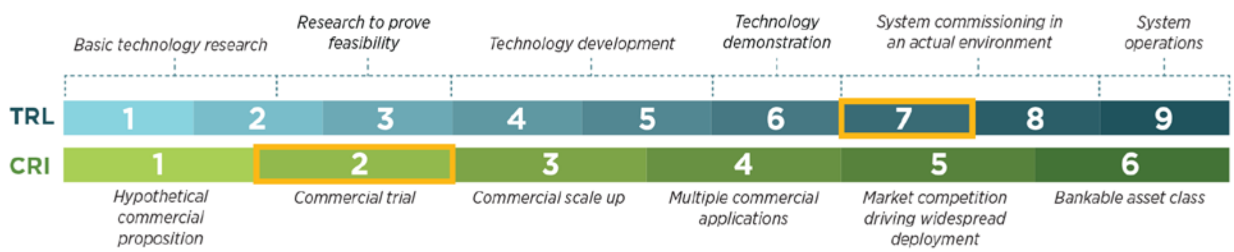
Technology Sector Energy Storage Product Category Active Balancing Last Updated 01/18/2019	 *Figure 1: Shows how passive balancing compares to different active balancing technologies. Figure from TesVolt* [1].

Product Category Overview

Traditional "passive" balancing of energy storage cells (specifically lithium-ion cells) of a battery pack is done by dissipating the extra stored energy in a resistor. This wastes energy from the cells and lowers the battery pack's efficiency. It also produces waste heat, which can increase the demands on the cooling system, increasing system parasitic loads. Active balancing systems transfer the energy from full cells to empty cells rather than dissipating it. This increases the efficiency of the battery pack and reduces the need for cooling.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Using active balancing, energy is transferred from cells with a higher capacity to cells with a lower capacity rather than "burned" in a resistor, increasing the battery's efficiency and reducing energy losses. Additionally, the transfer of energy from these cells allows the full capacity of every cell in the battery pack to be used such that the energy that the battery can store is no longer limited by the weakest cell. This increases the usable capacity of the battery pack, so more energy can be extracted from the cells. This also slightly reduces the heat generated by the battery pack (~1W/cell), which can lower the need for cooling of the battery system.

Non-Energy Benefits

Since active balancing allows the full capacity of each cell to be used, the battery has a larger effective capacity, which allows the nameplate size of the battery to be smaller, reducing its price. The useful life of the battery pack is also extended since the weaker cells no longer limit the performance of the whole pack. This also makes use of second-life cells more practical since their capacities have a larger variation which can be more effectively compensated for using active balancing.

Product Category Differentiation

The current method—passive balancing—uses resistors to discharge the more full cells and dissipate their excess energy to allow the less full cells to contine charging. Active balancing uses capacitors, switches, and inductors to transfer the energy from the full cell to the less full cells.

Installation Pathway and Dependencies

There are no additional requirements for installation of this technology beyond those already incurred by installing energy storage. If energy storage is already installed, additional systems integration work will be required, but no changes to the building or location of the EES.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
REC [2]	Active BMS	BMS with active balancing.	Pack to cell and cell to pack energy transfer.
TESVOLT [1]	Active Battery Optimizer	BMS with active balancing	Integrated with their own battery packs to be sold as a complete energy storage system with active balancing.
AutarcTech [3]	N/A	BMS with active balancing	'Turn key' BMS with active balancing for 48V battery packs.
EST-Floattech [4]	N/A	BMS with active balancing	BMS that continually balances the cells (as opposed to top and bottom balancing).

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Pisa, Italy	Lab Test. Baseline: passive balancing. Energy transfer efficiency and speed (power) were measured for each balancing method. Compared the following active balancing methods with passive balancing: cell to cell, cell to pack, pack to cell and cell to/from pack.	Cell to cell balancing was found to be the most efficient, at 95% compared to passive balancing of 0%. This technology does not directly reduce peak load, however by increasing the efficiency of battery packs, they can operate for longer during peak loads.	[5]
Bristol, UK	Lab Test. Baseline: passive balancing. Energy transfer efficiency and speed (power) of each balancing method were measured.	Compared a selective flyback converter active balancing system to passive balancing. Active balancing was found to lose 60% less energy than passive balancing. This technology does not directly reduce peak load, however by increasing the efficiency of battery packs, they can operate for longer during peak loads.	[6]
Coimbra, Portugal	Lab Test, based on electric and hybrid vehicle applications. Baseline: passive balancing. Usable energy in the battery pack Compared 10 different active balancing methods with passive balancing to evaluate the effect of EV and HEV range.	Found that a single-inductor type active balancing system provided the greatest increase in range, 3% for new cells, and 8.4% for aged cells when compared with passive balancing. This technology does not directly reduce peak load, however by increasing the efficiency of battery packs, they can operate for longer during peak loads.	[7]

