Ibid., 186.
[192] Ibid., 185.
[193] Eric Wesoff, "Breakthrough in Energy Storage: Isentropic Energy," *GreenTechMedia.com*, February 23, 2010, http://www.greentechmedia.com/articles/read/breakthrough-in-utility-scale-energy-storage-isentropic/ (accessed November 21, 2011).

Solar Thermal Energy Storage

Solar thermal energy storage systems store energy produced by concentrated solar thermal power (CSP) plants. Unlike photovoltaic solar power plants, which create electric current directly from sunlight, CSP plants generate electricity by concentrating sunlight onto "solar power towers" where it heats molten salt.[194] The molten salt is then used to heat water, which powers a steam turbine.[195] Another CSP design uses reflective parabolic troughs to concentrate sunlight on pipes containing molten salt or other "heat transfer fluids."[196] Since CSP already uses heat to produce electricity, TES can easily be added to CSP systems without the need for energy conversion and the resulting energy losses. In fact, all TES requires for such an application is a thermal storage tank that holds and insulates the excess molten salt not being used for immediate power production.

The benefits of adding energy storage systems to CSP plants are numerous. Probably the most apparent advantage is the fact that storage can add extra energy capacity to a solar facility, allowing it to continue operating while clouds are passing over and long after the sun has set.[197] As a report by the National Renewable Energy Laboratory (NREL) states, "storage can allow the plant to be built with a larger solar field because excess thermal energy can be placed into storage for use later" with a 98.5% efficiency.[198] While this benefit alone is quite substantial, the largest benefits of TES are related to the ability to firm electricity production and shift it to periods with higher

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[194] Edgar G. Hertwich and Xiangping Zhang, "Concentrating-Solar Biomass Gasification Process for a 3rd Generation Biofuel," *Environmental Science & Technology* 43 (2009): 4208.
[195] Ramteen Sioshansi and Paul Denholm, *The Value of Concentrating Solar Power and Thermal Energy Storage* (Golden, CO: National Renewable Energy Laboratory, February, 2010), 1.
[196] Ibid.
[197] Vazquez et al., 3885.
[198] Sioshansi and Denholm, 2.

electricity prices. By firming production, TES can allow solar plants to be integrated into the grid without the need for natural gas spinning reserve plants. Without intermittence resulting from clouds passing overhead, CSP plants would be capable of "replacing conventional power plants as opposed to just supplementing their output."[199]

Furthermore, they could continue generating up to ten hours after the sun goes down, making them much more flexible overall.[200] This extra capacity could then be used to improve the economics of the CSP plant by shifting production to periods of higher demand and, therefore, higher prices.[201] Essentially, CSP, with thermal energy storage, decouples power generation from the availability of sunlight, allowing these facilities to generate when it is most advantageous to do so. In keeping with this idea, CSP plants with TES can also expand their services to include ancillary services such as reserve capacity—a market never previously available to typically intermittent, renewable resources. Together, these advantages can increase the profitability of concentrated solar thermal power while making it competitive with traditional generation resources.[202]

At the same time, thermal energy storage coupled with CSP is still subject to weather over longer time frames. Southern California Edison notes that the technology "is potentially limited by overall energy availability (i.e. energy cannot be stored if there is limited sun for one or more days and thus the system may no longer be available for dispatch)."[203] Thus, one of the advantages of this type of TES—that it does not require energy conversion—can become a limitation since no storage is possible without, at least,

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199 Ibid., 1.
200 Vazquez et al., 3885.
201 Sioshansi and Denholm, 1; Senate Committee, *Grid-Scale*, 40.
202 Sioshansi and Denholm, 24.
203 Rittershausen and McDonagh, 32.

somewhat regular sunlight. This disadvantage is more a characteristic of CSP, than of associated thermal storage systems, and can be mitigated by locating CSP plants in regions with adequate sun. Nonetheless, in this respect, other methods of storage are valuable since they can store energy from electricity provided by any generator on the grid.

The first application of CSP with integrated thermal energy storage was constructed in the Mojave Desert in 1981. The 10-MW solar power tower plant, called Solar One, was a pilot project for CSP technology that "included a TES tank used to test the performance of thermal storage within oil, rocks, and sand media.[204] Eventually molten salt at 565^{o}C was determined to be the best storage material." The plant had a storage capacity of 182 MWh and operated from 1982 to 1986. It was subsequently upgraded (changing its name to Solar Two), adding more heliostats, but was ultimately decommissioned in 1999.[205] Many more installations have been constructed in Spain, including AndaSol One—a parabolic trough CSP plant with 7.5 hours of storage capacity.[206] Recently, TES has gained more attention with BrightSource Energy's announcement that it will add the technology to its CSP plants in California and Nevada.[207] Overall, this form of thermal energy storage is likely to grow alongside solar as renewable portfolio standards become more stringent; however, TES can also be useful without being coupled with CSP.

