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Alternate Revenue Stream Analysis for a Residential Battery Connected to a PV Rooftop

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by

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Abstract

The market for emergency backup power for residential homes in the U.S. has been increasing ever since natural disasters like hurricane Irene, Katrina and Sandy have caused widespread, long durational blackouts. Lithium ion battery storage has a great potential to capture this market, but it has a high capital cost of investment that dissuades most homeowners from investing in it. However, recent advances in lithium-ion technology as well as policy changes have opened exciting avenues for research studies into the capabilities of these batteries for services like energy arbitrage and frequency regulation. These new business cases enable batteries to be a source of revenue, while also serving its primary purpose of providing emergency backup power.

A lithium ion battery is a hefty investment of anywhere between 400-1000 $/kWh of storage at current market rates. Keeping this battery idle for only backup purposes in case of an emergency is underutilizing its potential and is too high an investment for most residential homeowners. What if this battery could provide backup in case of an emergency and also simultaneously provide a steady revenue stream by participating in market services like energy arbitrage and frequency regulation? This research looks to answer that question and simulate scenarios where the battery can become a revenue-generating asset. By maximizing revenues of the battery system, this research further tries to find an alternative economic metric to quantify the cost of emergency backup power to a homeowner. The study is using a system based out of the GridSTAR residential research facility at the Navy Yard in Philadelphia.

Table of Contents

List of Figures

List of Tables

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Chapter 1

Background

The 5th Intergovernmental Panel on Climate Change (IPCC) report states that accelerated global climate change is a real phenomenon and it is “very likely” (above 90% statistical confidence) due to anthropogenic influence (IPCC, 2013). The anthropogenic influence talked about is mainly the release of CO_2 in the atmosphere. According to the EPA, 57% of CO_2 released is due to the burning of fossil fuels, out of which, 41% is emitted by the burning of fossil fuels for electricity generation. (Figure 1-1)

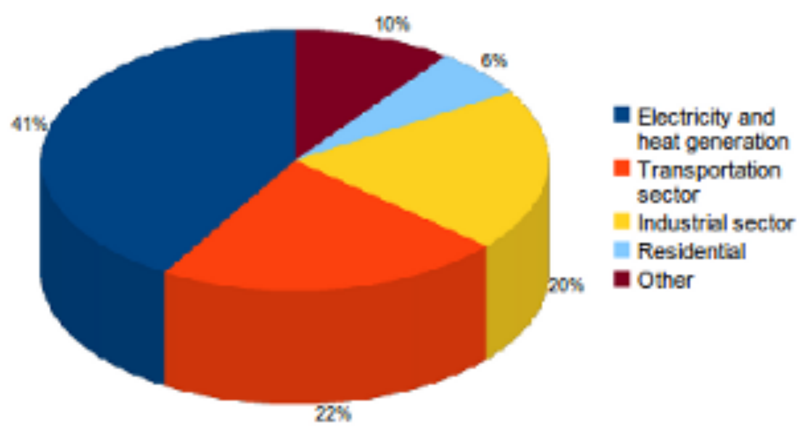


Figure 1-1: CO_2 emissions from fossil fuel combustion (Source: Le Quere et al., 2013)

Climate extremes and natural disasters like wildfires, hurricanes, earthquakes and tsunamis are occurring more frequently and with higher intensity (Dilley, 2005). A 2014 report published by the Climate Central states that there has been a tenfold increase in grid outages caused by extreme climate events between the mid-1980s and 2012 (Figure 1-2).

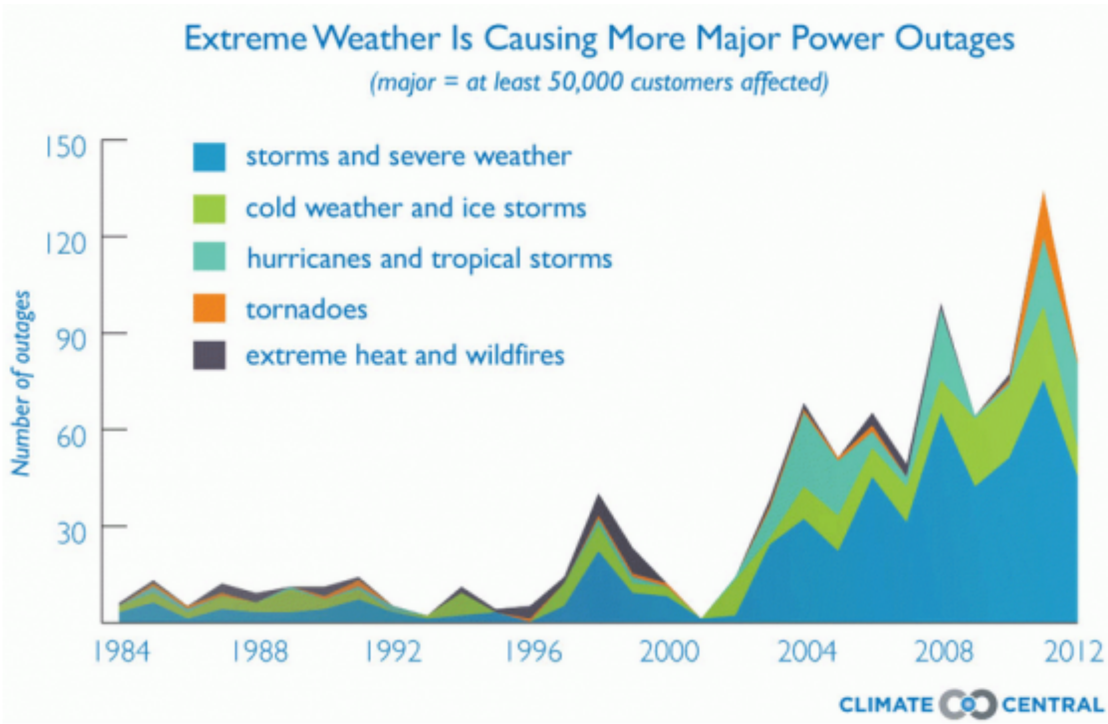


Figure 1-2: Breakdown of outages according to weather event. (Source: Climate Central, 2014)

Hurricane Sandy that struck the east coast of the United States in October 2012 is one such example of a high intensity weather event. Apart from the damages exceeding $50 billion (US Dept. of Commerce, Service Assessment, 2012), Hurricane Sandy brought to the forefront a critical issue facing the country's electricity grid infrastructure- a lack of resiliency. Sandy knocked out power to 8.1 million customers across 20 states (Clayton, 2012) and the severity of outages can be seen in the following image (Figure 1-3).

