Joint Institute for Strategic Energy Analysis

Hybrid Storage Market Assessment

A JISEA White Paper

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Executive Summary

The costs of battery storage technologies have dropped in recent years, resulting in a seven-fold increase in installed capacity over the last decade (1). These technologies offer an attractive rate of return in some locations; however, cost and regulatory barriers still limit the market for storage. Hybridizing a battery (combining the battery with a generator) can in some instances reduce total system costs and increase value compared to separate installations. The fast ramping and dispatchability of a battery can complement the generator to provide services that neither battery nor generator could provide alone. Battery hybrids also benefit from some policy incentives and may be better able to meet market and regulatory requirements. This paper evaluates which markets are best suited for battery storage and storage hybrids and reviews regulations and incentives that support or impede the implementation of standalone storage and battery hybrids. The following are key findings from this study.

1. **The market for battery storage is poised for rapid growth.** Battery costs have declined by more than 65% in the last 7 years and are expected to decline further (2). An analysis conducted by HOMER Energy, a microgrid modelling software development company, on the effect of storage price on battery installation shows that once the cost of storage declines past a threshold level, the economic installation size can expand by an order of magnitude. While the threshold varies across markets, for specific applications, battery storage is now cost competitive with alternatives. Battery and system cost declines are forecasted to drive a 22-fold increase in battery storage and hybrid system capacity in the United States over the next 6 years (3).
2. **While the battery storage market is expected to grow rapidly, it still faces barriers.** High battery costs, regulatory uncertainty, and market structures that do not always properly remunerate energy storage or storage enabled services pose hurdles for the technology.
3. **Battery hybrid storage can lead to synergies that increase the value of both battery and generator.** Constructing a single hybrid unit instead of two separate units reduces hardware and installation costs and can increase battery charging efficiency (4). Battery hybrids can also provide value streams that neither component alone could provide.

   Pairing storage with utility-scale wind or solar can enable reduced energy curtailment and generation variability and may increase capacity payments. Pairing storage with a natural gas peaking plant allows the plant to sell into spinning reserves by increasing the effective start-up time of the plant. The combination of battery and generator can also allow for black-start capabilities. Additionally, a battery-renewable-diesel combination can cost-effectively provide cleaner electricity to islands and off-grid locations. In the HOMER modeling of a sample large island, battery-solar-diesel hybrids enabled additional renewable sources, while also improving the operational efficiency of the fossil-fueled generation. Finally, storage paired with distributed solar can reduce demand charges and provides resilience during outages.
4. **The market potential for battery storage and battery hybrid storage varies by grid application and geographic location.** Capacity markets provide the largest potential market application for utility-scale battery storage, while the primary applications for

distributed storage are to reduce consumer demand charges and enable greater resiliency and emergency power.

California is the most attractive geographic market for U.S. battery storage because of its storage mandates, high renewable penetration, and regulatory framework conducive to battery storage projects.

5. **Isolated grids and remote locations offer significant opportunities for battery hybrids due to system features and overall economic competitiveness.** Islands represent a near-term opportunity for utility-scale batteries and battery hybrids due to increasing penetration of renewable generators that reduce high fuel costs for thermal generating plants. A HOMER analysis of island and developing-country markets found that under the expected range of conditions, the most economic system configurations include generator (of various types) plus storage and other hybrid technologies.
6. **Battery hybrid storage systems can be eligible for incentives for which storage alone would not be eligible.** In the United States, batteries paired with renewable generation may receive up to a 30% investment tax credit and an improved depreciation schedule (5). Battery hybrids are also eligible for grants aimed at improving grid security and reliability. Similar incentives exist in other countries and markets.
7. **The regulatory market for batteries is improving but is still uncertain.** The Federal Energy Regulatory Commission (FERC) plans to “remove barriers to the participation of electric storage resources and distributed energy resource aggregations in the capacity, energy, and ancillary service markets" (6). Future regulatory changes may be favorable to battery storage and battery hybrids, but when these regulatory changes might occur is uncertain. In the meantime, policies and market costs vary significantly between states and countries, presenting a patchwork regulatory market.

Introduction

Battery storage is becoming an important component of the energy grid. A correlation can be drawn between the growth in renewable energy and the expected growth in battery storage. Since 2004, world variable renewable energy installed capacity (largely solar and wind) has grown 25% annually (7). In the United States, wind and solar have grown from producing 0.37% of total generation in 2004 to 6.5% in 2016. The market for battery storage today in many ways reflects the market for renewable energy in 2004 (1). The growth in battery storage, however, is expected by some to be even more dramatic (3) (8).

As shown in Figure 1, global battery storage capacity increased seven-fold in 10 years and by 50% in 2016 alone (1). In the next 6 years, U.S. battery capacity is forecasted to grow 22-fold (3).

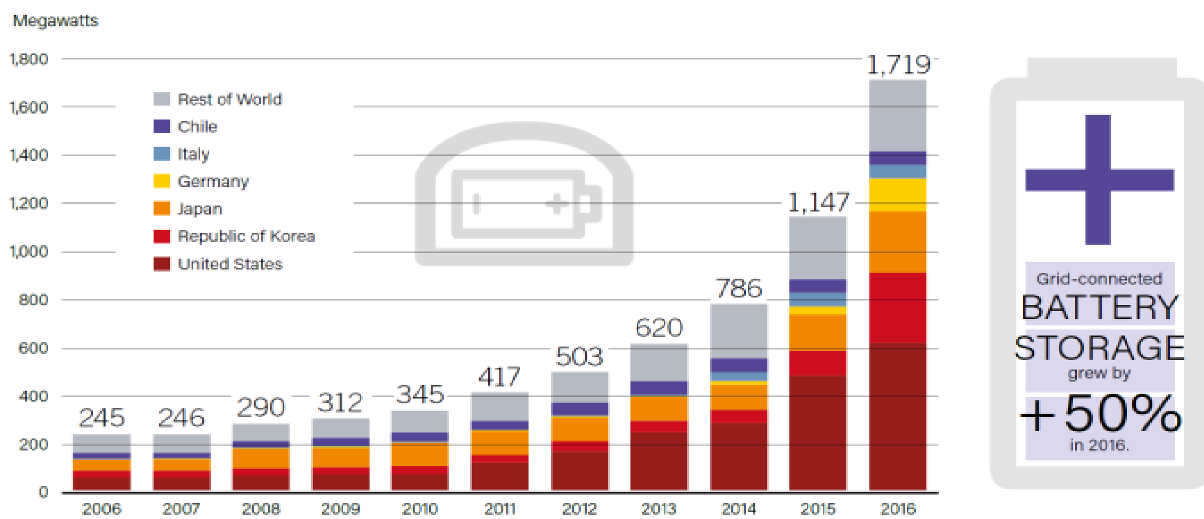

Figure 1. Battery storage installations. ***Figure from (1)***

Reductions in battery costs are making the economics of battery storage more compelling (9). Prices for lithium-ion batteries declined by 14% annually from 2007 to 2014 (10) for a total price decline of more than 65% in 7 years, and similar future cost reductions are expected (2).

Batteries are dispatchable, have fast response times, have zero end use emissions, and face fewer siting restrictions than most conventional generation. Thus, battery storage can provide value to both utilities and customers through a number of generation, transmission, and distribution applications. However, current high costs and regulatory restrictions may be barriers to overcome for battery storage technologies if the projected growth is to be realized.

A battery hybrid—a battery system paired operationally with a generation system—can help overcome the cost and regulatory limitations of standalone storage. Along with increasing the performance of services that batteries already provide, battery hybrids are able to capture value streams where standalone batteries cannot.

Scope and Purpose

In this paper, we discuss the uses of battery storage and battery hybrids. We provide a high-level analysis of markets that are best suited for battery storage and storage hybrids. We also discuss regulations and incentives that support or impede the implementation of standalone storage and battery hybrids. This paper primarily focuses on U.S. markets, though many of the insights can be generalized to global applications. Furthermore, we provide market size estimates for global markets along with an appendix that provides modeling by HOMER Energy on six case studies with global applications.

The rest of this paper is separated into seven sections and an appendix, which are arranged as follows:

1. **Costs**. This section presents current and projected future storage construction and installation costs, along with a discussion of how hybridization can reduce costs through engineering synergies.
2. **Value streams**. This section describes potential revenue streams and market size for battery storage and battery hybrids.
3. **Regulatory framework and policy incentives.** This section describes important regulations and policy incentives for battery storage and battery hybrids.
4. **Market considerations.** This section describes key near-term markets that will be profitable for battery storage and battery hybrids.
5. **Case studies.** This section provides four case studies to illustrate real-world applications of battery storage and battery hybrids.
6. **Market potential.** This section provides market size estimates for battery storage and battery hybrids.
7. **Conclusion and key findings.** This section summarizes the key takeaways from the paper.
8. **Appendix.** The appendix explores the economic value of hybrid systems over grid-only or diesel generator-only power generation systems using HOMER Pro modeling of six locations as examples of the main hybrid markets. Findings from these models are included throughout the previous sections.

1 Costs

Falling battery costs are quickly improving the economics of battery storage. Driven largely by economies of scale from increasing electric vehicle sales, battery prices fell by 65% from 2010 to 2015 (2).

Total capital costs for an 8-hour storage system are projected to decline by 34% to 81%, with an expected decrease of 57% by 2050 (11). In other analysis, a recent paper by Schmidt et al. uses estimates of battery pack prices settling around $175 per kilowatt-hour (kWh) and total installed capital costs around $340 per kWh. (12) Depending on deployment rates, these prices are expected to be reached between 2027 and 2040 (12).

HOMER Modeling Insight: Price Thresholds

For the Indonesian (small) island example, reducing battery price from $600/kWh to $450/kWh results in a 14% increase in storage size. Meanwhile, a battery price of $300/kWh results in a 17.6 times larger battery size. Similarly, in the energy access market, a $300/kWh battery, compared to a $600/kWh battery, would result in an 80% larger PV system, and a battery system that is 19 times as large.

The effect of battery prices on optimal battery size is nonlinear, with optimal battery size increasing dramatically once battery prices fall below a given threshold.

Balance of System Costs

While the battery pack is the most costly single component, balance-of-systems (BOS) costs make up a larger share of total costs than the battery itself. BOS costs consist of all non-battery-related costs. BOS costs include hardware, labor, permitting, overhead, customer acquisition, and construction.

Figure 2 displays projected BOS costs for utility-scale storage over time (13). Container and inverter expenditures represent the two largest portion of total expenditures; however, customer acquisition (CA) and engineering, procurement, and construction (EPC) expenses are considerable (13).

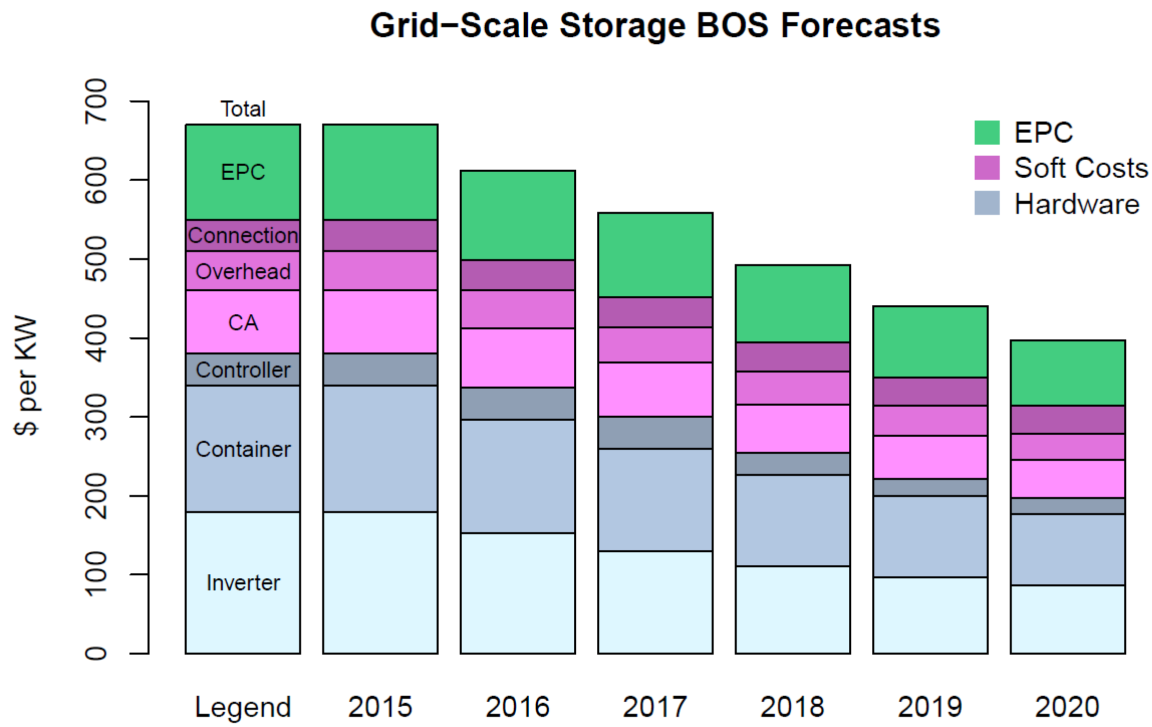

Figure 2. Projected BOS (without battery) costs for utility-scale storage through 2020. ***Data obtained from (13)***

Project Costs

Costs vary by size of project, type of battery, and duration of storage. A wide array of battery compositions exists, each with different price points and technical characteristics. Even among lithium-ion batteries, prices and technical parameters vary by battery composition and system configuration.

In addition to battery type, two characteristics are important to consider when determining total costs—battery size and storage duration. In general, larger battery projects are cheaper on a per kilowatt (kW) or per kilowatt hour (kWh) basis due to economies of scale. In 2016, all-in costs for commercial and industrial behind-the-meter uses were 25% more than larger utility-scale projects, on average (3).

Short duration storage is best suited for high power applications such as frequency regulation and spinning reserves, while long duration storage is best suited for applications with longer runtime requirements, such as providing resilience or capacity (9). BOS costs generally scale with maximum output (kilowatts) while battery pack costs scale with output duration (kilowatt hours).

Figure 3 displays current and forecasted total systems costs per kilowatt of storage for a 30-minute and a 2-hour system, while Figure 4 displays the systems costs per kilowatt hour of storage. The first bar is for a 30-minute system and the second bar is for a 2-hour system. The 30-minute system has lower costs when compared on a per-kilowatt basis due to lower battery costs, while the 2-hour system has lower costs when compared on a per-kilowatt-hour basis due to lower BOS costs.

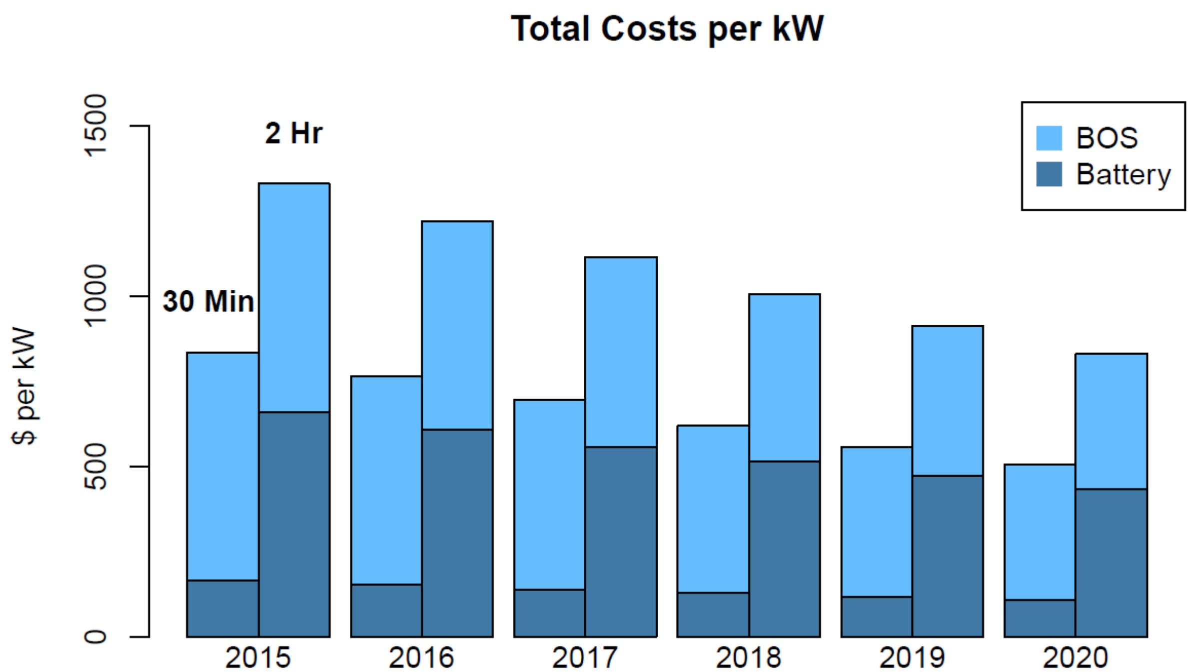

Figure 3. Current and forecasted total systems cost per kW of storage for a 30-minute and a 2-hour utility-scale system. ***Data obtained from (13)***

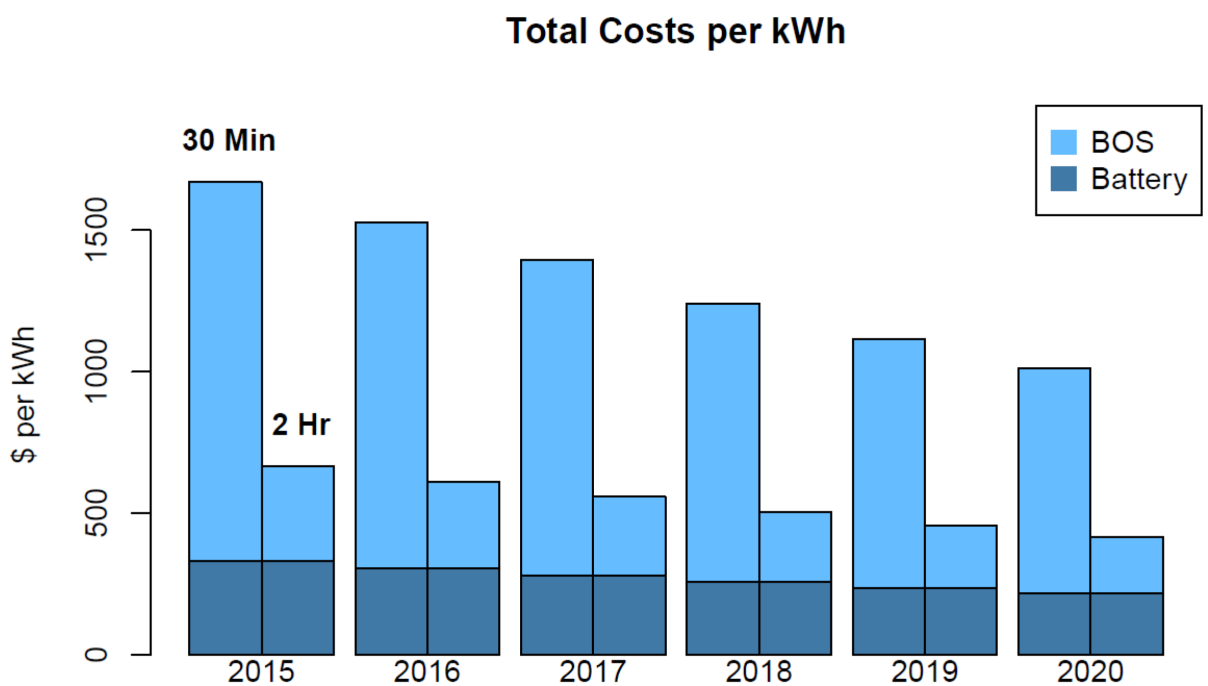

Figure 4. Current and forecasted total systems cost per kWh of storage for a 30-minute and a 2-hour utility-scale system. ***Data obtained from (13)***

Cost Savings from Hybrids

Engineering synergies can make hybrid systems cheaper than building a separate storage and generator. Cost reductions from hybridization can be separated into soft cost savings and savings from sharing hardware.

Soft costs such as permitting and customer acquisition scale by project; therefore, these costs are reduced when the storage and generation system are built at the same time. Labor costs and administrative overhead are also lower for hybrid systems than for separate systems (4).

Hardware cost savings from hybridization come from shared hardware and reduced efficiency losses. As displayed in Figure 5, solar photovoltaic (PV)-storage hybrids can share an inverter, leading to additional savings. Furthermore, peak production, which would otherwise be clipped due to generation exceeding inverter capacity, can now go towards recharging the battery.[1] Charging efficiency also increases due to avoided DC-AC conversion losses.