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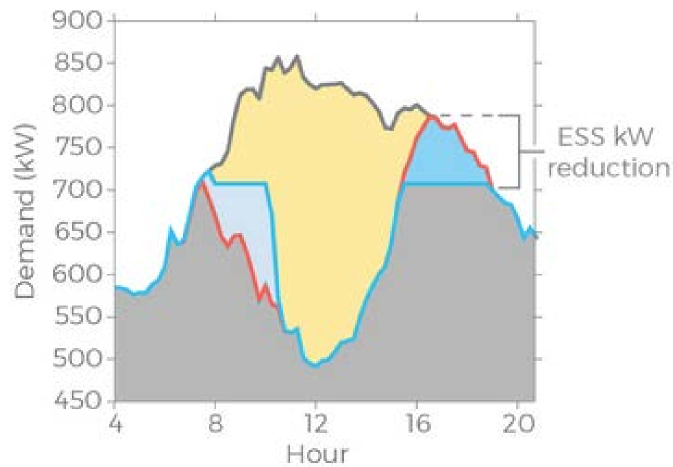
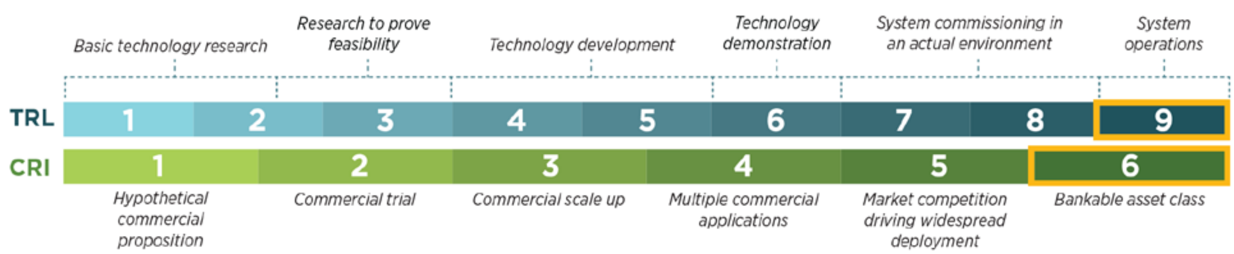
Technology Sector: Energy Storage Product Category: “Cloud” and “AI” Based Control Last Updated: 01/08/2019	 *Figure 1: Diagram showing the effectiveness of an EES controller that incorporates elements of machine learning. Source: Geli* [1].

Product Category Overview

Energy storage companies can offer internet-based services that automatically control their customers’ storage systems based on the large amount of data available to them compared to the data available at the local level. This control type can help increase the reliability of the grid, reduce peak-time electricity use, and is more dynamic than typical controls, which can increase energy savings. These systems typically use machine learning to optimize the use of stored energy, again taking advantage of data from a large number of customers to increase the efficiency of all of them.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Machine learning-based controls are typically deployed by energy customers to minimize their bills. However, since the cost of electricity is an approximate function of the system load (i.e. cost is higher during peak hours), this electrical energy storage (EES) control method may work to reduce system costs by reducing system peak demands. This will only work if the customer energy pricing is aligned with the actual demand curve.

Non-Energy Benefits

Machine learning-based controls help electricity customers minimize their electricity bill by dispatching the EES optimally based on demand, pricing, and likely future demand. When the model's "incentives" correctly align with the goals of the utility (i.e. reduced peak demand, a more level load), these control modes on the customer side will result in a more efficient grid.

Product Category Differentiation

Machine learning type controls are different from typical EES dispatching algorithms in that they are not rule-based. They are statistically optimized to perform a specific goal, such as minimizing an energy bill. They can also be written such that each instance of the controller continually "learns" based on its own real-world performance in its specific application. Other EES dispatching mechanisms have to be manually programmed or have settings modified to be optimized for each site.

Installation Pathway and Dependencies

This technology requires electrical energy storage (EES), load monitoring system and of course the machine learning-based EES controller. Buildings implementing this type of system must have space to install sufficient energy storage. If there is not enough space or no energy storage is currently installed, construction or renovation will be required. If EES is currently installed, the building has no additional requirements however more work on systems integration may be required to retrofit the EES controller.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
STEM [1]	Athena	EES controller based on machine learning.	"AI", marketing. Ability to participate in utility whole-sale markets through STEM as an aggregator (California only).
Geli [2]	EOS	EES and microgrid controller system with some machine learning functions.	Systems integration. More mature and varied product. Will sell just controller without EES. Ability to participate in whole sale markets through Geli as an aggregator.
Engie Storage [3]	GridSynergy	Internet based EES controller with machine learning for EES dispatch.	Controller uses data from other customers of Engie to help optimize dispatch.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Tokyo, Japan	Lab test. Opportunity charging and Heuristic Flowchart (HF) battery management. Carbon intensity and electricity cost were measured.	Battery life was reduced by 40% for non-machine learning methods due to 20-40% higher depth of discharge of the cells. Grid imports were “significantly” decreased, but not specified. Peak loads were reduced by about 15%.	[4]
Guangzhou, China	Lab test. Simulated islanded microgrid with battery, PV, wind, and diesel generator. Proportion-integral-derivative controller. Microgrid energy consumption was measured.	41% reduction in power needed from diesel generator was observed when using the machine learning based algorithm compared to the PID controller.	[5]
N/A	Lab test. Compared to rule based controller Simulated a microgrid with various Distributed energy resources with the goal of maximizing critical load uptime.	The machine learning based controller maintained power to the critical loads 100% of the time and increased the time non-critical loads were served by 10%. It also extended the life of the EES through reduced depth of discharge. However, it also incurred a higher grid dependence, importing and exporting more energy. The deterministic controller also powered the critical loads 100% of the time, but used 6% higher battery depth of discharge.	[6]