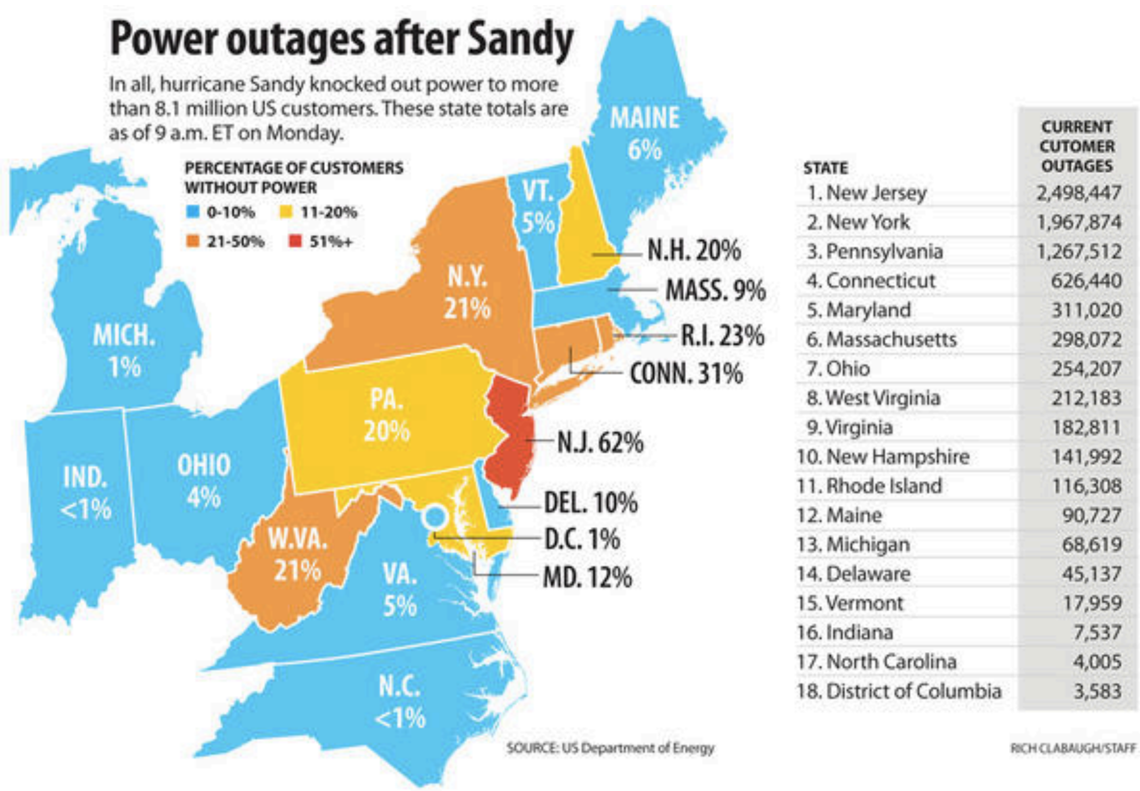


Figure 1-3: Power outages after hurricane Sandy. (Source: U.S. D.O.E.)

Grid Failures

The frequency of blackouts has increased over the years, and there is a statistically significant increase in blackout frequency during the peak hours of the day as well (Hines et al., 2009). While Hines does not comment on the duration of the blackouts, he says that 2/3^{rds} of the grid failures are due to natural events, and that the largest blackouts tend to be either due of these natural events or due to cascading grid failures. This is also verified by a recent 2014 report published by Climate Central which reports that weather related power outages have increased in the last decade (Figure 1-

4). For these long duration blackouts (>5 min), a customer will be without power for 120 minutes on average, 1.2 times every year (LaCommare et al., 2006).

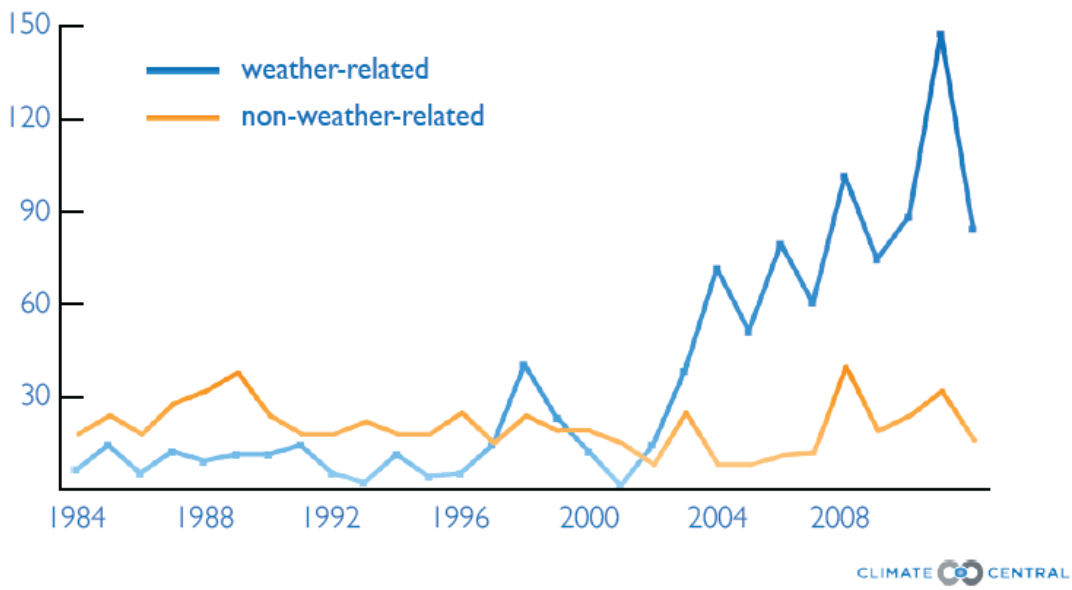


Figure 1-4: Trend of the frequency of power outages categorized by weather-related and non-weather-related events. (Source: Climate Central, 2014)

A study conducted by Lawton et al. in 2003 collected data on the cost of grid failure to different types of customers. For large commercial and industrial (C&I) companies, the average cost per event for all regions is $59,983. For small-medium commercial and industrial units, the average for all regions is $1,859. A positive sign is that the cost of blackouts has decreased over the years - the average cost of a 1 hour blackout for large C&I customers fell from $37,000 (pre 2000) to $29,000 (post 2002).

As far as the residential customers are concerned, the damages cannot be quantified in terms of lost business, so instead the Lawton study did a survey of the homeowners' willingness to pay for uninterrupted power in case of grid failure. On an average, a customer is willing to pay about $7 an hour for continuous power during an outage. The LaCommare 2006 study did a survey on the residential customer losses during outages, which included cost of consumable goods (flashlights, candles etc.) and the cost of inconvenience (activities like resetting clocks, changing plans, mental anguish etc.). Interestingly, customers said their losses amounted to $2.70 for an hour of outage. Although the methodology of both researches differs slightly, there is a clear discrepancy observed between a customer's willingness to pay for reliable supply and the perceived cost of a power outage. Customers are willing to pay a premium for backup power, which is a value greater than their perceived economic losses.

This section identifies an increasing market for residential backup storage due to grid failures. Emergency backup is the proverbial cure for grid failures, but there is an even more essential precaution that can be taken – improving grid resiliency by using distributed generation, distributed solar in particular. The next section talks about the distributed solar market and how it can help improve grid resiliency. Since this research is based on a residential rooftop PV-battery system, it is important to explain the role of both solar and battery storage.

Distributed Solar

Rising costs of fossil fuels for electricity generation and increasing Renewable Electricity Standards (RES) (Figure 1-5), combined with innovative clean energy financing schemes have paved the way for an exponential growth of renewable energy installations in the United States.

