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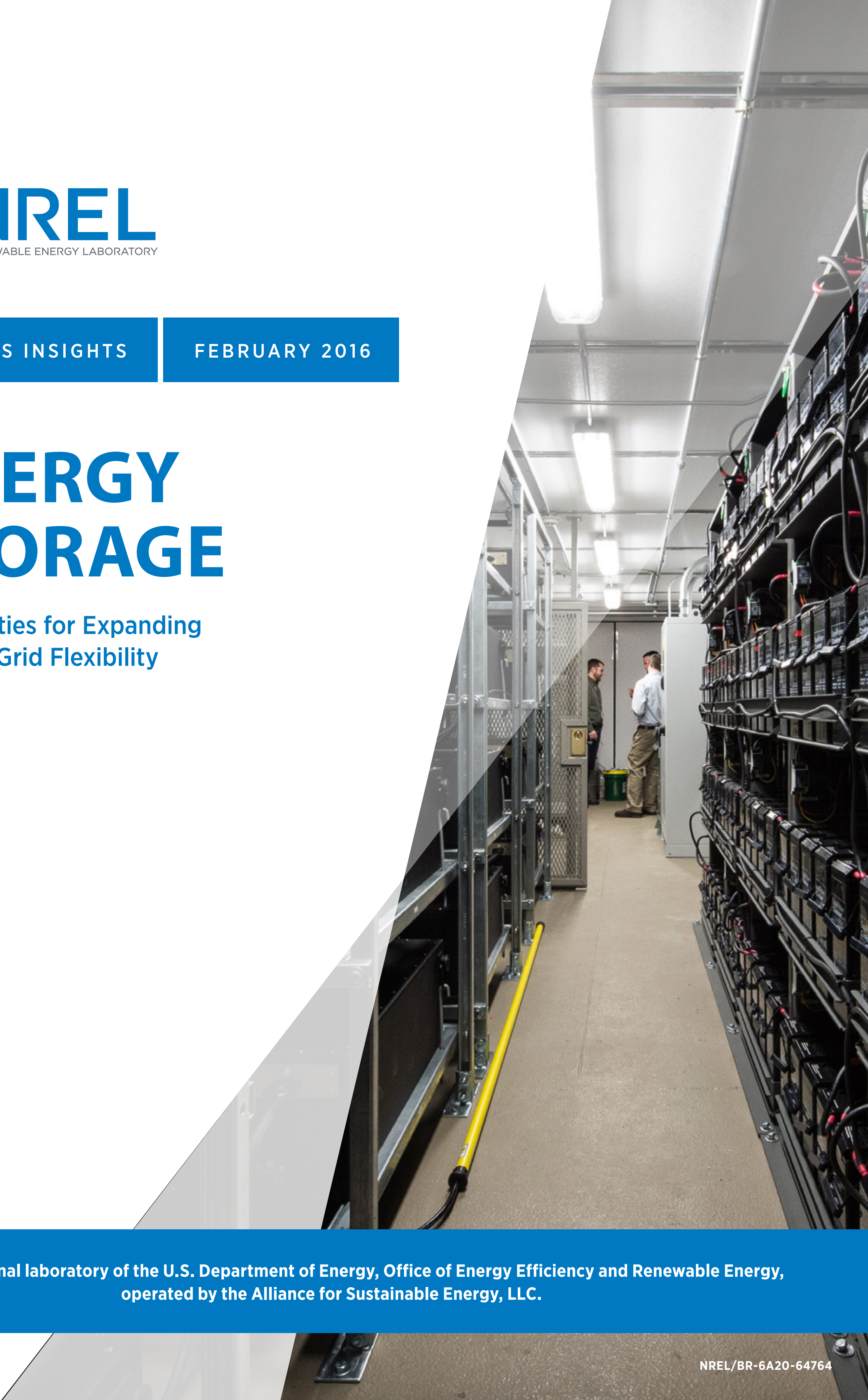
NATIONAL RENEWABLE ENERGY LABORATORY