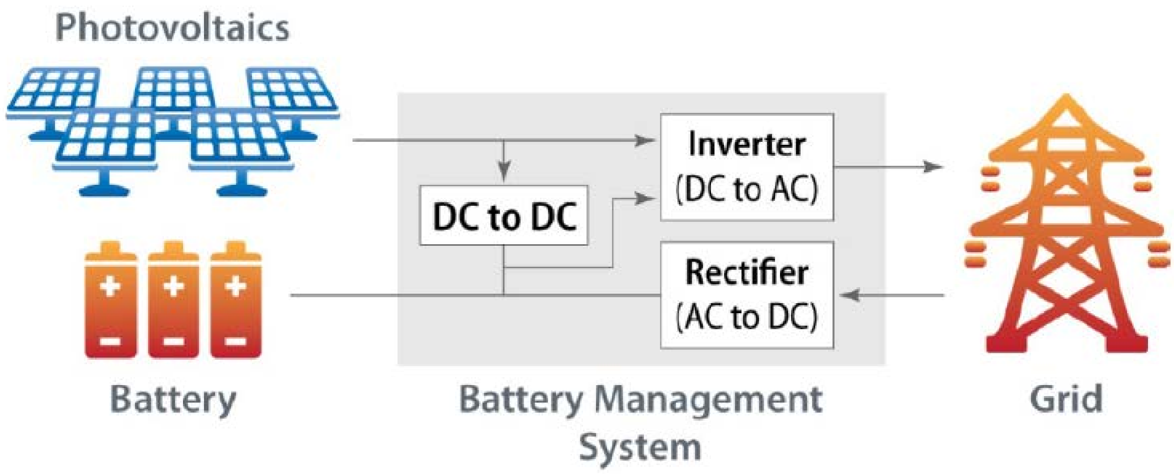

Figure 5. Solar-storage hybrids can share an inverter. ***Figure from (14)***

Savings from hybridizing can be significant. A recent National Renewable Energy Laboratory (NREL) report estimates that installing a separate residential PV and battery system is 18% more expensive than simultaneous installation (4).[2] Although the percentages for utility-scale savings are lower, they are still positive and non-negligible. Coupling a battery with utility PV saves an estimated 36% of battery BOS costs, which relates to roughly 8% of total project installation costs (15).[3] Furthermore, rapidly declining battery costs mean the fraction of total costs from BOS are increasing (16). This increases the relative benefits of hybridization.

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[1] Solar panels seldom produce at their maximum capacity. It is therefore optimal to have an inverter loading ratio (ILR), the ratio of solar capacity to inverter capacity, greater than one (14). A larger ILR increases the inverter capacity factor but also increases the percentage of electricity that must be clipped due to insufficient inverter capacity.

[2] Installation estimates are for a 5.6-kW PV and a 3 kW, 6-kWh solar-storage system. All-in cost estimates were $27,703 for simultaneous installation and $32,786 for separate installation. (4)

[3] The project that was analyzed consists of a 65-MW fixed tilt solar farm with a 50-MW inverter and a 30-MW, 120-MWh lithium-ion battery.

2 Value Streams

Batteries can ramp quickly, have zero end use emissions, face fewer siting restrictions than traditional generators, and are dispatchable. Fast ramping makes storage well-suited to provide ancillary services such as frequency regulation (9). Storage may be sited downstream of transmission nodes to reduce congestion and defer transmission upgrades. Finally, storage can provide behind-the-meter power to customers when it is needed most. This allows batteries to provide resilience during blackouts and reduce demand and time-of-use (TOU) charges to customers.

Along with the cost reductions from co-location, hybridizing storage with a generator can provide added value by combining the rapid response and dispatchability of storage with the long potential run time of the generator. Hybrids also benefit from policy incentives and may be better situated to navigate a changing regulatory framework.

This section discusses eight applications for energy storage:

1. Energy arbitrage
2. Frequency regulation
3. Spinning reserves
4. Generation capacity
5. Transmission deferral
6. Demand charge reductions
7. Resilience and reliability
8. Decreased diesel generation.

Each section contains a brief summary of the application, approximate market size, how storage can provide the service, and how hybridization can add value.

Energy Arbitrage

A battery participating in energy arbitrage stores energy when prices are low and sells energy when prices are high. The possible market size for energy arbitrage is large, but revenues are not sufficient to fully support current battery costs (9). Energy arbitrage is best-suited as a secondary revenue stream paired with other services to increase profitability.

Energy arbitrage pairs well with value streams such as generation capacity, transmission deferral, demand charge reductions, and resilience and reliability, which only use the battery a portion of the time.

Pairing storage with variable generation can increase revenues from energy arbitrage. Periods of high production from variable generation increase line congestion and may exceed line capacity, leading to low or even negative localized prices. Pairing storage with variable generation allows the battery to charge during these periods of low prices. As the penetration of variable renewables on utility grids increase, it can be expected that this value stream will grow. This value stream was captured in all of the following three grid-connected HOMER cases (see cases 4, 5, and 6 in the appendix).

Hybridization also benefits behind-the-meter applications in areas without full net metering laws. The battery can be charged when energy would otherwise be curtailed or sold back to the grid at low rates (17).

> **HOMER Modeling Insight: PV Self Consumption**
>
> For an industrial site in Chennai, India that does not have well-established net metering laws, installing batteries in a system with existing PV generation reduced the energy sold to the grid by approximately 31%.

Frequency Regulation

Frequency regulation is the automatic response of power to a change in frequency due to an imbalance between generation and load (18). The fast response characteristics of batteries make them well-suited for this service (9).

Storage is already playing an important role in some regulation markets. PJM, a U.S. regional transmission organization (RTO), has seen an especially large influx of frequency regulation from batteries and flywheels due to market changes to better compensate resources providing fast response. Storage currently accounts for nearly 40% of PJM fast response regulation capacity requirements (19).

Market rule changes enacted in 2016 have significantly decreased the profitability of storage in PJM, lowering the estimated yearly revenue of a 20-megawatt (MW)/5-megawatt-hour (MWh) system from \$623 in 2014 to \$86 today (20).[4] The PJM rule changes demonstrate the importance of market structure and regulations on the value of storage, along with the risk that policy change poses for storage projects.

While frequency regulation is currently profitable in some locations, the market remains small. The total U.S. market for frequency regulation is around 2 gigawatts (GW) (21), so it may be saturated if storage is deployed on a large scale.

Spinning Reserves

To maintain grid reliability in the case of an unexpected plant outage, utilities are required to keep generation capacity that is partially loaded but may come online quickly. Spinning reserves have the requirements that they must be synchronized to the grid and must be able to ramp to full capacity within 10 minutes. The average U.S. market size for spinning reserves was 5.4 GW in 2014 (21).

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[4] Importantly, the PJM rule changes moved from a 15-minute energy neutral dispatch to a 30-minute conditional neutral dispatch. Thus, storage with 15 minutes of capacity must de-rate to meet the new signal and must operate outside its original design specifications, thereby reducing revenue and increasing wear and tear on the system.

As shown in Figure 6, spinning reserves provide significantly higher revenue per MWh of total capacity than non-spinning reserves. This is due to the added cost of keeping generators synchronized with the grid.

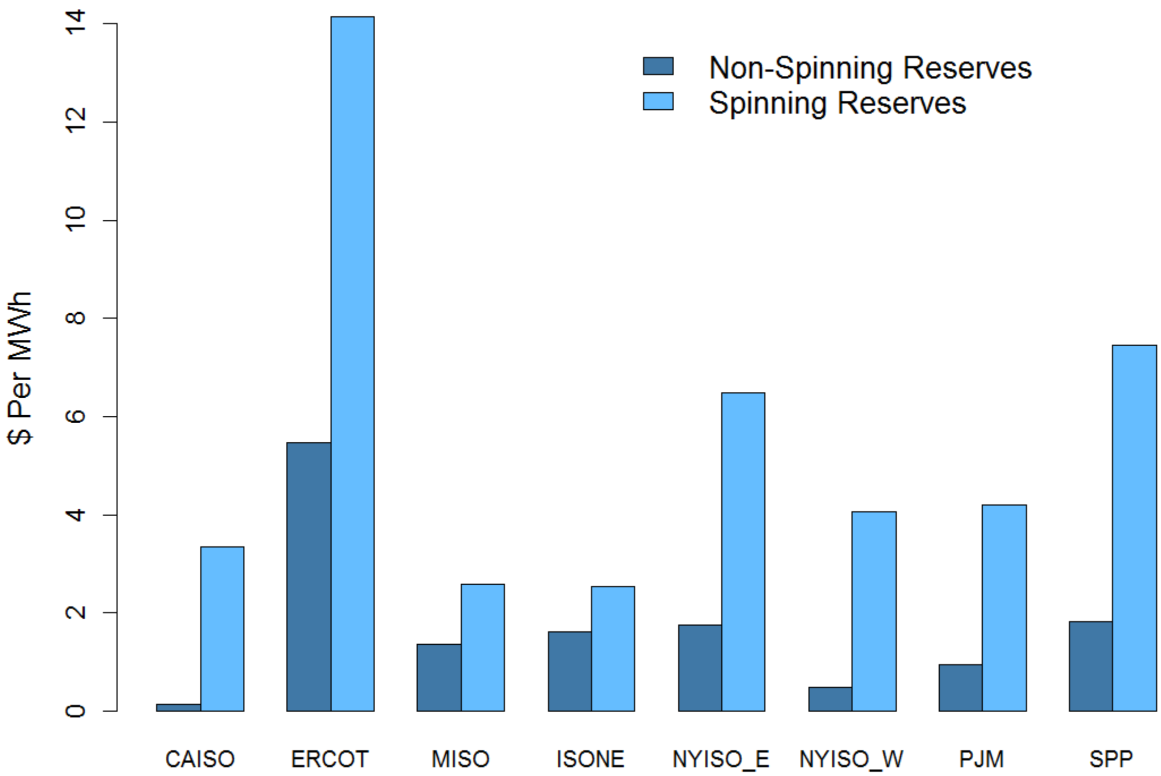


Figure 6. Prices of spinning reserves and non-spinning reserves in 2014. *Data from (21)*

Storage, especially hybrid storage, is well-suited to the spinning reserves market. Traditional generators providing spinning reserves must run at part capacity to remain synchronized to the grid, which is less efficient than when they are running at full capacity. The fast response times of batteries mean they are always synchronized with the grid, even when not discharging.

While spinning reserve prices alone do not currently support storage capacity costs, it may be combined with other value streams. For example, transmission deferral, demand charge reductions, and peaking capacity rarely require the battery to discharge. The rest of the time the battery may sell its capacity into the spinning reserves markets.

The profitability of using storage for spinning reserves is hindered by the high costs of storage capacity and by the requirement that spinning reserve assets be able to discharge for an extended period. Requirements vary by region, ranging from 30-minute to 2-hour minimum run times (21).

Pairing storage with a generator to provide spinning reserves is currently profitable in some markets. A hybrid battery and natural gas generator allows for participation in the spinning reserves market without requiring a long duration battery or a generator inefficiently operating at part load. The fast response of the battery complements the low cost of capacity of the natural gas generator. The battery discharges while the generator ramps and the generator produces for the rest of the period requirement.

> **HOMER Modeling Insight: Ramping Synergies**
>
> The battery fast response also has synergies with diesel generators. Ramping reduces generator efficiency and generator lifespan. A paired battery can smooth generator use, resulting in lower fuel and maintenance costs. This synergy value is captured in both of the HOMER island case studies (see appendix, cases 1 and 2).

Capacity

To ensure long-term grid reliability, some markets pay generators for generation capacity. Capacity payments are potentially a large source of revenue for battery storage and battery hybrids. For example, capacity payments in PJM for 2016 accounted for 22% of total wholesale electricity payments and can greatly increase the profitability of storage (22), (23). Furthermore, because capacity is only needed for a few hours during days with especially high peak demand, capacity payments are well-suited to be stacked with other services. However, as shown in Figure 7, capacity markets can be quite volatile.

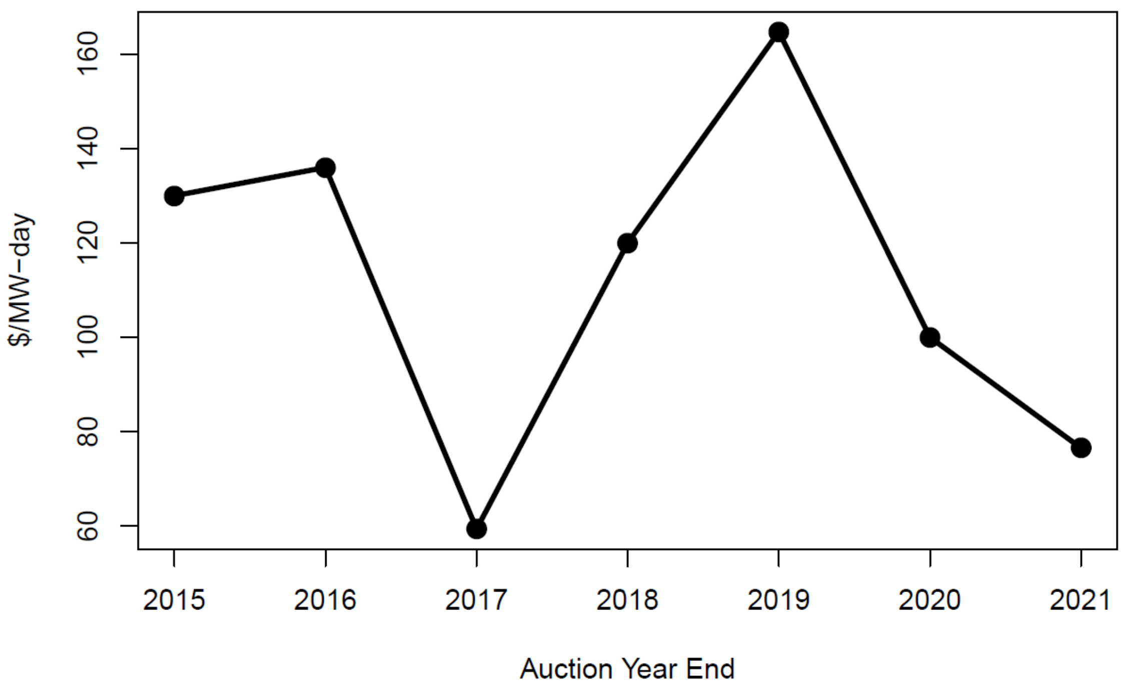


Figure 7. Capacity prices for the PJM market[5]

The primary barrier for storage to sell into capacity markets is a regulatory structure that was originally designed without considering the characteristics of battery storage.

[5] PJM capacity auctions occur three years in advance, so the auction for 2020/21 was held in 2017.

Table 1 displays the different capacity market requirements across U.S. RTOs/independent system operators (ISOs). CAISO and NYISO both have 4-hour requirements to participate in capacity markets. While ISO-New England and PJM do not have minimum-duration requirements, they both have a "no-excuses policy," which requires capacity resources to provide their capacity obligation for the duration of performance events or face significant financial penalties. Because performance periods in these markets have no maximum duration, storage with limited discharge duration faces considerable risk (24).

Table 1. Different Capacity Market Requirements in U.S. RTOs/ISOs

Market	Storage Eligibility	Minimum Availability/Operating Capacity
CAISO	Yes	At least 4 consecutive hours for more than 3 consecutive days
PJM	Yes	No minimum time, but storage resources must be able to offer capacity whenever PJM determines an emergency condition exists to qualify as capacity performance or during weather operation to qualify as base capacity
ISO-NE	Yes	No minimum time, but a penalty is applied if the storage resource is called on in a shortage event and cannot provide energy for the entire period. Maximum output must be greater than 1 MW
NYSO	Yes	Energy-limited resources must be able to provide at least 1 MW of grid injection for at least 4 consecutive hours.
MISO	No	MISO aims to clarify the rules for energy storage participation in the capacity and/or energy and ancillary service markets.

Information obtained from (25).

Declining battery costs are beginning to improve the economics of longer-duration batteries. The year 2016 saw a shift from short duration storage providing frequency response to longer duration storage providing capacity. In response to the Aliso Canyon gas leak, more than 100 MW of 4-hour duration storage came online to provide capacity in California (26). Due to the much larger size of capacity markets as compared with frequency regulation markets, the trend towards longer duration storage is expected to continue.

Battery hybrids selling into the capacity market may be able to benefit from increased capacity payments. While 4 hours of storage are mandated to sell into many capacity markets, most of the time the peak demand period lasts for less than 4 hours. A battery discharging for 1 hour could meet an estimated 46% of peak demand periods, while a battery with 2 hours of capacity could fully produce for 66% of peak demand periods (25). Pairing a battery that can discharge in less than 4 hours with variable generation, such as wind or solar, could increase the hybrid's capacity factor above what the generator and battery, de-rated to meet the 4-hour requirement, could provide.

Pairing batteries with variable generation may also add value in markets with performance penalties. Hybridization can decrease the risk of performance penalties for both battery and generator. The battery faces the risk of having insufficient energy while the variable generation faces the risk of insufficient production during the performance period. The battery can firm total output while the generator increases output duration.

Increasing capacity payments will potentially be an important revenue stream for battery hybrids in the near future. However, some markets prohibit battery hybrids from selling into capacity as a single resource and, in markets where they are allowed, battery hybrids face significant burdens to prove increased reliability in order to receive increased capacity payments (24).

Transmission Deferral

The electricity grid is in constant need of repair and expansion. As demand changes, transmission lines can become congested and must be upgraded. However, maximum loads occur for only a few hours per year, and in many cases the highest annual load occurs on a single day of the year (9).

Storage sited downstream of congested nodes can defer or eliminate the need for transmission upgrades. Transmission deferral can be very valuable, with savings exceeding $500/kW/yr in some cases (18). Furthermore, because storage providing transmission upgrade deferral only needs to discharge for a few days per year, transmission deferral can be stacked with other services to increase profitability.

Hybridization with distributed PV can add value in areas where the duration of maximum load is uncertain or exceeds the battery maximum discharge time. The dispatchability of the battery complements the PV generation to provide dispatchable distributed generation.

Storage can also be paired with wind generation to reduce transmission requirements for wind farms. High wind production often occurs during periods of low demand, and the highest quality wind resources are often located far from demand centers, requiring the construction of new transmission lines to access the resource (27). The variable nature of wind production means transmission lines are underutilized during periods of low production, and energy is curtailed when high production exceeds line capacity.

Co-locating storage with wind can reduce transmission requirements, which can lead to significant cost savings (27). Importantly, storage charged with eligible renewables receives an added 30% tax credit, further improving the economics (5). We discuss the tax credit in more detail in the regulatory framework and policy incentives section.

Demand Charge Reduction

Unlike energy charges, which are based on total energy used, demand charges are based on the highest instantaneous, daily, weekly, monthly, or yearly load. The market for demand charges is large and potentially profitable. Nearly every commercial and industrial facility faces demand charges, and demand charges can constitute more than 50% of a commercial customer's bill (28).

Demand charges lead to high marginal cost of electricity. The dispatchable nature of storage allows batteries to supply power during these periods. The yearly value of battery storage for demand charge reduction ranges from $50/kW to $250/kW, depending on the rate structure (29). Battery storage is an especially economical option for customers facing high demand charge rates or demand charge ratchets, and for customers who are close to the cutoff between two rates.

Demand charge reduction is one of the most valuable uses of storage for many behind-the-meter customers. Figure 8 shows cost savings for a representative California affordable housing apartment complex.

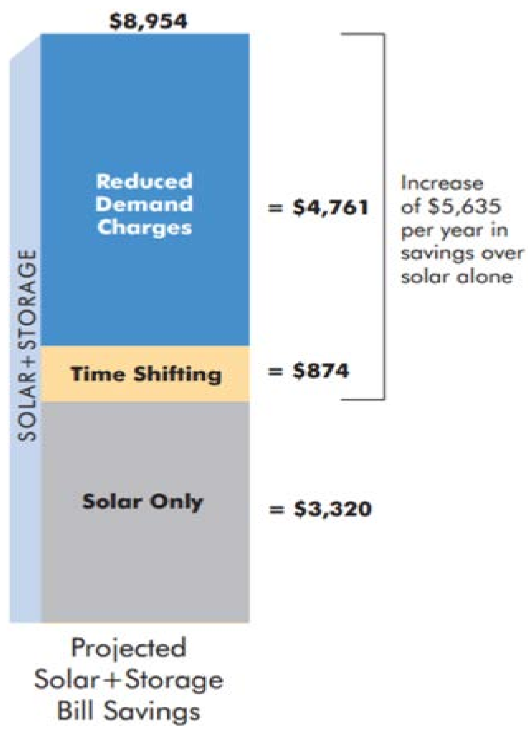


Figure 8. Cost savings for a representative California affordable housing apartment complex. ***Figure from (30)***

To effectively reduce demand charges, the battery must have sufficient capacity to discharge during the peak period. Pairing a battery system with a PV system can allow for a smaller battery to achieve the same demand charge reductions (29). The PV system reduces most of the demand peak while the battery discharges during periods of cloud cover or when solar resource is not available (i.e., evening).