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[204] Carl Begeal and Terese Decker, "Solar Thermal Energy Storage," in *Large Energy Storage Systems Handbook*, ed. Frank S. Barnes and Jonah G. Levine (Boca Raton, FL: CRC Press, 2011), 206.
[205] Ibid.
[206] "Andasol-1 and Andasol-2: Dispatchable Thermosolar Power Plants," European Solar Thermal Electricity Association, http://www.estelasolar.eu/index.php?id=32 (accessed November 21, 2011).
[207] Eric Wesoff, "BrightSource Adds Storage to Its Solar Thermal CSP," *GreenTechMedia.com,* August 3, 2011, http://www.greentechmedia.com/articles/read/brightsource-adds-storage-piece-to-solar-thermal/ (accessed November 21, 2011).

<u>Pumped Heat Energy Storage</u>

Pumped heat energy storage can operate without being directly coupled with a generating plant since it converts electricity into thermal energy and back again. This technology is newer, and less well known, but has the potential to create very cheap, small-scale utility storage.[208] Isentropic Energy, the company advancing the technology has termed it pumped heat electricity storage (PHES). Once again, just as the name suggests, PHES uses "a highly reversible heat engine/heat pump to pump heat between two insulated storage vessels containing gravel."[209]

Charging a PHES device involves transferring heat from one vessel to the other until the former is cooled to -160^{o}C and the latter is heated to 500^{o}C. Electricity is generated when this process is reversed and heated, pressurized gas passes through the heat engine. Since this technology is in its very early stages, there is not much information available about its practicality. Nonetheless, Isentropic Energy's chief technology officer, Jonathan Howes, "claims the installed cost of energy storage using the PHES system is currently $55/kWH, dropping to perhaps $10/kWh with utility-scale systems" with an efficiency of 72–80%.[210] The system should be scalable, but is currently pursuing 2-MW, 16-MWh designs.[211] Given the state of the technology currently, it is unlikely to be a large factor in energy storage in the near term; however, its low cost may make it attractive for peaking or ancillary services.

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[208] Wesoff, "Breakthrough in Energy Storage."
[209] Peltier, under "Pumped Heat Electricity Storage."
[210] Ibid.
[211] Wesoff, "Breakthrough in Energy Storage," under "Pumped Heat Electricity Storage."

Distributed Ice Energy Storage

Finally, thermal energy storage can be scaled to commercial and residential applications. This type of end-use TES is usually used to reduce peak demand by shifting some load to off-peak hours.[212] End-use TES accomplishes this peak reduction by cooling tanks of water with cheap, off-peak power to create blocks of ice. During the day, when air conditioning would normally create large spikes in electricity demand, the ice is used as a heat sink for the air conditioning system.

These "ice energy" storage systems can be combined with HVAC systems, allowing commercial buildings to actually install smaller, more efficient units.[213] Thus, when TES systems are factored into the design of a new building they can essentially have an immediate return on investment from the decreased HVAC unit costs.[214] With this capability, TES not only uses cheaper electricity to cool a building, but also uses less. The technology is also useful for existing buildings which can still benefit from lower electricity bills and payback periods of one to three years.[215] According to Ice Energy, a manufacturer of end-use TES systems, "daytime energy demand from air conditioning—typically 40% to 50% of an average commercial building's electricity use during peak hours—can be reduced by as much as 95%.[216]

[212] Vazquez et al., 3885.
[213] Peltier, under "Electricity as Thermal Energy."
[214] Baxter, 152.
[215] Ibid.
[216] Peltier, under "Electricity as Thermal Energy."

Currently, Ice Energy has a contract with the Southern California Public Power Authority to shift up to 64-GWh of electricity demand off-peak.[217] To do so it will install about 6,500 TES units at 2,000 sites in Southern California by 2012.[218] Clearly, this project represents a major step forward for end-use thermal energy storage. If this project is successful, it is likely that TES applications will expand greatly.