ANALYSIS INSIGHTS | FEBRUARY 2016

ENERGY STORAGE

Possibilities for Expanding Electric Grid Flexibility



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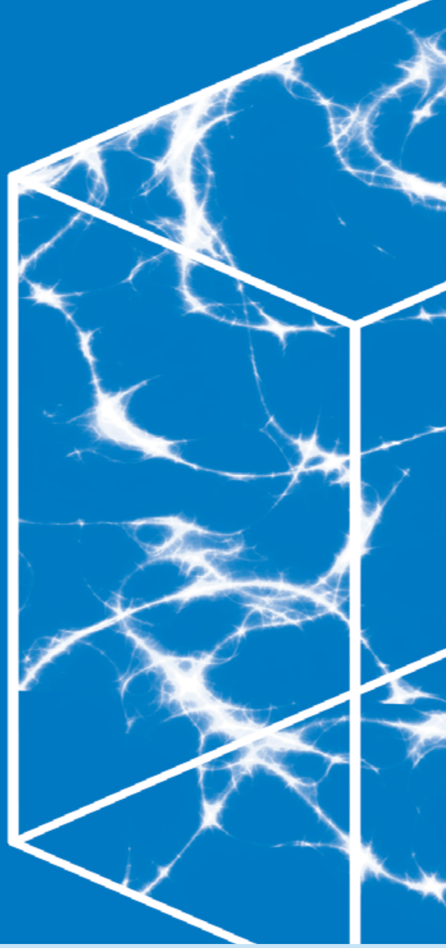
NREL/BR-6A20-64764

ENERGY STORAGE— ONE BUILDING BLOCK OF A CLEANER POWER SYSTEM

Energy storage technologies are receiving a great deal of attention today because of their potential to play a key role in the transformation to a low-carbon, clean energy future. Traditionally, utilities have changed the output of generators (the electricity supply) to adjust to variable but largely predictable demand. With the introduction of more variable renewable generation resources, the equation becomes more complex because RE output is not "dispatchable" the way conventional generation is. Storage can help utilities manage this variability in RE output by providing a broad array of grid services that generally make the power system more flexible, a recognized key to integrating high penetrations of wind and solar. However, storage technologies are still relatively costly compared to other alternatives. The U.S. power system can move forward with renewable deployment and make great strides toward decarbonization without energy storage. But several analyses indicate that very high penetrations of variable renewable generation—with a common tipping point of about 50%—will require access to more affordable energy storage. NREL analysis provides objective insights and data that are helping utilities, regulators, and state and local governments develop policies that address these challenges and expand the potential value streams for energy storage in the grid of the future.