Hybrid systems are not applicable in all cases. The profitability of behind-the-meter storage is dependent on the demand charge rate, and the profitability of a PV system is dependent on the size and structure of TOU charges. Solar panels are best suited for regions with a high TOU rate that corresponds to peak solar production. Solar-storage hybrids are best suited for areas where high demand charges intersect with TOU charges conducive to solar.

Resilience and Reliability

Some businesses and government facilities require that a critical load be met at all times. The economic consequences of a blackout for data centers and many industrial processes can be devastating. For hospitals, other critical care facilities, and critical public services such as police and fire stations, continued power is essential.

Resilience and reliability differ by grid characteristics and outage type. Resilience is the ability to continue power during a natural disaster or major power outage. Resilience commonly implies a stable grid in a developed country, which has infrequent but potentially lengthy power outages.

Reliability refers to the ability to maintain consistent power on an unreliable grid. Reliability commonly implies an unstable grid in a developing country, which has frequent but often short power outages. While self-generation is required for both resilience and reliability, battery requirements and profitability vary between the two. See appendix cases 4, 5, and 6 for examples of resilience and reliability.

There is no formal market for resilience, so size and value of resilience are hard to quantify, but resilience is still valuable. Between 2003 and 2012, weather-related power outages are estimated to have cost the U.S. economy between $18 billion and $33 billion annually (31). To provide resilience, the United States has more than 170 GW of distributed generators built for emergency generation during outages (32).

While diesel generators are traditionally used for backup power, hybridized storage solutions may be a more effective way to provide resilience and reliability. For example, in New York City, regulations prohibit backup generators from storing more than 250 gallons of fuel at any location, meaning they can run out of energy during extended blackouts (33). Furthermore, for areas with unreliable grids, fuel and maintenance costs from frequent generator use can increase electricity costs. In some international markets, the lower reliability of utility power creates stronger drivers for the use of hybridized storage solutions instead of traditional fossil-fueled backup generators. Solar-storage hybrids have also been the solution of choice for energy access solutions and remote health care in developing countries, and for enabling small and medium enterprises.

Storage paired with solar and a diesel generator allows for critical loads to be met with a smaller generator and less fuel (33). This increases resilience length and can reduce costs. Storage-solar-diesel hybrids do have higher capital costs than standalone diesel generators, but reduced fuel use and reduced generator wear, along with added benefits from the solar-storage component, can make up for higher initial costs.

HOMER Modeling Insight: Resiliency and Reliability

The value of hybridized storage solutions for *resiliency* depends on fuel supply limitations. The modeling of a critical industrial load shows that if there are no constraints on the use of fuels like natural gas or diesel, the economics of storage are limited. Limitations on fuel supply, however, could drive the use of hybridized storage solutions.

The desired solution for ensuring reliable power varies based on the *reliability* of a customer's utility provider. Two case studies have been modeled using HOMER Pro—a very unreliable grid in Chennai, India, with existing expensive backup power, and a campus in the United States with occasional, short-duration outages. In the former, it was found that hybridizing the existing grid by adding other sources like PV and storage improves the reliability of the grid by ensuring continuous supply of power and alleviates the severity of frequent outages. In addition to the improved reliability in the face of frequent outages, the system also reduced grid purchases by approximately 25%. In the latter case with fewer utility outages, it was found that customers with steam and thermal loads could use combined heat and power (CHP) to reduce operational costs while increasing reliability. It was also found that CHP can be complementary to PV and storage investments.

Decreased Diesel Generation

Islands, remote communities, mines, and military forward operating bases offer unique challenges and opportunities for energy production. Many have significant energy requirements but no connection to a larger grid. Diesel generators currently provide the bulk of power at these locations, meaning electricity is much more expensive than at grid-connected sites. Island electricity prices, for example, are three to five times higher than prices in large connected grids (34).

Paired storage with wind or solar is already an economic alternative to diesel generation in off-grid applications. Generation from solar or wind removes the need to transport fuel, while the battery offers multiple system-level services that enable economical reliable and resilient power. For example, an estimated 5 gigawatt-hours of energy storage capacity paired with solar is already economical on small islands because of the high costs of diesel generation (35).

Solar-storage-diesel combinations are especially attractive for microgrids. The low variable cost of solar combines with the availability of the diesel generator. The battery allows for energy smoothing and optimal generator use.

Homer Modeling Insight: Diesel-PV-Storage Hybrids

Hybridizing a battery with solar and a diesel generator in most cases offers more benefits than a standalone generator at a lower levelized cost. A diesel-PV-storage hybrid system in an off-grid system for a medium island provides savings of $14 million in net present cost while also saving approximately 5,000 tons of CO_2 per year compared to a generator-only system.

See cases 1, 2, and 3 in the appendix for more information on how and when hybrid systems are economic for island systems and energy access.

3 Regulatory Framework and Policy Incentives

This section provides a brief overview of some of the most influential national and state policies that affect storage projects. The United States alone has more than 3,000 utilities, eight electric reliability councils, and thousands of engineering, economic, environmental, and land use regulatory authorities (36). Because the profitability of a storage project depends on national, state, and local policies, further analysis is required before embarking on any specific project.

Regulatory Framework

Energy markets were originally designed with a separation between generation, transmission, and consumption. Battery storage does not fit readily into any of these categories, although it can provide generation, transmission, and customer services; therefore, in many jurisdictions, current market regulations do not fully compensate storage for its services (18).

Succinctly, resource participation in electric markets is governed by participation models that consist of market rules for different types of resources. In November 2016, FERC filed a notice of proposed rulemaking to establish participation models for utility-scale and aggregated distributed storage (6). FERC proposed rules to address the fact that, "current tariffs that do not recognize the operational characteristics of electric storage resources serve to limit the participation of electric storage resources in the organized wholesale electric markets and result in inefficient use of these resources." (6).

Regulatory reform is continuously evolving, suggesting that battery storage projects must consider not only which services can be provided but also which services may be monetized today and in the future. Market rules addressing customer-sited storage are often less mature than wholesale market structures, which prohibits clear approaches for remuneration of possible multiple value streams to the distributed system owner and negatively impact the system economics.

Combining battery storage with generation can allow the hybrid resource to meet regulatory requirements, such as minimum production times and minimum ramp rates, that the storage or generator could not meet on its own.

Federal and State Incentives

Policy incentives vary by region and are often different for utility-scale and behind-the-meter applications. Furthermore, some incentives are only applicable to batteries paired with renewables.

At the federal level, storage charged with renewable energy is eligible for a 30% federal investment tax credit (ITC) and an accelerated depreciation schedule. Figure 9 displays the structure of the ITC and the modified accelerated cost recovery system (MACRS). Battery storage charged with at least 50% renewable energy follows a 5-year depreciation schedule instead of a 7-year schedule. Storage that is charged from at least 75% renewable energy receives a tax credit equal to 30% of the portion charged by renewables.[6]

[6] For example, a system charged by renewables 80% of the time receives a 30% x 80% = 24% tax credit.

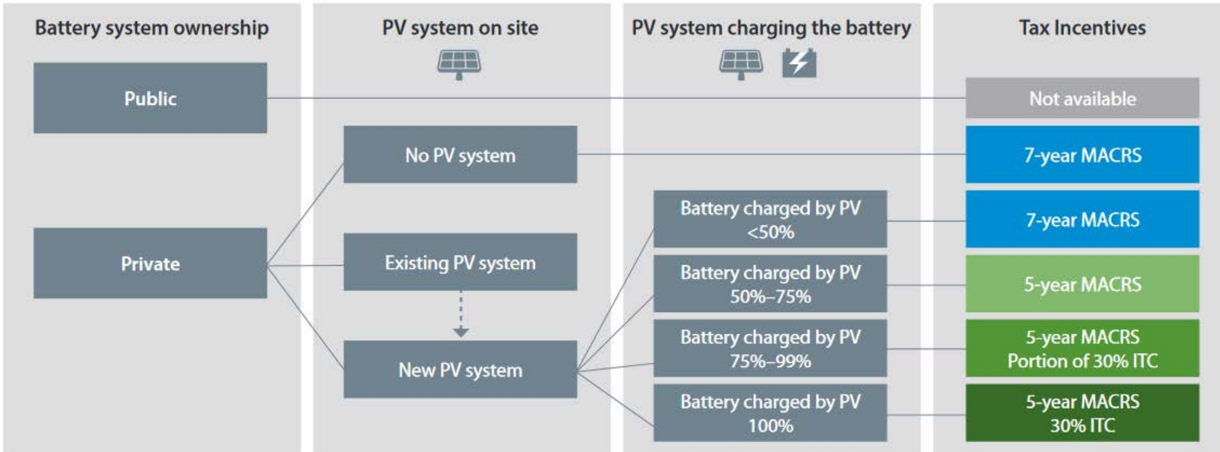


Figure 9. Federal tax incentives for battery storage systems. ***Figure from (5)***

Because the storage and generation must be in close proximity and under common ownership to receive the tax benefits, these tax incentives are especially beneficial to renewable hybrid systems.

At the state level, different levels of policy support have led to very different levels of storage deployment. California has several energy storage incentives and mandates. Assembly Bills 2514 and 2868 mandate more than 1.3 GW of energy storage procurement by 2020, and California's Self-Generation Incentive Program (SGIP) provides incentives for behind-the-meter storage. Combined, these have led to California supporting the bulk of utility-scale and behind-the-meter storage in the United States.

The majority of battery deployments are located in California, Hawaii, and the Northeast. California is the largest market, with the bulk of storage projects installed to provide capacity after the Aliso Canyon gas leak (26) (3).

Resilience programs in the Northeast, such as the New Jersey Resiliency Bank, are also beginning to provide grants for solar-storage projects to provide backup power during natural disasters (37).

4 Market Considerations

There are several market opportunities for battery storage and battery hybrids. Each market is differentiated by primary application and project location. Not all generator pairings are applicable for all applications or locations. This section provides an overview of key markets for battery storage and storage hybrids. Note that this report does not consider the small off-grid market, but recognizes that it is also a large and important market.

Grid Types

We divide grid types into three categories: large grids, microgrids, and islands and remote locations. Large grids may be further divided into developed and developing grids.

- **Large Developed Grid.** The U.S. electricity grid is an example of a large developed grid, providing reliable energy at a low cost. Primary storage markets for large grids include ancillary services, transmission deferral, and customer demand charge reductions. Increasing reliability and reducing diesel fuel use are not primary concerns.

- **Large Developing Grid.** India is an example of a large developing grid (see case study 6 in the appendix for details on developing grids). A large developing grid provides low-cost energy, relative to the cost of a diesel generator, but blackouts are common. Increasing reliability is an important market for developing grids.

- **Microgrid.** Examples may include universities, hospitals, and military bases. A microgrid is connected to a larger grid but has the ability to produce its own electricity for demand charge and resilience purposes. Microgrids may be further subdivided by the size of the load.

- **Islands and Remote Locations.** Examples include mines, off-grid communities, and, of course, islands. Islands and remote locations are not connected to a larger grid and generally face higher energy costs because most energy production comes from diesel generators. Thus reducing diesel fuel use is the primary application for battery storage in these markets.

Storage Location on Grid

Along with the type of grid, storage applications change depending on where on the grid the battery is located. Battery storage can be located at the transmission level, distribution level, or behind the meter. Not all services can be provided at all locations. Large utility-scale batteries are located at the transmission level and used primarily for frequency regulation, capacity, and energy arbitrage. Smaller distributed batteries are primarily used for demand charge reduction, transmission deferral, and resilience or reliability. However, distributed storage may provide wholesale services as well.

In general, the closer to the customer load a battery is sited, the more services it can perform (18). For example, storage providing transmission deferral must be sited downstream of congestion, and batteries used for demand charge reduction must be sited behind the meter.

Although battery storage is more modular than most electricity resources, it is still affected by economies of scale. As such, larger-scale projects have lower marginal costs than smaller projects. In 2016, batteries used for commercial demand charge reduction were, on average, 25% more expensive than utility-scale battery storage (13). Wholesale markets also have minimum size requirements to participate. While small storage can be aggregated, coordination and customer procurement adds to aggregation costs.

Markets for Utility-Scale Storage

The largest potential application for utility-scale battery storage in large developed and developing grids is as a replacement for peaking plants (16). Along with replacing peaking plants, storage-gas turbine hybrids have widespread potential market applications for providing spinning reserves. While currently only used in Southern California, these hybrid systems can offer attractive economics in most markets where regulations allow for hybrid participation.

Large islands represent attractive markets for utility-scale storage because they have especially high fuel costs. Islands with large current or planned renewable penetration are especially attractive for battery hybrid systems because high levels of renewable penetration allow the battery to be cheaply charged during periods when energy would otherwise be curtailed.

California represents the biggest U.S. market for battery storage due to its storage mandate and favorable market conditions. California currently accounts for 54% of total U.S. storage deployments (16). Furthermore, nearly 80% of current projects under development or contracted in the United States are in California (3).

Markets for Distributed Storage

Distributed storage can reduce demand charges, defer transmission upgrades, and provide resilience and reliability.

In large developed grids, areas with high demand charges offer the best opportunities for distributed storage. New York and California present the largest U.S. markets for distributed storage due to high demand charges, distributed storage mandates, and tax incentives for storage. However, there are many regions across the country where high demand charges present opportunities for distributed storage. Figure 10 displays U.S. demand charges by utility service territory.

For batteries providing customer services, large facilities that have economies of scale offer the best market opportunities. Batteries with sufficient capacity, either 100 kW or 1 MW depending on the region, can also participate in capacity, wholesale energy, and frequency regulation markets.

Large potential energy storage customers include universities and college campuses, hospitals, laboratories, large office buildings, industrial sites, water treatment plants, municipalities, energy cooperatives, hotels and resorts, mining operations, and military bases.

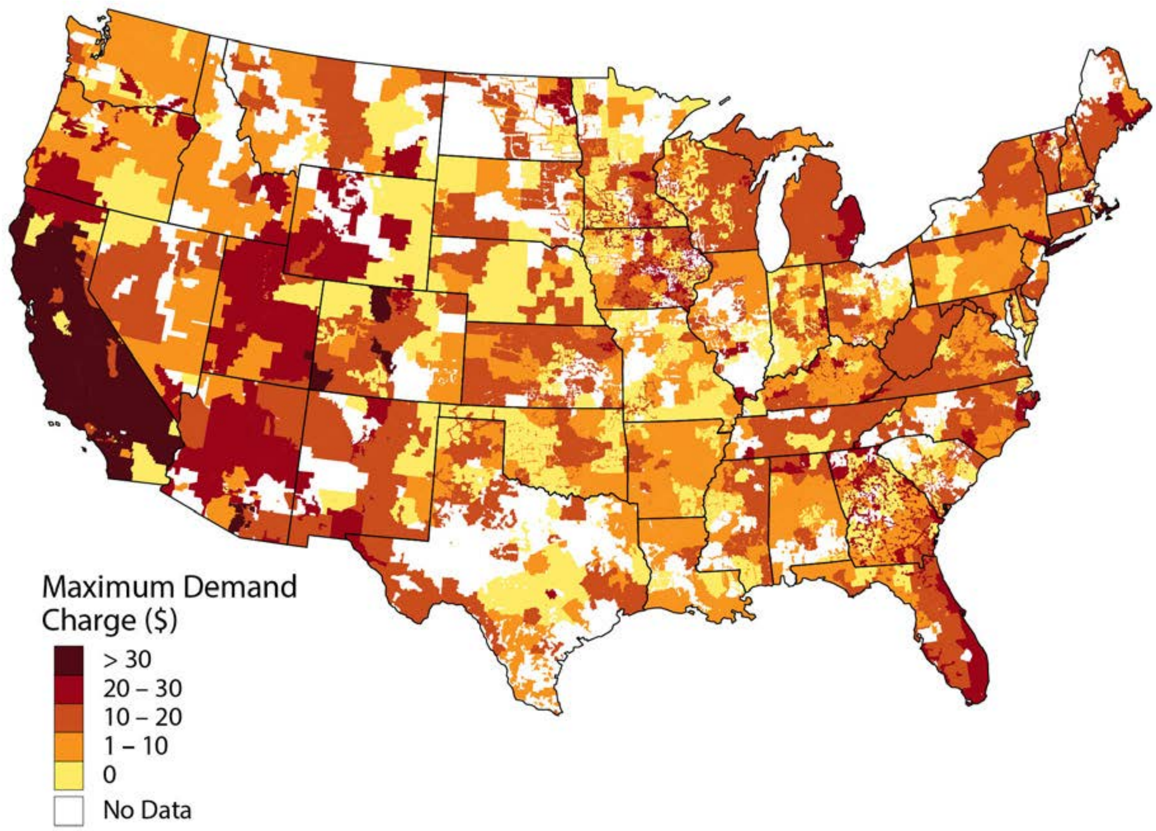


Figure 10. Maximum demand charge rates by utility service territory. ***Data obtained from (38)***

In large developing grids, providing reliability represents the largest market potential. Batteries paired with solar and diesel generators are becoming increasingly attractive options for providing reliable power.

Small islands and remote locations present attractive markets for distributed storage. The battery pairs with diesel generation and renewable energy to reduce fuel costs. See cases 1, 2, and 3 in the appendix for more information.

HOMER Modeling Insight: Distributed Generation

There are a range of potential distributed generation options, including CHP, solar, batteries, diesel generation, and a hybrid of these solutions. The ideal system will vary based on a particular customer's energy demands, available resources, and needs. Compare cases 4 and 5 in the appendix to see how a large campus may have access to CHP and need reliable power during infrequent outages (Case 5), whereas other customers may be interested in resilience during longer-duration outages and may not have on-site thermal loads (Case 4). Some combination of these solutions will likely be beneficial to the customer, and it is useful to use modeling tools to identify the options that make the best economic case for customer-sited solutions.

Summary of Markets

Table 2 summarizes the major markets for battery storage and battery hybrids. Primary application refers to the value stream that provides the majority of the revenue. Secondary applications refer to value streams that can be stacked to increase profitability.

Table 2: Major Hybrid Markets

Primary Application	Primary Market	Battery Location	Secondary Applications	Generator Pairings
Capacity	Large Grids	Utility/ Large Distributed	Energy Arbitrage, Frequency Regulation	Wind, PV
Frequency Regulation	Large Grids	Utility/ Large Distributed	-	-
Spinning Reserves	Large Grids	Utility	Frequency Regulation, Black Start	Natural Gas Turbines
Transmission Deferral	Large Grids	Utility (Distributed)	Energy Arbitrage, Frequency Regulation, Black Start (Demand Charge Reduction, Resilience)	Wind, PV
Demand Charge Reductions	Large Grids and Islands	Distributed	Resilience, Transmission Deferral, Energy Arbitrage	PV, CHP
Resilience (Reliability)	Developed Grids (Developing Grids)	Distributed	PV Self-Consumption, Demand Charge Reduction	PV, Diesel-PV
Decreased Diesel Generation	Islands and Remote Locations	Utility/Distributed	Decreasing Diesel Ramping[7]	PV, Diesel-PV, Wind

[7] Decreased diesel ramping refers to the battery-reducing wear and tear on the generator. See HOMER modeling in the appendix for more information on battery-diesel-PV hybrids

5 Case Studies

This section provides four case studies of storage applications. Each case study provides insight into uses for battery storage and battery hybrids, and the types of markets battery storage and battery hybrids are likely to serve in the coming years.

Kaua'i Solar-Storage Hybrid Projects

Both the AES Corporation and Tesla recently constructed solar-storage hybrid projects on the Hawaiian island of Kaua'i (Figure 11). In 2017, the Kaua'i Island Utility Cooperative (KIUC) signed a power purchase agreement with AES for a 28-MW PV system paired with a 20-MW/100-MWh battery (39). Tesla also opened a 13-MW solar farm combined with a 13-MW/52-MWh battery installation in 2017.

High costs of power from petroleum-fired generators led KIUC to aggressively adopt renewable generation. KIUC currently provides 36% of its generation from renewables and plans to reach 70% by 2030 (39). During peak solar hours, 77% of electricity is already produced by solar energy. Without storage, continued solar additions would lead to increased solar curtailment. The high levels of renewable penetration also cause a significant amount of ramping on the system.

The battery systems smooth generation and allow for a higher level of total generation to be produced from solar. Pairing the battery with solar both reduces costs and allows the battery to receive the 30% federal ITC. The combination of high electricity prices from petroleum-fired generators, high penetration of renewables, and the federal ITC makes the Kaua'i project economically viable (39).