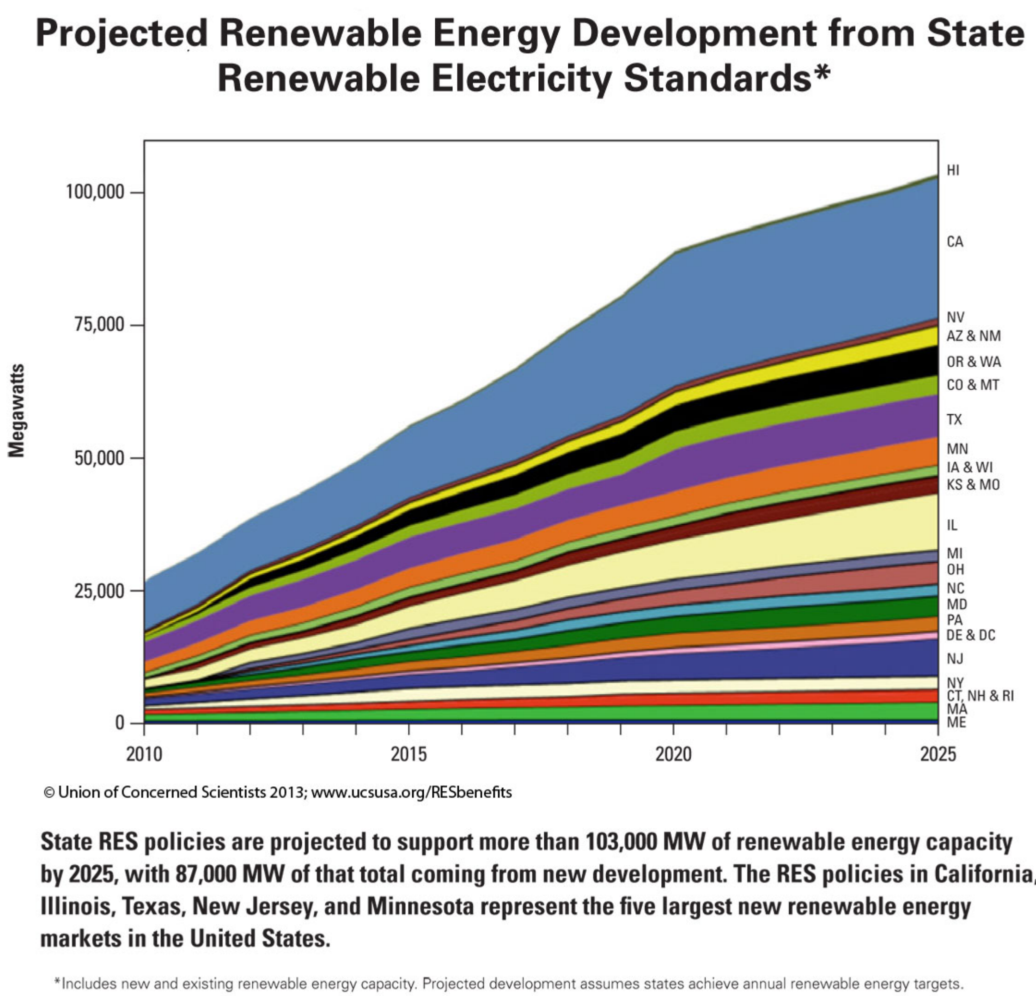


Figure 1-5: Projected growth of renewables according to states. (Source: www.ucsusa.org)

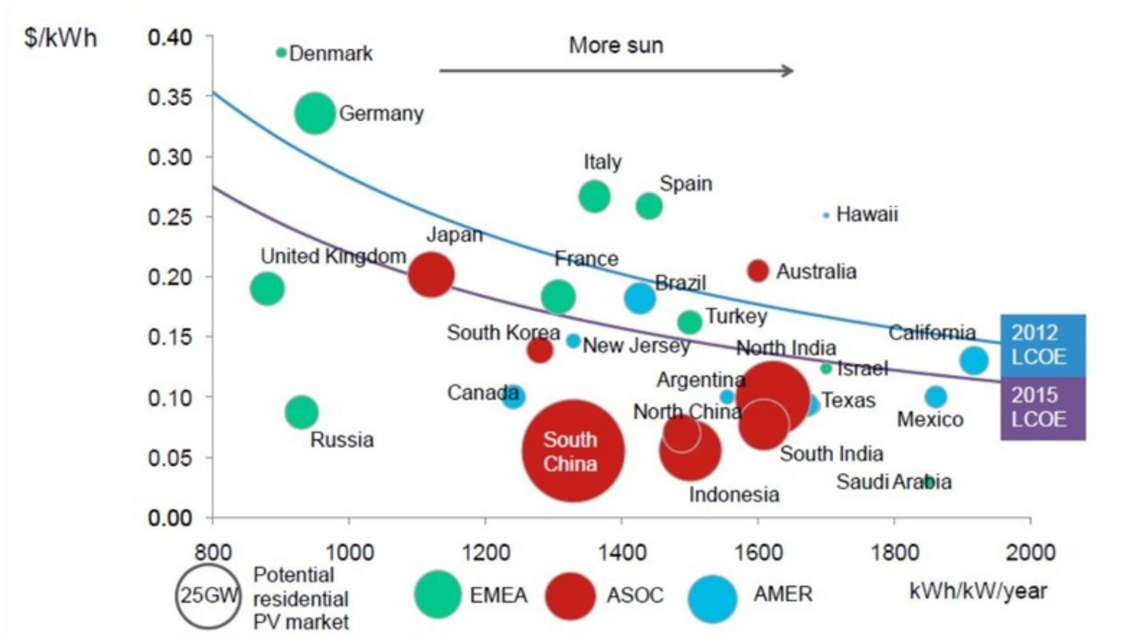


Figure 1-6: Solar power costs less than retail power rate (grid parity) in countries above the blue line (in 2012) and purple line (in 2015). (Source: BNEF)

We are now seeing a market where it is becoming economically feasible to generate electricity from renewable sources like solar and wind, comparable to fossil fuelled power plants. According to a 2012 report published by Bloomberg New Energy Finance (Morris, 2012), Solar power has already gained grid parity in a few countries and even more countries will see solar being cheaper in the coming years (figure 1-6). When the levellized cost of solar is equal to the existing electricity prices, grid parity has been attained. Parts of the United States like Hawaii, California, New Jersey and Texas have either achieved grid parity or are very close to attaining that position.

USA saw an unprecedented growth in solar installations in the year 2013 with a total installation of 4,751 MW, a 41% increase compared to 2012 (SEIA Solar Industry Data, 2013). Solar rooftop installations have been growing steadily over the years and with the Solar Investment Tax Credit (ITC) (SEIA Solar Investment Tax Credit, n.d.)

about to expire in 2017, it is expected that there will be a rush of installations in all three sectors of the solar industry - residential, non-residential and utility.

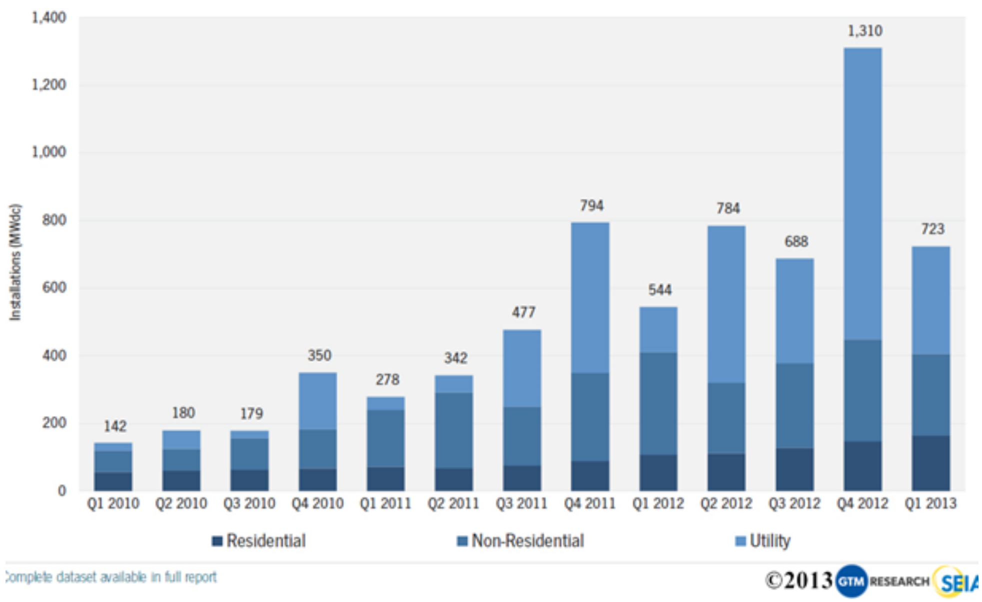


Figure 1-7: U.S PV Installations by Market Segment (Source: GTM research, 2013)