References

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Technology Sector
Energy Storage

Product Category
Off-Grid Power

Last Updated
12/19/2018

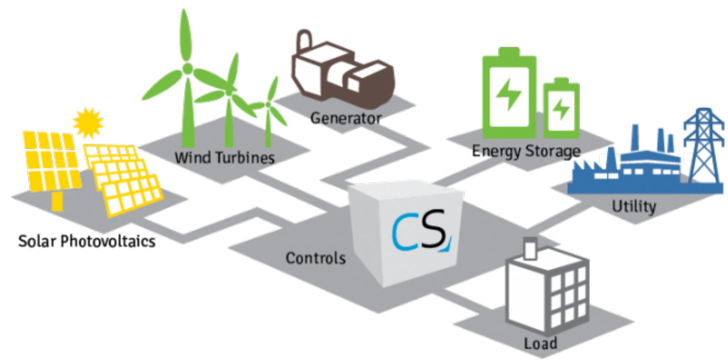
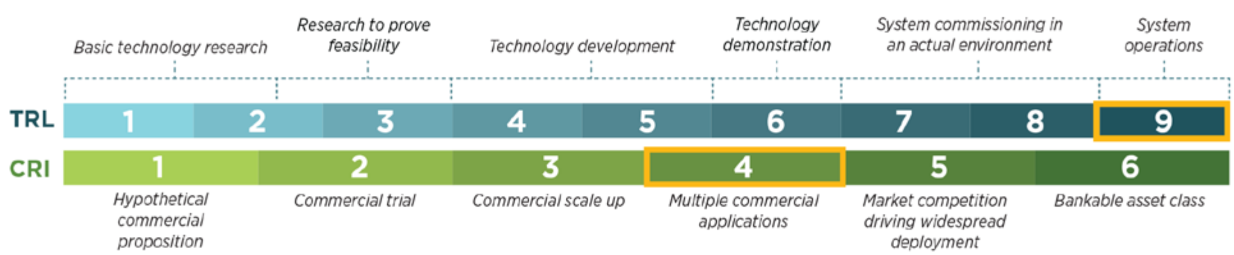


Figure 1: Energy storage enables off-grid power

Product Category Overview

Energy storage systems can be combined with traditional or renewable electricity generators to provide off-grid power during utility outages. Lead acid batteries, for example, have long been used to transition facilities such as data centers to backup diesel generators during interruptions in grid power. More recently, energy storage has been paired with small-scale, intermittent renewable generators (e.g. rooftop PV) in "microgrid" settings. In these cases, on-site generators and energy storage are used for off-grid power during outages but also during normal grid operations to reduce energy costs, improve power quality, achieve sustainability goals, etc. In the context of microgrids and backup power, the most prevalent technology options include batteries of various types, flywheels, and supercapacitors. Finally, energy storage can be used in remote areas to create standalone microgrids where larger transmission and distribution systems do not reach, but this opportunity is not the primary focus of this report.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy storage is often deployed alongside distributed generators and control systems to provide backup power to critical facilities such as hospitals, schools, data centers, and military bases in the event of grid outages. In these cases, the microgrid enters "island mode." The energy storage system discharges to maintain power quality, then it traditionally transitions the facility to a fossil fuel-powered backup generator. The energy storage system and backup generator may then be operated in tandem to reduce backup generator size requirements and increase generator efficiency. However, energy storage systems can also be paired with intermittent, renewable generators to provide consistent power with or without a traditional fossil fuel-powered generator. When the broader grid is functioning normally, the microgrid operates in “grid-connected mode,” and the energy storage system may provide other services. These include demand charge management, energy arbitrage, ancillary services in wholesale markets, and more. In standalone microgrids, energy storage is critical to maintaining reliable operation if the generators’ fuel supply is intermittent in any way.

Non-Energy Benefits

The primary non-energy benefit of energy storage for off-grid power is reduced downtime during grid outages. For a commercial or industrial building, this benefit may be quantifiable in the form of increased profits. For a community center, decreased downtime may mean boosted morale and a sense of safety following natural disasters such as hurricanes and wildfires. For a hospital, less interruptions directly translate to lives saved. Finally, because energy storage supports the cost-effective operation of intermittent, renewable generators in microgrid settings, it may decrease air pollution, greenhouse gas emissions, and fossil fuel costs.

Product Category Differentiation

Energy storage for off-grid power is differentiated from other microgrid technologies in that it responds more quickly and can thus rapidly transition facilities to backup generators. Also, it enables islanded microgrids to run on intermittent, renewable generators by smoothing their output. While energy storage may be paired with diesel or natural gas generators in off-grid settings, these conventional backup generators also may be substitutes for energy storage. In other words, planners have the option to exclude energy storage and thereby tolerate lengthier outages between grid shutdown and backup generator startup. Similarly, energy storage may complement or compete with combined heat and power (CHP) systems, depending on the facility. CHP systems with consistent supplies of fossil fuel or biomass may provide off-grid power without energy storage, but they are most suitable for large-scale microgrids with significant thermal energy requirements, such as universities. Fuel cells such as the Bloom Box may also be operated continuously, but they too are slower to respond than most energy storage systems, and they require a constant fuel source such as hydrocarbons or hydrogen.

