Home Battery Storage Systems — A Look into the Market, Their Energy Efficiency and Performance

Prepared for NRDC by
David Houghton PE
and Chris Calwell
Ecos Research

November 30, 2017

Executive Summary

This report looks at emerging residential battery systems that can provide backup power, store and reclaim excess solar energy, and offer reserve grid capacity to a utility or third party. While these systems are in the very early stages of adoption, with only a few thousand units installed to date nationally, the number of installations is expected to skyrocket given decreasing purchase costs, the growing number of homes with roof top solar panels, and increasing interest in having round-the-clock access to electricity during/after extreme events such as hurricanes, forest fires, or earthquakes. Storage systems can also help grid operators integrate higher fractions of renewable energy into their systems and help policy makers achieve zero-net energy goals for new homes.

A typical residential battery system is about the volume of a file cabinet and is wall- or floor-mounted in a garage or utility space. A system that costs about $10,000–$15,000 can store 10 kWh of energy (enough to supply a typical home for a day), with peak power output of 10kW. Current costs are in the range of $1,000-$2,000 per kWh; cost reductions to $250-500 per kWh, as some project, would open up large-scale markets for home battery systems.

The research for this report took a high-level view of available products and trends, with a focus on overall efficiency and energy losses in standby and active modes. This report also reviews the status of test procedures and regulations for battery systems. The main findings include:

- Residential batteries form a nexus with solar PV systems and electric vehicles, with potential economic and performance benefits flowing from combined systems.
- There is currently a lack of official consensus on test methods and standards for residential battery systems, although national stakeholder groups are aware of the need to develop them.
- Long-term performance needs to be considered in battery selection, sizing, and operation, as system capacity degrades over time.
- Most grid-tied residential batteries are sold as backup power systems, creating the potential to harness unused capacity for grid services, such as peak load management, voltage support, and spinning reserve.
- The most common storage configuration is AC coupling (where all DC devices convert their power to AC), but DC coupling could improve efficiency. For example, sending DC power directly from solar panels to batteries (without converting to AC) reduces conversion losses.

- Residential battery systems can "consume" roughly 300-500kWh per year—about as much as a typical home refrigerator consumes annually. This consumption or energy loss occurs in two ways: a) energy lost during conversion from incoming DC power from the solar panel to the battery, and b) standby power losses from a fully charged battery.
- Variation in published round-trip (RT) efficiencies and standby power losses appear to be significant, but without standardized testing it is difficult to tell the difference between products, and harder still to tell how unit performance in the field will compare to claims.
- Opportunities to support the development of residential batteries include:
    - Coordination of standards and test methods by working through IEC TC120 and other forums
    - Field testing and measurement of real-world cost and performance
    - Building on European and Australian experience, where thousands of systems have been operating for a year or more
    - Inclusion of energy storage into building, energy, and electrical codes. Measures could include safety and sizing requirements, efficiency minimums, and elements such as "storage-ready" electrical system design.

Introduction

Although battery systems have been available for home use for many years, they are primarily older lead-acid designs requiring regular maintenance and intended solely for off-grid use. With the advent of compact, maintenance-free lithium ion technologies and steady declines in cost, grid-connected home energy storage systems are now emerging in the U.S. marketplace. This technology promises multiple benefits for electricity consumers and providers, but it is not yet clear how best to use these systems, and how well they will perform.

Recent advances in Li-ion battery performance and costs have driven three main grid-connected product areas: utility-scale systems (front-of-meter), commercial-scale systems (behind-the-meter), and residential-scale systems (behind-the-meter). Of these three, residential systems have received the most attention in the popular press (thanks largely to the Tesla Powerwall), yet to date have received relatively little attention from utilities and regulators.

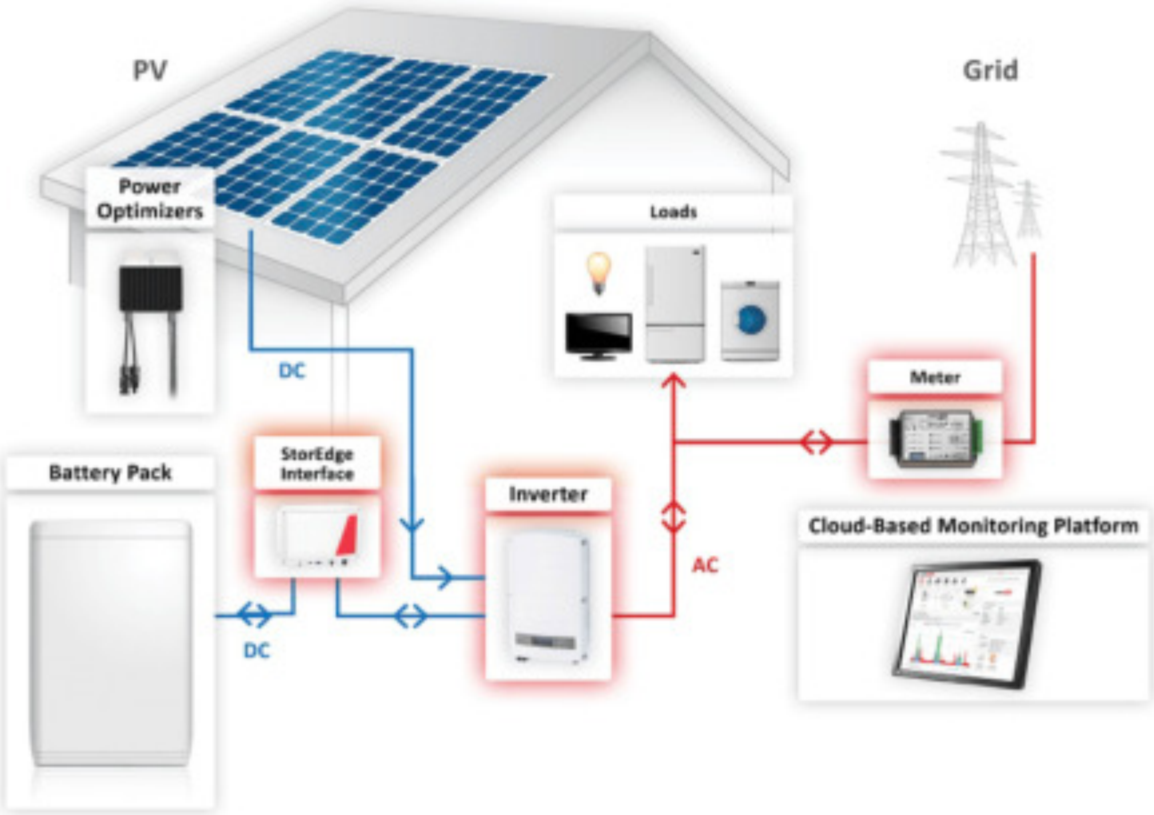
Residential battery storage systems are in the very early stages of adoption. To put things into perspective, well over a million residential rooftop PV systems are in place today across the US, but only a few thousand battery systems—less than one percent of solar-equipped homes. In this paper, we review today's product offerings, performance claims, key metrics, and recommend technical and policy steps to support this emerging technology.