Such exponential growth of solar is disruptive to the electricity grid due to the irregularities in supply due to intermittency issues. One way to flatten the solar-PV curve and also account for a sudden drop in irradiance due to cloud cover is to use storage technologies. An interesting consequence of increasing solar penetration in the energy mix is the effect on net supply during sunrise and sunset. This can be understood better from the 'Duck Chart' (Figure 1-8) created by the California Independent System Operator (CAISO), which shows the non-PV generation requirements of the grid during the day. Due to PV generation during the day, the other generator requirements are lesser, but we see a very steep ramping up and ramping down of generation requirements at sunrise and sunset. This steep ramp rate will require fast ramping generators that will significantly increase the price of electricity at those hours. A way to reduce usage of fast ramping resources is to use battery backup to smoothen the upward curve.

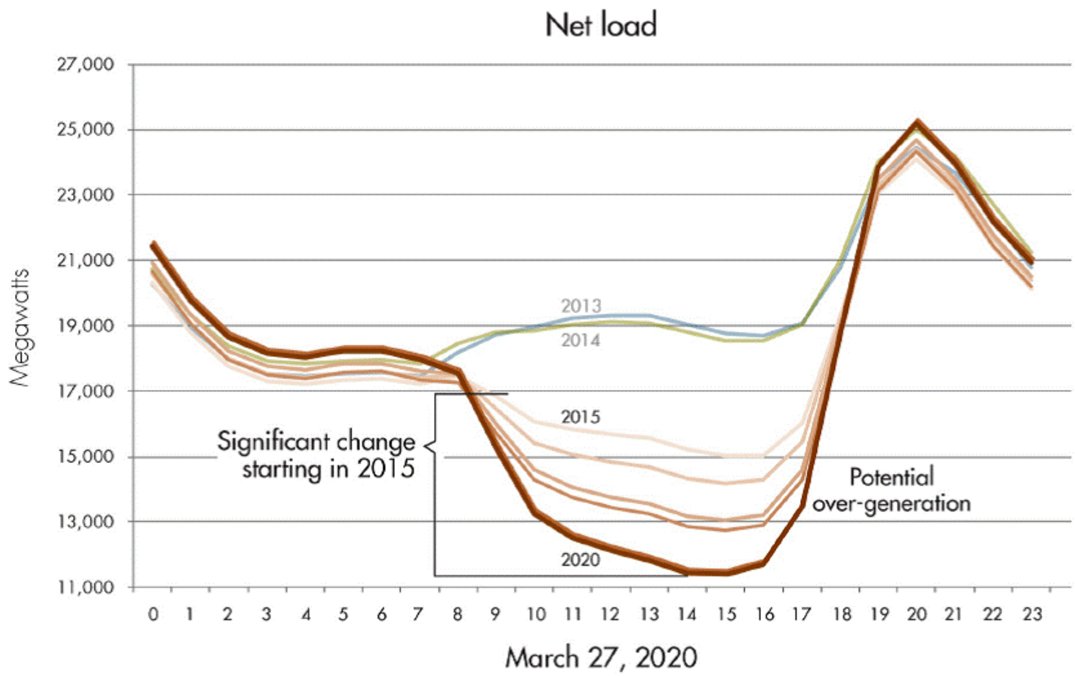


Figure 1-8: The 'Duck Chart'. Each line represents the net load of different years from 2012-2020. (Source: CAISO)

At a residential level, figure 1-9 shows us the load profile of the home and solar power generated by the 3.5 kW PV system used in this thesis. We can see an excess of PV between 11 am and 5 pm, which could be fed back into the grid or stored in the battery.

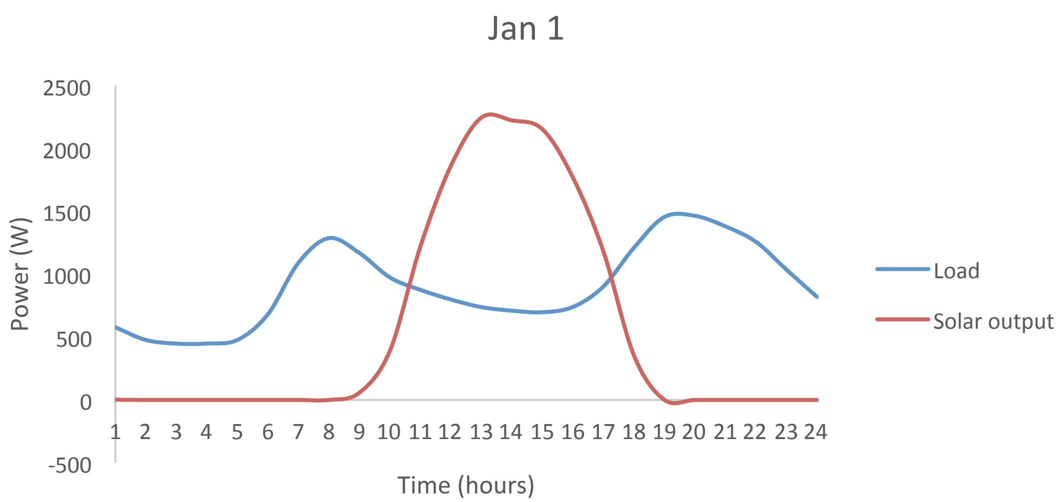


Figure 1-9: PV output and load profile (Residential unit, Philadelphia Airport region, TMY3 data)

The groundbreaking storage mandate AB 2514 was passed by the California Public Utilities Commission (CPUC) in August 2013 which requires the largest 3 California utilities (Southern California Edison, Pacific Gas & Electric, and San Diego Gas & Electric) to install 1325 MW of grid storage by the year 2020. This is to supplement the state's renewable energy generation targets of achieving 33% by 2020 (California Renewable Energy Overview and Programs. (n.d.)). Although the California storage mandate is not directly relevant to this research, it tells us that state policy makers are gearing up for implementing smart grids with distributed solar and battery storage. That this research will have an impact on how the business cases can be made for these battery technologies.

The next section will give a brief overview of different types of residential backup systems that are currently in use.

Residential Backup Systems

Emergency power for residential units has traditionally been supplied by fuel-powered generators or by lead-acid battery banks. In the recent years though, lithium ion batteries have started gaining prominence due to decreasing manufacturing costs. Backup generators and battery storage will be discussed in this section.

Generators

Generators are devices that burn fuels to provide electricity output. Gensets consist of a fuel tank, a motor that is connected to an alternator and a control panel. The alternator converts mechanical energy into electrical energy. There are two types of fuel-powered generators available for backup power – portable and permanent standby generators. Portable generators are cheap and are used for critical loads like light bulbs, refrigeration, and charging necessary appliances like cell phones and computers. Standby generators on the other hand can provide for the entire household's demand when the grid goes down. These are fixed outside the house on firm ground and are directly connected to the residential unit's electrical panel. They automatically turn on when the grid goes down if they are connected via an automatic transfer switch.