Installation Pathway and Dependencies

Critical facilities such as hospitals and data centers are typically constructed with backup generators and uninterruptible power supply (UPS) systems, a type of short-duration energy storage for off-grid power, so these processes are well-defined. However, existing facilities interested in retrofitting electrical systems to enable off-grid operations must generally collaborate with utilities, perform a site assessment, establish site-specific project objectives, and finalize a customized project design. To retrofit an existing system to create a microgrid capable of islanding, one must procure a microgrid controller and isolating device in addition to energy storage. Additional hardware upgrades may also be required to maintain frequency and voltage during island mode and re-synchronization with the grid. For example, a hybrid (i.e. bidirectional) inverter is required for solar PV arrays to supply both alternating current (AC) power to the grid in grid-connected mode and direct current (DC) power to the host site in island mode. For individual residential or commercial sites, a single service provider may simply bundle energy storage for off-grid power with a rooftop PV array during installation. For a large industrial site or complex of buildings, however, collaboration with numerous hardware, software, and service providers may be required to design, install, and operate a microgrid system equipped with energy storage for off-grid power.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Eaton	9PXM	Lead acid battery	Uninterruptible power supply (UPS) with a modular and scalable design, which allows for resizing over time. Suitable for a wide range of IT equipment.
Dell	SURT20KRMXLT	Lead acid battery	Low-cost UPS with a runtime of five minutes. Tight voltage and frequency regulation. Suitable for servers, medical labs, and light industrial applications.
Pika Energy	Harbor Flex	Lithium-Ion battery	With a usable capacity of 6 kW and 11.4 kWh, runtime could be multiple hours. Capable of managing energy charges and supplying backup power. Wall-mounted.
Dynapower	BTM-250	Lithium-Ion battery	250 kW, 527 kWh capacity. Capable of rapid transition to island mode, backup power supply, and demand charge management.
ABB	SG Series	Flywheel	High power density, high efficiency, long lifespan, low maintenance costs, low energy density.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Australia	Economic dispatch model The aim of the study is to design cost-effective upgrades to the Flinders Island standalone microgrid. Upgrades will transition the system from 100% diesel generation to include solar PV, wind turbines, and a lithium-ion battery system. Three microgrid design and dispatch strategies are compared: a standard grey wolf optimizer (GWO), a novel fuzzy logic grey wolf optimizer (FL-GWO), and a rules-based approach.	The FL-GWO approach reduced the levelized cost of electricity by 24% over the rules-based approach and 14% over the GWO approach. The optimal upgrades and FL-GWO dispatch method result in 25%-60% reductions in GHG emissions, depending on the season.	[1]

Location	Application	Results	Reference
China	Economic dispatch model Two microgrid design and dispatch strategies are compared: a static dispatch approach with no battery and a dynamic dispatch approach with a battery. The example microgrid is powered by wind turbines, solar PV, fuel cells, and a diesel engine, and it may operate in grid-connected mode. Operating costs are compared.	The static dispatch approach optimizes generation separately in each hour, while the dynamic dispatch approach includes a 30 kW, 300 kWh battery, honors state-of-charge constraints, and optimizes total operating costs over a 24-hour period. The dynamic dispatch approach with a battery reduces microgrid operating costs by 5%-38% over the static approach, depending on electricity price and grid status.	[2]
California, USA	Economic dispatch model An economic linear programming model was developed to design and schedule a grid-connected microgrid in Davis, California based on biomass combined heat and power. Solar PV, battery storage, wind turbines, and thermal energy storage were also considered in potential design configurations. Levelized cost of energy was minimized to arrive at an optimal microgrid design.	Inclusion of some battery storage reduced the lifetime cost of energy in all feasible scenarios. The total microgrid load typically varied between 100 kW and 200 kW. The optimal battery capacity was between 125 and 175 kWh in the lowest cost scenarios. The ideal design produced a levelized cost of energy around $0.17/kWh and featured wind turbines, solar PV, and battery storage in combination with the biomass combined heat and power unit.	[3]

References

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Technology Sector
Energy Storage