Why would a homeowner want a battery system? The main reasons:

- *Backup power*. Vendors maintain that this is currently the most compelling benefit that leads to sales. Brochures often will show a blacked-out residential street, with one house lit up.
- *Environmental benefits*. Many solar customers are increasingly uncomfortable with using coal-dominated baseload power from the grid when the sun is not shining, leading to interest in storing their solar energy production for use at night.
- *Utility bill savings*. Savings can come from arbitrage (buy cheap power late at night, sell expensive power during the afternoon/evening) or improved solar self-consumption in areas where net metered is discouraged, disallowed, or hobbled by unfavorable rates.
- *Selling grid services*. Groups of home batteries can provide voltage support, frequency regulation, renewables firming, spinning reserve, and other services that generate revenue or avoid costs for the utility or for third-party aggregators.
- *Off-grid operation*. Lead-acid batteries have offered grid-free living for decades; cheaper and better batteries may encourage existing utility customers to detach from the grid and become their own electrical islands. Most observers contend that massive "grid defection" is unlikely, however.

Battery system taxonomy & schematics

Batteries and their surrounding electrical components can be deployed in several configurations and used in a wide variety of ways. The battery cells in home systems have no value for consumers until they are integrated into a product and installed as a system.



Energy storage vendors are essentially systems integrators that combine battery cells or modules with power conversion, software and controls to create products for specific markets. Most batteries will be installed in homes that already have solar power, or installed together with new solar power systems.

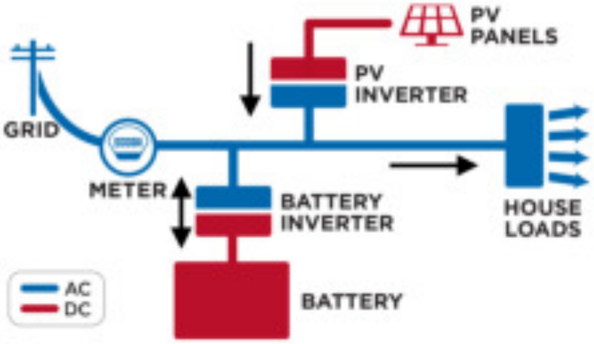
Nearly every home battery brochure includes a spaghetti-like diagram showing electrical components and connections, sometimes in overwhelming detail. Chemical batteries are direct current (DC) devices, so connecting to the alternating current (AC) grid, requires *inverters* to convert from DC to AC power. Similarly, going from AC to DC requires a *rectifier*.

Each of these conversions consumes some energy exacts an "energy penalty", so the fewer the better. Some battery systems are able to charge with DC power directly from solar PV panels (also DC devices), which can potentially improve overall efficiency by eliminating two power conversions. Some may also offer the ability to output DC power directly from the battery to loads that can utilize the power in that form, such as electric vehicle charging, avoiding additional inverter and rectifier losses. The potential system arrangements depend on the combination of storage elements, PV panels, electric vehicle (EV) chargers, and backup circuitry. In general, the options can be simplified into the following types.

AC Coupled Battery + PV

In this arrangement, the battery and PV systems each have their own inverters, and the wiring combines on a common AC bus at 120V or 240V. This is the most common system type, as it avoids the complications of coordinating DC voltage and current management. The battery system vendor can sell the product regardless of the type of PV system, and it can be retrofitted to one of the more than one million households that already have rooftop PV.

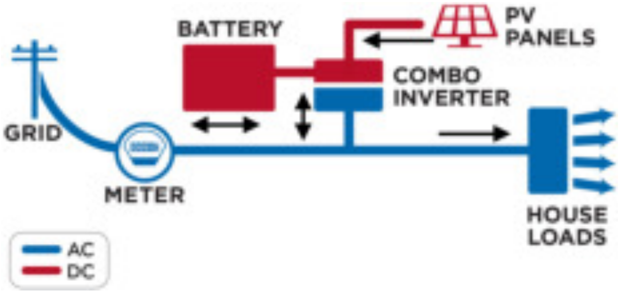
Figure: AC-Coupled Battery+PV System



DC Coupled Battery + PV

This system combines the PV and battery inverters into a single unit. The advantages are twofold: cost reduction (one inverter instead of two), and direct DC-DC battery charging from the PV system for higher efficiency. However, the PV and battery systems generally must be compatible, and either installed or planned at the same time.