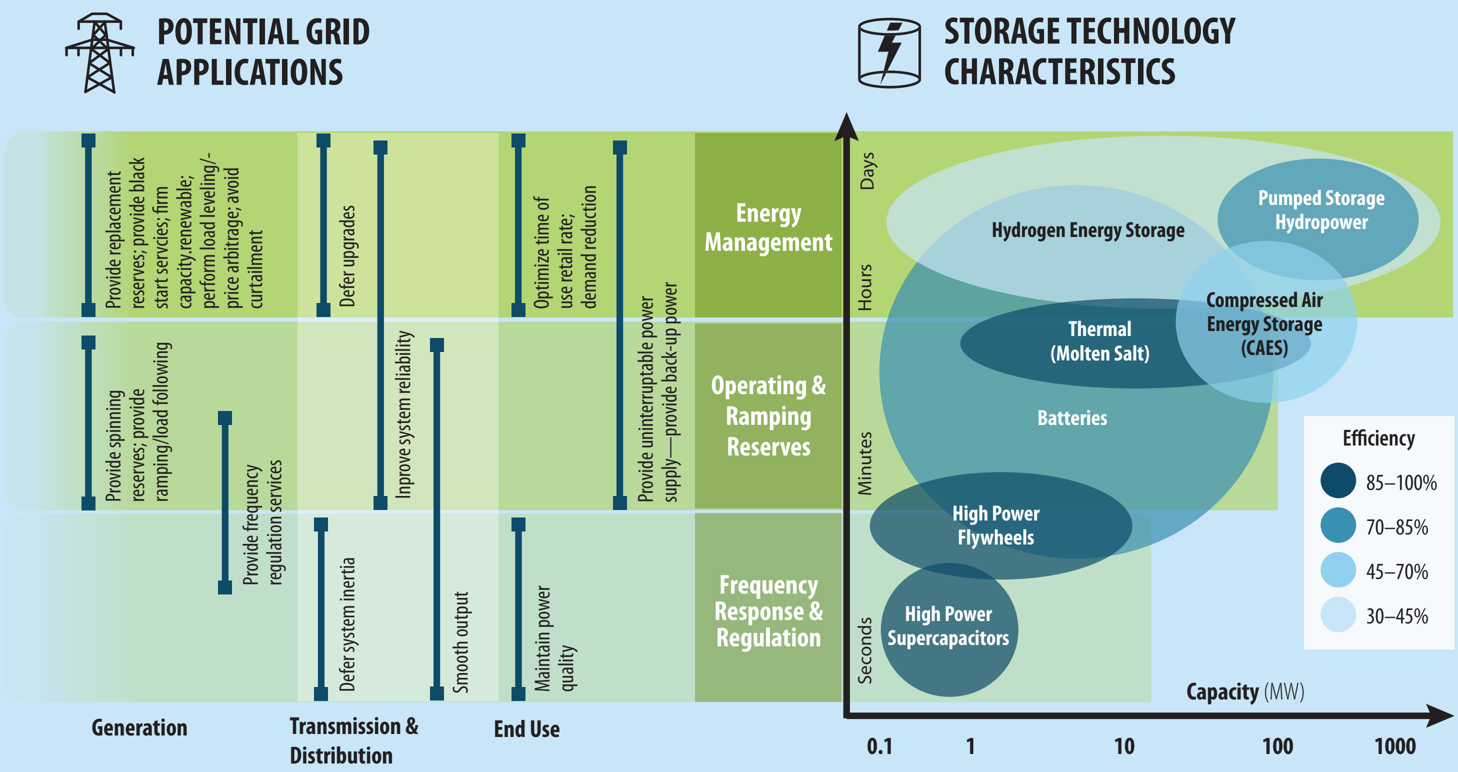


Figure 1. "Storage" is a broad category of technologies and applications that can help utilities balance power supply and demand by holding energy for later use, like a bank account for energy. Storage technologies are distinguished primarily by capacity and discharge time. Different storage technologies can be used for each of three main electric sector goals: energy management for daily/hourly scheduling, operating and ramping reserves for load following, and frequency response and regulation to maintain power quality.

Increasing Variable Renewable Generation on the Grid Enabled by Additional Flexibility

NREL's grid integration studies indicate that with changes in operational practices, such as sharing of generation resources and loads over larger areas and sub-hourly generator dispatch scheduling, the grid can economically accommodate:

- **Up to about 20% variable generation on an annual energy basis without the need for energy storage**
- **Up to 35% variable generation with the introduction of lower-cost flexibility options such as greater use of demand response.**

NREL's *Renewable Electricity Futures* study showed that higher penetrations of variable generation (>50%) increase the need for all flexibility options including energy storage. In the core 80% *RE Futures* scenarios (which included ~50% variable wind and solar PV), for example, storage deployment was found to increase from approximately 20 GW in 2010 to 100–152 GW in 2050. In the *RE Futures* scenarios, storage deployment increased with higher levels of wind and solar penetration and/or lower levels of system flexibility.

Today's power systems typically employ energy storage in the form of pumped hydropower resources, which store off-peak electricity during periods of low demand and release it during periods of high demand. Energy storage is one of many technologies proposed and utilized to increase grid flexibility and enable greater use of variable renewable generation, as highlighted in Figure 2.

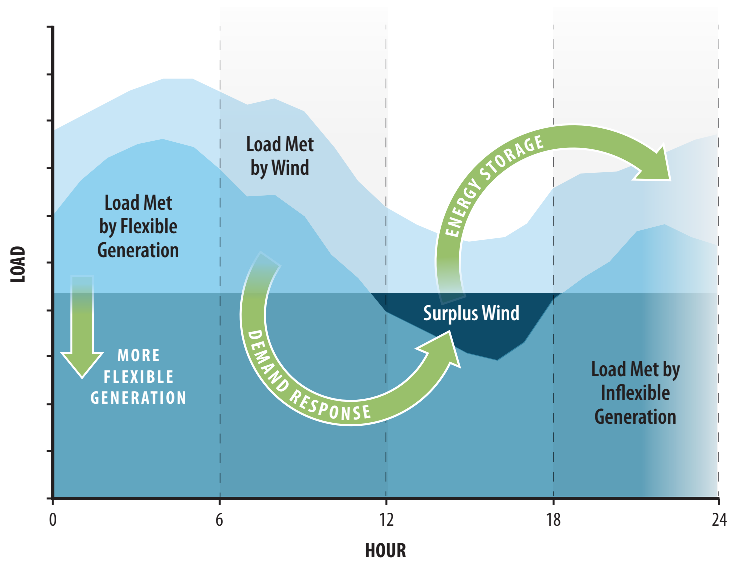


Figure 2. Flexible generation, demand response, and energy storage are sources of power system flexibility that increase the alignment between renewable energy generation and demand. For example, storage technologies can store excess wind generation for use in times of relatively low wind generation and high load.
Source: NREL/FS-6A20-63041