Product Category
Peak Shaving, Peak Shifting and Demand Response

Last Updated
12/05/2018

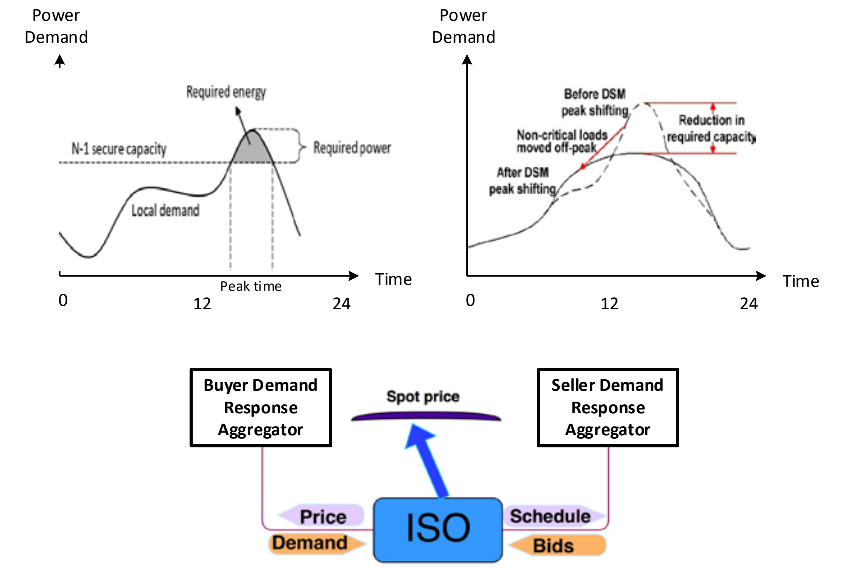
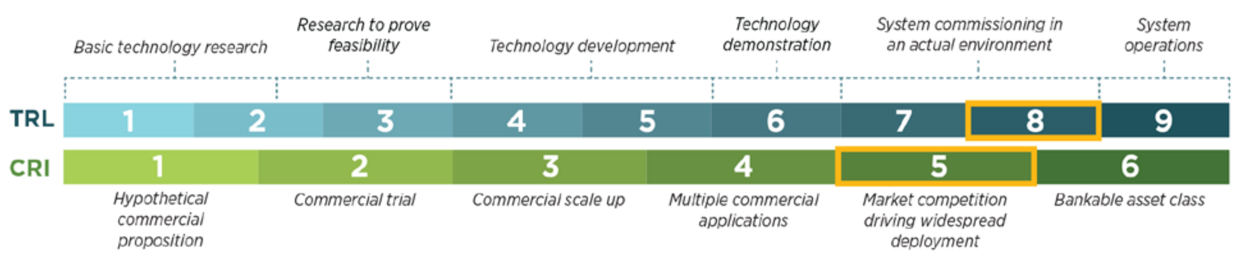


Figure 1: Peak shaving (top left, peak shifting (top right) and demand response (bottom)

Product Category Overview

Energy storage system (ESS) controls monitor building electrical demand to find periods of high usage, which incur significant cost penalties for commercial and industrial customers. Peak shaving uses stored energy to supply electricity for additional peak demand to maintain building energy use below either a set threshold or a dynamically calculated and optimized threshold. This process increases grid power quality, reduces the need for “peaker” power plants, and increases grid efficiency. Peak shifting uses energy stored in the battery during the peak hours to minimize average power demand from the utility during peak hours. The battery is then recharged during off-peak hours, either from the utility or from on-site generation. Customers can also elect to have their ESS connected to the utility or independent system operator (ISO) control systems. Such operation of the ESS is called demand response (DR). Peak shaving, peak shifting, and DR reduce customer electricity costs and the size of the demand peak observed by the utilities.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Peak shaving, peak shifting, and DR help the utility provide maximum base load power without starting expensive and less efficient peaking generators. In the long term, peak shaving, peak shifting, and DR let the utility improve grid efficiency by reducing its investment in peaking generators.

Non-Energy Benefits

Commercial and industrial customers save on their electricity bills by reducing peak demand. Non-Energy benefits also include greenhouse gas reduction and improved grid stability and air quality.

Product Category Differentiation

Peak shaving, peak shifting and DR are fundamental demand side management functions of the ESS. Similar results can also be achieved by a wide range of actions which can be taken at the customer side of the electricity meter in response to particular conditions (signals) within the grid. This product category differentiates from such energy management technologies in that peak shaving, peak shifting and DR achieved by the ESS does not limit the use of electricity.

Installation Pathway and Dependencies

This technology requires electrical energy storage (EES), a load monitoring system, and an EES controller. If no such equipment is available, new construction or major renovations are necessary for installation. The California Public Utility Commission's Self-Generation Incentive Program (SGIP) provides incentives to support existing, new, and emerging distributed energy resources. SGIP provides rebates for qualifying distributed energy systems installed on the customer's side of the utility meter. [1]

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Tesla, Inc.	Power wall, Power pack	ESS for peak shaving and shifting.	The top selling brand on market today.
JLM Energy	Phazr	Small storage that is directly integrated with solar panel.	Highly efficient DC coupled system. Easy rooftop installation.
SunPower	Helix Storage	Solar/Battery large scale storage for microgrid.	Advanced predictive analytics and a portfolio of support services combine to deliver a simplified, turnkey solution for lowering energy costs.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Jamestown, Australia	Peak shifting, renewable self-consumption, ancillary services.	90% cost reduction for grid power quality control.	[2]

Location	Application	Results	Reference
Port Angeles, Washington, USA	Energy storage was installed in a mall to provide peak load reduction as part of a DR initiative by the local utility. Included HVAC units that could be turned off by the utility to reduce demand. A wind turbine was also installed at the site to charge the battery at night.	Demonstration failed by battery fire caused by the wind turbine.	[3]
Port Angeles, Washington, USA	Demand response for industrial facility (paper mill). EES was used for 10 minute capacity reserve and pre-schedule imbalance capacity compensation with the goal of reducing peak demand and deferring transmission upgrades.	Local utility determined that EES for DR is feasible and successful at reducing peak loads. Found pre-scheduled DR to be more effective. Using energy storage to change demand rather than adjusting load behavior was found to be more financially viable for industrial processes.	[4]
Queens, New York, USA	Demand charge management, renewable self-consumption. EES was installed at convenience stores by an EV charging company in cooperation with the local utility. The goal was to enable the utility to have block-by-block control over demand to reduce peak demand and prevent over-loading aging power lines. In addition, the store owners were able to use the EES for demand charge reduction to lower their energy bills.	25% reduced operational peak load, while being 1/4th the cost of upgrading the distribution network.	[5]
Detroit, Michigan, USA	Renewable generation grid integration, demand response, peak shaving, aggregated storage. A Rural community installed small, distributed energy storage units to demonstrate value of distributed storage to the utility.	5% reduction in community (distributed) peak load.	[6]