Figure: DC-Coupled Battery+PV System



Stand-alone Battery (no PV)
Most storage systems are combined with PV generation. Stand-alone systems are a simplified version of the AC coupled system, but without PV.

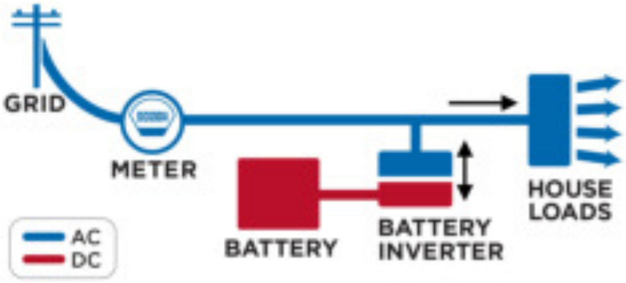


Figure: Stand-alone Battery System

Battery/PV/EV
Today's electric vehicles (EVs) are generally chargeable only with AC power, usually via a Level 2 (240V) charger. In this system type, the charger is just another connection on the AC bus, and the AC-DC conversion to the car's battery is handled with onboard electronics.

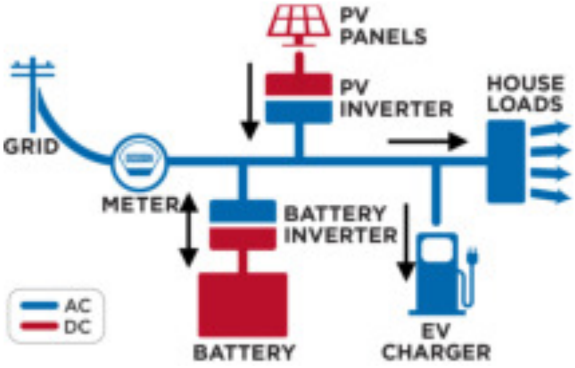


Figure: AC-Coupled Battery+PV+EV System

If the car can be charged with DC power, another simplification is possible—a single DC power converter that handles PV input, battery input and output, and EV output. This offers the fewest conversion losses and highest efficiency of all possible arrangements.

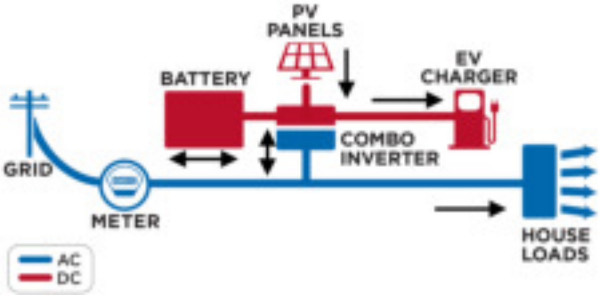


Figure: DC-Coupled Battery+PV+EV System

Backup Power Subpanel
At this point in the development of the home battery market, backup power is a key part of the sales pitch. To actually do this, however, requires either a critical-loads subpanel (very unusual in most home wiring) or a system big enough to handle the entire house for a meaningful length of time (uneconomical if the house has large loads such as air conditioning). Any of the system types described above can be modified to do this by connecting the AC side of the battery inverter to a "critical loads" subpanel—one such arrangement is shown here.

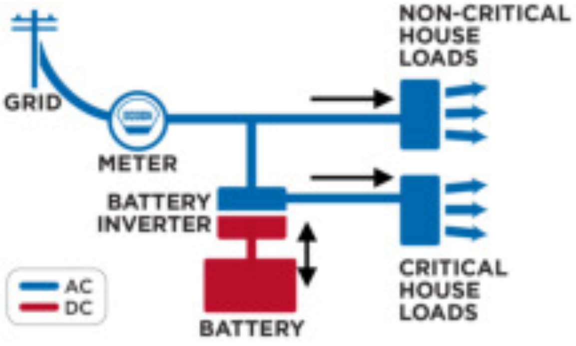


Figure: Battery-Critical Backup System

Several years ago, California's Title 24 building code began including provisions to make new construction "solar ready" by allocating physical space and electrical infrastructure for PV systems. Similar provisions could be employed in future codes to encourage or require building to be "storage ready." These measures could include wiring for a critical-loads subpanel, physical space for batteries, and robust electrical connections to allow for high-amperage 240V sources and loads—PV, EVs, and batteries.

Key metrics

Battery specification sheets list several attributes. The most common are:

- Energy capacity (in kWh)—may or may not be de-rated to provide a performance buffer
- Power capacity (in kW)
- Power capacity (in kVA)—may include short bursts of power above normal capacity
- Round-trip AC efficiency
- Round-trip DC efficiency (if applicable)
- Maximum charge rate (in amps or watts, often expressed as a rate of total capacity per hour, i.e. 1C equals complete discharge in one hour, 2C equals double that rate, and so on)
- Maximum discharge rate (same units as charge rate, i.e. 1C, 2C, etc.)

Additional metrics that are important for residential systems—but are less commonly provided in product information—include:

- Daily discharge (losses from simply holding a charge, in % per day, or standby power, in watts)
- Degradation over time and charge/discharge cycles, both in energy capacity and in round-trip efficiency
- Degradation in performance under extreme operating temperatures or other environmental stresses. This is particularly important in solar-friendly climates such as Arizona and Nevada, where batteries may be located outside and subject to very high temperatures.

Metrics that are more relevant to larger utility-dispatched systems include response time, ramp rate, internal resistance or impedance, and reactive power measurements. Some of these qualities may be applicable for fleets of residential systems.