Super Capacitors and Superconducting Magnetic Energy Storage

Super capacitors, also known as electric double-layer capacitors, store energy physically in the electrostatic charges of two plates. As their name suggests, they are derived from traditional capacitor technology; however, super capacitors have energy densities on the order of one hundred times that of conventional capacitors: since the energy stored is proportional to the area of the plates, the energy density can be increased dramatically by using porous carbon to maximize surface area.[219] Although their energy density is still lower than that of most batteries, super capacitors have faster charge/discharge cycles (a unit can be charged in about 10 seconds)[220], higher power densities, and "are capable of cycling millions of times and are thus virtually maintenance free."[221] Moreover, since they store energy physically, they can be deeply discharged without suffering capacity losses or damage.[222] Given these characteristics, super

[217] Elkind, 7.
[218] Peltier, under "Electricity as Thermal Energy."
[219] Mairaj ud din Mufti et al., "Super-Capacitor Based Energy Storage System for Improved Load Frequency Control," *Electric Power Systems Research* 79 (2009): 226; Vazquez et al., 3883.
[220] Huang Wei et al., "Discussion on Application of Super Capacitor Energy Storage System in Microgrid" (paper presented at the International Conference on Sustainable Power Generation and Supply, Nanjing, China, April 6, 2009).
[221] Mufti et al., 227.
[222] Vazquez et al., 3884.

capacitors could potentially be a valuable technology for frequency regulation or other applications that require short, high power bursts of energy. While they have been used in uninterruptible power supply systems, super capacitors are a relatively young technology that will require significant cost reductions before it can be commercialized and made useful on a grid-scale.[223]

Superconducting magnetic energy storage (SMES) systems use a magnetic field, rather than physical or chemical mediums, to store energy. An SMES unit stores energy by running direct current though one or more solenoids (conducting coils) cooled with liquid helium to -269°C to achieve a lossless, superconducting state.[224] As current flows through the solenoid, it creates a magnetic field which stores energy. To discharge this energy, "switches tap the circulating current and release it."[225] Like super capacitors, super conducting magnetic energy storage systems can provide high levels of power very quickly, though charging takes longer—minutes as opposed to milliseconds.[226] Furthermore, "SMES provides one of the highest densities of any power storage method" with more than 90% efficiency.[227] Disadvantages of SMES include the "parasitic losses" from the refrigeration equipment necessary to maintain superconducting temperatures (which actually detract from the devices' efficiency), safety issues related to the creation of magnetic fields, and pressure changes that could occur if cryogenic temperatures are

[223] Baxter, 135; Rittershausen and McDonagh, 33.
[224] Vazquez et al., 3885; Boyes and Clark.
[225] Boyes and Clark.
[226] Vazquez et al., 3885; Boyes and Clark.
[227] Vazquez et al., 3885.

not preserved.[228] Furthermore, while the device itself does not have any moving parts, the refrigeration system does, and may impose significant maintenance costs.[229]

SMES technology was promoted for utility and industrial applications as early as 1969.[230] According to Richard Baxter, "more than 100 MW of these units (with the average unit being 3 MW or less) are estimated to be currently in operation around the world)."[231] For the most part, SMES is used to provide voltage control for industrial facilities and, more recently, utility-scale applications.[232] For instance, the Wisconsin Public Service Corporation (a utility) uses six SMES units for voltage control and the deferment of planned transmission upgrades.[233] Nonetheless, like super capacitors, SMES technology will still need to be developed more before they can be used widely by utilities for voltage control applications.[234]

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[228] Boyes and Clark.
[229] Matthew Deal, Susannah Churchill, Larry Chaset, and Christopher Villarreal, *Electric Energy Storage: An Assessment of Potential Barriers and Opportunities* (California Public Utilities Commission, July 2010), 4.
[230] Baxter, 143.
[231] Ibid.,148.
[232] Boyes and Clark.
[233] Baxter, 148.
[234] Rittershausen and McDonagh, 33.

Chapter 4: Regulation and Integration of Energy Storage Systems

As described in the previous section, currently there are a multitude of energy storage technologies being developed. Since each of these technologies has unique characteristics, storage can be applied to a wide variety of grid services including price arbitrage, renewable integration, ancillary services, improving generator efficiency, and deferring generation and T&D system upgrades. Nonetheless, energy storage faces significant challenges before it can be employed on a wide scale for these applications. There is a complex array of regulations that govern the electric grid, which currently reflects the conventional model of just-in-time generation. Under these regulations, storage devices are undervalued and, thus, cannot always be economically justified. This issue is exacerbated by the already high cost of most energy storage technologies, and the fact that there is, currently, no mechanism for internalizing the costs of fossil-fuel generators.