The different types of generator fuels are diesel, gasoline, biodiesel, natural gas, propane, and sometimes even hydrogen for fuel cells. For heavier loads, diesel fuelled generators are mostly used, but diesel generators do not function well in cold climates below 0^{o}C. Natural gas and propane generators are preferred if there is an existing gas pipeline supply to the house that can be used to power the standby generator.

Small and midsized portable generators are sized between 3 and 8.5 kW. They are much cheaper than standby generators and range from $400 to $1000. Portable generators use mostly diesel or gasoline, which release harmful carbon monoxide when burnt, which is why they can never be used inside the house. To be used, they need to be removed from storage, filled with fuel, manually started and finally connected to the load panel. They need to be constantly refilled to provide power for longer hours, which means that the homeowner needs to store flammable fuels near the premises. They are popularly useful for outdoor activities like camping but are not a very trustworthy source of reliable backup power. For contingency planning for long durational blackouts, a standby generator is more suitable to the homeowner.

Standby generators can be as small as 7 kW and there is no upper limit to the power output. Larger generators can basically act as a mini power plant, but they're generally not found in many residential units due to permitting and space constraints. They have about 15-30 seconds of startup time and need to be used in conjunction with a UPS (Uninterruptible Power Supply) to maintain a continuous power supply between the time the grid goes down and the generator is running. These are usually connected to a fuel source like a natural gas or propane pipeline, so do not require refilling and are more convenient to use. For locations with greater frequency and duration of power outages, these types of generators are more useful. A downside is their higher costs ranging between $3,000 to $10,000.

Generator lifespan depends on the type of fuel used, the assembly components, the rpm of the engine, the type of cooling system used and the maintenance undertaken. Amongst fuel types, the diesel gensets last the longest. A generator running at 1800 rpm will last 2-3 times longer than a faster one running at 3600 rpm. A liquid cooled genset has more runtime than an air-cooled genset. Properly maintained liquid cooled, diesel gensets can run for 15,000 to 20,000 hours. The price of the generator increases as the expected running hours increase.

On the downside, gensets are loud, need space outside the home, are polluting, have unreliable startup times and operational failures, require external effort for startup- either through a battery bank or manually, and have a startup time. They are also dependent on an external fuel source, so if the fuel source is cut off in case of an emergency, the genset is basically useless. Also, since fuels freeze in very cold climates, generators may not be a good option in regions with prolonged icy winters. Although portable generators are cheap, they have many maintenance hassles and will not be recommended as a very reliable source of backup for the home. Standby generators can provide sufficient backup if sized properly and regularly maintained, if the homeowner is willing to pay the high price tag.

Batteries

A battery is an energy storage device in which electrical energy is converted to chemical energy via an electrochemical reaction inside the cell that consists of two electrodes and an electrolyte. The reaction causes electrons to transfer from one electrode to another via an external circuit. The desired output current and voltage can be obtained by connecting the individual cells in series or parallel or a combination of both. The important parameters that characterize batteries are capacity, power rating, charge-discharge efficiency, total number of cycles, operating temperature, depth of discharge and of course, their manufacturing cost. All these parameters depend on battery chemistries and electrode materials used (Divya et al., 2009). Due to their smaller size and higher safety ratings, lead acid and lithium ion batteries are the most common batteries used in a residential setting.

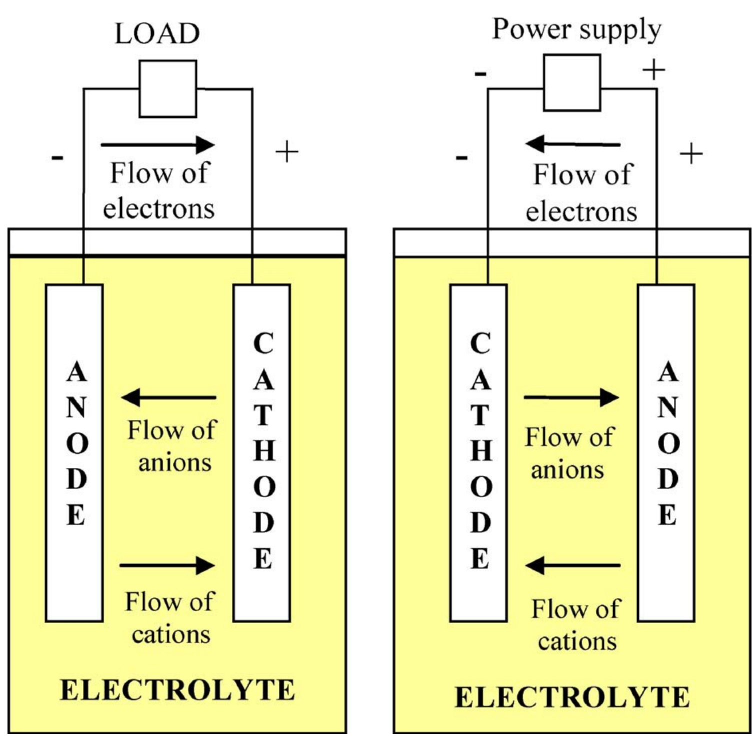


Figure 1-10: Working of a battery during discharging and charging.

The biggest disadvantage of a battery that is used for emergency backup is the limited capacity. For prolonged outages that last for days, a standalone 10 kWh battery would run out of power without being recharged. This is why batteries make so much more sense when paired with solar PV systems when used for backup. During emergencies, the solar panels can provide the homeowner electricity during the day, and excess power can be used to charge the battery, which can run the home when the sun is not shining.

Lead acid

A lead acid battery is the most mature type of rechargeable battery technology that exists, and its most common application is in car batteries. The cathode material is lead (IV) oxide, the anode is made of lead and the electrolyte is sulphuric acid. It has a nominal cell voltage of 2V. Lead acid batteries have relatively lower efficiencies compared to lithium ion batteries and the efficiency depends on the charge and discharge rate. Slower the rate, higher is the efficiency. They have the advantage of a lower capital cost, recyclability, low maintenance costs and is a trusted, mature technology. Their disadvantages are a shorter number of total charge-discharge cycles, lower efficiencies, and shallow depths of discharge. They show significant degeneration and loss in performance at temperatures above 25^{o}C, but can withstand lows of -40^{o}C. They are used for long-term energy storage and peak load shifting applications.

Lithium Ion

Lithium ion batteries consist of a lithiated metal oxide and layered graphitic carbon structure as the cathode and anode respectively. The electrolyte is a generally lithium salts dissolved in organic carbonates. The light weight lithium metal causes the cell to have a higher cell voltage (≈ 4V) and high energy and power densities. The cathode is typically made of either a layered oxide, a polyanion or a spinel structure. The anode is usually graphite. Significant research is being done in the materials aspect of lithium ion batteries to tailor make batteries according to their end use.

Lithium ion batteries show the most promise when it comes to grid scale storage technologies because they have a variety of desirable characteristics like high energy density, efficiencies above 90%, low self-discharge rate and negligible maintenance requirements (Dunn et al., 2011). The discernible drawbacks are the high capital costs and the detrimental effect of over charging and discharging on battery life. (Hall et al., 2009). Also, thermal runaway is a major concern - the 2013 Boeing 787 Dreamliner incidents with their lithium ion batteries catching fire being a major recent controversy. If the battery is overcharged, it can cause significant thermal buildup, which can cause a fire.