Test methods

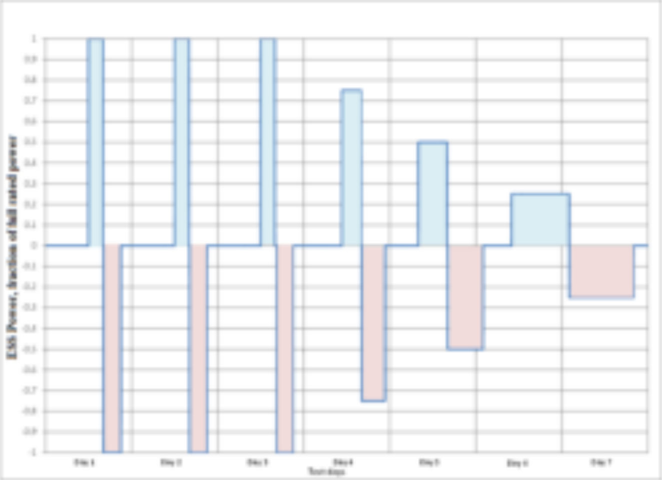
For this study, we looked for evidence of any uniform test methods for residential battery system performance. This search included phone calls and direct discussions with residential battery stakeholders (including EPRI, CSA, NEMA, PNNL, CEC, EPA, and PG&E) and manufacturers/vendors (including Enphase, Sonnen, Simpliphi, Sunverge, Eguana, Ideal Power, Adara, and Pika). All parties agreed that there are currently no such standardized test methods. Most vendors seemed willing to support standardized testing, a few were neutral, and at least one was wary; those in the latter two categories expressing the opinion that they did not think lack of uniform testing was a major problem.

We also observed a range of manufacturing claims regarding efficiency and standby power use. For example, some published efficiency values don't state whether they are AC-AC or DC-DC, a significant difference, and standby values are seldom given. Further standardization of test methods and presentation of performance claims will create a more level playing field for manufacturers and help shield consumers from exaggerated or unrealistic claims.

Although home battery test standards do not yet exist, the last year has seen significant progress in characterizing energy storage system performance. The *EPRI ESIC Test Manual V1.0*, published in December 2016, lays out foundational principles and detailed procedures for testing grid-connected battery systems. This manual was created for larger systems, but its guidance is relevant to home-scale systems. Underwriter's Laboratories (UL), Sandia National Laboratory, and Pacific Northwest National Lab (PNNL) are also involved in advancing test procedures.

Here are key elements of the testing procedures defined in the ESIC Test Manual:

Figure: ESIC Test Manual Duty Cycle for roundtrip efficiency



- **Definitions**. More than twenty terms—such as Available Discharge Energy Capacity, State of Charge, and Rated Continuous Power— are defined to build a framework for calculations.
- **Test setup**. The Manual specifies a test chamber maintained at 73F±4F, but also has allowances to test at other temperatures if the system will be operated outdoors, or if a climate-controlled test chamber is not available.
- **Duty Cycle**. For round-trip efficiency testing, a seven-day test is specified, with a full-power discharge/charge cycle on each of the first three days, and reduced-power (75%/50%/25%) discharge/charge cycles on the last four days. Different duty cycles are specified to measure Rated Continuous Power, Response Time, and Settling Time.
- **Auxiliary loads**. Loads for heating, cooling, controls, and anything else required to operate the battery system must be measured (and if possible, measured separately) to factor into power and efficiency calculations.
- **Data Logging**. One-minute data must be logged for current, voltage, reactive current, and other variables.
- **Other Tests**. The procedures for testing efficiency and power availability are fairly well defined in the current version (1.0), while other test methods—to determine Remaining

Useful Life, Self-Discharge Rate, and Black Start capability, among others—are still to be drafted by the ESIC group.

In April 2016, PNNL updated the *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems*, a document that was coordinated with the ESIC. The Protocol applies to all types and sizes of electric energy storage, and was first published in 2012. Its content is organized around measurements for specific grid applications, such as PV smoothing or voltage support. This is significant, as the performance and efficiency of residential energy storage systems will vary if they are used merely for peak-shaving vs daily arbitrage between peak and off-peak rate periods vs grid backup only.

The discussion above applies to electrical performance metrics for battery systems. Safety standards for batteries and inverters are already in place, including:

- UL1741 (for inverters)
- UL1973 (for batteries)
- UL 9540 (for systems that combine batteries and inverters)
- IEEE 1547
- FCC Class B

Test method gaps and difficulties

The obvious test method gap is the lack of a standard metric for roundtrip efficiency, which depends on rate of discharge/charge, depth of discharge, temperature, and other factors. Standardized means to measure round trip efficiency is important because there is not yet agreement on whether it should be measured on a DC/DC basis (which will produce a higher efficiency rating) or AC/AC basis. Some battery chemistries do very well while inactive (i.e. lead-acid) while others with high auxiliary loads fare poorly if they are not deeply and regularly cycled (i.e. liquid electrolyte “flow” batteries). Residential systems nearly all use lithium-ion battery cells, so there is some uniformity in this category, and they perform relatively well in both standby and heavy cycling modes.

Figure: Sonnen Battery in modular cabinet

Another factor is the modularity of home battery systems. For example, Sonnen offers systems ranging from 4 to 16 kWh of nominal storage, with different ratios of inverter capacity to cell capacity. The efficiency of these varied system combinations is unlikely to be exactly the same—a problem similar to the issue of sizing solar panels to take maximum advantage of inverter capacity. This gives rise to several questions:

- If several battery packages can be run under a single inverter/controller, do they need to be tested in each configuration to earn an efficiency rating?
- Vendors often switch suppliers for their Li-ion cells, as the batteries themselves approach commodity status—does a change in cell supplier require retesting?
- Can combinations of components earn ratings based on computer simulations, as was done with NFRC window calculations in the 1990's?
- Should batteries be rated on the basis of their normal storage capacity when new, or their typical average lifetime storage capacity?