Paradoxically, one of the greatest strengths of energy storage—its ability to serve multiple grid functions—can also be one of the foremost barriers to its adoption. As a white paper by the California Public Utilities Commission [CPUC] explains, "the benefits of EES [electric energy storage] often cross the traditional boundaries of generation, transmission, distribution, and at times, load."[235] Previously in this paper, this flexibility was described as an advantage of energy storage; however, it also makes the technology

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[235] Matthew Deal, Susannah Churchill, Larry Chaset, and Christopher Villarreal, *Electric Energy Storage: An Assessment of Potential Barriers and Opportunities* (California Public Utilities Commission, July 2010), 5.

hard to classify for utilities, which "recover their costs from the ratebase according to specific asset classes" as determined by federal and state regulators. In other words, utilities must justify their expenditures—and the rates they charge customers in order to recover these costs—to regulators. Regulators have a framework that allows certain asset classes, or types of grid resources, to receive certain returns on investment. Since no such asset class exists for storage, it must be categorized in an asset class that does not accurately reflect its full benefits.[236] Thus, there is no incentive for utilities to invest in energy storage devices if they are more expensive than traditional resources, even when they would otherwise be more economical than those traditional resources overall. For instance, the ability of storage to improve generator efficiency and defer generation and T&D upgrades can save utilities, and their customers, money; "however, transmission operators generally regard energy storage as power generation rather than as a transmission upgrade. They usually do not allow the cost recovery for the application of energy storage technologies as part of, or in lieu of, investment in transmission upgrades."[237] Without the ability to capitalize on the full range of benefits from energy storage, utilities end up resorting to tried-and-true methods that can provide reliable returns on investment, regardless of their relative inefficiencies.

Even when energy storage is chosen over traditional generation resources, its benefits are still undervalued. Once again, this challenge is symptomatic of regulations tailored for the capabilities of conventional generators. For instance, currently most

[236] Ethan N. Elkind, *The Power of Energy Storage: How to Increase Deployment in California to Reduce Greenhouse Gas Emissions* (UC Berkeley School of Law's Center for Law, Energy & the Environment and UCLA School of Law's Environmental Law Center & Emmett Center on Climate Change and the Environment, July 2010), 14.
[237] Chi-Jen Yang and Eric Williams, "Energy Storage for Low-carbon Electricity," *Climate Change Policy Partnership Technology Policy Brief Series* (January 2009): 9.

tariffs (prices paid to service providers) for regulation services factor in a "10 minute ramp requirement."[238] Whereas this 10 minute ramp time is often required for natural gas turbines, energy storage technologies like batteries and flywheels can provide services almost instantaneously. Furthermore, they can do so more accurately than combustion turbines, thereby lowering the actual amount of regulation services needed.[239] Nonetheless, tariff rates still factor in the inaccuracy of natural gas plants. Thus, due to the limitations of natural gas turbines, storage technologies receive a highly discounted tariff for much higher quality ancillary services.[240] As John Wellinghoff, former chairman of the Federal Energy Regulatory Commission (FERC), explains in his testimony to the Senate Committee on Energy and Natural Resources, "most existing tariffs or markets do not compensate resources for superior speed or accuracy of regulation response. But such payments may be appropriate as system operators gain experience with the capabilities of storage technologies."[241] Similarly, many regulators require overly large power and energy capacity requirements in order to provide ancillary services, essentially ruling out many storage technologies that are optimized to more low power or quick-response applications.[242]

To make energy storage more competitive in these markets, it must first be defined by regulators and methods for integrating and evaluating its benefits must be established. Acknowledging storage technologies as an asset class in a regulatory

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[238] *Energy Storage—a Cheaper Faster, & Cleaner Alternative to Conventional Frequency Regulation* (Berkeley, CA: California Energy Storage Alliance), 11.
[239] Zhenguo Yang et al., "Electrochemical Energy Storage for Green Grid," *Chemical Reviews* 111 (2011): 3579.
[240] California Energy Storage Alliance, 11.
[241] Senate Committee on Energy and Natural Resources, *Grid-Scale Energy Storage*, 111th Cong., 1st sess., 2009, 14.
[242] California Energy Storage Alliance, 11.