References

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Technology Sector
Energy Storage

Product Category
Power Quality Improvement

Last Updated
01/04/2019

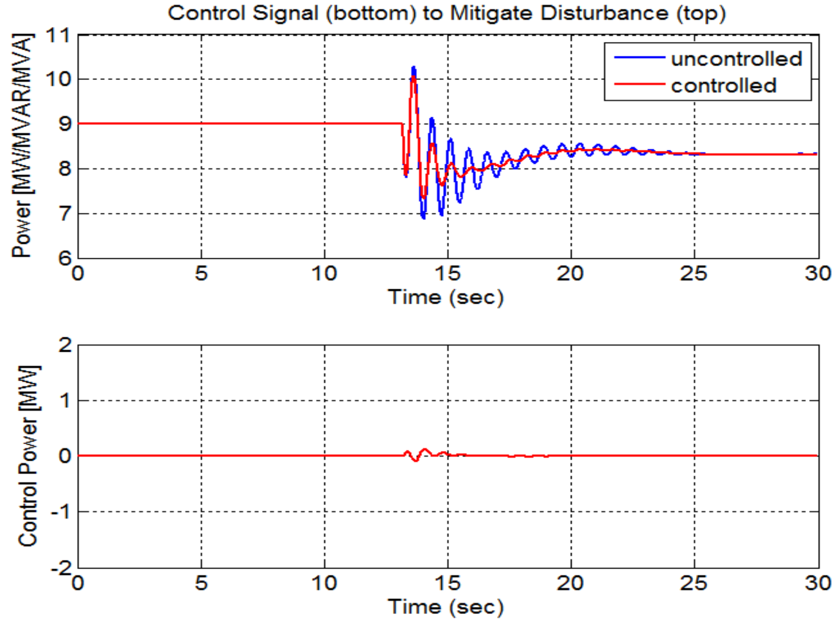
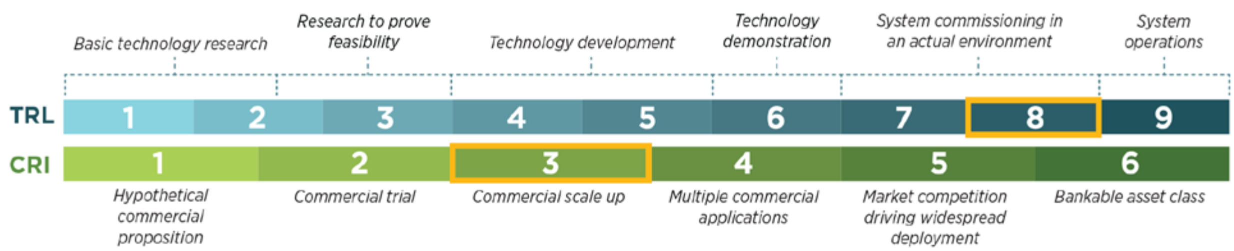


Figure 1: Mitigation of grid oscillation (3 MW) using 125 kW power

Product Category Overview

Energy storage is ideal for making adjustments to the frequency or voltage of the grid to maintain stability and power quality. Grid transients can occur nearly instantaneously, but generators have inertia and cannot respond to these changes quickly. Batteries are connected to solid-state inverters that can quickly charge or discharge the battery to counter-act transients on the grid to maintain stability, quality, and potentially prevent blackouts. On a local level, power quality improvement can ensure the safety of sensitive equipment.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Electric power quality involves voltage, frequency, and power factor. Good power quality can be defined as a steady supply of voltage and frequency close to the rated value. Energy storage can regulate voltage and frequency of the grid and therefore improve the reliability and efficiency. Although immediate energy benefits of power quality improvement may not be significant, in the long term, it will reduce the energy cost of customers by improved grid efficiency.

Non-Energy Benefits

The renewable power injection into an electric grid affects the power quality due to the nature of the renewable generators. Energy storage can mitigate such issues and will promote the integration of renewable generators. It will result in reduced greenhouse emission and improved air quality.

Product Category Differentiation

This product category differentiates itself from other energy management technologies with energy storage systems in that it is specifically focusing on mitigating grid instability issues which is very critical to increase solar and wind energy resources for the future renewable grid.