Battery testing procedures depend on an important but difficult-to-measure quantity: State of Charge (SOC). This is not as simple as measuring battery voltage and applying an algorithm, which is how mobile phones work. On utility-scale battery systems, the battery management system (BMS) does its own internal calculations based on cell and module voltages (which can number in the hundreds or thousands of measurements), as well as integrations of current values. This method, known as "coulomb counting," is non-linear, and non-trivial. The reliance of test methods on self-reporting SOC calculations is a potential weak spot in any attempt to standardize testing, as it is hidden from view and could be tilted to produce favorable results.

Another challenge is quantifying battery performance over time. As we know from our lithium-battery-equipped cell phones, capacity degrades with frequent use. How much capacity is lost over time depends on cell chemistry and design (which are continually evolving), depth and rate of discharge, number of discharge cycles, operating temperature, the extent to which advertised capacity is under- or over-stated, and other factors. Development of testing standards should include some provision for evaluating this aspect of battery systems. This could include, for example, rating battery capacity on the basis of lifetime average performance rather than new (similar to the comparisons in lighting between initial and mean lumens), or stating that capacity may only be claimed in marketing materials to the extent it is covered by warranty to a certain number of full discharge cycles, years of operation, or total capacity cycled.

As one recent comparison among the leading residential energy storage systems found, Tesla provided a 10 year warranty for its 13.5 kWh PowerWall 2.0 system, but no specifics on how performance and remaining storage capacity might degrade over that period. Its warranty for the original PowerWall system was more specific but less encouraging. It only guaranteed 85% of initially claimed capacity in the first 2 years, and 60% in the first 10 years, provided that capacity is measured under optimal temperature and discharge conditions and the device has not already exceeded pre-specified aggregate discharge amounts.[1] Sonnen warrants its 4 kWh products for 10 years to 70% remaining capacity. Aquion Aspen warranted its 2.2 kWh modular products for 10 years to 70% remaining

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[1] John Peterson, "Why Tesla's Semi Will Almost Certainly Be Shelved," *Seeking Alpha*, 11/20/17, https://seekingalpha.com/article/4126621-teslas-semi-will-almost-certainly-shelved.

capacity (before the company recently declared bankruptcy). LG Chem warrants its 3.3, 6.5 and 10 kWh products for 10 years to 60% remaining capacity. [2]

Energy Consumption

All batteries consume some amount of energy during the power conversion process and while storing power, sometimes referred to as "leakage". While the inclusion of battery storage systems in a home may provide an array of benefits, they will increase the home's total net energy consumption. There are generally two types of losses: the energy lost through a discharge-charge cycle ("roundtrip" (RT) losses), and the energy associated with simply maintaining a full charge ("parasitic," "standby," or "self-discharge" losses). The former is captured by the roundtrip efficiency metric, and is usually quoted in product specification sheets, although inconsistently. Published efficiency descriptors include "AC," "DC," "AC-AC," "DC-DC," "grid-battery," or sometimes simply "roundtrip" (without any qualifier). Standby losses are seldom mentioned in current literature; our review of thirteen products found values of 3W (Eguana), <10W (Nissan), and <30W (Powerstation).

The tables below present representative energy calculations based on currently published performance values and costs. These calculations use the EIA 2013 US average residential electricity rate of $0.121/kWh—a value that is much lower than the typical costs in regions where energy storage is likely to be installed—so these results are conservative.

The first table shows that a 5kW system with standby power of 30W will consume 263kWh of energy per year, costing $32 per year at the US average residential electric rate. This is the energy lost in a backup-only application, assuming the system is never actually used (transferring energy in a power outage would incur additional losses).

Table: Effect of Standby Loss

Item	Qty	Unit	Notes
Standby Power	30	W	Published (max) value for Powerstation 5kW PowerModule
Energy per year	262.8	kWh/y	At 8760 h/y
Energy rate	$0.121	$/kWh	US average residential rate, 2013 (EIA)
Energy cost	**$31.80**	**$/y**	At average electric cost

The next table shows that a 5kW system that is cycled daily at 90% efficiency will consume 324 kWh per year in transfer losses, costing $39 per year. Note that many utilities in sunny parts of the United States where PV installations are prevalent now have separate morning and evening peaks with a valley in the middle of day when solar output is peaking. As a result, their time of use rate structures will increasingly encourage residential battery owners to charge at two different times of the day (middle of the night when grid power is expensive and middle of the day when solar output is high) and discharge during both the morning and evening peaks. The effect of two charge cycles per day will be to increase

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[2] "How do solar batteries compare? Tesla Powerwall vs. Sonnen batterie vs. Aquion vs. LG Chem RESU," http://news.energysage.com/tesla-powerwall-vs-sonnen-eco-vs-lg-chem/.

annual energy losses associated with round-trip energy conversion and hasten loss of battery capacity with age.

Table: Effect of Roundtrip Loss (Single System)

Item	Qty	Unit	Notes
System size (power)	5	kW	Typical value
System size (energy)	10	kWh	Typical value
Cycles per year	365	d/y	One cycle per day
Cycle depth	80%	%	Percent of nominal kWh capacity
Efficiency	90%	%	Midpoint of typical values
Energy discharged	2920	kWh/y	Per values above
Energy to charge	3244	kWh/y	Discharge energy / effcy
Energy loss	**324**	**kWh/y**	Charge-discharge energy
Energy rate	$0.121	$/kWh	US average residential rate, 2013 (EIA)
Energy cost	**$39.26**	**$/y**	At average electric cost

What is the effect of higher vs lower roundtrip efficiency? The table below shows that this works out to about $39 per year for the typical residential customer. (The energy cost from this comparison is similar to the energy cost of the average roundtrip losses calculated above—both are about 10 percent of throughput.)