framework will allow utilities and grid operators to analyze its cost-effectiveness more accurately. Furthermore, utilities can be guaranteed a return on their investment in a storage device if the framework is present to build it into the utility's rate structure. Currently, in California, a first step has been made as the CPUC evaluates the "appropriate targets, if any, for each load-serving entity to procure viable and cost-effective energy storage systems" in accordance with California Assembly Bill 2514 (A.B. 2514).[243] This law, which was signed in 2010, could help to promote a regulatory framework for storage technologies as the CPUC examines them further. While A.B. 2514 is a significant and encouraging step forward for energy storage, similar efforts on the federal level have resoundingly failed. One attempt at such a bill—the Energy Storage Technology Advancement Act of 2007— passed in the House but never made it to a vote in the Senate.[244] A subsequent attempt in 2009—the Storage Act of 2009—did not leave committee.[245] The only success on the federal level was the Energy Policy Act of 2005, which "directs the Federal Energy Regulatory Commission (FERC) to encourage 'advanced transmission technologies,' including energy storage."[246] Without more successful national legislation, progress concerning the definition and evaluation of energy storage will likely be slow and piecemeal.

Along the same lines, the determination of tariff rates must be adapted to proportionally compensate energy storage devices for the faster, more accurate services they provide. Increasing these tariff rates in accordance with the actual value of storage

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[243] California Assembly Bill No. 2514, Statutes of 2010: Ch. 469.
[244] "H.R. 3776: Energy Storage Technology Advancement Act of 2007," GovTrack.us, http://www.govtrack.us/congress/bill.xpd?bill=h110-3776 (accessed November 21, 2011).
[245] "S. 1091: STORAGE Act of 2009," GovTrack.us, http://www.govtrack.us/congress/bill.xpd?bill=s111-1091 (accessed November 21, 2011).
[246] Yang and Williams, 9.

technologies can improve their overall economic viability and has the potential to replace inefficient, polluting combustion turbines in the ancillary services market. According to Wellinghoff's Senate testimony, FERC is encouraging "the ISOs [independent system operator] and RTOs [regional transmission organization] that are under our jurisdiction to formulate these tariffs that will compensate storage technologies in a way that they can develop a business model that can be sustainable."[247] FERC is doing so through regulatory Order 890, which was issued in 2007. So far, the New England ISO has implemented a pilot project that prices tariffs in accordance with the speed of response, granting a considerable advantage to storage technologies.[248] Additionally, the Midwest ISO (MISO) "filed a request to create an entirely new regulation resource category—Stored Energy Resources (SER) on April 25, 2008."[249] As more ISOs follow, battery and flywheel technology should be able to make a much larger impact in the regulation market.

Another issue to consider with energy storage technologies is their high cost relative to natural gas turbines and other generation resources. While some types of storage are well established, overall the technologies involved are relatively new and expensive to produce.[250] Costs should decline as storage is researched and developed further.[251] To this end, the Department of Energy (DOE) committed $185 million to 16 demonstration facilities as part of the American Recovery and Reinvestment Act

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[247] Senate Committee, *Grid-Scale*, 20.
[248] Ibid., 13.
[249] Yang and Williams, 10.
[250] Elkind, 16.
[251] Rodica Loisel et al., "Valuation Framework for Large Scale Electricity Storage in a Case with Wind Curtailment," *Energy Policy* 38 (2010): 7333.

(ARRA).[252] This investment is definitely beneficial to the advancement of storage technologies; however, typically the DOE's funding for energy storage is closer to "a few million dollars—a trivial amount compared to the R&D budgets for fossil energy, nuclear power, or renewable energy."[253] For real research and development to be sustained, the current level of commitment will need to be maintained after ARRA funding runs out. Furthermore, DOE needs to move beyond demonstration projects, which tend to benefit technologies that are already near commercial viability instead of those at earlier stages of development.[254]

In reality, investment tax credits may be more effective since they "would spur more investors to finance these projects and could potentially offset the high upfront costs of deploying and developing cutting edge technologies."[255] Energy storage could also benefit from loan guarantees like the ones currently offered to renewable energy projects.[256] Whereas, the Energy Policy Act of 2005 granted loan guarantees for "'innovative technologies' that avoid greenhouse gases," it did not consider energy storage as one of those technologies.[257] If energy storage projects had access to federal loan guarantees they could obtain financing much more easily, making technologies with high upfront costs more viable. Similarly, energy storage stands to benefit from feed-in tariffs like those for renewable energy since they would guarantee investors price stability

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[252] Senate Committee, *Grid-Scale*, 8.
[253] Yang and Williams, 7.
[254] Ibid., 8.
[255] Elkind, 16.
[256] Ibid.; Senate Committee, *Grid-Scale*, 36.
[257] Yang and Williams, 17.

and more certain returns on investment.[258] Essentially, these policies would spur further investment in energy storage technologies and, consequently, help reduce costs.