Figure 11. Tesla solar-storage facility in Kaua'i

Sterling Municipal Light Department

In 2016, the Sterling Municipal Light Department (SMLD) in Sterling, Massachusetts, built a 2-MW/3.9-MWh battery system to pair with an existing 3.4-MW solar array. SMLD, a wholesale aggregator of power in the ISO-New England region, uses the storage system for power resilience and demand charge reduction.

Because the solar-storage system provides backup power for critical response functions in the case of a power outage, SMLD received a $1.46 million grant from the Massachusetts Department of Energy Resources as part of the Community Clean Energy Resiliency Initiative. SMLD also received a $250,000 grant from the U.S. Department of Energy.

While SMLD did not benefit from reduced construction costs because the solar panels were built at a different date than the battery storage, hybridization still provides resilience benefits that the battery or PV alone could not deliver.

Along with resilience, the battery provides value through a combination of arbitrage, frequency regulation, and demand charge reductions. ISO-New England has monthly regional network service payments and a yearly capacity payment (40).[8]

Table 3 shows projected yearly profits per MW for the project.

Table 3. Projected Revenue

Application	Arbitrage	Frequency Regulation	Monthly Peak Demand Reduction	Yearly Peak Capacity Reduction	Total
Revenue ($/MW-yr)	13,321	60,476	98,707	115,572	288,076

Estimates from (40)

More than two-thirds of yearly revenues for the SMLD project come from the battery operating a few times each year to reduce demand charges. This fact demonstrates the importance of demand charge on battery storage profitability. However, the resilience grants also significantly improved the project economics.

At an estimated total system cost of $1.7 million per MW of capacity, the project has a payback period of less than seven years before the grants for resilience are considered. With the grants, the payback period is cut roughly in half to a 3–3.5-year payback period.

Irvine Ranch Water District

In September 2016, Advanced Microgrid Solutions (AMS) and Irvine Ranch Water District (IRWD) in Irvine, California, signed a private-public partnership for the installation of a 7-MW/34-MWh battery storage system. AMS will install batteries at 11 water treatment facilities and pumping stations to provide capacity and reduce demand charges (41).

The batteries will be aggregated to sell into capacity and ancillary service markets as a single unit. AMS will own and operate the batteries to manage requests from Southern California Edison for load reduction as part of a 10-year power purchasing agreement. At the same time, AMS receives payment from IRWD for demand charge reductions. The water district benefits from expected annual cost savings of $500,000.

[8] The Regional Network Service payment is based on the hour load that is coincident with the largest aggregate network load for the month, while the capacity payment is based on electricity usage during the network yearly peak hour.

Southern California Edison Spinning Reserves

In April 2017, the first of GE's 50-MW LM6000 gas turbines paired with a 10 MW/4.3-MWh battery storage system came online. The hybrid system provides spinning reserves and primary frequency response while the turbine is offline (42).

The storage provides power during the turbine's five-minute ramp time, and the generator provides power during the rest of the required run time. This allows the turbine to sell its entire 50 MW of capacity into the spinning reserves market while offline. The turbines were retrofitted to reduce startup times from the usual 10 minutes to 5 minutes in order to reduce the required battery size.

The battery addition generates $1.4 million in additional yearly revenue from spinning reserves (43). At around $5 million for the battery and related BOS, the payback period is a little over 3 years.

In addition to attractive economics, the hybrid system reduces water use and air emissions. The demonstration that battery storage can be profitably paired with generators to provide spinning reserves opens up a large potential marketplace for storage hybrids.

6 Market Potential

In this section, we provide a high-level analysis of market size for battery storage and battery hybrid uses. Accurately estimating the market size for battery storage and battery hybrids is a difficult challenge. Local regulations, policies, and market conditions each play an important role in determining the profitability of a project. Furthermore, even if market conditions are conducive to battery hybridization, physical conditions, such as whether a site has a quality solar resource, place further barriers. The numbers produced in this section should be viewed as indicating general market size. We recommend further analysis be performed before any policy, regulatory, or business decisions are taken.

We first estimate a market upper bound for storage for each application, and then estimate the fraction that battery storage and battery hybrids will comprise. A detailed description of the estimation methodology we employ can be found in (44).

We use estimates of U.S. battery storage market upper bounds from Sandia National Laboratories (44). To estimate world market upper bounds we assume the ratio of transmission and ancillary services to total generation capacity is equivalent across regions. We then use data on generation capacity by region from (45) to estimate world maximum market potential.

To estimate future market size we use a synthesis of market forecasts from (3), (47), (48), and (49), along with consultations with industry experts. We use estimates from (46) for market upper bounds and market size for battery hybrids to decrease diesel generation.

Table 4 contains 10-year estimates of cumulative installed battery capacity. Note that the numbers in Table 4 refer to installed capacity in megawatts instead of megawatt-hours.

Market Upper Bound refers to the maximum market size battery storage could reasonably supply for each application. Market Estimate represents a 10-year forecast of total installed battery capacity, while Hybrid Estimate represents a 10-year forecast for *only* battery hybrid capacity.[9]

[9] Battery hybrid capacity here denotes battery capacity for a hybridized system. Thus a 10-MW battery paired with a 50-MW generator will have a battery hybrid capacity of 10 MW.

Table 4. Estimated Market Size

	U.S. Market Potential (MW of capacity)[a]			World Market Potential (MW of capacity)		
Primary Application	Market Upper Bound[b]	Market Estimate[c]	Hybrid Estimate[d]	Market Upper Bound	Market Estimate	Hybrid Estimate
Capacity	18,000	9,000	4,500	112,000	40,000	20,000
Frequency Regulation	2,000	600	0	12,000	3,000	0
Spinning Reserves	6,000	400	400	37,000	2,500	2,500
Transmission Deferral	10,000	2,000	1,000	62,000	12,000	6,000
Demand Charge Reductions	32,000	8,000	5,000	200,000	30,000	20,000
Resilience and Reliability	9,200	1,300	1,000	57,000	8,000	6,000
Decreased Diesel Generation[e]	-	-	-	50,000	15,000	15,000
Total	77,200	21,300	11,900	530,000	110,500	69,500

[a] Measured in cumulative capacity additions.
[b] U.S. Market Upper Bound Estimates from Sandia National Laboratory (44).
[c] Market Estimates from (3), (46), (47), (48), (49) and communication with industry experts.
[d] Hybrid numbers for battery capacity in hybrid.
[e] Estimates from (46).

Navigant Research estimates 94 GW of world installed battery capacity by 2025, with 21.6 GW installed in 2025, putting their estimates in line with our forecast of 110.5 GW of capacity by 2028 (47). Similarly, estimates of 27.4 GW for distributed solar-storage hybrids by 2026 coincide with our estimates of 26 GW of solar-storage hybrids for resilience and demand charge reductions (49). Greentech Media Research (GTM) forecasts U.S. annual battery storage deployments to be 7.2 GWh by 2022, equating to roughly 2.5 GW of annual capacity additions (3). Thus GTM estimates of cumulative U.S. additions are within the same range of 21.3 GW by 2028.

Our estimates indicate the majority of utility-scale battery deployments will be for energy capacity as a replacement for peaking plants. Demand charge reduction also has a large market potential. Finally, battery hybrids to reduce diesel fuel use are expected to have a large market potential in the near future. The reader should keep in mind, however, that high levels of uncertainty in future battery costs and regulatory and policy decisions make any market forecast imprecise.

7 Conclusion and Key Findings

The market trends for battery storage and battery hybrids are positive. Decreasing costs, an improving regulatory framework, and an increasing understanding and acceptance of storage technology by utilities and customers are all contributing to the rapid growth in storage installations. However, high capital costs and an uncertain regulatory framework remain as barriers that today's battery storage projects must overcome.

Compared with building separate systems, pairing storage with a generator can decrease costs, increase revenue, and benefit from regulatory design and policy incentives. The fast response and dispatchability of a battery system can complement the longevity and lower capital costs of a generation system. Battery hybrid systems also share soft costs and hardware, reducing construction and installation costs relative to separate systems.

Hybrid storage projects are already providing critical resilience, increasing the efficiency of spinning reserves generators, and reducing the cost of power on islands and remote locations. In this paper, we have described the primary market applications for battery storage and battery hybrids. We have discussed regulatory framework and policy incentives that affect the profitability of storage. Finally, we described some of the key market considerations for battery storage and battery hybrids. Key takeaways of this paper are listed below.

Battery Costs

- Lithium-ion battery costs fell by more than 65% between 2010 and 2015, and costs are expected to continue to decline.
- Battery costs are most significant for applications such as transmission deferral and selling into capacity markets, which may require 4 or more hours of discharge duration. BOS costs are relatively higher for short-duration applications, such as frequency regulation.
- Battery hybrids can reduce BOS costs by building one hybrid unit instead of two individual storage and generator units.
- Solar-storage hybrids can further reduce costs by sharing an inverter and other system equipment.

Value Streams

- Battery storage can provide multiple value streams, including energy arbitrage, frequency regulation, spinning reserves, generation capacity, transmission deferral, demand charge reductions, resilience and reliability, and island and off-grid generation.
- Combining value streams can increase profitability.
- Hybrids work best when the strengths of battery storage—fast response and dispatchability—are paired with generator strengths — lower capacity costs and unlimited duration.
- A storage-gas turbine hybrid can sell into spinning reserves while the generator is offline, eliminating the need for the turbine to inefficiently run at part capacity.
- Depending on regulatory decisions, paired storage-variable generation hybrids may be able to increase the capacity factor of both.

- Pairing solar, storage, and a diesel generator can be economic in areas with high fuel costs, such as islands and remote locations.
- Solar-storage hybrids can more effectively reduce demand charges than either a battery or PV system alone.
- Storage hybrids can provide grid resilience during power outages.

Regulatory Framework and Policy Incentives

- Currently in the United States, the 30% investment tax credit provides an incentive to hybridize battery storage with renewables.
- Further regulatory changes beneficial to storage, especially at the federal level, are still several years away.
- In the nearer term, state mandates and incentives can improve battery storage and battery hybrid economics.
- Grants and initiatives for power resilience can improve the economics of battery hybrids.

Market Considerations and Market Potential

- The largest application for utility-scale storage is peaking capacity, while the largest application for distributed storage is for demand charge reductions and resiliency.
- The near-term market opportunities for utility-scale storage include large islands and markets with high capacity payments.
- Utility-scale battery hybrids can help meet specific market regulations, such as ramp requirements and minimum discharge times, and avoid nonperformance penalties. Tax credits and incentives also increase the profitability of hybrid projects.
- The customers for distributed storage and hybrid projects are those with large energy loads, such as demand aggregators, universities, mines, and municipalities with sufficient load to support economies of scale.
- Hybrids used for resilience and reliability could be especially beneficial for unreliable grids and customers for whom blackouts are especially costly or endangering.
- Customers in areas with both large demand charge reductions and high TOU charges that coincide with solar production could benefit most from solar-storage hybrids.

Works Cited

1. REN21. *Renewables 2017 Global Status Report,* 2017.

2. McKinsey & Company. *An Integrated perspective on the Future of Mobility.* Bloomberg New Energy Finance, 2016.

3. GTM Research Group. *U.S Energy Storage Monitor Q2 2017 Full Report.* Wood Mackenzie, 2017.

4. Kristen Ardani, Eric O'Shaughnessy, Ran Fu, Chris McClurg, Joshua Huneycutt, Robert Margolis. *Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016.* NREL, 2016.

5. Emma Elgqvist, Kate Anderson, Edward Settle. *Federal Tax Incentives for Battery Storage Systems.* NREL, 2017.

6. Federal Energy Regulatory Commission. *Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent Systems Operators.* Notice of Proposed Regulation. Section 12. FERC, November 2016.

7. REN21. *Renewables 2005 Global Status Report.* 2005.

8. Navigant Research. *Advanced Batteries for Utility-Scale Energy Storage,* 2016.

9. Abbas A. Akhil, Georgianne Huff, Aileen B. Currier, Benjamin C. Kaun, Dan M. Rastler,. *DOE/EPRI Electricity Handbook in Collaboration with NRECA.* Sandia Laboratories, 2015.

10. Björn Nykvist, Måns Nilsson. *Rapidly Falling Costs of Battery Packs for Electric Vehicles.* Nature Climate Change, 2015.

11. Wesley Cole, Cara Marcy, Venkat Krishnan, Robert Margolis. *Utility-scale Litium-Ion Storage Cost Projections for Use in Capacity Expansion Models.* IEEE, 2016.

12. O. Schmidt, A. Hawkes, A. Gambhir, I. Staffell. *The Future Cost of Electrical Energy Storage Based on Experience Rates.* Nature Energy, 2017.

13. Luis Ortiz, Ravi Manghani. *Grid-scale Energy Storage Balance of Systems 2015-2020.* GTM Research, 2016.

14. David Feldman, Robert Margolis, Paul Denholm, Joseph Stekli. *Exploring the Potential Competitiveness of Utility-Scale Photovoltais plus Batteries with Concentrating Solar Power, 2015-2030.* NREL, 2016.

15. Paul Denholm, Josh Eichman, and Robert Margolis. *Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants.* NREL, 2017.

16. Manghani, Ravi. *Energy Storage State of the Industry Today.* GTM Research, 2017.

17. Travis Simpkins, Kate Anderson, Dylan Cutler, Dan Olis. *Optimal Sizing of a Solar-Plus-Storage System for Utility Bill Savings and Resiliency Benefits.* NREL, 2016.

18. Garret Fitzgerald, James Mandel, Jessee Morris, Herve Touati. *The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid.* Rocky Mountain Institute, 2015.

19. Monitoring Analytics, LLC. *State of the Market Report for PJM.* 2016.

20. Lacey, Stephen. *New Market Rules Destroyed the Economics of Storage in PJM. What Happened?* Greentech Media, 2017.

21. Zhi Zhou, Todd Levin, Guenter Conzelmann. *Survey of U.S. Ancillary Services Markets.* Argonne National Laboratory, 2016.

22. Monitoring Analytics, LLC. *State of the Market Report for PJM 2016.* 2017.

23. Paul Denholm, Jennie Jorgenson, Marissa Hummon, Thomas Jenkin, David Palchak, Brendan Kirby, ookie Ma, Mark O'Malley. *The Value of Energy Storage for Grid Applications.* NREL, 2013.

24. Energy Storage Association. *Comments of the Energy Storage Association on Electric Storage Participation in Regions with Organized Wholesale Elecric Markets,* 2016.

25. Harjeet Johal, Douglas Feitosa Tome, Kenneth Collision. *Ulocking the Hidden (Capacity) Value in Energy Storage.* ICF, 2016.

26. Munsell, Mike. *In Shift to Longer-Duration Applications, US Energy Storage Installations Grow 100% in 2016.* gtm Research, 2017.

27. *The Value of Compressed Air Energy Storage with Wind in Transmission-constrained Power Systems.* Paul Denholm, Ramteen Sioshani. Energy Policy, 2009, Vol. 37.

28. J. Neubauer, M. Simpson. *Deployment of Behind-The-Meter Energy Storage for Demand Charge Reduction.* NREL, 2015.

29. Alex Eller, William Tokash. *The Benefits of Solar+Storage for Commercial and Public Buildings.* Green Charge, 2016.

30. Wayne Waite, Seth Mullendore. *Solar Risk: How Energy Storage can Preserve Solar Savings in California Affordable Housing.* Clean Energy Group, 2017.

31. Executive Office of the President. *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages,* 2013.

32. Department of Energy. *The Potential Benefits of Distributed Generation and Rate-Related Issues that may Impede their Expansion,* 2007.

33. Kate Anderson, Kari Burman, Travis Simpkins. *New York Solar Smart DG Hub-Resilient Solar Project: Economic and Resiliency Impact of PV and Storage on New York Critical Infrastructure.* NREL, 2016.

34. Kaitlyn Bunker, Stephen Dolg, Kate Hawley, Jesse Morris. *Renewable Microgrids; Profiles from Islands and Remote Communities Across the Globe.* Rocky Mountain Institute, 2015.

35. *Assessment of the Global Potential for Renewable Energy Storage Systems on Small Islands.* P. Blechinger, R. Sequin, C. Cader, P. Berhau, Ch. Breyer. Energy Procedia, 2014.

36. Regulatory Assistance Project. *Electricity Regulation in the US: A Guide,* 2011.

37. Olinsky-Paul, Todd. *Resilient Power: A Guide to Resilient Power Programs and Policy.* Clean Energy Group, 2015.

38. Joyce McLaren, Seth Mullendore. *Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges.* NREL, 2017.

39. Bloomberg. *Case Study: AES Delivers Firm Solar with $110/MWh PV-and-storage PPA in Hawaii.* Bloomberg New Energy Finance, 2017.

40. *The Value Proposition for Energy Storage at the Sterling Municipal Light Department.* Raymond Byrne, Sean Hamilton, Daniel Borneo, Todd Olinsky-Paul, Imre Gyuk. Sandia National Laboratories, 2017.

41. Maloney, Peter. *Tesla, AMS ink 34MWh storage deal with California Water System*, Utility Dive, 2016.

42. —. *Gas Plant Makers Embrace Batteries With Hybrid Machines*, Utility Drive, 2017.

43. Martin, Chris. *Slap a Battery on a Gas Turbine and Make an Extra $1.4 Million*, Bloomberg, 2017.

44. Jim Eyer, Garth Corey. *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*, Sandia National Laboratory, 2010.

45. International Energy Agency. *World Energy Outlook 2016*, International Energy Agency, 2017.

46. IRENA. *Off-grid Renewable Energy Systems: Status and Methodological Issues*, International Renewable Energy Agency, 2015.

47. Alex Eller, Anisa Dehamna. *Energy Storage for the Grid and Ancillary Services*, Navigant Research, 2016.

48. Alex Eller, Anissa Dehamna. *Market Data: Commercial & Industrial Energy Storage*, Navigant Research, 2016.

49. William Tokash, Anissa Dehamna. *Distributed Solar PV plus Energy Storage Systems: "Solar PV and Advanced Battery Energy Storage Applications for Residential, Commercial and Industrial, and Remote, Off-Grid Sectors: Global Market Analysis and Forecasts,"* Navigant Research, 2017.

50. Energy, AES Distributed. *Solar + Energy Storage Project Kaua'i, Hawaii,* 2017.

51. Dehama, Anissa. *Energy Storge Reduces Diesel Use in Microgrids*, Navigant Research, 2014.

Appendix: HOMER Energy Methodology and Results

To demonstrate the economic value of hybrid systems compared to grid-only or diesel generator-only power generation systems, HOMER Energy tested six example cases, which are representative of key hybrid markets.

Methodology

The HOMER Pro software is the global standard for rapid assessment of least-cost solutions for clean, reliable, distributed power and microgrids (see www.homerenergy.com). The HOMER Pro software evaluates various investment options for hybrid energy systems and optimizes the appropriate size of a system based on the net present cost (NPC). HOMER's results are technology agnostic, as the "winning" system is optimized for NPC; therefore, HOMER Pro is an ideal analytical tool to show how different technologies compete economically over the project lifetime.

HOMER Pro is a modeling tool for design optimization; it does not model specific power flow aspects like voltage or frequency. Subsequent engineering tools may refine the optimized system design that HOMER Pro recommends.

To create a model within HOMER Pro, the user defines the electrical and thermal load required for a project site. Then, the user selects the possible technology that could serve the load: generators, solar PV, energy storage, etc. For each technology selected, the user defines the cost for installation, replacement, and operations and maintenance (O&M). After defining the project's lifetime and the financials, HOMER Pro calculates the most economic combination of components that should be installed and the size of the system that should be installed, which serves the load and defined operating reserve.

The main hybrid markets identified by HOMER Energy include the island market, the energy access market, the resiliency market, and the reliability market. The island market generally has higher diesel and commodity costs; historically, an island relied on diesel generators to serve its electric load. In this study, HOMER differentiates between a small island, with its only renewable resource being solar, and a medium-sized island, which additionally includes a water resource and a geothermal resource. The small island may be similar, from HOMER's perspective, to the energy access market. Characteristics of the energy access market include no previous electricity source or limited diesel generation and smaller loads, and an uncertain load growth over the project lifetime. The resiliency market represents a market with a reliable grid, which may face outages a couple times over the course of the year. HOMER differentiates in this study between two examples of resiliency—one for a university campus and one for a critical process. The main reason for differentiating the campus from the critical process analysis is to align with JISEA's main analysis and the identification of these markets distinctly. The reliability market represents the market for adding supplemental technologies to an existing, but unreliable, grid. These four distinct markets and six distinct case studies are summarized below.

Table A-1 shows the location and other assumptions for the HOMER Pro models. The sensitivity analysis in HOMER Pro allows battery prices from the forecast to determine its impact on architecture, installed equipment size/capacities, and costs over the project lifetime.