Table: Effect of Higher vs Lower Roundtrip Efficiency (Single System)

Item	Qty	Unit	Notes
Energy Discharged	2920	kWh/y	Per calculations above
Lower RT efficiency	86%	%	Published RT AC effcy for Sonnen
Higher RT efficiency	95%	%	Published RT AC effcy for Eguana
Lower effcy energy to charge	3395	kWh/y	Discharge energy / effcy
Higher effcy energy to charge	3074	kWh/y	Discharge energy / effcy
Lower effcy loss	475	kWh/y	Charge-discharge energy
Higher effcy loss	154	kWh/y	Charge-discharge energy
Energy savings	**322**	**kWh/y**	Delta of losses
Energy rate	$0.121	$/kWh	US average residential rate, 2013 (EIA)
Energy cost savings	**$38.92**	**$/y**	At average electric cost

Extending this calculation to the projected 2022 US residential battery fleet (769MW—about 150,000 systems, assuming average sizing of 5kW/10kWh) shows that the efficiency spread makes a difference of nearly $6 million per year across the projected US fleet.

Table: Effect of Higher vs Lower Roundtrip Efficiency (US Residential Fleet—2022)

Item	Qty	Unit	Notes
Total battery fleet	2562	MW	GTM Q1 2017 Forecast for 2022
Res'l battery share	30%	%	GTM Forecast—approximate
Res'l battery fleet	768.6	MW	Total fleet * Residential share %
Average system size	5	kW	Typical value
Qty of res'l systems	153720	#	Fleet capacity / system size
Fleet energy savings	49446	MWh/y	Single system savings * Qty of systems
Average electric cost	$0.121	$/kWh	US average residential rate, 2013 (EIA)
Energy cost savings	**$5,983,000**	**$/y**	At average electric cost

At the moment, these impacts are low enough that the call for public action may be challenging to make. However, policies focused on net zero energy homes or on making solar homes storage-ready could demonstrate significant impacts within those particular homes. But a larger point also emerges. If a residential energy storage system has the potential to increase a home's annual energy consumption by an amount similar to adding another refrigerator, should their purchase and installation be widely promoted unless specific conditions are met? Will their societal benefits outweigh those extra costs?

Activities by other stakeholders

California Energy Commission

We recently corresponded with a staffer at the California Energy Commission (CEC) to get the Commission's informal opinion on its coverage of home battery systems in their regulations. Home battery storage systems are currently not covered by the state's appliance or building energy code regulations. California recognizes the potential benefits of residential storage systems, but are concerned about potential unintended consequences of the technology. They will be looking into gathering additional data on their performance to inform potential future regulations of this equipment.

International Electrotechnical Commission

The IEC is addressing energy storage through its *Technical Committee 120: Electrical Energy Storage (EES) Systems*. The stated scope of TC120 is: "Standardization in the field of grid integrated EES Systems," and:

- TC 120 focuses on system aspects on EES Systems rather than energy storage devices.
- TC 120 investigates system aspects and the need for new standards for EES Systems.
- TC 120 also focuses on the interaction between EES Systems and Electric Power Systems (EPS).

TC120 has produced documents including:

- *Unit Parameters and Testing Methods - General specification*
- *Planning and Installation - General specifications*

- *Guidance On Environmental Issues - General specifications*
- *Safety considerations related to grid integrated electrical energy storage (EES) systems*
- *Unit Parameters and Testing Methods - General specification*

The TC120 documents are available only to members of the Committee.

US Environmental Protection Agency
The EPA has produced scoping reports to consider including small and large electric energy storage systems in the ENERGY STAR labeling program.

Electric Power Research Institute
EPRI hosts the Energy Storage Integration Council, as mentioned above. Their work is divided into three Working Groups:

- WG 1—Grid Services and Analysis
- WG 2—Testing and Characterization
- WG 3—Grid Integration

The ESIC Test Method described above is a product of WG 2, chaired by Naum Pinksy (SCE). Jay Henderson of PG&E is the Testing Subgroup co-leader.

National Electrical Manufacturers Association
NEMA is aware of the emergence of energy storage devices and understands the need for testing standards. Their participation would be oriented around the interests of their member companies.

CSA Group
The original Canadian Standards Association has expanded into CSA Group, which provides testing and certification globally. They also are aware of the need for standardized testing procedures for energy storage systems.

Additional topics tied to home energy storage
This report provides a survey-level view of a rapidly developing technology, with a limited scope of inquiry. Several aspects of energy storage are candidates for follow-up study.