Installation Pathway and Dependencies

This technology requires a relatively small but high-power battery storage, phase measuring units (PMUs), and a fast bidirectional inverter. If no such equipment is available, new construction or major renovations are necessary for installation.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Tesla [1]	Power Pack	Energy Storage + Controller	Price, brand recognition.
ABB [2]	EssPro	Energy storage + controller	Industrial-grade.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Southern Australia	Field Test/Industrial Deployment. Natural gas peaking power plants and spinning reserves. Cost savings, response time, grid frequency reported.	Made profit of $1M in 2 days. Responded to grid voltage and frequency abnormalities in miliseconds. Mitigated grid-frequency shift of 0.2Hz due to failure of another generation station.	[3] [4]
Santa Rita California, USA	Field Test, microgrid power quality deployment. Provides generation and load balancing for islanded microgrid and ability to disconnect from utility when voltage or frequency are out of range. EES maintains voltage and frequency of local grid. Diesel generators, local power grid.	Peak load reduction of 15%. Eliminated blackouts and voltage sags due to unreliability of other generators installed in the microgrid. Electricity bill reduction of 6%.	[5]
Burlington, West Virginia, USA	Field test/commercial deployment. Installed 8MWh of lithium ion batteries to provide frequency regulation to correct power quality issues resulting from 98MW of wind generators. Compared to having no energy storage installed.	Increased wind plant availability to 95%.	[6]

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Technology Sector
Energy Storage

Product Category
Second-Life Battery Cells

Last Updated
01/07/2019

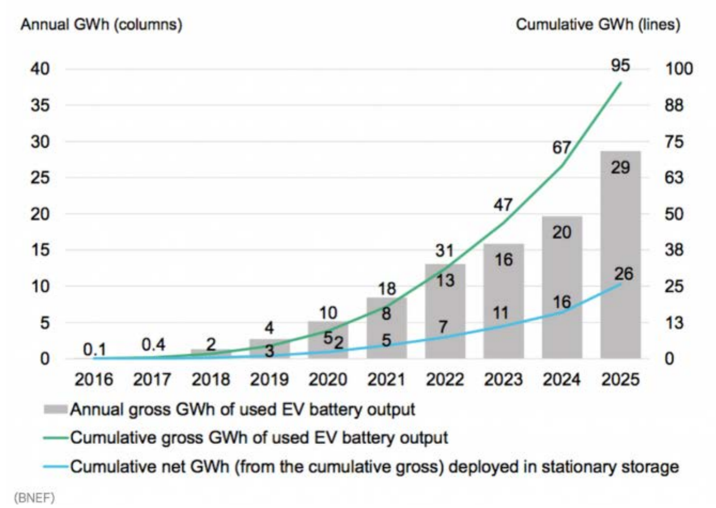
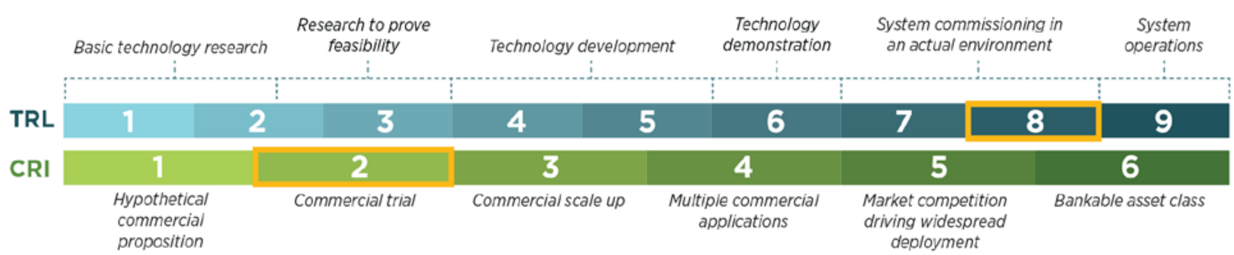


Figure 1: Used EV Battery Availability Will Far Exceed Stationary Storage Deployments

Product Category Overview

Lithium-ion batteries are difficult and expensive to recycle, so a vast majority of them are now landfilled. However, costly recycling processes and landfilling can be delayed by reusing lithium-ion batteries in secondary settings. Electric vehicle (EV) batteries, for example, may be transferred to stationary settings after their use in vehicles. This is especially promising given that 75% of EV batteries' initial capacity typically remains at the end of their useful lives in vehicles. Reuse mitigates the need to manufacture new battery cells, reduces the overall cost of battery storage, and increases the residual value of electric vehicles.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Second-life EV batteries can be used in stationary systems to provide the same types of energy benefits as a new stationary battery. While energy is lost in the form of heat during AC/DC power conversion, charging, and discharging, batteries have other highly desirable energy characteristics. These include batteries' ability to act as both an energy source and sink as well as their ability to dramatically change power output and/or input in seconds. When they are deployed by utilities or independent power producers at large scales (i.e. "in front of the meter"), they may provide energy and ancillary services in wholesale markets to maintain system reliability and affordability. When they are deployed at smaller scales (typically less than 1 MW) at customer sites (i.e. "behind the meter"), they may also be used to reduce retail electricity bills and to provide backup power. These bill savings can be realized both by reducing the host facility's energy consumption during peak periods and by reducing its overall peak power demand. With proper electricity rate design, these actions can also mitigate utilities' capital costs of upgrades to transmission and distribution systems.

Non-Energy Benefits

Because the costs of lithium-ion battery recycling exceed the value of the processes' end products by around three times, approximately 95% of lithium-ion batteries are currently landfilled [1]. Reuse of EV batteries in second-life systems can reduce the quantity of batteries in landfills and mitigate the need for new battery manufacturing, along with associated mining operations. Furthermore, maturation of the second-life EV battery market will enhance EV resale values, which may reduce the total cost of ownership of EVs and support EV adoption. Finally, energy storage enables continued long-term growth in intermittent, renewable generation technologies such as solar PV and wind turbines. In these ways, second-life EV batteries are well-aligned with California and other states' clean energy and climate goals.