Table A-1. HOMER Pro Model Parameters

Model	Small Island	Medium Island	Energy Access	Resiliency (Critical Infrastructure)	Resiliency (Campus)	Reliability (C&I[a])
Location	Indonesian Island	Caribbean island	Karo, Ethiopia	Albany, NY	Arizona University Campus	Chennai, India
Sensitivity Variables	PV Capital Expenditure (CAPEX), Diesel Price, Battery CAPEX	Wind Resource, Hydro Resource, Diesel Fuel Price	PV CAPEX, Discount Rate, Battery CAPEX	Energy Charges, Demand Charges, Battery CAPEX Natural Gas Fuel Price	Demand Charges, Natural Gas Fuel Price, Battery CAPEX	Outage Frequency and Repair Time, Energy Charges, Battery CAPEX, Natural Gas Fuel Price
Base Case	3x1 MW Diesel Genset	7x8 MW Diesel Gensets	1x100 kW Diesel Genset	Grid + 2 x Gas Turbines	PV, Grid	Grid + Gas Turbine
Load	2.5 Megawatt peak (MWp), 850 (Kilowatt Average (kWavg)	50 MWp, 37.46 Megawatt Average (MWavg)	400 kWp, 135 kWavg	2.75 MWp, 1.5 MWavg	23 MWp, 40MWavg	1.5 MWp, 1 MWavg
Generator Size, Fuel, Pricing	Three Generic 1-MW Diesel ($0.5, $1, $1.5/Liter (L) Diesel Fuel)	Generic 7x8 MW Diesel Genset (at $300/kW CAPEX, 0.01$/kW-hr O&M)	Generic 100 kW Fixed Cap Diesel Genset, ($300/kW CAPEX, 0.01$/kW-hr O&M)	2 x 1.5 MW Gas Microturbine. ($1,000/kW CAPEX, $0.01/kWh Operating Expense [OPEX])	Backup Gas Gen: 5MW, 15MW ($1,000/kW CAPEX, $0.01/kWh OPEX) CHP additional	1x2 MW Gas Microturbine. ($1,000/kW CAPEX, $0.01/kWh OPEX)
PV Price	Generic Flat Plate PV ($1/W, $2/W, $3/W)	Generic Flat Plate PV - $2,000 CAPEX	Generic Flat Plate PV - $2,000	Generic Flat Plate PV - $1,750 CAPEX	Generic Flat Plate PV - $1,500 CAPEX	Generic Flat Plate PV - $1,500 CAPEX
Storage Price for Li-Ion	Generic 1 kWh Li-Ion ($150, $300, $450, $600, $750/kWh)	Generic 1 kWh Li-Ion - CAPEX - $500/kWh	Generic 1 kWh Li-Ion - CAPEX - $600/kWh	Generic 1 kWh Li-Ion - CAPEX - $400/kWh	Generic 1 kWh Li-Ion - CAPEX - $400/kWh	Generic 1 kWh Li-Ion - CAPEX - $400/kWh
Geothermal	N/A	2x5MW Turbines. $2,500/kW CAPEX, $0.02/kWh OPEX. Sensitivity on the Resource	N/A	N/A	N/A	N/A
Wind	N/A	1.7 MW - CAPEX -$3M. Sensitivity on the Resource	N/A	N/A	N/A	N/A
Hydro	N/A	$7,350/kW CAPEX, $147/yr OPEX.	N/A	N/A	N/A	N/A
Converter	CAPEX - $300/kW	CAPEX - $300/kW	CAPEX - $300/kW	CAPEX - $300/kW	CAPEX - $300/kW	CAPEX - $300/kW
Grid	N/A	N/A	N/A	0.05, 0.1, 0.15 $/kWh Energy Charges. 0, 10, 20$/kW Demand Charges.	0, 10, 20$/kW Demand Charges	Energy Charges: 0.03, 0.05, 0.125, 0.20 $/kWh

[a]critical infrastructure

Results

Case 1: Island—Indonesia

This case study is representative of a small remote island, which is considering the value of supplementing its aging diesel generation technology with solar and storage. The community has a choice to install a new generator system or a hybrid microgrid. HOMER Pro calculates the economics of the system based on the parameters listed below.

Generator: Size, Fuel, Pricing	Three Generic 1-MW Diesel Gensets CAPEX: $300/kW Replacement: $200/kW after 15,000 hrs O&M: 0.02$/kW-hr $0.50, $1, $1.5/L diesel price
PV: Price	Generic Flat Plate PV $1000, $2000, $3000/kW O&M: $10/kW-yr
Storage Price for Li-Ion	Generic 1-hour 1 kWh Li-Ion $150, $300, $450, $600, $750/kWh O&M: $10/kWh -yr
Converter	CAPEX: $300/kW O&M: $0/yr
Sensitivities: Diesel Price	Diesel Price, PV Price, Battery Price

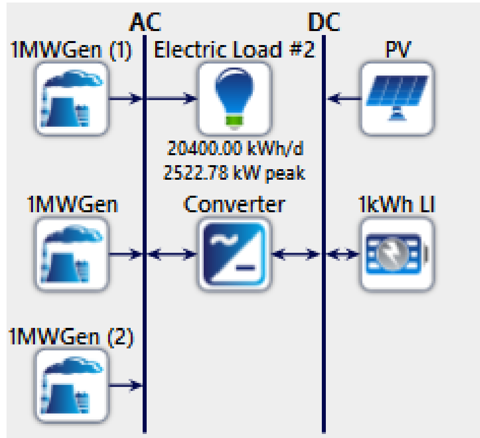


Figure A-1. System schematic

The battery modeled in this system is a 1-hour Li-Ion battery.

An OST (optimal system type) chart shows how the lowest-cost design changes as the sensitivity inputs vary. The different colors represent the same combination system architectures. Because the hybrid system (with all three generators, PV, and batteries) is most economical—based on NPC, there is only one color in the following OST chart across the modeled sensitivity values.

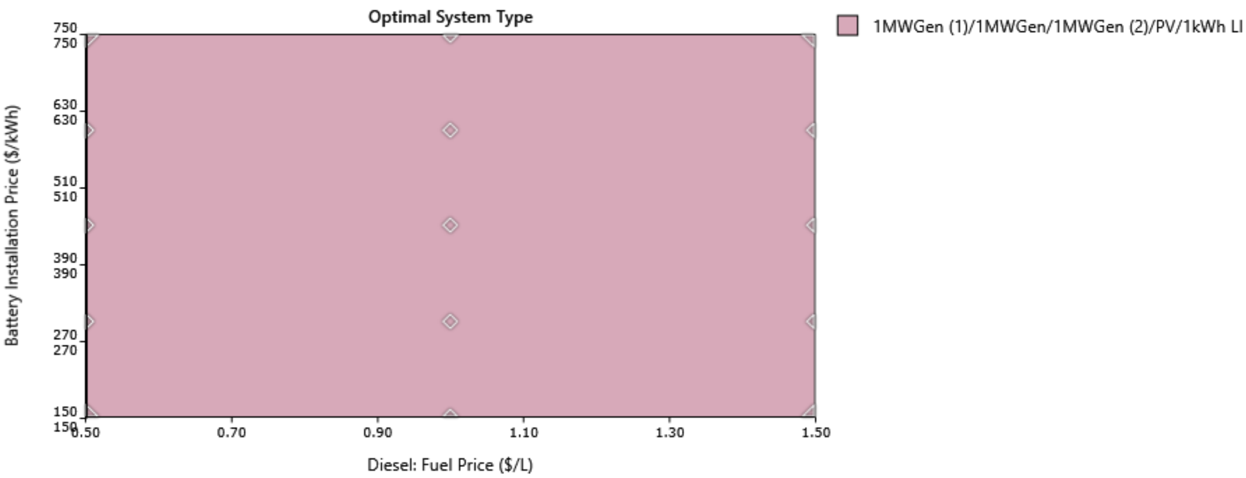


Figure A-2. OST for a $2/W PV price

Figure A-2 assumes a $2/W PV price, though the OST chart looks similar at $1/W and $3/W PV prices. Across the range of sensitivity value models, the question is not “which technologies are most cost-effective together” but “what level of PV and batteries is most economic.” To visualize this, see Figure A-3.

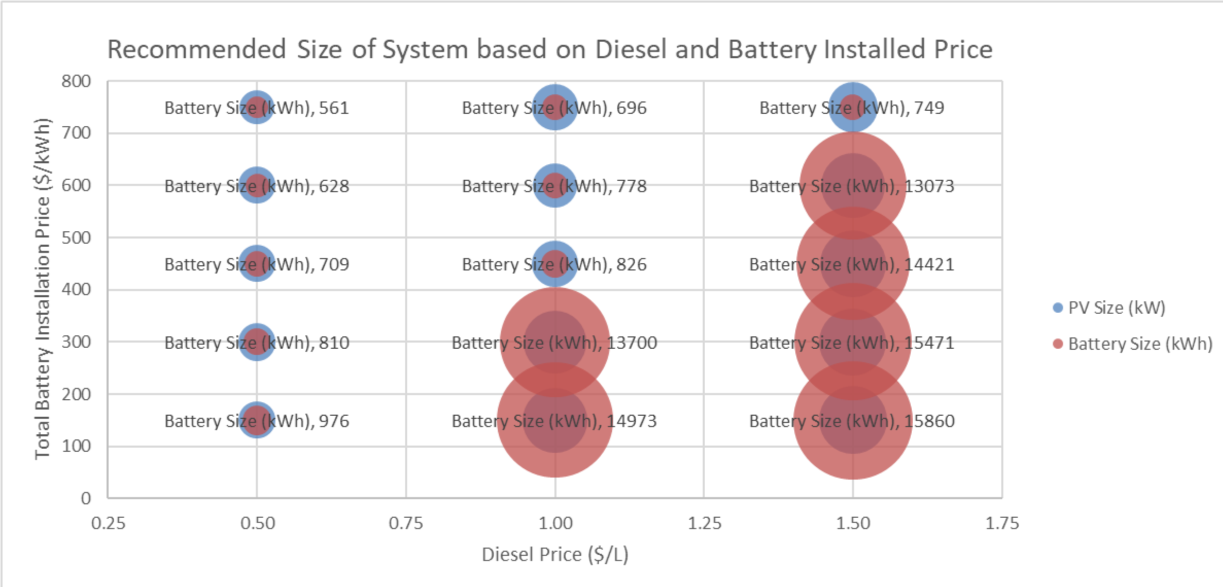


Figure A-3. Bubble chart showing PV and battery energy storage system (BESS) installation size, as affected by battery and diesel price

As the diesel price increases, more batteries and PV are recommended. As the battery price decreases, more batteries are recommended. There is an inflection point at diesel prices higher than \$0.50/L and battery prices lower than \$750/kWh where the recommended battery installation increases by an order of magnitude. Inflection points make forecasts and predictions with respect to batteries particularly difficult.

As visible in Figure A-3, the diesel price and the battery price are important variables. A spider plot can show how the sensitivity variables affect the NPC (Figure A-4).

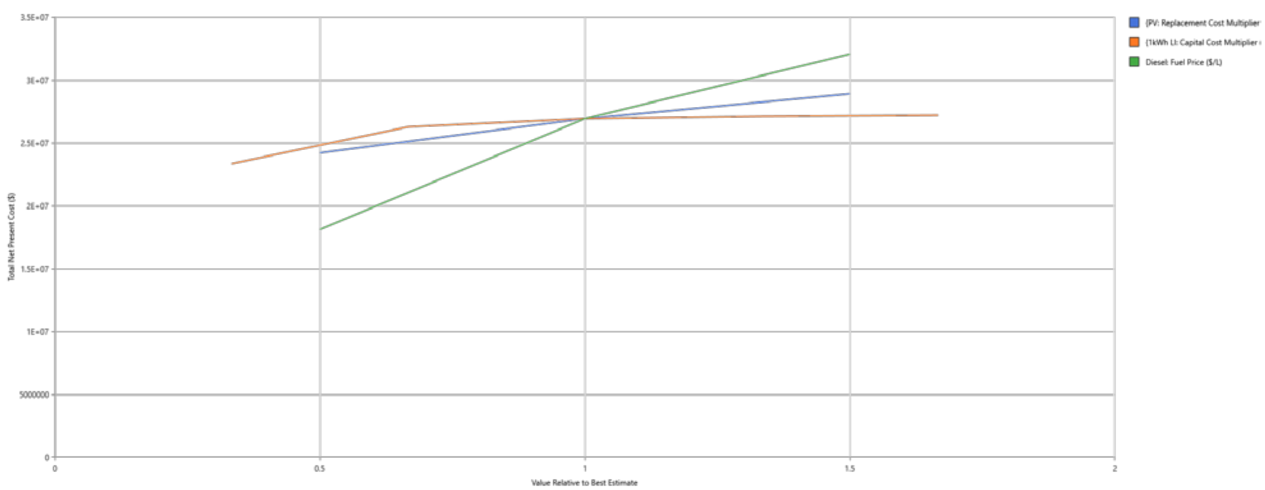


Figure A-4. Spider plot: Comparison of sensitivities

The spider plot shows which of the sensitivity variables tested had the largest impact on the total NPC; the steeper the slope, the more impact a change in this variable has on the NPC. Diesel price has the largest impact: a \$0.50/L diesel price will have half the NPC of a system with \$1.5/L diesel price. At a battery price lower than \$300/kWh, however, the battery price becomes more influential than the PV price. Figure 4 forecasts 2020 storage prices of $415/kWh compared to the $450/kWh and $300/kWh modeled.

Figures A-3 and A-4 show an inflection point for the size of installed batteries. Once the battery price gets low enough, there is an order of magnitude increase in the size of battery installations.

The reported 2017 battery cost of $558/kWh as shown in Figure 4 is modeled as $600/kWh to account for the challenges in installing in a remote area. The 2020 forecast for the battery price of $415/kWh is compared to the $450/kWh and $300/kWh sensitivity analysis in this case study. The impact of a $300/kWh price, compared to the current price of $600/kWh, results in a 17.6 times larger size with a slightly lower annualized cost. The impact of a $450/kWh price, compared to the $600/kWh, results in a 6% increase in storage size. Therefore, the most interesting developments for the storage industry may occur after the 2020 projection of $415/kWh, shown in Figure 4.

The importance of the diesel and the PV price on the levelized cost of electricity is shown in Figure A-5.

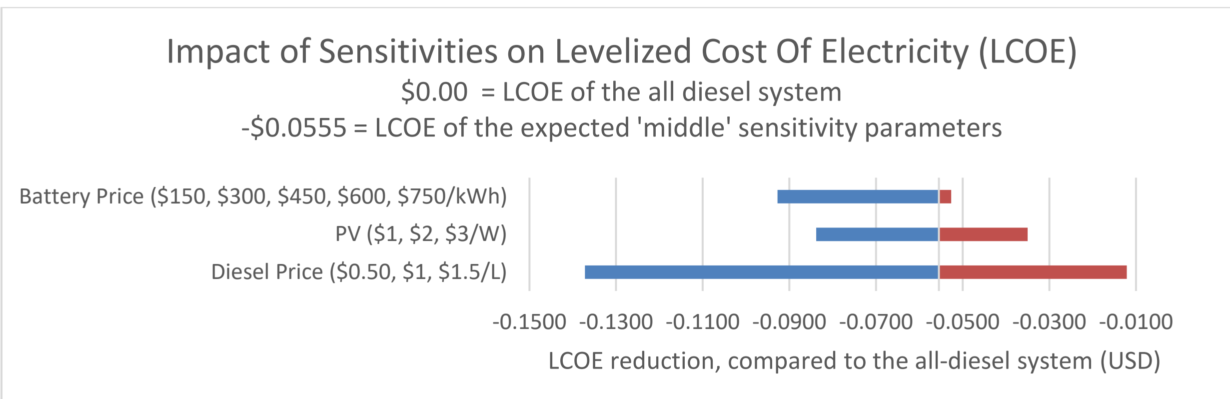


Figure A-5. Tornado graphs based on change of LCOE from the base case

The recommended hybrid system—meaning the system with the lowest NPC—with the $2/W PV price, $1/L diesel price, and $450/kWh battery price is expected to reduce the LCOE by $0.0555/kWh compared to the base case of an all-diesel power generation system. The bar chart above shows how the different sensitivities can impact the energy savings. If the diesel price were $1.5/L instead of $1/L, the LCOE savings could go up to 13.7 cents per kWh. However, if the diesel price were $0.5/L instead of $1/L, there may be only a $0.012 LCOE savings between the all-diesel case and the hybrid case.

Similarly, if the PV cost were $3/W instead of $2/W, the LCOE savings would only be $0.035/kWh. However, if the PV installation costs were $1/W instead of $2/W, the LCOE savings compared to the all-diesel case could reach $0.08/kWh.

With respect to the internal rate of return (IRR), in the case of a high ($1.5/L) diesel price and the lowest ($150/kWh) storage and ($1/W) PV price, the IRR can be up to 28%. The expected IRR for the middle case of $2/W PV and $1/L diesel and $450/kWh storage is 14%.

The small island market can be profitable and interesting, especially if procurement costs are low for storage and PV but the diesel price is high.

Case 2: Island—Caribbean

This case study represents a large Caribbean island. It focuses on finding the value of adding hybrid energy systems of which geothermal, solar PV, hydro power plant, and battery storage (1-hour Li-Ion battery) are considered in this study in addition to its already existing diesel generator capacity of 56 MW.

Diesel fuel price, solar global horizontal irradiance (GHI), and wind speed were modeled as sensitivity variables to study their impact on the overall system configuration and performance. The OST plot below shows different configurations best suited for combinations of different diesel fuel prices and wind speeds. The GHI had the smallest impacts on results, so in Figure A-7, the solar GHI has been fixed at 5 kW/m^2/day.

Base Case Generator: Size, Fuel, Pricing	7 x Generic 8 MW Diesel CAPEX: $300/kW O&M: 0.01$/kW-hr
Geothermal Generator	Geothermal 5 MW CAPEX: $2,500/kW O&M: @0.02/kW-hr
Hydro Turbine	1x10 MW CAPEX: $7,350/kW O&M: $147/kW-yr
PV: Price	Generic flat plate PV CAPEX: $2,000 O&M: $10/kW-yr
Storage Price for Li-Ion	Generic 1 kWh Li-Ion CAPEX: $500/kWh O&M: $10/kWh-yr
Converter	CAPEX: $300/kW O&M:$0/yr
Sensitivity: Diesel Price	$0.50, $1, $1.5/L diesel
Sensitivity: Solar Irradiation	4, 5, 6 kWh/m^2/day
Sensitivity: Wind Speed	4, 6, 8 Meter/Second (m/s)

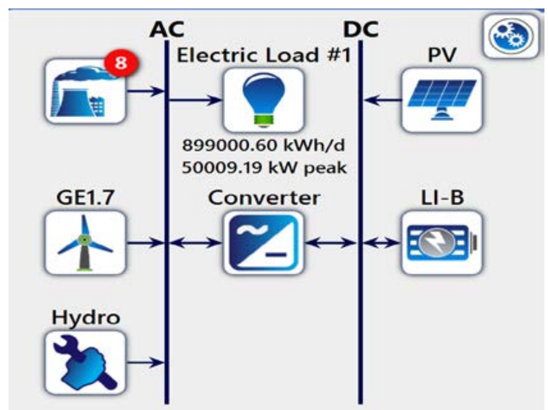
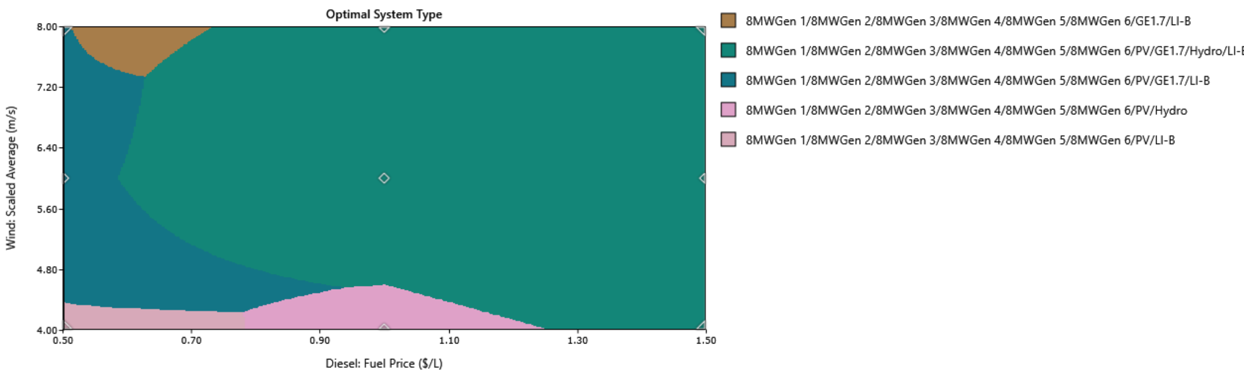


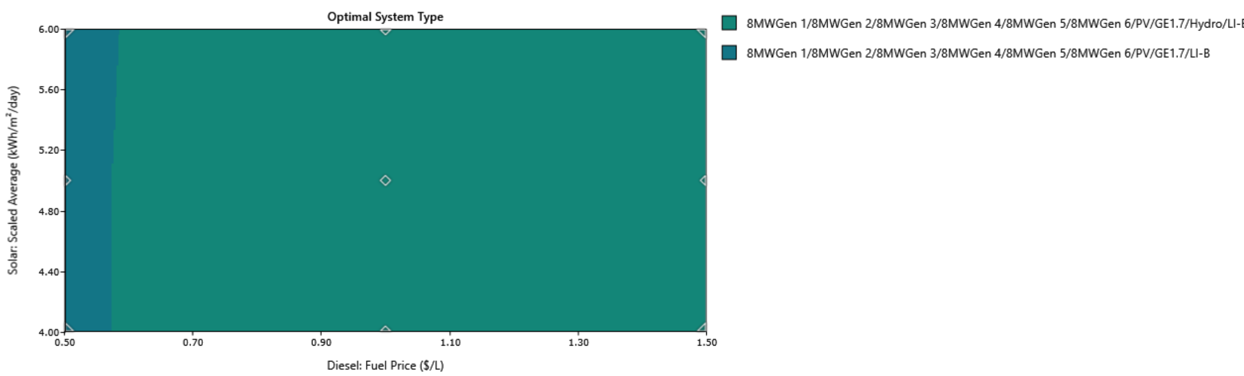
Figure A-6. System schematic

It can be observed that the hybrid system, including all the suggested sources, is the most economical for most of the sensitivity variable values considered. For significantly low wind speeds, other technologies are preferred, while for wind speeds of above 4.5 m/s, wind generators are part of all the category winners. Batteries are part of the least-cost system for almost all sensitivities considered except low wind speeds, at which hydropower seems to replace batteries for a more economical system. PV is also included in all winning system configurations except when there are high wind speeds and wind turbines replace PV. Hydropower is preferred only for diesel fuel prices higher than $0.6/L.