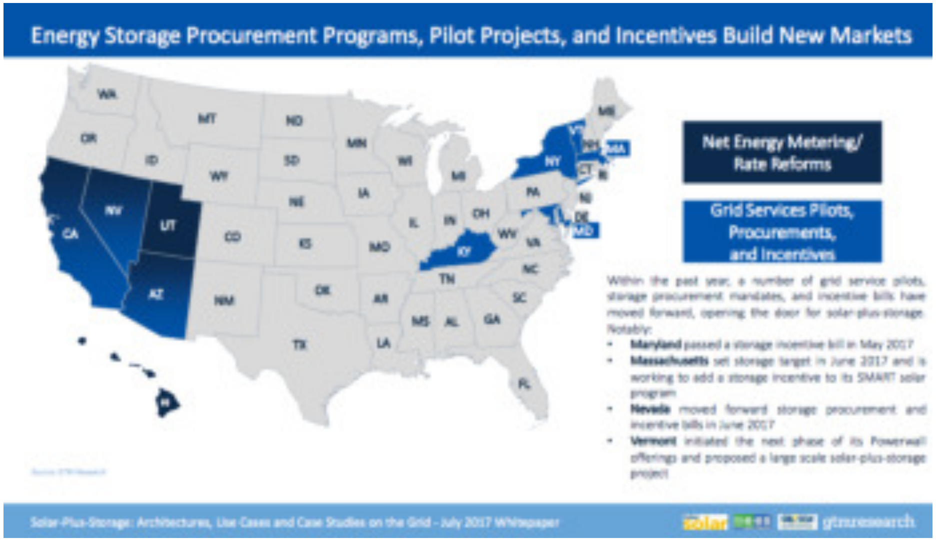
The PV-EV-Battery "Triangle"
Batteries share many commonalities with solar PV systems and electric vehicle (EVs)—all are large DC energy loads and/or sources that have just emerged over the last decade. As car manufacturers shift to electric vehicle production, they are also developing terrestrial (non-mobile) storage systems —examples include Nissan, Mercedes, and Tesla. Residential storage installations overlap heavily with solar PV systems since they both use inverters, and are likely to overlap with EV ownership as that market develops. As the above diagrams indicate, these systems offer opportunities for performance and efficiency benefits when considered together. The connections between these markets should be monitored for leverage on all three technologies.

One example of the crossover between cars and home energy storage is the area of vehicle-to-grid (V2G) technology, where a car battery can store electricity for potential use in the home during certain times of the day, or for home backup power. Many EVs now offer onboard energy storage of 40 to 70 kWh—significantly larger than typical daily household consumption, which averages about 27kWh per day nationally. The potential benefits of V2G have generally been discouraged by car manufacturers to protect their warranted batteries, as frequent and/or deep cycling can degrade the battery over time. However, using a vehicle for occasional house backup (i.e. 3 or 4 times per year) could provide substantial benefit without taxing the battery health. EV manufacturers could also charge a fee for V2G services that might prove more cost-effective than installing a stationary system in the home. Eventually, it is likely that some form of two-way energy flow will be possible, or even common, from electric cars. Nissan's 2018 Leaf now offers this capability. (Note that there is no reason to attempt to charge EVs from home storage; the latter has lower capacity, and the controllability of EV charging time eliminates any such imperative.)

Marketing approaches and market characterization

Selling home battery systems for anything other than backup protection is completely reliant on utility rates and the regulatory environment in which they are set. For most of the US, home batteries cannot be justified on this basis, but several states are evolving rate structures and incentives that are changing the situation. The figure below shows that at least twelve states are promoting energy storage, the most prominent examples being Hawaii, California, Nevada, Massachusetts, and Arizona. California's Self-Generation Incentive Project (SGIP) is offering $57 million in funding for residential (<10kW) systems, and Vermont leads the nation in Powerwall installations with a lease program that was recently re-priced at $15 per month. As net metering rate design progresses to its 2.0 and 3.0 implementations, the case for energy storage (via increased solar "self-consumption," which storage enables) will grow more financially sound.

Figure: States promoting energy storage



Energy Storage Procurement Programs, Pilot Projects, and Incentives Build New Markets

Net Energy Metering/ Rate Reforms

Grid Services Pilots, Procurements, and Incentives

Within the past year, a number of grid service pilots, storage procurement mandates, and incentive bills have moved forward, opening the door for solar-plus-storage. Notably:

- **Maryland** passed a storage incentive bill in May 2017
- **Massachusetts** set storage target in June 2017 and is working to add a storage incentive to its SMART solar program
- **Nevada** moved forward storage procurement and incentive bills in June 2017
- **Vermont** initiated the next phase of its Powerwall offerings and proposed a large scale solar-plus-storage project

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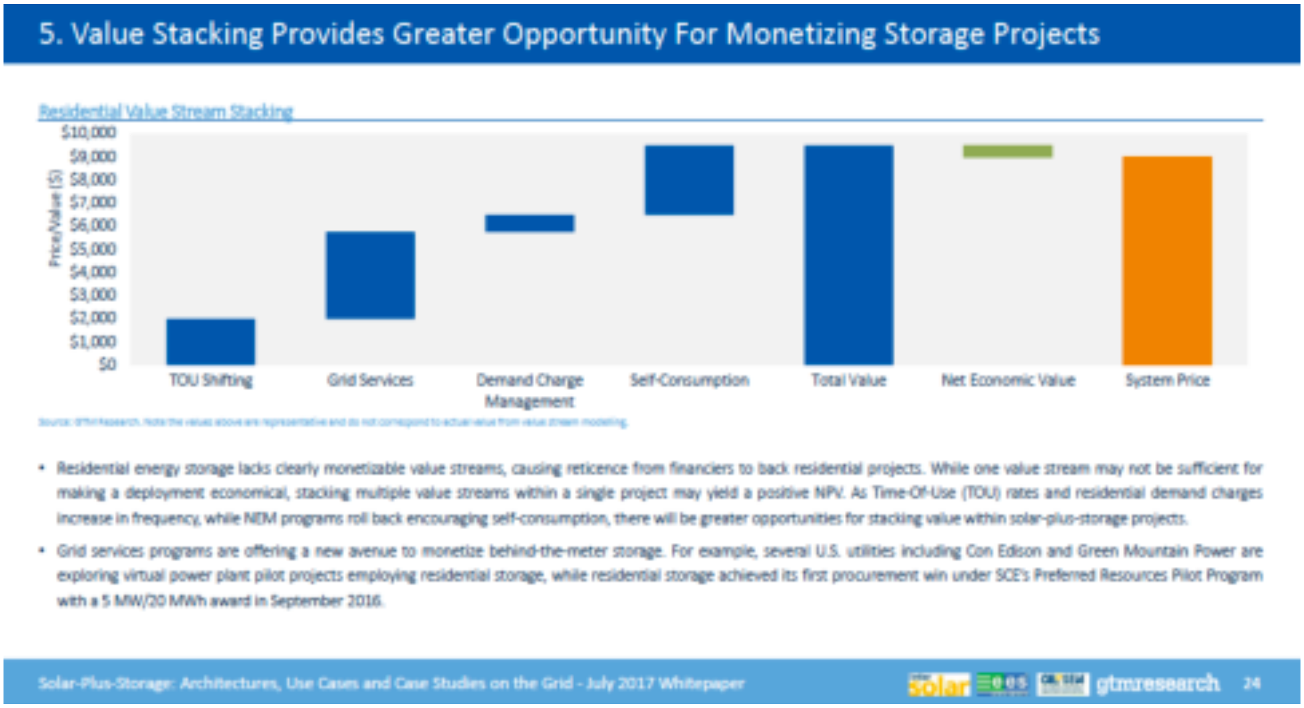
Source: GTM Research