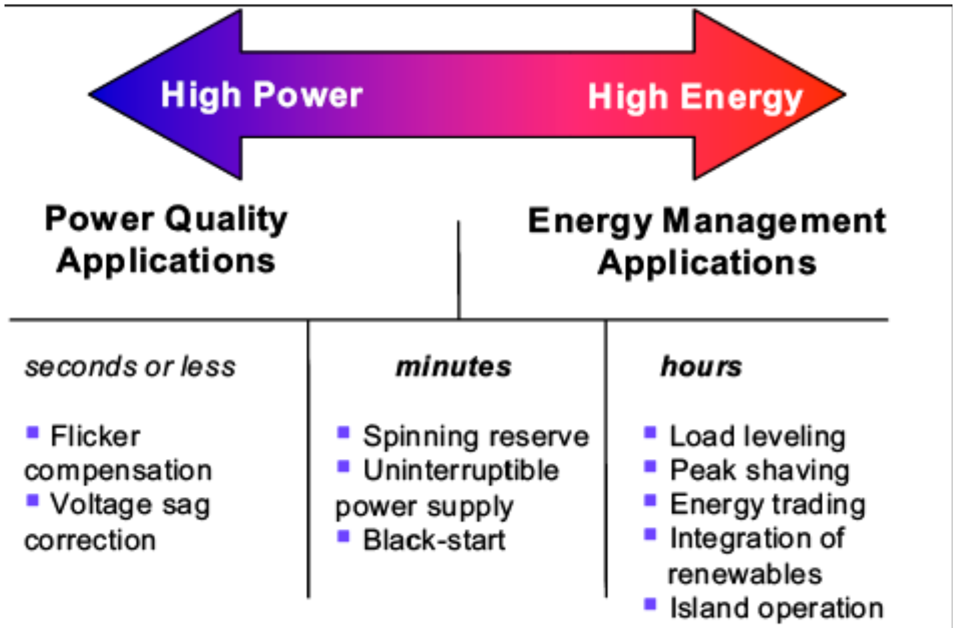


Figure 1-11: Applications of batteries based on their power vs energy capabilities. Source: (Oudalov et al., 2006)

Depending on their characteristics, batteries can be used for power quality applications or energy management applications (figure 1-11). Batteries with a high power density are more suited for power quality applications while batteries with a greater energy density are used for energy management. Lithium ion batteries can be used for energy storage, fast acting ancillary services like regulation and reserve, and also for peak shifting and load leveling. Common and well-practiced applications of batteries connected to solar PV are for solar smoothing, peak shifting and energy arbitrage. For a residential system like the GridSTAR, solar smoothing is not of financial importance since there are no tangible revenue streams arising from it, and the MPPT and inverter in combination are capable of smoothing out the voltage fluctuations arising out of PV intermittency. Peak shifting plays no role in residential units as utilities have not yet enabled a tiered pricing model for residences based on peak power consumption. Energy arbitrage on the other hand is a very feasible option for gaining revenues with the battery since time-of-use pricing enables storage of excess PV to be sold to the grid when electricity prices are high.

Chapter 2

Problem Definition

After hurricane Sandy struck the east coast of North America in 2012 and left millions of people without electricity, residential battery backup storage caught the eye of investors, customers as well as researchers. Battery storage along with distributed rooftop solar is an integrated system with which a home could be powered for long durations during power blackouts. But battery systems are currently too expensive for feasible deployment across the country as the high investment cost of the batteries outweighs the benefits of uninterrupted power supply for homeowners.

Residential, backup batteries are currently utilized only during times of grid failures. The rest of the time the capacity lies idle. There is a potential in this idle battery capacity that can be utilized to gain revenues. Oudalov et al. in 2006 analyzed the value of load leveling, primary frequency regulation and end-user peak shaving. They came to the conclusion that for load leveling, it was cheaper to upgrade grid infrastructure instead of using batteries to satisfy increasing loads. Peak shifting for batteries was profitable, but provided much lesser revenues as compared to regulation. A 2MW battery had an annual profit of 0.6M€ with a payback of 11 years. Beer et al. in 2012 determined that battery energy systems installed in buildings do not reach their break-even point of investment without participation in regulation reserve. These energy management systems are beneficial to microgrid services to serve the internal loads of the building as well as for providing frequency regulation. Clastres et al. in 2009 analyzed ancillary services for residential scale PV systems in Europe. Their methodology involved uncertainties in the supply of PV and demand loads and concluded that within certain uncertainty limits, these systems could be used for gaining revenue via regulation market participation.

This research aims to find profitable revenue streams that can be used to recover the capital cost of the battery, while providing varied levels of backup power to the homeowner. Imagine a scenario where the battery is continuously cycled to provide power to the home instead of using grid power. Although money is being saved by not purchasing grid power, the batteries capacity is being utilized and will degrade till it cannot cycle anymore and needs to be replaced. It is vital to the homeowner that the total money saved be greater than the investment cost of the battery, for otherwise it does not make any economic sense. To ensure that the revenue stream will always be greater than the investment cost, this research has amortized the battery capital over its lifespan and has called it the *battery degradation cost*. Barley et al. in 1996 and Dufo-Lopez et al. in 2007 have used a similar parameter and they have called it the 'cost of battery wear' and 'cost of cycling' respectively. This value is used to maximize revenues so that the battery is either cycling profitable or not cycling at all.

Chapter 3

Grid services

A Regional Transmission Organization (RTO) in the United States is a neutral, independent party that coordinates the movement of wholesale electricity through large, interstate areas. PJM is one such RTO in the northeast region. It began in 1927 when three utilities started sharing their generation and transmission resources. Over the years, PJM expanded to include both utilities and transmission systems and currently operates in all or parts of 14 states of the eastern coast as seen in figure 3-1. PJM became the nation's first fully functioning RTO in 2001 and comes under the scrutiny of the Federal Energy Regulatory Commission (FERC).