Finally, it is worth noting the costs of traditional combustion turbines that are externalized to society through pollution and greenhouse gas (GHG) emissions. If these costs were internalized, energy storage technologies would be much more competitive before any of the above strategies were even implemented.[259] As discussed previously, grid energy storage can allow for more efficient fossil-based generation. More importantly, coupled with renewable energy sources like wind farms, storage can allow for reliable, clean power without the need for GHG-emitting gas reserves. Thus, if rules limiting or taxing GHG emissions took effect, energy storage would benefit greatly. One such effort, California's Global Warming Solution Act of 2006 (AB 32), which "requires that California reduce statewide greenhouse gas ("GHG") emissions to 1990 levels by 2020" will spur investment in storage directly and indirectly through the increased adoption of renewable energy sources.[260] Similarly, stringent renewable energy portfolio standards have the potential to make storage options favorable regardless of any cost premium.[261] As the proportion of intermittent energy sources on the grid grows, the ability to regulate, firm, and shift these sources of production will become more and more valuable, allowing for energy storage applications to take root.

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[258] Ibid.; Goran Krajačić et al., "Feed-in Tariffs for Promotion of Energy Storage Technologies," *Energy Policy* 39 (2011): 1424.
[259] Krajačić et al, 1423.
[260] Deal et al., 1.
[261] Elkind, 19.

Chapter 5: Conclusion

Energy storage has the potential to entirely transform the electric grid and the energy industry. Currently, grid operators and utilities must greatly overinvest in generation, transmission, and distribution capacity in order to meet short periods of peak demand. Furthermore, they must do so while accommodating the fluctuations in electricity demand and renewable generation by incorporating peaking and reserve plants that are less efficient and more expensive to operate than baseload or intermediate facilities. These problems are symptomatic of a system modeled around just-in-time generation—a system that will face escalating problems going forward as renewables make up a greater portion of generation and overinvesting in grid capacity becomes less sustainable.

If energy storage is employed on a large enough scale, it can eliminate the emphasis on the just-in-time generation model, in favor of more stable generation and better use of grid resources. Instead of cycling generation—a technique that can be expensive, both in terms of wear-and-tear and plant efficiency—grid operators will be able to charge and discharge storage facilities. Not only will this decrease cycling costs on baseload and intermediate generators, it will help achieve price arbitrage, shifting cheaper, off-peak electricity to on-peak hours. As the composition of generation resources changes due to renewable portfolio standards and the falling costs of renewable technologies, energy storage will be essential to make this energy dependable, dispatchable, and available at peak hours. Thus, establishing grid-scale storage will be an integral element to achieving energy independence and crucial greenhouse gas emission reductions.

As discussed in Chapter 3, there is a wide array of energy storage technologies, with a broad range of power and energy capacities, cycling capabilities, and costs. Though it is much too soon to determine which technologies will ultimately be practical, it is clear that storage, in general, is capable of providing multiple, valuable grid services including reserve capacity, deferral of T&D upgrades, frequency and voltage regulation, in-basin generation, and load-shifting—for both supply and demand-side applications. Establishing storage systems will, no doubt, be difficult and costly at first; however, as seen with natural gas, integrating storage into a market is not only possible, it is greatly beneficial. As storage technologies are developed further, costs will come down and become more competitive with traditional generation and T&D resources.

Nonetheless, without more support on a federal level, the development of grid storage will be significantly stunted. FERC Order 890 is an important first step, encouraging ISOs and RTOs to accommodate storage technologies, but more explicit legislation and regulation is needed to accelerate this accommodation. Specifically, energy storage must be defined in a way that will allow utilities to value it properly—taking into account its multiple benefits across generation and T&D, and its faster, more accurate response times. Furthermore, given the considerable benefits of storage, it is worth adopting tax incentives, feed-in tariffs, and even loan guarantees to spur more investment and development. ARRA funding levels should also be maintained to foster more experimental storage technologies.

If regulations are improved to value storage correctly, and incentives are put in place to allow for higher levels of investment and development, there is no doubt that energy storage systems will become an integral element of the grid. Once established, storage should allow better utilization of existing grid assets, better integration of renewables, and overall cost reductions. Moreover, increasing the efficiency of fossil-fuel generators, and improving the quality and accessibility of renewable generation will allow for significant greenhouse gas abatement, promising even more value for storage technology. Ultimately, energy storage has the potential to take the grid from an inefficient, outdated system, to a modern, mature market ready to meet the challenges of the 21^{st} century.

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