Policy and R&D Drive Energy Storage Deployment

Although energy storage has technical capabilities to increase power system flexibility, a combination of economic, market, and regulatory factors have limited its deployment. Today, the United States has approximately 22 GW of utility-scale electric storage capacity installed[1], which equates to just over 2% of the nation's total existing generation capacity.[2] Nearly all of current U.S. storage capacity (20.38 GW of 21.39 total) is in the form of pumped hydropower storage.[3]

Research and development efforts are typically focused on advances to bring down the costs of storage technologies with the goal of creating new opportunities for storage on the grid—particularly for technologies that can provide very fast response at high efficiencies. For example, NREL analysis indicates that with technological advances, batteries can provide load shifting and operating reserves services now provided most often by highly flexible, natural-gas combustion turbines. Depending on battery life, batteries can enable a system with equal or lower overall life-cycle cost even if the capital cost of batteries is higher than the capital cost of a combustion turbine of equal

1. http://www.energystorageexchange.org/projects/data_visualization
2. http://www.eia.gov/beta/aeo/#/?id=9-AEO2015&region=0-0&cases=ref2015&start=2012&end=2040&f=L&linechart=9-AEO2015.4
3. http://www.energystorageexchange.org/projects/data_visualization

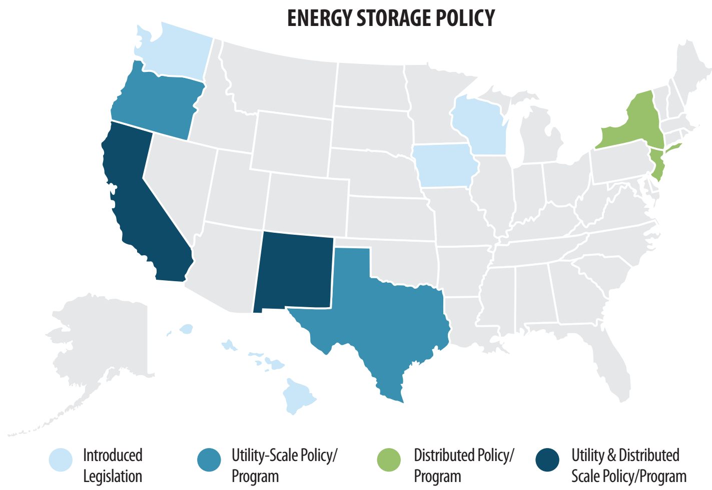


Figure 3. Between 2011 and 2014, at least 10 states introduced policies and regulatory actions focused on energy storage. Source: NREL/BR-7A40-62726

capacity. This is because the batteries enable use of renewable technologies like wind and solar, which have zero marginal fuel costs. Over time, the marginal fuel costs of conventional technologies can be greater than the costs of battery systems. In a modeled situation in which batteries provide 4% of overall system peak net demand (demand minus solar and wind output), a battery with a lifetime of less than 10 years would likely need a capital cost similar to combustion turbines. With a 20-year life, battery capital cost could approach twice that of a combustion turbine. Additional analysis could assess actual battery size needed to provide system-wide capacity benefits (considering forecast uncertainty) and to examine whether batteries can compete with traditional peaking generation in restructured wholesale markets.

Policies are starting to support energy storage deployment, and markets and regulations are moving to catch up. Between 2011 and 2014, at least ten states (California, Florida, Hawaii, Iowa, New Jersey, New Mexico, New York, Oregon, Texas, Washington, and Wisconsin), shown in Figure 3, introduced a total of 14 bills related to energy storage. The bills generally focused on

AUTOMOTIVE LITHIUM-ION BATTERIES: WHERE ARE THEY BUILT AND WHY?