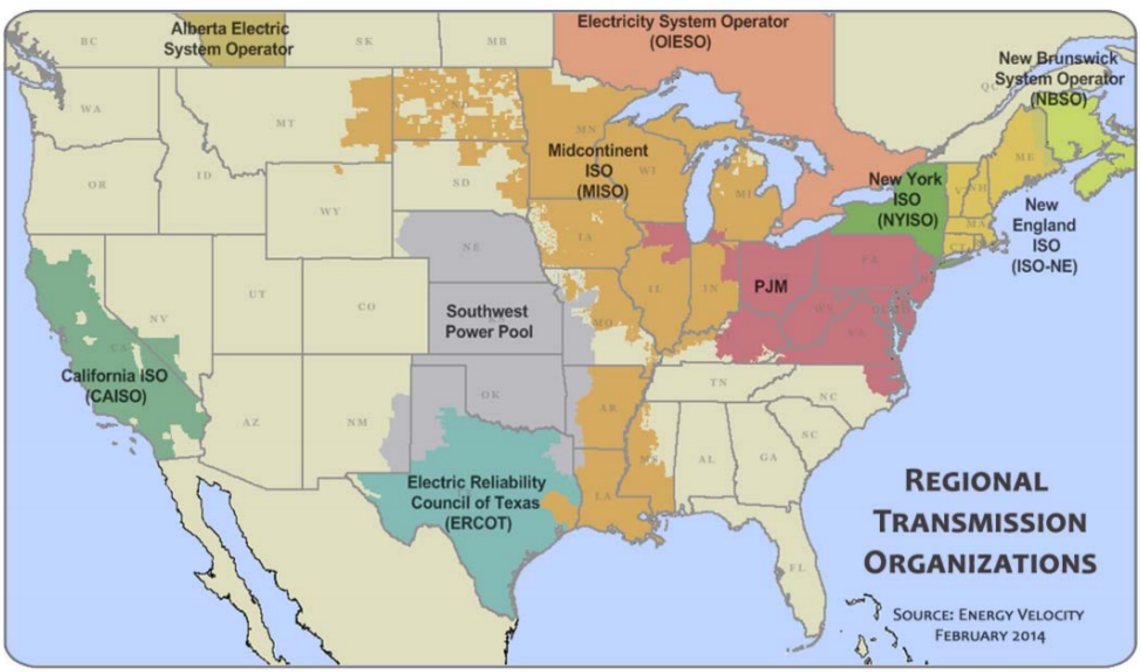


Figure 3-1: List of RTO's in the United States as of 2014

There are distinct advantages of interconnection of generation resources. Power pooling provides PJM members the benefit of procuring power from other locations through the interconnected grid. This is particularly useful when there is a resource scarcity in one part, in which case electricity can be ramped up at another location and dispatched to the resource scarce area to ensure timely supply of power to customers and maintaining grid stability. Also, due to the large area that PJM covers, it has a variety of generation resources under its belt that the consumer has the right to choose from. This allows for a fair, open market and ensures customers get delivered the lowest cost power available to meet demand at any given time.

Because the interconnection is so vast and there are so many power flows, the RTO has to ensure that demand and supply is balanced at all nodes of the grid. If there is an imbalance between demand and supply, the grid will fail. The grid is stabilized primarily by balancing larger energy flows. This can either be done by increasing the generation to match the load or decreasing the load to match generation. Decreasing load is done from the end user side and this is called demand response. A secondary aspect of grid stability is the balancing of power flows in a shorter time frame, which is done by ancillary service providers.

PJM categorizes ancillary services as the services “required to support the reliable operation of the transmission system as it moves electricity from generating sources to retail customers.” (PJM Ancillary Services, n.d.). These services are offered by power generators that supply real power that the system operator uses over various time spans to maintain instantaneous and continuous balance between generation and load. It is estimated that poor power quality causes productivity losses of around $400 billion to the US economy every year (Hall et al., 2008). The ancillary services ensure that the power quality in the grid is maintained within permissible limits. PJM classifies ancillary services into 3 categories –

a) Synchronized Reserve

b) Black Start Service

c) Market-Based Regulation

Synchronized Reserve

It has been remarked, "it is not a question of whether or not a particular piece of equipment will fail, but rather when it will fail" (Pereira et al., 1992). On the supply side of the grid, power generation failures can occur at any moment and without warning. The grid operator needs to have a contingency plan to compensate for the resulting lack of power generation. This contingency plan is called synchronized reserve and is the additional generation capacity scheduled in the PJM market above the expected load for a short duration of time. The time span for different reserves is shown in figure 3-2.

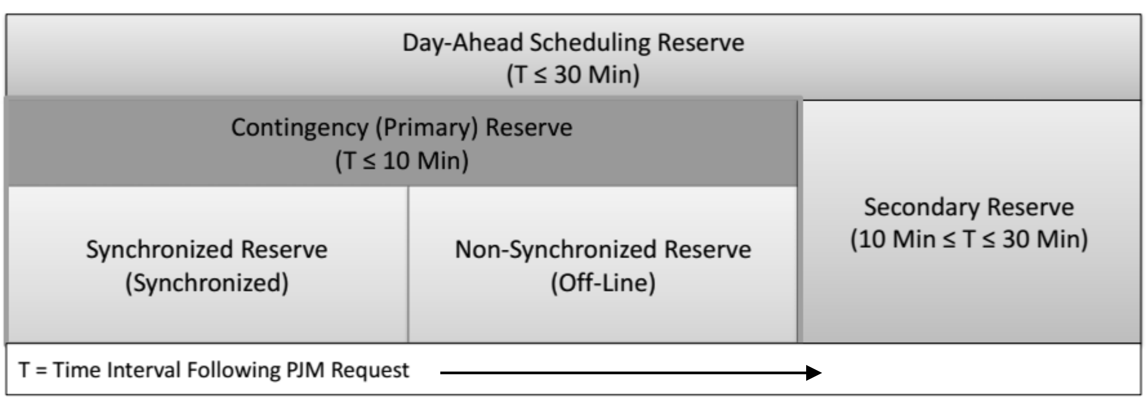


Figure 3-2: Time scale of reserve services (Source: PJM)

Black Start Service

Black start generators are those that do not require any external source of AC power to start and synchronize with the grid. They are typically combustion turbines or hydro units. They are critical for system restoration and used in case of a total system shutdown to provide startup power for the non-black start units. This is a cost based service, not market based and is very location specific. Black start units must also be able to run for 16 hours continuously and maintain frequency and voltage under varying load.

Market-Based Regulation

For grid stability, there has to be an instantaneous balance of demand and supply of active (real) power. The difference between the sum of all real power sources and sum of all real power sinks is reflected in the increase or decrease of system frequency. (Lazarewicz et al., 2004). The system frequency in the United States is kept at 60 Hz.

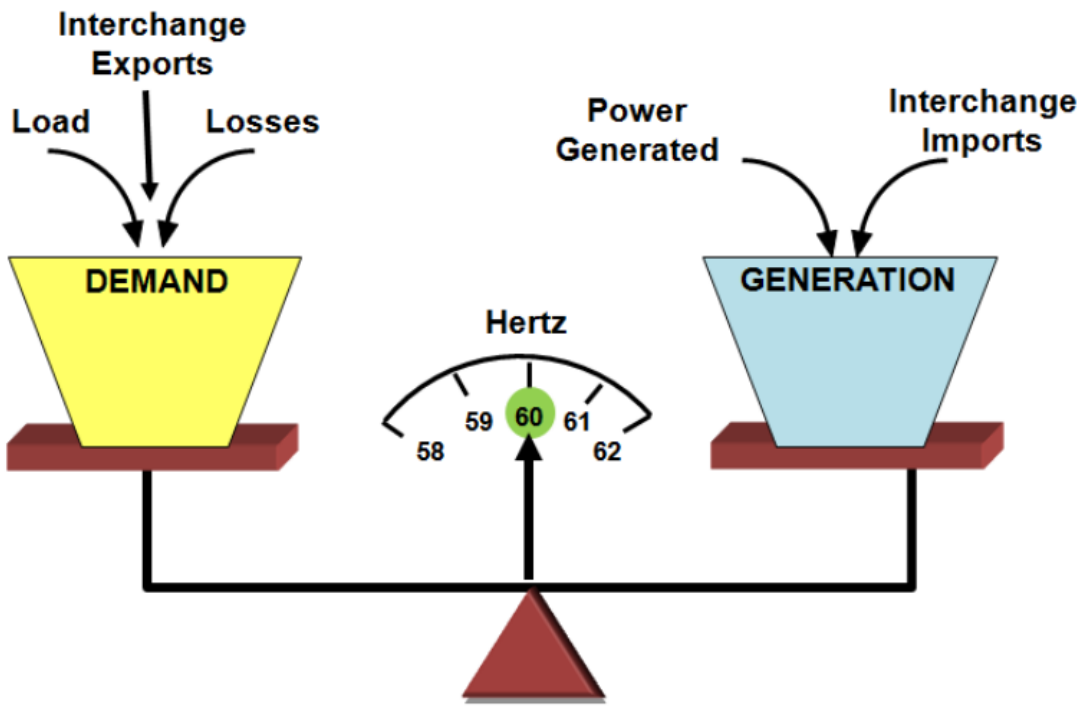


Figure 3-3: Frequency dependent parameters of the grid. Supply and demand should be balanced to maintain frequency around 60 Hz.