Benefit Bundling or "Stacking"

Residential energy storage systems can promise several separate value propositions. These will differ regionally, but the following example from Green Mountain Power's pilot residential energy storage program in Vermont is illustrative, in which five separate benefits add up to justify system cost. (No value is given to backup power capability—the current leader in a homeowner's perceived value of battery systems!) Several other studies have reached similar conclusions: that battery systems must serve multiple functions to earn their keep. This is at odds with the current residential storage market where backup power is the main sales pitch, but represents the potential that will drive future system marketing.



5. Value Stacking Provides Greater Opportunity For Monetizing Storage Projects

Residential Value Stream Stacking

Source: GTM Research. Note the values above are representative and do not correspond to actual value from value stream modeling.

- Residential energy storage lacks clearly monetizable value streams, causing reticence from financiers to back residential projects. While one value stream may not be sufficient for making a deployment economical, stacking multiple value streams within a single project may yield a positive NPV. As Time-Of-Use (TOU) rates and residential demand charges increase in frequency, while NEM programs roll back encouraging self-consumption, there will be greater opportunities for stacking value within solar-plus-storage projects.
- Grid services programs are offering a new avenue to monetize behind-the-meter storage. For example, several U.S. utilities including Con Edison and Green Mountain Power are exploring virtual power plant pilot projects employing residential storage, while residential storage achieved its first procurement win under SCE's Preferred Resources Pilot Program with a 5 MW/20 MWh award in September 2016.

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This diagram treats all of the value streams similarly and sums them, but of course some of the monetized benefits flow to the homeowner/billpayer, some of them flow to the utility, and some flow to society as a whole. If the homeowner is being asked to make the investment in the energy storage system, the direct financial benefits to them must be large enough to justify the expense, or the utility or government would likely need to offer incentives reflecting the value to the utility and society of the other benefits of the system. Finally, the utility would need to be able to have some control over the timing of charging and discharging of the battery to realize those benefits.

Cost trends

Data on the real installed costs of battery systems is hard to come by, but currently published costs range from $1000 to $2000 per kWh of capacity. If costs can be reduced to $250-$500 per kWh, many more possibilities will open up. Assuming a 10kWh system and the midpoint of these cost ranges, this is the difference between spending $15,000 today or

$3,750 in the future. Batteries are unlikely to get cheaper as fast as solar panels have recently, however.

Microgrid developments

Every backup-capable battery system is effectively a microgrid. Research and development of microgrids, particularly in the area of controls and communications, will spur home battery capabilities.

Micro-inverters

Most of this report is organized around "string inverters" with relatively high electrical capacity (1-5kW) in one desktop-sized box. Micro-inverters, like those from Enphase, are sandwich-sized units that connect single solar panels (200-300W) with AC wiring, which simplifies some aspects of system design. The modularity of micro-inverters has the potential to harmonize the AC and DC loads and sources in a home.

Recommendations

This study raises technical and policy issues around residential battery technology, and is intended to spur discussion of possible actions to support the emergence of products that address the very real challenges facing the future of our electrical system—renewable energy penetration, grid stability, utility reliability, and consumer protection. Some starting points for that discussion and future action:

- *Develop uniform testing methods* for home batteries. The building blocks to create test methods already exist—thanks to efforts oriented toward larger systems—but standardized procedures for residential systems are not yet in place.
- *Design and implement field testing* of residential batteries to determine how the promise of these systems squares up with real-world operation, both when first installed, over time, and with aggressive cycling.
- *Access manufacturer data* showing how their products are actually being used, including data on cycle frequency and depth.
- *Establish "storage ready" criteria* for new construction and major retrofits, similar to the "solar ready" requirements in Title 24.
- *Encourage uniform labeling* and minimum warranty coverage for residential battery systems.
- *Follow activities in Europe and Australia*, where thousands of residential batteries have already been installed.
- *Participate* in IEC TC120 (requires membership on the committee), where development of test methods and standards are discussed.
- *Establish a network* to facilitate information sharing and to coordinate activities between stakeholders including those listed above.
- *Educate the public* on the multiple benefits of battery systems. Currently, most batteries are being marketed as backup systems or in combination with solar PV installations. Fleets of batteries that sit idle until a power outage are a missed opportunity, and represent new residential load.

- *Monitor product developments and claims for veracity*—do kWh capacity and round-trip efficiency claims hold up under actual use?
- *Set minimum efficiency standards*, and/or provide incentives for higher-efficiency systems.
- *Establish compatibility criteria* for DC-coupled battery products—namely standardized voltages—that would allow easier retrofitting of battery systems to homes with existing PV systems
- *Consider utility incentives* that target the intersection of grid modernization and customer benefits. Further study is needed to determine the case for storage.