Like many clean energy technologies, energy storage devices and their components are manufactured through a complex global supply chain. To help illuminate how and where the growing demand for clean energy technologies will likely be met, the U.S. Department of Energy (DOE) established the Clean Energy Manufacturing Analysis Center (CEMAC), a multi-lab consortium housed at NREL and operated by the Joint Institute for Strategic Energy Analysis. In a published assessment of the regional competitiveness of manufacturing lithium-ion battery cells for the automotive uses, CEMAC evaluated key trends, market and policy developments, and cost drivers—including labor, materials, facilities, and other factors—for six regional production scenarios. While Asia currently dominates automotive Li-ion cell production, the analysis indicates that the United States and Mexico could competitively manufacture automotive Li-ion cells under certain conditions. If Mexico's low cost of labor could be combined with a low cost of capital, this scenario could sustain the most competitive prices on the global market (Figure 4).

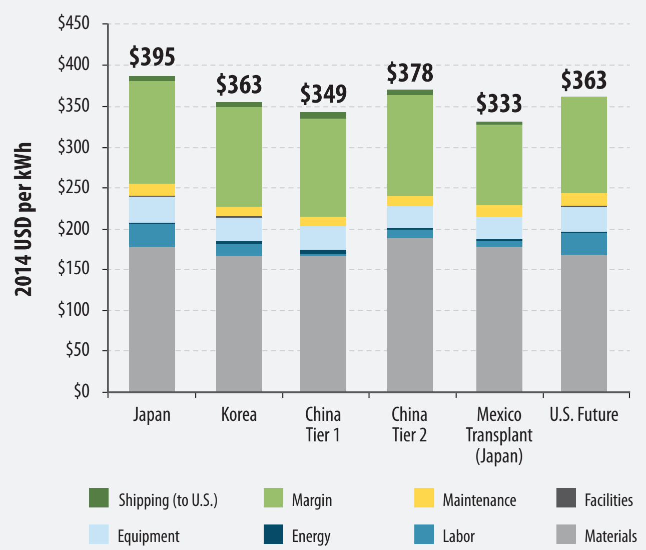


Figure 4. Cost modeling indicates that the United States and especially Mexico may be competitive in automotive Li-ion battery manufacturing under certain conditions. Source: http://www.afdc.energy.gov/uploads/publication/lithium-ion_battery_supply.pdf

1) establishing financial incentives for both utility-scale and distributed storage facilities; 2) initiating technical potential analysis and possible policy pathways; and 3) using specific energy storage procurement standards or adding multipliers to existing renewable portfolio standard policies in order to encourage storage adoption. Four of these bills passed in California, New Mexico (two), and Texas.

Estimating Value of Energy Storage for Grid Applications

Setting an appropriate value for storage has proven difficult in today's restructured markets. The markets typically classify grid assets as generation, transmission and distribution, or end use. Storage technologies and services often cross between these asset classes, and that can lead to under-valuing their total contribution to the energy system. In addition, storage may help defer new system upgrade or maintenance investments, reduce power line losses, and enable renewable energy sources, all of which are potential benefits that historically have not been captured, valued, or monetized.

But this is beginning to change. Federal Energy Regulatory Commission (FERC) Orders 755 and 784 are part of a wave of market rules that are opening new avenues to capture value for all storage applications. These rules opened the ancillary services market to energy storage sources by requiring utilities to consider speed and precision when deciding on which source to buy. In addition, in November 2013, FERC Order 792 added energy storage as a power source that is eligible to connect to the grid, following procedures similar to those for small generator interconnection.

NREL has completed a series of analyses to begin to quantify some of the value streams and operational benefits of electricity storage—such as load leveling, spinning contingency reserves, and regulation reserves. Using PLEXOS, a commercial grid operations simulation tool, NREL estimated the operational value of storage (measured by its ability to reduce system production costs) for storage devices providing various grid services for a representative utility system in the western United States. The model assumed power generation to be primarily from fossil fuels. Key insights from this analysis:

- **The modeled system provided a relatively large market for load leveling services, but the service was of relatively low value as a stand-alone offering and by itself unlikely to yield a positive cost-benefit ratio for most existing storage technologies.**
- **Operating reserves, such as regulation and contingency reserves, are higher value and economically more favorable because they require devices with much lower energy storage capacities, but the market for operating reserves is small relative to that for load leveling.**
- **The revenue obtained by storage in restructured markets appears to be substantially less than the net benefit provided to the system due to suppression of on-/off-peak price differentials and incomplete capture of system benefits (such as the cost of power plant starts).**
- **Understanding the value of storage in providing reliable system capacity—the historic role of pumped storage hydropower plants—is essential to capturing its full value and ultimately determining whether storage technologies and services can be cost-competitive in the energy marketplace.**