Figure A-7 shows the OST plot comparing the diesel fuel price and the solar GHI resource with a fixed wind speed of 6 m/s. For low diesel prices, below 0.60$/L, the system uses more diesel generators and hence eliminates the need for a hydro plant. In all other considered sensitivity values, a hybrid system with all the sources was the most economical solution, which conforms to the inferences obtained from the previous graph.



(a)



(b)

Figure A-7. Optimal system type plot: (a) Diesel fuel price versus wind speed; (b) Diesel fuel price versus solar irradiation

The spider plot in Figure A-8 provides a comprehensive comparison of the impact of different sensitivities considered in this study. Note that diesel fuel price and the wind speed have a higher impact than the solar GHI on the system total NPC. A moderate amount of wind resource and a decrease in diesel fuel price in the near future would eliminate the need for a hydro power plant, which would potentially lead to huge investment savings.

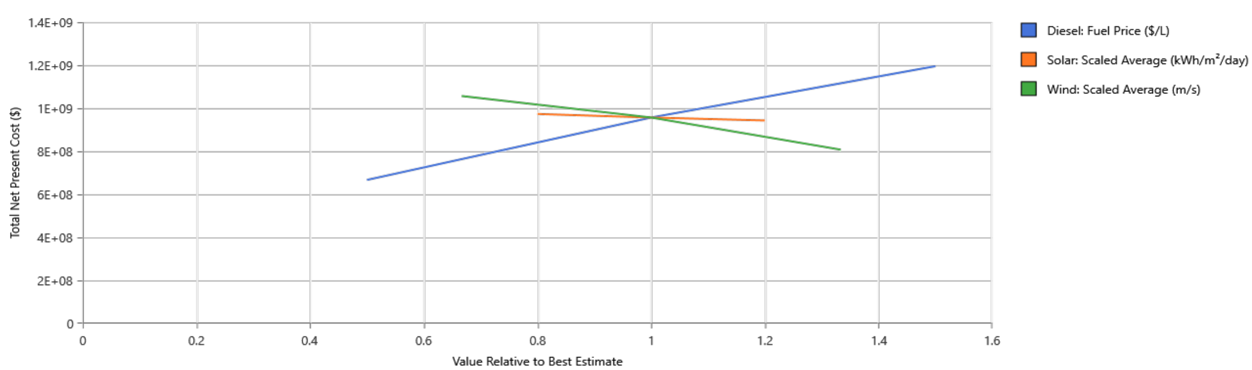


Figure A-8. Spider plot

The bubble chart in Figures A-9 and A-10 demonstrates the variation in sizes of PV, wind, and BESS for different values of the solar GHI and diesel fuel price. There is a linear increase in the size of PV and BESS with increasing diesel price. There isn't a significant change in PV size with the solar GHI for any particular diesel fuel price. For a diesel fuel price of 1.5 $/L and a solar GHI of 6 kW/m^2/day, the size of BESS is high. The wind generator's size seems to remain fairly constant irrespective of changes in both the solar GHI and diesel fuel price.

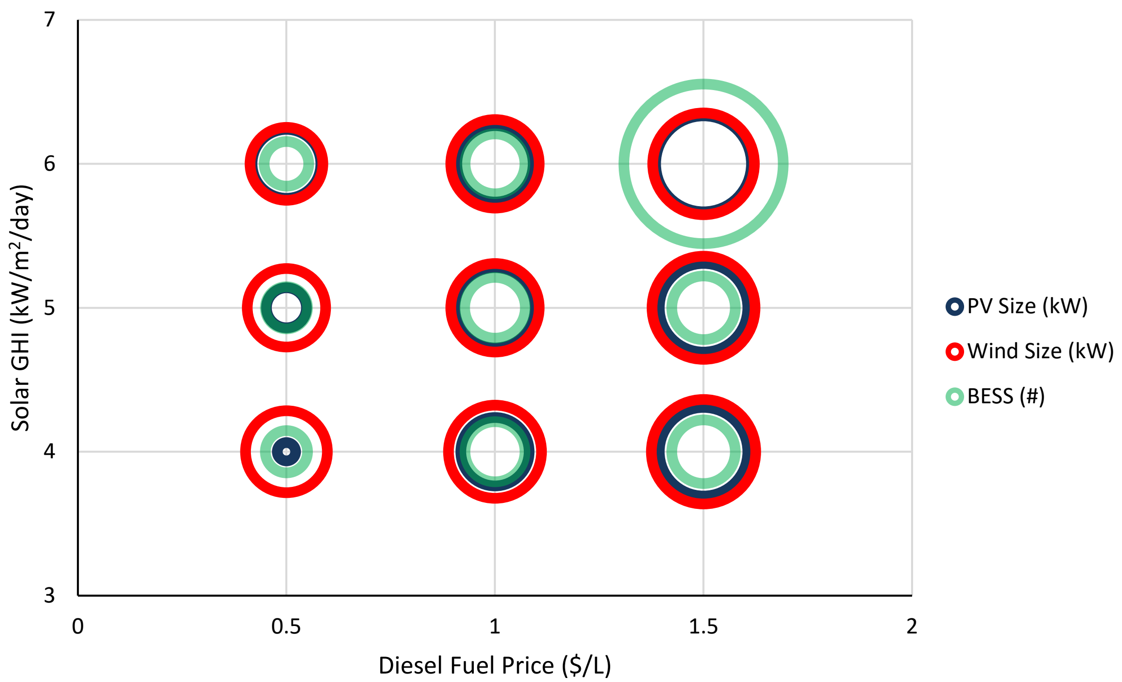


Figure A-9. Bubble chart: Solar GHI versus diesel price

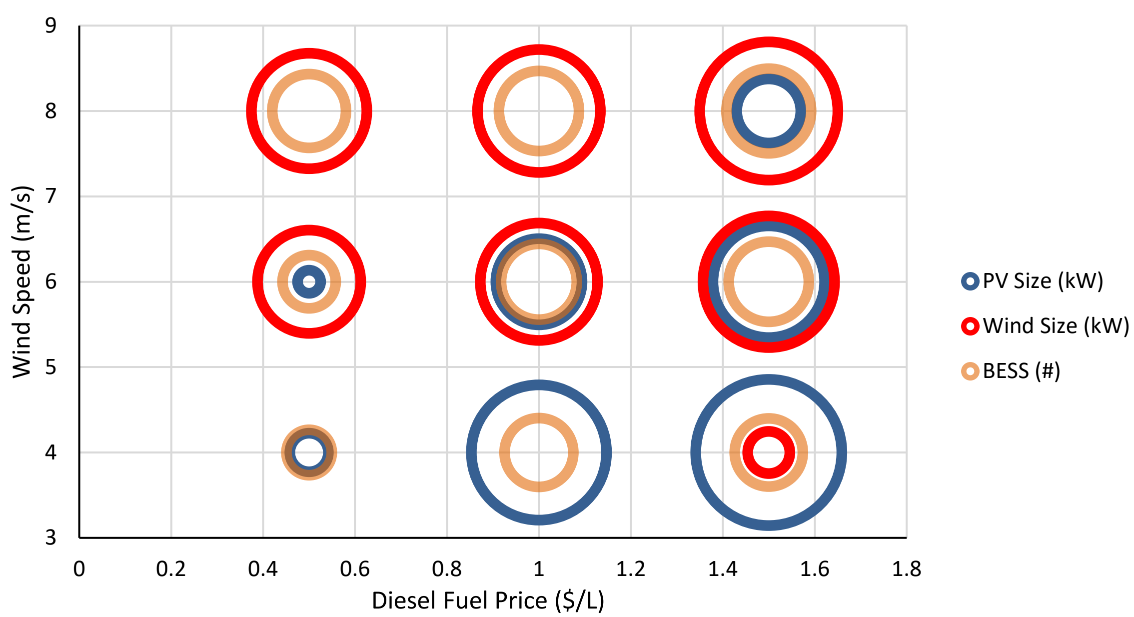


Figure A-10. Bubble chart: Wind speed versus diesel price

The bubble chart compares the system sizing for different diesel prices and wind speeds. The wind speed has a huge impact on sizing the wind turbines. Wind turbines are not included in the optimal system configuration for a very low wind speed of 4 m/s. For a given wind speed, considerably greater than 4 m/s, the diesel fuel price doesn't affect the inclusion of wind turbines significantly. The addition of wind turbines reduces the amount of PV installed in the system. At a high wind speed of 8 m/s, PV is not an economical option unless the diesel price approaches $1.5/L. If the wind were land-constrained, we wouldn't see this result, because the economics would be dominated by the additional possible wind, and wind would "squeeze-out" the PV. The size of the BESS remains almost constant for all cases except for low diesel fuel prices. A hybrid system is more economical when the diesel fuel price is $1/L or higher.

Case 3: Energy Access

To enter the energy access market, smaller technology sizes are necessary. The following case study represents a village power example in Africa. The village has the choice to invest in an all-diesel system or to supplement a diesel system with PV and batteries.

Given battery price estimates in 2017 of $558/kWh and battery price estimates in 2020 of $415/kWh (see Figure 4), the battery prices considered for the energy access market are $600/kWh and $300/kWh, plus a high-cost example of $900/kWh.

Base Case Generator: Size, Fuel, Pricing	Generic 500-kW Diesel Genset CAPEX: $300/kW Replacement Cost after 15,000hrs: $200/kW O&M: 0.02$/kW-hr
Generator 2: Size, Fuel, Pricing	Generic 100-kW Diesel CAPEX: $300/kW Replacement: $200/kW O&M: 0.02$/kW-hr
PV: Price	Generic flat plate PV CAPEX: $2,000 O&M: $10/kW-yr
Storage Price for Li-Ion	Generic 1-hour 1 kWh Li-Ion CAPEX: $600/kWh O&M: $10/kWh-yr
Sensitivity: Nominal Discount	6%, 8%, 10%
Sensitivity: Fuel Price	$0.50, $1, $1.5/L
Sensitivity: PV Price	$1/W, $2/W, $3/W
Sensitivity: BESS Price	$300/kWh, $600/kWh, $900/kWh

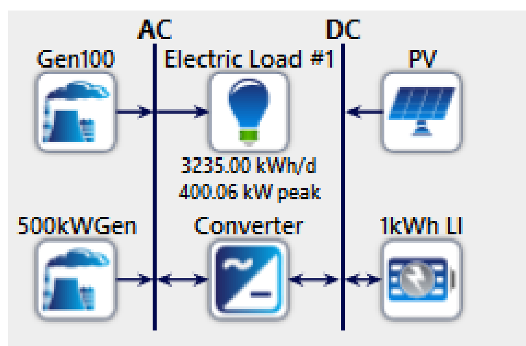


Figure A-11. Schematic for energy access

The battery modeled in this system is a 1-hour Li-Ion battery.

The sensitivities considered include nominal discount rate, diesel fuel price, and PV and BESS costs. Based on the spider plot, the variables with the largest impact on the NPC are the nominal discount rate and the diesel fuel price, as those have the greatest slope.

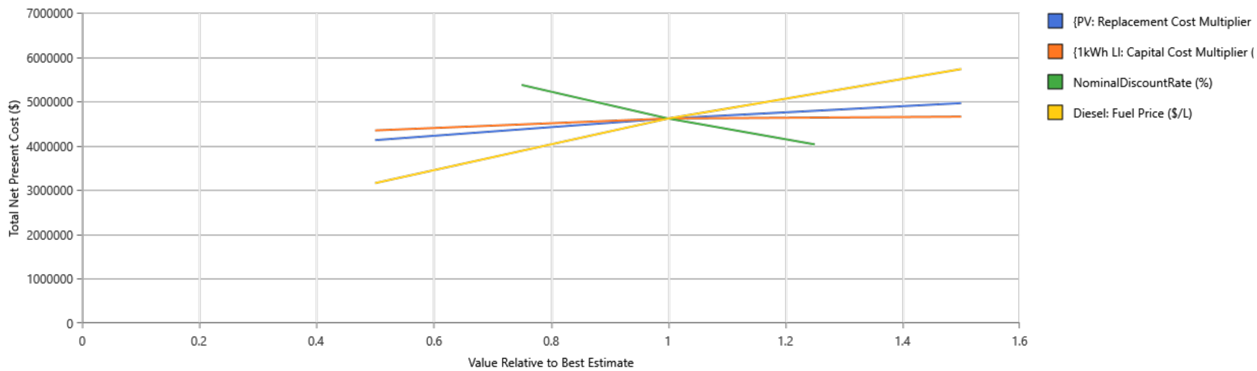


Figure A-12. Spider Plot: Comparison of sensitivities

The nominal discount rate can change the NPC approximately +/-15%, according to Figure A-12. The diesel price can affect the NPC by approximately +/- 25%. Based on the spider plot, the most influential sensitivity variables on the NPC are diesel price and nominal discount rate. The battery price matters very little in the energy access market.

The nominal discount rate is especially interesting to discuss in the context of the energy access market because of currency instability and inflation. In developing countries, the value of money today may be much higher than the value of money in the future.

The optimal system architecture is a fully hybrid system, throughout all of the range of sensitivity variables and ranges tested. The OST may not be visually interesting, because the plot just shows one color for one system architecture. However, it provides a compelling case for hybridized systems. It is not a question of whether to include PV and BESS, it is a question of how large should the PV and BESS be.

The bubble chart in Figure A-13 shows the size of the recommended battery and PV installation, as it varies by the diesel price and discount rate. Depending on the onsite price of diesel, the recommendation for the BESS sizing varies dramatically.

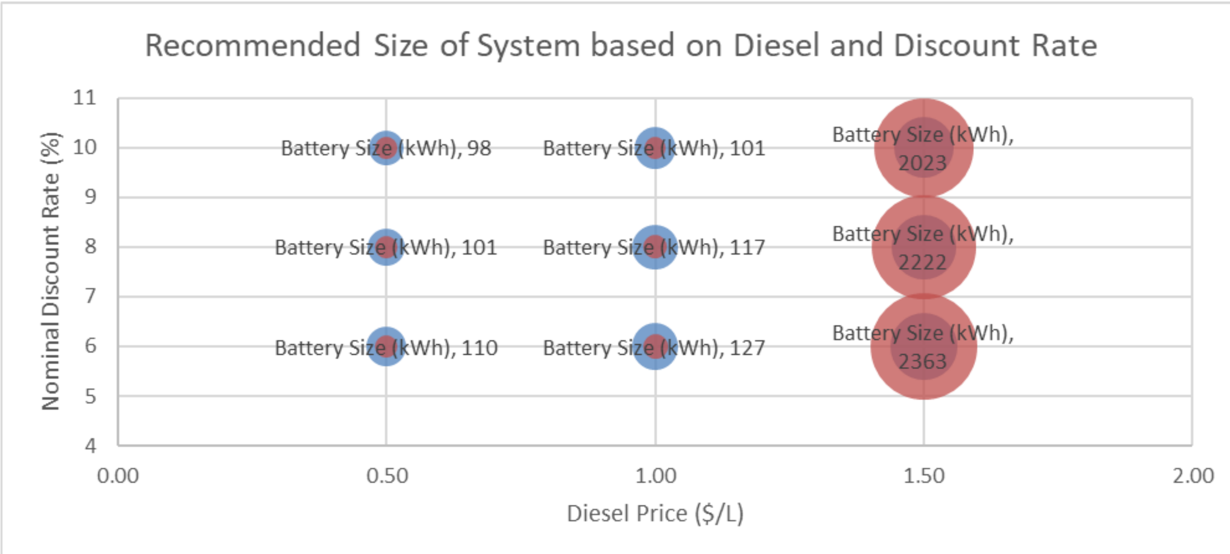


Figure A-13. Bubble chart: Discount rate versus diesel price

There is an inflection point at diesel prices of over $1/L, where the recommended size of batteries increases by an order of magnitude. Markets with diesel prices over $1/L are highly attractive for hybrid system installations. The change in battery sizing shows the development from a diesel-driven system with renewables to a renewable-driven system with diesel backup.

Given that the recommended system size varies on the sensitivities chosen, the tornado plot below shows the effects that the sensitivities can have on the LCOE. Diesel price has the highest influence on the cost of energy. At $1/L for diesel, $0.17/kWh could be saved by installing a hybrid instead of the all-diesel system; at $0.50/L for diesel, only $0.09/kWh could be saved; at $1.5/L for diesel, as much as $0.27/kWh could be saved.

All of the sensitivity variables, which were modeled in this analysis, result in a more favorable, lower LCOE, compared to the all-diesel system. The tornado plot in Figure A-14 shows that the battery price and the discount rate have lesser effects on the cost of energy than the diesel price and the PV price. That battery price matters very little in the energy access market is very interesting. Given the middle case for the sensitivities, a hybrid system will be $0.17/kWh cheaper than the diesel-only case.

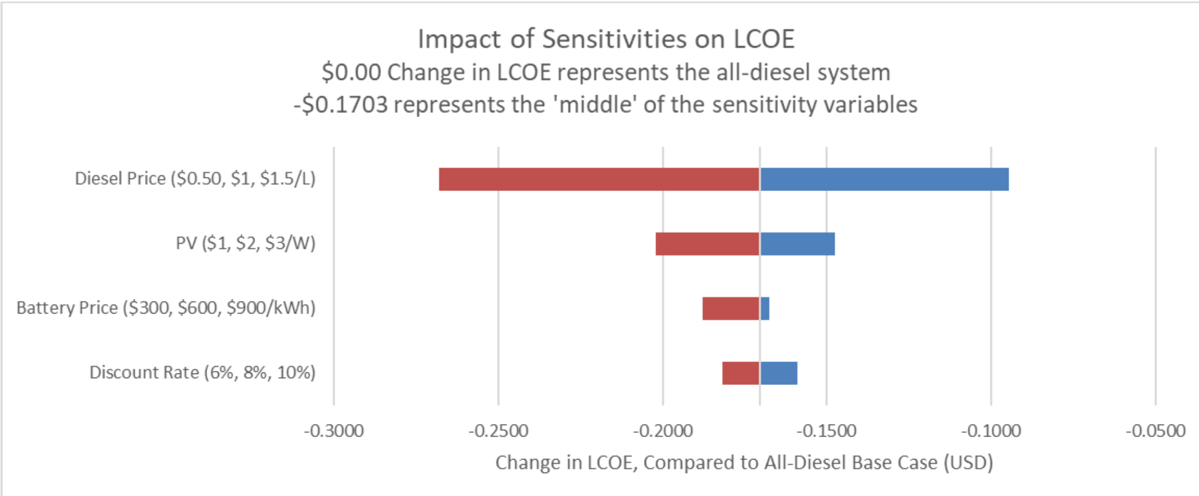


Figure A-14. Tornado chart

In Figure 4, with regard to its battery price forecast for 2020 of $415/kWh and today's price of $558/kWh, this case considers a reduction between $600/kWh and $300/kWh. The 50% lower battery price would encourage a PV system larger by almost 80% and a battery system 19 times as large. The lower battery price would offer a 5% reduction in the annualized energy costs.