Product Category Differentiation

Second-life EV battery systems may be deployed at lower capital costs than new battery alternatives. Additionally, they appeal to corporate end users with strong sustainability goals and private end users who prioritize environmental sustainability. The tradeoffs to lower capital cost include shorter system lifetime and larger system footprint.

Installation Pathway and Dependencies

Deployment of a second-life EV battery system behind the meter typically does not require significant upgrades to utility infrastructure, but significant space is required to house new hardware, including batteries, inverters, meters, racks, wires, and fire suppression systems. Furthermore, the energy density of second-life batteries is generally lower than new battery alternatives due to legacy designs and partially degraded cells. As a result, footprint requirements may rule out second-life batteries for some highly space-constrained utility customers in urban areas, for example.

Expedient installation also requires adherence to building codes and the existence of well-defined safety standards and local permitting processes. California and New York governments, for example, are currently defining and streamlining permitting processes, but their reports do not specifically address second-life systems. In late 2017, California's Governor Brown signed a bill which directs all local governments to post documentation and accept battery storage permit applications online, among other requirements [2]. In April 2018, NYSERDA published an energy storage permitting and interconnection process guide for New York City [3]. These early actors may serve as models for other governments and regulators.

For a front-of-the-meter second-life system, installation requires approval from the appropriate regulator, such as the California Public Utilities Commission. For behind-the-meter systems, private project developers must convince the host site's energy manager and/or executive leadership to commit to the deal, so a significant amount of customer education is required. In all cases, IT systems integration is a non-trivial challenge given the fragmented, immature nature of current energy storage markets.

Finally, widespread deployment of second-life systems is predicated on a sufficient supply of EV batteries. This constraint does not appear problematic; BNEF predicts EV battery production will remain more than twenty times greater than stationary energy storage requirements [4]. Furthermore, 70% to 80% of EV batteries' initial energy capacity commonly remains at the end of their first lives in vehicles [5].

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Box of Energy AB	Pro Multi	Commercial Industrial	Reuses Volvo batteries. Available in Sweden.
Aceleron	Circa Stationary	Commercial	Uses an adapted battery management system from Brill Power (Oxford University startup). Active Cooling. Replaceable cells. Available in the UK.
Eaton	xStorage Buildings	Commercial	Customers can select systems built with new batteries or used Nissan Leaf Batteries. Accepting pre-orders in UK, Norway, and Germany.
Renerage	REN30	Commercial	Uses an adapted battery management system from PM Grow (South Korean battery company). Accepting pre-orders in USA.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
California, USA	Field test of a PV + battery system. Two state of charge (SOC) estimation techniques were compared: full scale extended kalman filter (EKF) and worst-difference EKF. Three operating modes were also compared: (1) economic, (2) self-consumption, and (3) hybrid. SOC Estimation error was measured for each technique.	The full-scale EKF estimator showed <4% SOC estimation error. The worst-difference EKF estimator showed comparable error at significantly lower computational cost. Mode 1 reduced grid consumption by 43% and maximized economic returns. Mode 2 reduced grid consumption by 100%, but less export revenue was earned. Mode 3 reduced grid consumption by 34%, and the energy consumption during peak pricing periods was higher than in Mode 1, which also resulted in fewer savings.	[6]

Location	Application	Results	Reference
Barcelona, Spain	Field test of Renault Kangoo battery at a library. Four scenarios are compared: (1) no battery, (2) battery with energy management system (EMS) only, (3) battery with EMS and primary frequency response (FR) participation, and (4) EMS with both primary and secondary FR participation. Economic returns are compared between the four scenarios. These are driven by bill savings, payments from the FR aggregator, and the calculated cost of degradation.	During the one-year study period, scenario 2 earned the library €345 in profit. Scenario 3 earned the library €653. Scenario 4 earned the library €741. The authors estimate that such a second-life system may be profitable in Spain with battery pack prices of about €50/kWh or less.	[7]
Germany and New Jersey, USA	Two systems of sizes 55 kW (Germany) and 120 kW (New Jersey), built from BMW i3 batteries, are field-tested in a frequency regulation application. Load profiles and other aspects of system performance are compared.	During one week of testing, both systems successfully perform frequency regulation with no outages. System efficiencies are greater than 80%, and signs of degradation are minimal. The authors recommend an active cooling system for temperatures above 25 degrees Celsius to limit ageing. The authors suggest greater possible profits through the dual applications of frequency response and peak demand shaving.	[8]
European Union	Simulations of Net Present Value are performed. Five potential investments in seven European countries are considered: residential battery only, residential PV + battery, commercial/industrial battery only, commercial/industrial PV + battery, and utility-scale battery for frequency response. The effect of feed-in tariff structures, electricity prices, battery life, and battery prices are considered via scenario analysis.	Batteries deliver negative returns for all commercial/industrial users at the time of writing because electricity prices and demand charges are not high enough in the studied markets. Utility-scale systems are profitable with frequency response service priced above €20/MWh, and commercial/industrial systems may also be used to provide this service. At residential scale, economic returns are prevalent in Germany and France for PV + battery and in Germany, Spain, Italy, and Sweden for battery only when used battery prices are 120 €/kWh or less.	[9]

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