Energy Storage Can Support Integration of Variable Generation

The *DOE Demand Response and Energy Storage Integration Study* examined how the value proposition for energy storage changes as variable generation penetration increases from 16% to 55%. Overall, significant charging from renewables, and consequently a net reduction in carbon emissions, is not observed until variable generation (VG) penetration is in the range of 40%–50%, where significant curtailment occurs without storage, undermining the cost-effectiveness of RE investments. In addition, increased VG penetration increases the value of energy storage by lowering off-peak energy prices more than on-peak prices, leading to a greater opportunity to arbitrage this price difference. Increased penetration of VG also increases the potential value of storage when operated as reserves because reserve requirements increase with increasing RE penetration.

Thermal Energy Storage Increases Value of Concentrating Solar Power

Concentrating solar power (CSP) technologies show variable and uncertain output similar to solar photovoltaic (PV) technologies. Coupling thermal energy storage (TES) with a concentrating solar power (CSP) plant results in a highly dispatchable integrated system that stores the thermal energy from the CSP plant until it is needed to generate electricity to meet demand. This increased flexibility can significantly increase the economic viability of CSP by improving its ability to provide capacity- and energy-related services. In addition, relative to mechanical or chemical storage technologies, TES offers low capital costs ($72- $240/kWh for TES versus >$300/kWh for electrochemical batteries) and very high operating efficiencies of up to 98%.

The addition of TES increases the value of energy sold by a CSP plant, and reduces curtailed production, typically increasing overall revenues for the CSP-TES plant by at least 35%. In addition, when compared to variable-generation PV, NREL analysis estimates that CSP-TES provides additional value of about 5 cents per kilowatt-hour to utility-scale solar energy in California under the 2020-mandated 33% RPS, or about 6 cents per kilowatt-hour under a 40% RPS. As VG increases, the relative value of dispatchable resources such as CSP-TES will likely increase. Additional analysis is focused on examining the operational and economic impacts of a changing grid generation mix, which includes higher levels of renewable electricity generation, and exploring alternative CSP-TES plant configurations.

Battery Storage System Improves Ramping Performance of Wind

One of the largest wind battery systems deployed in the United States supports Hawaii's Kahuku Wind Plant on the island of Oahu. Kahuku's 15-MW battery system (comprised of ten 1.5 MW/1-MWh battery packs), which was designed to meet requirements for ramp rates and power fluctuations set by the Hawaiian Electric Company, helps maintain system reliability, avoid wind curtailments, and reduce the need for costly reserve services by conventional generation. NREL's analysis of operating data from the 30 MW Kahuku Wind Plant is the first detailed insight into minute-by-minute ramping performance of a utility-scale battery system coupled with a multi-MW wind power plant based on actual field data. Data show more significant reduction in 1-minute ramp rates in net plant power (wind and batteries) than wind-only power (see Figure 5). In addition, the battery system significantly reduces frequency of large positive and negative ramp rates.

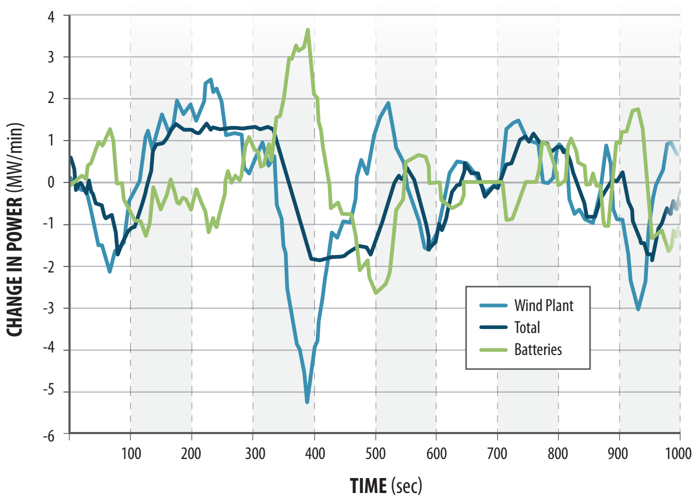


Figure 5. The 1-minute ramping operation of the Kahuku Wind Plant wind-energy battery storage system illustrates the reduction in ramping resulting from batteries being charged or discharged to limit the rate of change of wind power. These ramp rates show a more significant reduction of the total ramps (wind and batteries) than wind-only ramps. Source: http://www.nrel.gov/docs/fy14osti/59003.pdf

Emerging Opportunities for Energy Storage in the Electric Grid

Emerging synergies between the transportation and power sectors along with the expansion of smart grid technologies present potential new opportunities for energy storage that benefit consumers and the power system overall.