The expected case of $1/L diesel, $600/kWh storage, 8% discount rate, and $2/W has an IRR of 28%. The returns for the energy access market can range from 13% to 48%, varying by the sensitivity conditions.

The energy access market can be attractive for selling for smaller hybrid products. The market structures surrounding the energy access market are highly variable, flexible, and often locally based. Many communities may need support in access to capital.

The energy access market is a promising market for hybrid systems because in all cases tested, the hybrid system is more economically viable than the diesel-only system, based on the lowest NPC. However, entering the energy access market requires offering smaller-scale products with minimal maintenance, understanding local financial structures, and offering flexible payment options for customers.

Case 4: Resiliency—Critical Infrastructure

This case study was conducted for Albany, New York, to study potential hybridization of the existing grid supply for improved resiliency and to ensure a seamless transition during grid outages. The existing grid supply is assumed to have very minimal outages with two gas generators of 1.5 MW for backup. Inclusion of an AC-connected PV system with a DC-connected storage system (1-hour Li-ion battery) has been studied.

Base Case	Grid only + Gas Turbine
Generator: Size, Fuel, Pricing	2x Generic 1,500 kW Gas Microturbine CAPEX: $1,000/kW O&M: 0.01$/kW-hr
PV: Price	Generic Flat Plate PV CAPEX: $1750 O&M: $10/kW-yr
Storage Price for Li-Ion	Generic 1 kWh Li-Ion CAPEX: $400/kWh O&M: $10/kWh-yr
Converter	CAPEX: $300/kW O&M:$0/yr
Sensitivity: Grid Power Price	$0.05, $0.1, $0.15/kWh
Sensitivity: Grid Demand Rate	$0, $10, $20/kW/mo
Sensitivity: BESS Price	$200, $400, $600/kWh
Sensitivity: Fuel Price	0.3, 0.5 $/m^3

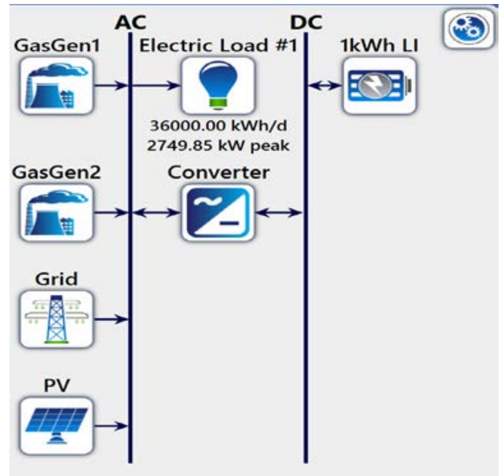


Figure A-15. System schematic

This system has been modeled to have five outages per year with an average repair time of 16 hours.

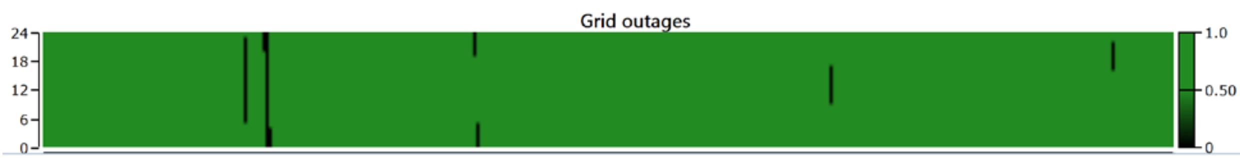


Figure A-16. Grid outages

Battery storage was not part of the least-cost design because peak shaving to limit customer demand charges wasn't modeled explicitly in this system. Depending on the demand rate, storage may be added to implement peak shaving. It can also be used to improve power quality. Both of these value streams would require a comparatively lesser number of batteries than bulk backup storage and renewable energy arbitrage.

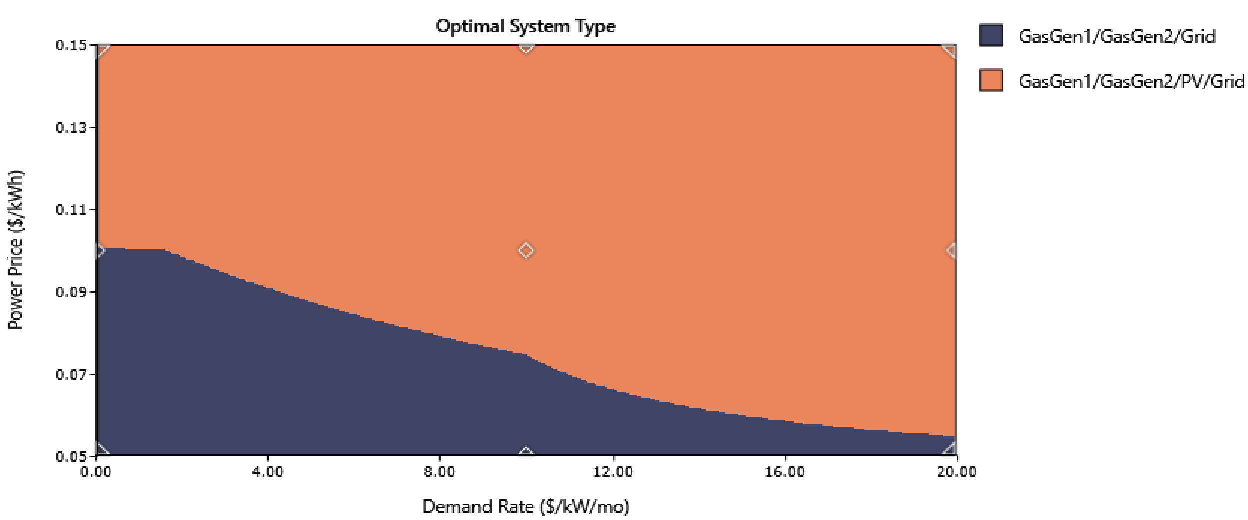


Figure A-17. Optimal system type plot: Demand rate versus power price

The bubble plot shown in Figure A-18 compares the change in PV size and grid purchases with power price and demand rate. It can be seen that for lower power prices and demand rates, PV doesn't contribute to the most economical configuration, but as the power price and demand rate increase, the grid purchases are drastically reduced and more PV is added in the system. For a power price of $0.15/kWh, the contribution of PV is significantly higher compared to power prices of $0.05 and $0.1/kWh. It can also be observed that the PV price doesn't change with the demand rate for a given power price.

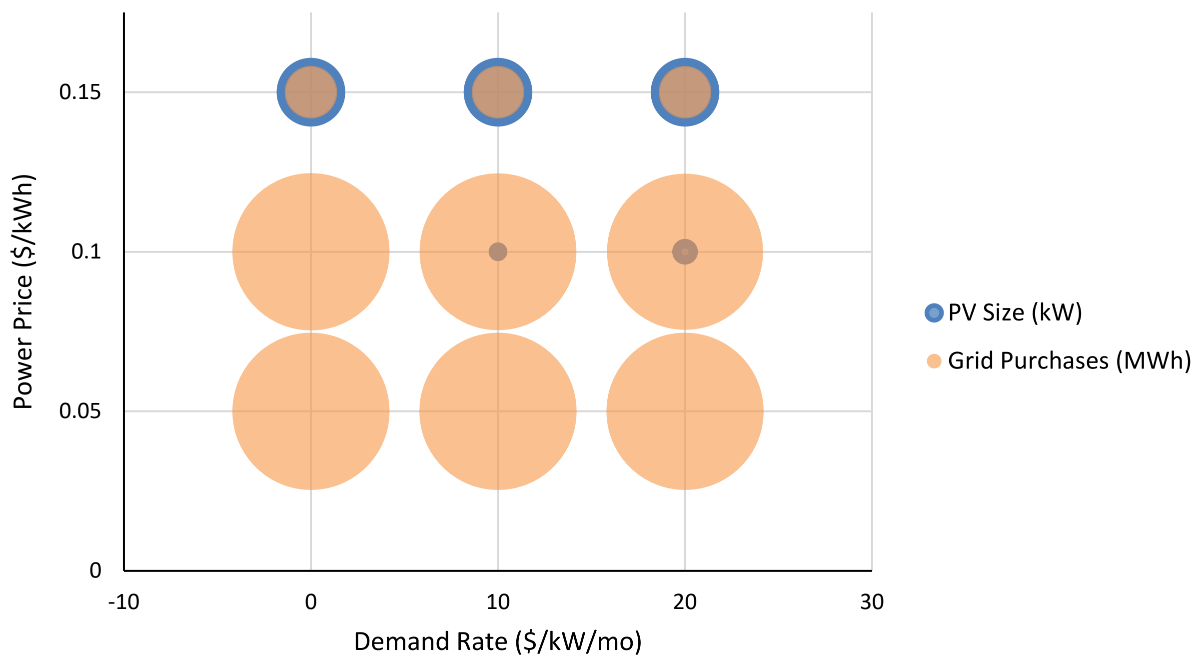


Figure A-18. Bubble chart for critical infrastructure case

The spider plot shown in Figure A-19 aligns with the previously discussed results in this section. Battery cost and natural gas fuel prices have negligible to no impact on the system NPC. The power price and demand rate seem to influence the system NPC entirely.

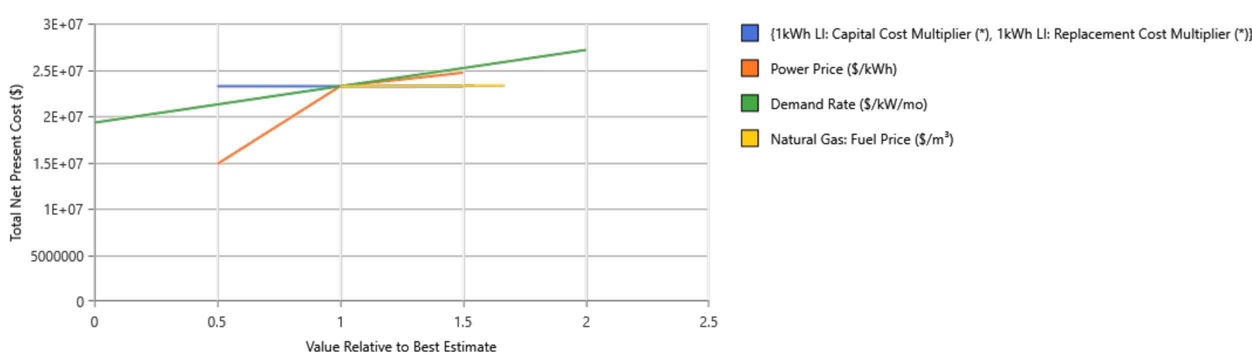


Figure A-19. Spider plot for critical infrastructure

For an industrial location that has a high demand rate ($20/kW/mo) and power price ($0.15/kWh), there was a saving of $0.002/kWh in LCOE and reduced grid purchases by 215 MWh, thus ensuring a more reliable system. Although not modeled in this exercise, a storage component for peak shaving and/or improving power quality could also provide a pathway to improve the reliability of the system.

Case 5: Reliability—Campus

Campuses looking to achieve renewable energy targets represent another market for hybrid systems. This case study uses the electrical and thermal load from Arizona State University in Tempe, Arizona, for 2016, which has already invested in distributed energy. To maintain a more general analysis, however, assume no previous renewable installations. The university has the option to rely on the grid and a CHP (combined heat and power) generator and boiler system or to supplement these technologies with PV and storage. The base case, therefore, is the grid plus CHP and boiler system and is compared to the hybrid systems.

CHP Generator	Generic Gas Microturbine with CHP Size: 15 MW CAPEX and Replacement: $1,000/kW O&M: $0.01/kW-hr
Grid	Energy: $0.10, $0.15, $0.05/kWh Power: $0, $10, $20/kW No Limit on Amount of Power from Grid No Outages Modeled
PV	Generic Flat Plate PV CAPEX: $1,500 O&M: $10/kW-yr
Boiler	$0.20, $0.30, $0.40/m3 gas 85% Efficiency
Storage Price for Li-Ion	Generic 1-hour 1-kWh Li-Ion CAPEX: $400/kWh O&M: $10/kWh-yr
Converter	CAPEX: $300/kW O&M: $0/yr
Sensitivity: Gas Price	$0.20, $0.30, $0.40/m3 gas
Sensitivity: Power Price	$0.05, $0.10, $0.15/kWh
Sensitivity: Demand Charge	$0, $10, $20/kW
Sensitivity: BESS Price	$200/kWh, $400/kWh, $600/kWh

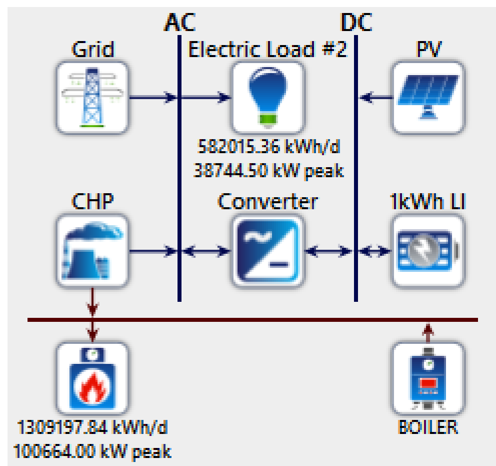


Figure A-20. System schematic

The battery modeled in this system is a 1-hour Li-Ion battery.

This resiliency case assumes an average of five outages with a mean repair time of two hours. The grid was modeled with the following outages:

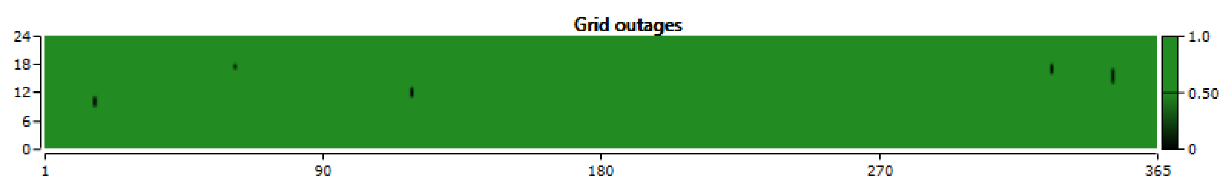


Figure A-21. Outages for campus case

Trends can be seen in the OST chart in Figure A-22; at low power prices and low demand charges, the grids supplemented with batteries are the most economical option to serve the electrical and thermal load. At medium power prices and higher demand charges, the most economical (based on NPC) system involves installing CHP to supplement the grid. At high power prices, PV should complement the grid and CHP generator.

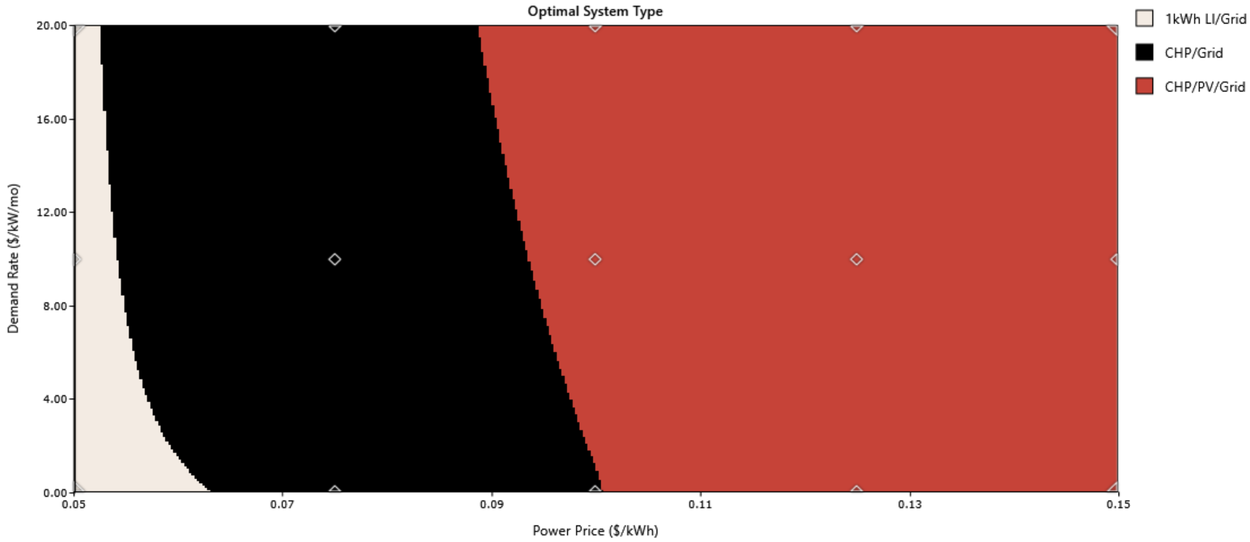


Figure A-22. Optimal system type chart for $400/kWh batteries and $0.20/m^3 natural gas

As the power price increases, a greater PV installation becomes most economic. Based on the OST chart, a company looking to provide a PV or storage solution to campuses for resiliency applications should first target universities that experience a utility power price higher than $0.10/kWh.

The most important sensitivity variables—natural gas price and power price—can be seen on the spider plot in Figure A-23.

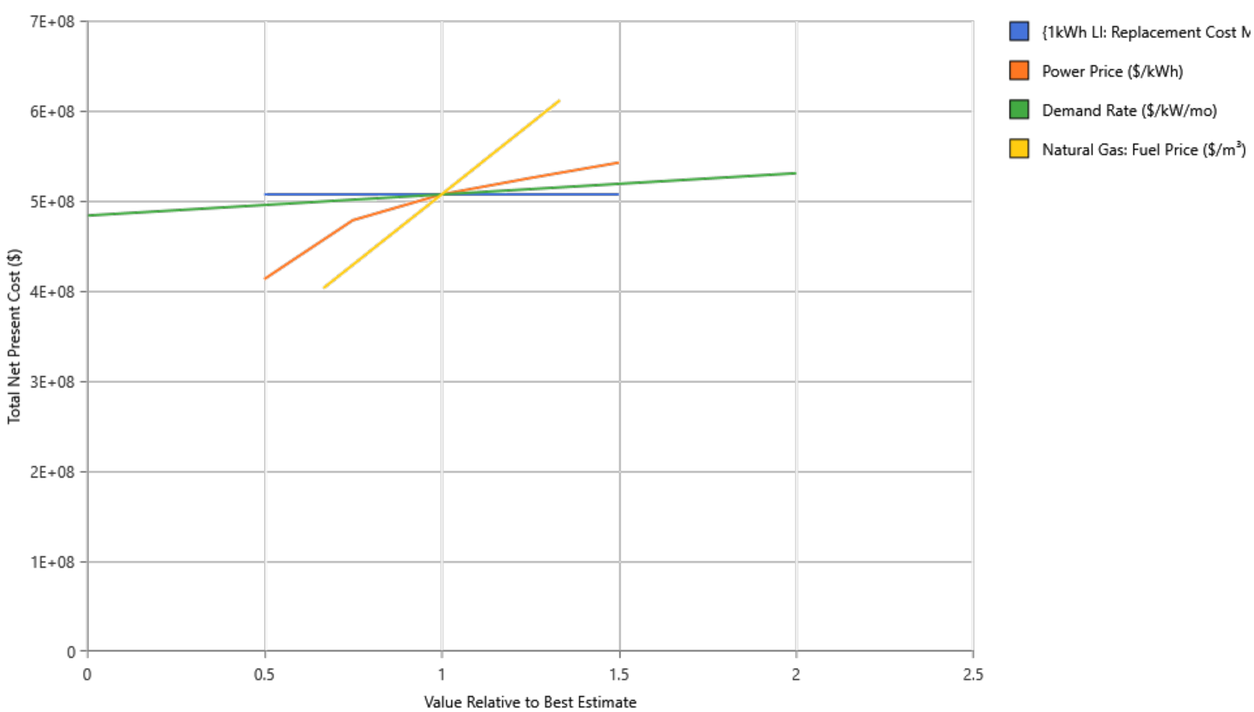


Figure A-23. Spider plot: Comparison of sensitivities

The spider plot shows that the price of natural gas has a large impact on the NPC, followed by the power price. Demand charge has a larger effect on NPC than do battery prices.

For this campus case study, batteries are the complementary solution to the grid when the power price is low. PV should be installed when the utility power price is high (above \$0.075/kWh) and the natural gas price is high (above \$0.30/m^3). Two key values of storage—peak shaving and power quality—are not explicitly modeled in this analysis, and this leads to undervaluing storage.