Electric Vehicle Battery Second Use on the Grid

The cost of batteries is a key challenge to deployment of grid-connected energy storage systems as well as the market penetration of plug-in electric vehicles. Battery second-use strategies—in which a battery first serves an automotive application and then, when its overall performance no longer meets more stringent automotive requirements, is redeployed into a secondary grid application—could help address both issues. Extracting additional services and revenue from the battery in a post-vehicle application may increase the total lifetime value of the battery, offset the cost of the battery to the

SAM HELPS DETERMINE BATTERY SUPPORT FOR PV SYSTEMS

How can batteries enhance value of a PV system? NREL's popular System Advisor Model (SAM) now allows analysts to answer questions like this, thanks to a recently added generic battery model. With SAM, analysts can investigate the performance and economics of lead-acid or lithium-ion batteries coupled with a PV system. The model predicts parameters such as state-of-charge, terminal voltage, and capacity fade resulting from cycling and temperature. In addition, users can simulate performance over time to predict variable capital costs associated with battery bank replacements. Different dispatch strategies including manual scheduling and automated peak-shaving can be explored to determine ideal ways to use battery storage and mitigate demand charges in behind-the-meter applications.

primary users, and create a reduced-cost supply of batteries for secondary users.

NREL found that second-use batteries are most promising as a provider of peak-shaving services that can replace grid-connected combustion turbine peaker plants. Under modest use, second use battery lifetimes could be on the order of 10 years. The value to the broader community could be more significant: decreased cost of peaker plant operation on the order of 10%–20%, reduced greenhouse gas emissions, and reduced fossil fuel consumption.

Hydrogen Storage Potential to Integrate Power and Transportation Sectors

Hydrogen could provide additional utility-scale energy storage options and unique opportunities to integrate the transportation and power sectors. Although hydrogen is currently a high-cost option, it offers some advantages over competing technologies, including that it has a high storage energy density and a potential for co-firing in a combustion turbine with natural gas to provide additional flexibility for the storage system.

NREL compared the economic viability of hydrogen—produced via electrolysis and then stored as a compressed gas in above-ground steel tanks and in geologic storage—with battery, pumped storage hydropower, and compressed air energy storage (CAES) technologies using HOMER, an optimization model for distributed power. Analysts modeled a simple arbitrage scenario for a mid-sized energy storage system with a 300-MWh (megawatt-hour) nominal storage capacity charged during off-peak hours (18 hours per day on weekdays and all day on weekends) and discharged at 50 MW per six peak hours on weekdays to produce electricity in either a fuel cell or combustion turbine. Initial cost analysis indicates that hydrogen systems could be competitive with battery systems for energy storage and could be a viable alternative to pumped storage hydro and CAES at locations where these latter two technologies are not favorable. In addition, the analysis shows that the cost of producing larger volumes of hydrogen to support both grid energy storage and hydrogen fuel cell vehicles could be competitive with the cost of producing hydrogen for fuel cell vehicles in a dedicated hydrogen production facility. R&D efforts focused on lowering the cost of electrolyzer and fuel cell technologies and increasing round-trip efficiency of storage[4] have potential to improve value and environmental performance. Additional analysis is required to understand the potential contribution of hydrogen storage to power system operating reserves.

Behind-the-Meter Energy Storage for Demand Reduction

In 2015, Tesla announced its Powerwall battery storage system for home and commercial use. The announcement generated a lot of discussion about the potential and cost of behind-the-meter storage systems. For commercial facilities subject to demand charge rate structures, adding controllable behind-the-meter energy storage can help manage building peak demand and reduce electricity costs. NREL's analysis using the Battery Lifetime Analysis and Simulation Tool (BLAST), a tool developed specifically for assessing behind-the-meter scenarios, shows that—regardless of solar PV power levels—small, short-duration batteries are cost-effective in reducing short load spikes on the order of 2.5% of peak demand. Small battery systems capable of fully discharging in 30–40 minutes offer optimal payback periods of less than 3 years when installed costs reach $300/kW (power basis) and $300/kWh (energy basis). R&D efforts to reduce battery and inverter costs, along with changes to utility rate structures, could encourage the use of this technology.

4. In addition to being charged for the amount of energy consumed, many commercial customers of electric utilities are subject to a rate structure that includes a demand charge—a fee proportional to peak power rather than total energy. In some instances, demand charges can constitute more than 50% of a commercial customer's monthly electricity cost.

Energy Storage and Grid Flexibility

Energy storage has the potential to offer multiple benefits to the power grid and to be an enabling and complementary technology for increasing penetrations of variable renewable energy resources. NREL evaluates the role and value of storage through continued analysis, improved data, and new techniques to model the operation of a more dynamic and intelligent grid of the future.

Learn More

Increasing Variable Renewable Generation on the Grid Requires Additional Flexibility

Renewable Electricity Futures Executive Summary
http://www.nrel.gov/docs/fy13osti/52409-ES.pdf

Policy and R&D Drive Energy Storage Deployment

Energy Storage for Power Grids and Electric Transportation: A Technology Assessment
https://fas.org/sgp/crs/misc/R42455.pdf

The Role of Storage and Demand Response
http://www.nrel.gov/docs/fy15osti/63041.pdf

The Role of Energy Storage with Renewable Electricity Generation
http://www.nrel.gov/docs/fy10osti/47187.pdf

Issue Brief: A Survey of State Policies to Support Utility-Scale and Distributed-Energy Storage
http://www.nrel.gov/docs/fy14osti/62726.pdf

Market and Policy Barriers to Deployment of Energy Storage
http://dx.doi.org/10.5547/2160-5890.1.2.4

Joint Institute for Strategic Energy Analysis
http://www.jisea.org

Clean Energy Manufacturing Analysis Center
http://www.manufacturingcleanenergy.org

Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations (June 2015)
http://www.nrel.gov/docs/fy15osti/63354.pdf

Estimating Value of Energy Storage for Grid Applications

Value of Energy Storage for Grid Applications
http://www.nrel.gov/docs/fy13osti/58465.pdf

Impact of Wind and Solar on the Value of Energy Storage
http://www.nrel.gov/docs/fy14osti/60568.pdf

Operational Benefits of Meeting California's Energy Storage Targets
http://www.nrel.gov/docs/fy16osti/65061.pdf

The Relative Economic Merits of Storage and Combustion Turbines for Meeting Peak Capacity Requirements Under Increased Penetration of Solar Photovoltaics
http://www.nrel.gov/docs/fy15osti/64841.pdf

Energy Storage Can Support Integration of Variable Generation

The Value of CSP with Thermal Energy Storage in the Western United States
http://www.sciencedirect.com/science/article/pii/S1876610214006250

How Thermal Energy Storage Enhances the Economic Viability of Concentrating Solar Power
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5893901

Ramping Performance Analysis of the Kahuku Wind Energy Battery Storage System
http://www.nrel.gov/docs/fy14osti/59003.pdf

Technoeconomic Modeling of Battery Energy Storage in SAM (Sept 2015)
http://www.nrel.gov/docs/fy15osti/64641.pdf

Economic Analysis Case Studies of Battery Energy Storage with SAM (Nov 2015)
http://www.nrel.gov/docs/fy16osti/64987.pdf

System Advisor Model
http://sam.nrel.gov

Emerging Opportunities for Energy Storage in the Electric Grid

Ability of Battery Second Use Strategies to Impact Plug-In Electric Vehicle Prices and Serve Utility Energy Storage Applications
http://dx.doi.org/10.1016/j.jpowsour.2011.06.053

Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries
http://www.nrel.gov/docs/fy15osti/63332.pdf

Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage
http://www.nrel.gov/docs/fy10osti/46719.pdf

Life-Cycle Cost Analysis Highlights Hydrogen's Potential for Electrical Energy Storage
http://www.nrel.gov/docs/fy11osti/48437.pdf

Deployment of Behind-The-Meter Energy Storage for Demand Charge Reduction
http://www.nrel.gov/docs/fy15osti/63162.pdf

Optimal Sizing of Energy Storage and Photovoltaic Power Systems for Demand Charge Mitigation
http://www.nrel.gov/docs/fy14osti/60291.pdf

National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

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Front page photo by Dennis Schroeder, NREL 32712 • NREL/BR-6A20-64764 • February 2016