Storage's ability to reduce demand charges as a peak-shaving application has not been tested here. Especially in those utility rates that have ratcheted rate schemes, the ability for storage to reduce demand charges is financially attractive. HOMER Pro, version 3.9, requires manual modeling to capture peak shaving impacts that makes generalizations difficult. However, HOMER Energy's coming product, HOMER DCR, is the correct tool in which to conduct this analysis. HOMER DCR is specifically designed to find the most economic size and combination of technologies to reduce the electricity charges from a defined utility tariff. HOMER DCR can determine whether it is more cost-effective to pay the utility's demand charge, or whether it is more economic to install storage or a backup generator and avoid these demand charges. HOMER DCR applies to the energy arbitrage and peak shaving markets. Given that the results presented do not include peak shaving, the value of storage as a solution for reducing demand charges must be discussed qualitatively.

Another major value that storage can provide is power quality assurance. HOMER does not model power quality and flow explicitly. Therefore, the value for storage to assist a site's power quality is not accounted for, and storage is systemically undervalued. For battery applications for power quality, only a small number of batteries will be necessary; they will be high power/low energy types of batteries.

The key values of storage for a campus/resiliency market are not included in the HOMER Pro analysis. Under high gas prices, high power prices, and high demand charges, storage is recommended, however.

To ensure a profitable hybrid system for the campus market, the most important variables are the price of natural gas, the demand charges, and the power price. CHP generators can cost-effectively provide for both thermal and electrical loads and offer backup capabilities.

Case 6: Reliability—Commercial & Industrial Facility (C&I)

This case study was performed for the city of Chennai in India. A city like this in India is prone to frequent outages throughout the year. The scope of this study is to enhance the existing grid infrastructure to provide a more reliable and continuous supply of power. A 1-hour Li-Ion battery was considered for modeling the microgrid system.

Base Case	Grid + Gas Microturbine
Generator: Size, Fuel, Pricing	1 x Generic 2,000 kW Gas Microturbine CAPEX: $1,000/kW O&M: 0.01$/kW-hr
PV: Price	Generic Flat Plate PV CAPEX: $1,500 O&M: $10/kW-yr
Storage Price for Li-Ion	Generic 1 kWh Li-Ion CAPEX: $400/kWh O&M: $10/kWh-yr
Converter	CAPEX: $300/kW O&M:$0/yr
Sensitivity: Grid Power Price	$0.03, $0.05, $0.125, $0.2/kWh
Sensitivity: Grid Failure Frequency	150, 730/yr
Sensitivity: Grid Mean Repair Time	1, 6 h
Sensitivity: BESS Price	$200, $400, $600/kWh
Sensitivity: Fuel Price	$0.3, $0.45, $0.6/m³

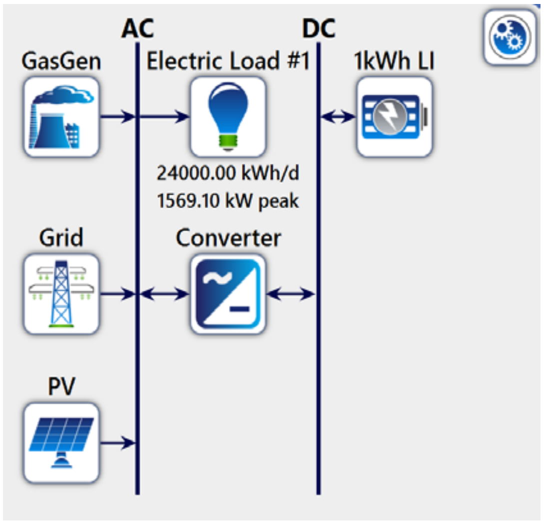


Figure A-24. System schematic

Grid outages and their repair time were modeled as sensitivities in this system. Two types of outages—outages on every other day and two outages every day—and two types of repair times—1 hour and 6 hours—were modeled to cover a wide spectrum of the current grid scenario in India (both rural and urban).

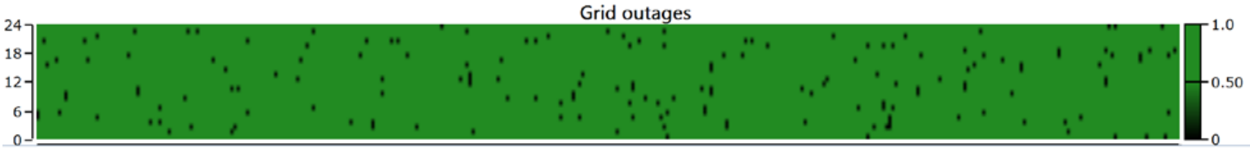


Figure A-25. Outages for C&I reliability case

The OST graph shown in Figure A-26 compares the system configurations for different battery prices and power prices. The grid outage frequency was set at 730 outages/year and the grid repair time at 6 hours. The fuel price was fixed at $0.45/m^3$. For extremely low power prices like $0.03/kWh, the base case of grid + gas turbine is the most preferred configuration. For any power price higher than $0.03/kWh, a hybrid system with gas turbine, grid, and PV is preferred. Inclusion of batteries is highly dependent on battery capital and replacement costs. For low battery prices and higher power prices, including battery storage in the system proved to be a more viable option that makes the system more seamless and reliable by reducing grid purchases.

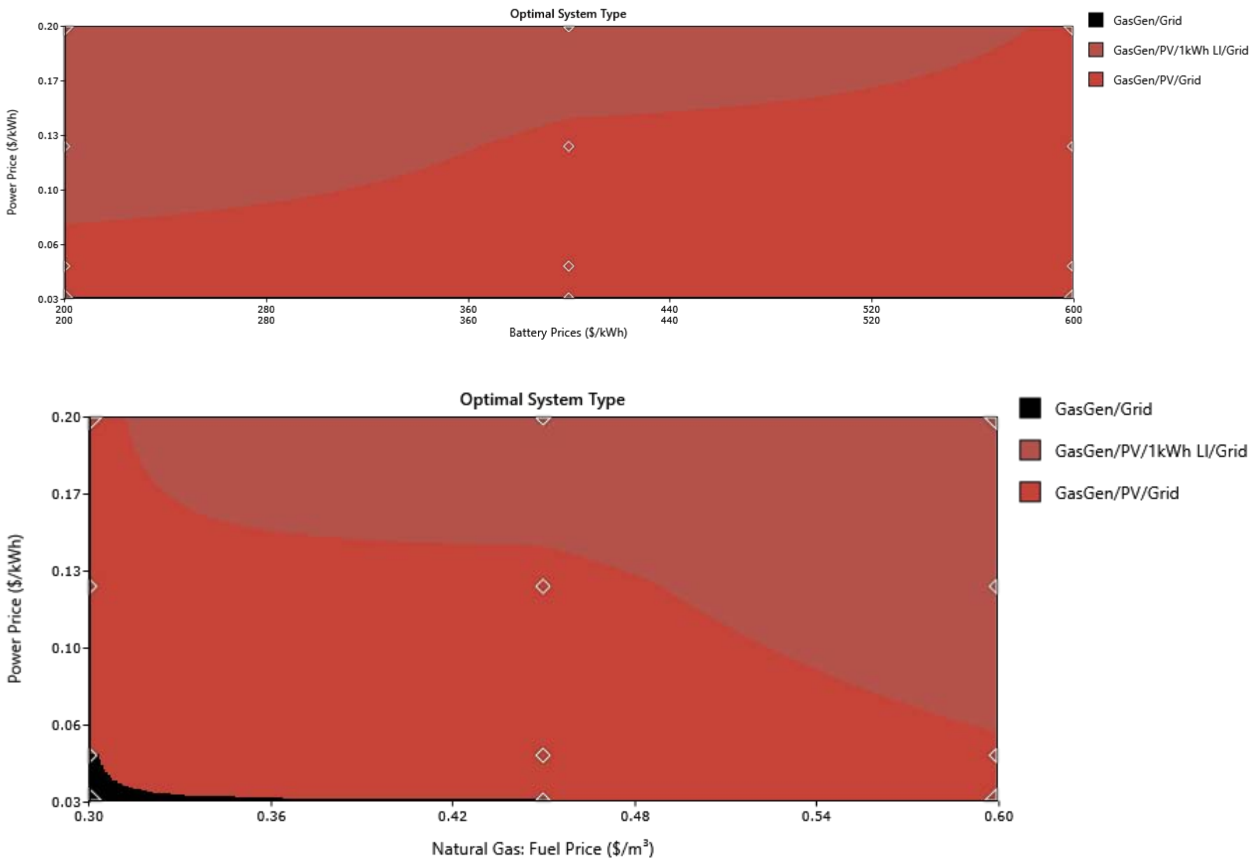


Figure A-26. OST chart for reliability

The OST plot shown above compares system configurations for varying grid power prices and natural gas fuel prices. The grid outage frequency was set at 730/year and the grid repair time at 6 hours. The battery costs were fixed at $400/kWh. For very low fuel prices and grid power prices, the grid + gas turbine base case was the least-cost system. As both the prices increased, more PV was included in the system. Higher natural gas prices made the addition of battery in the system more attractive.

The bubble plot shown in Figure A-27 depicts how PV and battery sizes vary with battery costs and power price. For a given power price, the PV size remains fairly constant. Battery costs impact the inclusion of batteries in the system. A PV-battery hybrid system seems economical at high power prices where batteries reduce the grid purchases.

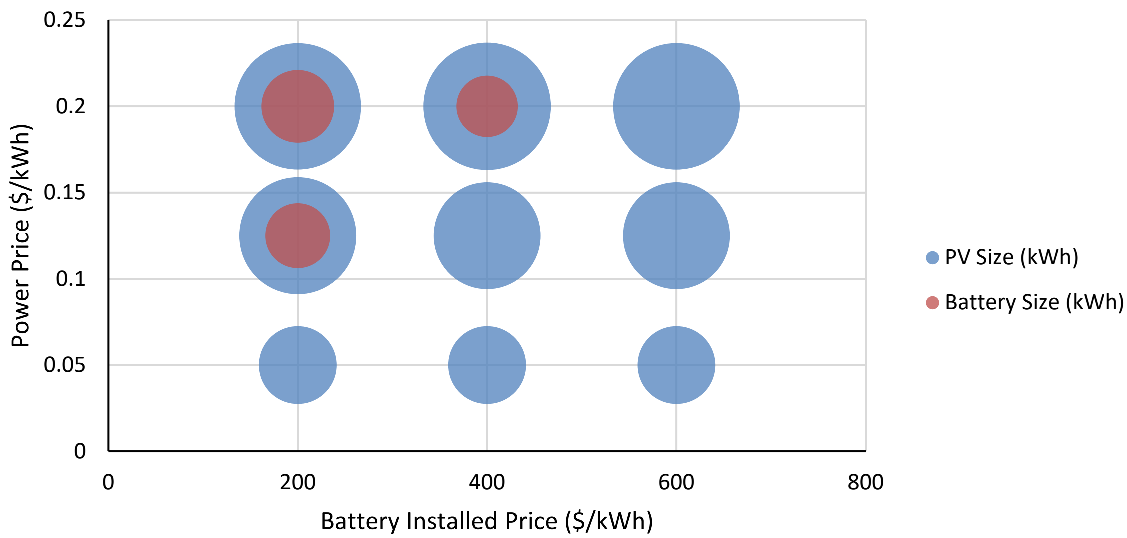


Figure A-27. Bubble chart for reliability

This bubble plot in Figure A-28 compares PV and battery sizes for different natural gas fuel prices and grid power prices. The grid-gas turbine-only combination seems economical for low power price and fuel price. As both these sensitivities increase, the size of PV-battery systems increases. The battery sizes included in the system vary between 450–550 kWh.

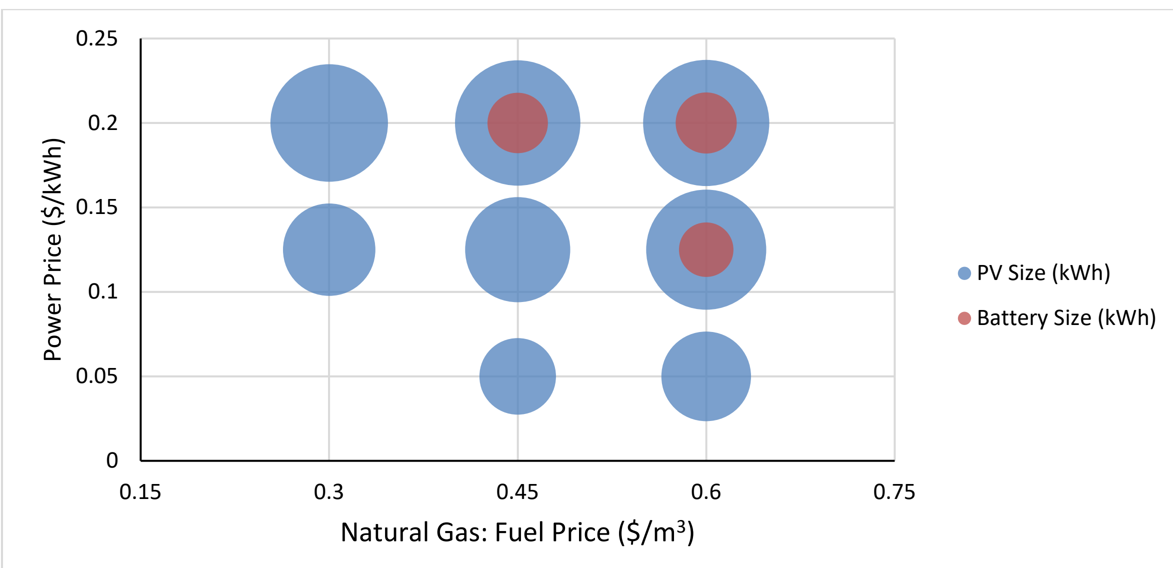


Figure A-28. Bubble chart for reliability

The spider plot in Figure A-29 compares all the sensitivities considered in this study. The battery cost has almost no significant impact on the system NPC, as the batteries were not part of the winning categories when their capital/replacement cost exceeded $400/kWh. In addition to the significant players like grid power price and natural gas fuel price, the frequency of outages and the repair time also played a role in determining the system NPC.

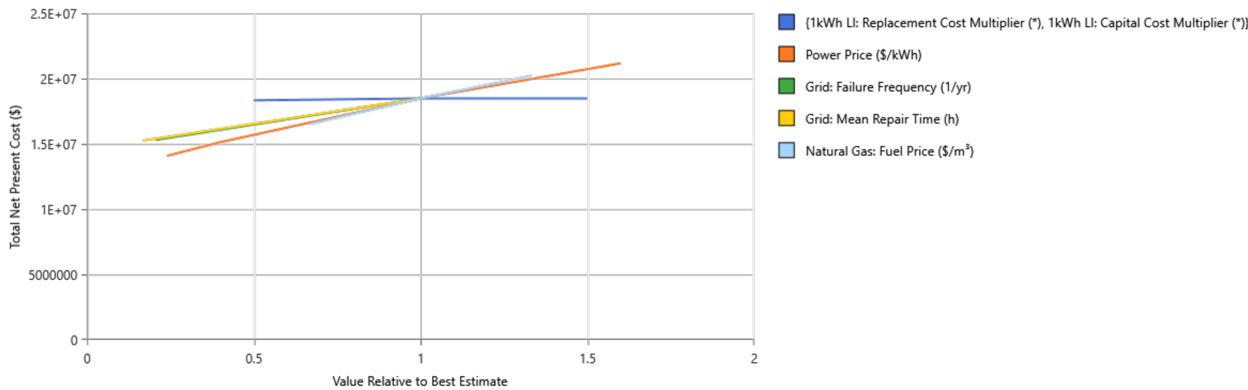


Figure A-29. Spider plot for reliability

For shorter outages like the ones modeled in this system, batteries are a great backup source because of their fast ramp up and grid synchronization characteristics. More storage can be added for peak-shaving purposes at higher demand rates. It could also be added to improve the supply power quality, which ensures a more reliable grid structure.

Conclusions from Modeled Case Studies

Following are key findings from the HOMER case study modeling.

Inflection points make battery forecasts and predictions difficult.

- Small-sized Island (Indonesia): There is an inflection point at diesel prices higher than $0.50/L and battery prices lower than $750/kWh where the recommended battery installation increases by an order of magnitude in the bubble chart.
- Energy Access: There is inflection point at diesel prices of over $1/L, where the recommended size of batteries increases by an order of magnitude. Markets with diesel prices over $1.0/L are highly attractive for hybrid system installations.
- Medium-sized Island (Caribbean): There is an inflection point when the diesel fuel price exceeds $1/L and the solar GHI is high (6 kW/m^2/day) where there is a significant increase in the size of the battery included. This complements the increase in PV capacity with increased GHI.

Reducing the battery cost by 50% often means hitting the inflection point.

- Small-sized Island (Indonesian): The impact of a $300/kWh price, compared to the current price of $600/kWh, results in a 17.6 times larger size storage with a slightly lower annualized cost. The impact of a $450/kWh price, compared to the $600/kWh, results in a 6% increase in storage size. Therefore, the most interesting developments for the storage industry may occur after the 2020 projection of $415/kWh, shown in Figure 4.
- Energy Access: With regard to the Figure 4 forecasted battery price forecast for 2020 of $415/kWh and today's price of $558/kWh, this case considers a reduction between $600/kWh and $300/kWh. The 50% lower battery price would encourage an almost 80% larger PV system and a battery system that is 19 times as large. The lower battery price would offer a 5% reduction in the annualized energy costs.

The hybrid system is (almost) always the most economical option with regard to NPC.

- Small-sized Island (Indonesia): One-color OST shows that under all sensitivity values tested, a hybrid system of PV, storage, and diesel generators is most economic.
- Energy Access: One-color OST shows that storage, PV, and diesel generators are most economical.
- Campus Resiliency: The fully hybrid system with PV and storage is always recommended at power prices of $0.10/kWh and higher and natural gas prices of $0.30 and higher.
- Medium-sized Island (Caribbean): Even for low diesel prices, the hybrid system, consisting of diesel generators, PV, wind, storage, and sometimes hydropower, proved to be the least-cost system.

For diesel base case systems, diesel price is the most important criterion determining the cost of the hybrid system.

- Small-sized Island (Indonesia): See Figure A-5, Indonesian island tornado chart. If the diesel price were $1.5/L instead of $1/L, the LCOE savings could go up to $0.137/kWh. However, if the diesel price were $0.5/L instead of $1/L, there may be only a $0.012/kWh LCOE savings between the all-diesel case and the hybrid case.
- Energy Access: The diesel price can affect the NPC by approximately +/- 25%. Based on the spider plot, the most influential sensitivity variable on the NPC is the diesel price. The diesel price also has the most influence on the cost of LCOE. At $1/L diesel, $0.17/kWh could be saved by installing a hybrid instead of the all-diesel system; at $0.50/L diesel, only $0.09/kWh could be saved; at $1.5/L diesel, as much as $0.27/kWh could be saved.
- Medium-sized Island (Caribbean): A $0.5/L increase in diesel fuel price increased total NPC by $250M.

For grid-connected systems, the power price is the most important criteria determining the cost of the hybrid system.

- Campus Resiliency: The most important sensitivity variables—natural gas price and power price—can be seen on the spider plot.
- Critical Infrastructure Resiliency: Grid power price was an important factor in determining the inclusion of PV in the system. A grid power price of more than $0.1/kWh reduced the grid purchases drastically and added more PV to the system.

Expected IRRs.

- Small-sized Island (Indonesia): With respect to the IRR, in the case of a high ($1.5/L) diesel price and the lowest ($150/kWh) storage and ($1/W) PV price, the IRR can be up to 28%. The expected IRR for the middle case of $2/W PV and $1/L diesel and $450/kWh storage is 14%.
- Energy Access: The middle case, of $1/L diesel, $600/kWh storage, 8% discount rate, and $2/W, has an IRR of 28%. The returns for the energy access market can range from 13% to 48%, varying by the sensitivity conditions.

Findings can be specific to each case:

- Small Island (Indonesia): The small island market can be profitable and interesting, especially if procurement costs are low for storage and PV, but the diesel price is high.
- Energy Access: Energy access is a promising market for hybrid systems, because in all cases tested, the hybrid system is more economically viable than the diesel-only system. However, entering the energy access market requires offering smaller-scale products with minimal maintenance, understanding local financial structures, and offering flexible payment options for customers.
- Medium-sized Island (Caribbean): A hybrid system including all the sources of generation is the most economically viable solution for this case, although the inclusion of the wind resource is constrained by the available land to deploy wind turbines.
- Critical Infrastructure Resiliency: A PV-gas turbine-grid hybrid system turned out to be the least-cost solution for this case. A small amount of battery storage can be added to provide for value streams such as peak shaving and power quality improvisation.
- Campus Reliability: A CHP generator cost-effectively serves thermal and electrical loads and can provide backup power in case of outages.
- Commercial and Industrial Reliability: A hybrid system inclusive of all sources was the least-cost solution for this case. The size of the batteries was highly dependent on grid power price and battery installed price. Batteries are a great source of backup power in such a system with frequent and short outages.