Frequency Regulation or simply Regulation is the ability of a load serving entity or end user equipment to absorb or generate power at short intervals of time according to an automatic signal from the system operator. Generating units or Demand Response Resources provide fine-tuning that is necessary for effective system control. Regulation is contracted on an hourly basis and the minimum capacity contract size is 0.1 MW for participating in PJM markets. The regulation capacity bid into the market must include equal parts regulation up and regulation down. A generator has to bid a minimum of 0.1 MW above and 0.1 MW below the baseline as a participation criterion as shown in figure 3-4. This means that it should have the capability to both absorb 0.1 MW and supply 0.1 MW of capacity every hour.

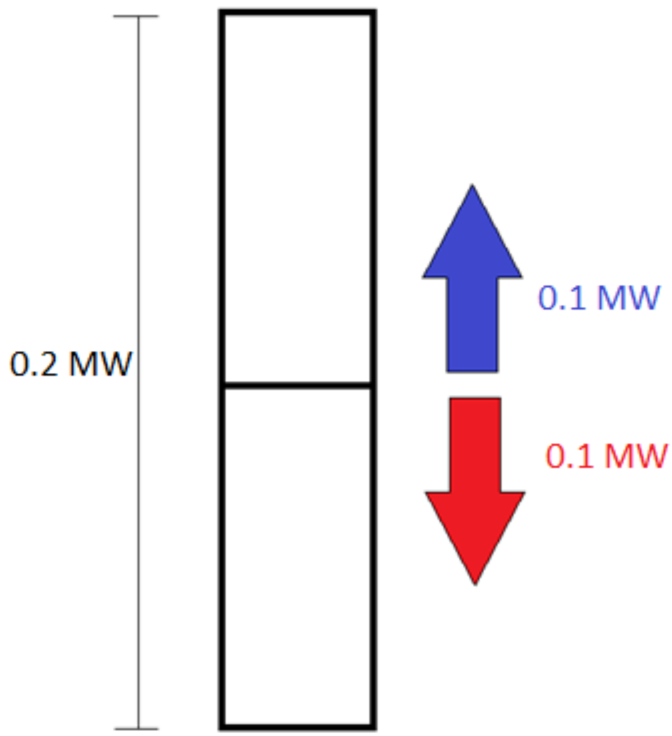


Figure 3-4: Minimum Regulation up and down capacity requirements for PJM markets

Load Serving Entities (Generators) as well as Demand Response Resources can participate in Regulation ancillary services. According to the FERC, Demand Response (DR) is defined as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." (Balijepalli et al., 2011). PJM is an ISO that allows demand side regulation services. Lithium ion batteries have the capabilities of providing ancillary services to the grid. A community of homes with aggregated, interconnected batteries can provide enough capacity to participate in PJM's services.

For an aggregated battery storage system like the one used in this research, the battery capacities can be combined to attain the 0.2 MW of total capacity. For modelling purposes, I am calculating revenues for a single battery regardless of the 0.1 MW floor capacity demanded by PJM. In the ancillary services market, the battery operator would bid a certain kW capacity of the battery into the regulation market and the bid would involve a cost associated with the running of the battery, something similar to the marginal cost of capacity. PJM would then call upon services as and when needed from the different players in the regulation market. It is not necessary that the entire capacity bid into the regulation market will be called upon by the ISO.

The ratio of the capacity actually used (performance capacity) to the bid capacity is called the dispatch to contract ratio. A dispatch to contract ratio of 0.10 would mean that for every 1 MW of capacity bid into the market, 0.1 MW would actually be called upon for use by the ISO. In 2013, Xi and fellow researchers analyzed historical PJM regulation data and found the highest ratio of 0.35 in some hours with the average ratio being much lesser at 0.10. Because of the bid capacity and performance capacity, the payments made by PJM to the battery are divided into two parts – a capacity payment and a performance payment. The capacity payment is made on the total capacity bid into the market. The performance payment is the payment made per unit of capacity actually called upon by PJM.

According to PJM, faster acting resources like batteries will be called upon more frequently than slower acting resources. It is why this research has used a much higher dispatch to contract ratio of 0.50 in the simulation model. Another reason for using this value instead of 0.35 is because Xi's analysis of PJM's historical data is up to the year 2009, a time where fast acting resources were not yet very prominent in the market.

A FERC mandate called Order 755 that was passed in 2011 ruled that payments made to frequency regulation providers should be proportional to the speed and accuracy of the service providers. This mandates that a fast acting resource in the ancillary service market like a battery or flywheel that has the capability to closely match the regulation signal provided by the ISO will get paid more than a slow acting resource like a natural gas or coal fired plant.

PJM has categorized resources into ramp-limited and energy-limited resources. The former consists of resources that have mechanical limitations to the rate of energy dispatch. These include steam and combustion turbines, combined cycle and hydroelectric dams. Energy limited resources have high power outputs that can provide sub second regulation (infinite ramp rates) and include batteries and flywheels. The traditional resources are ramp limited and are called RegA while the dynamic resources are called RegD. Figure 3-5 shows the difference in response time between the two signals.

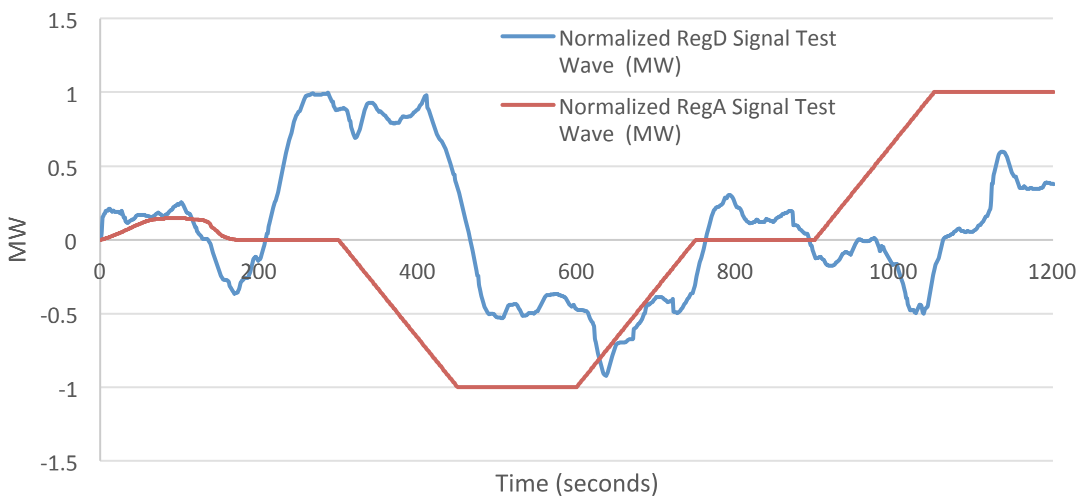


Figure 3-5: Plot of RegA and RegD test wave signal from PJM. (Data Source: PJM)

On a micro-storage level, smaller batteries installed in community residential units can be aggregated to provide significant capacity for grid stabilizing services. Little research has been done on smaller sized batteries being integrated with the grid to provide these services. The primary reason being the high initial cost of residential (Li-ion) batteries, that are currently in the range of 400-1000 $/kWh. This research will look at how this high cost of capital can be recovered by enabling the battery to participate in PJM's regulation market.

Chapter 4

System components

The system used in this research is located at a smart grid experience center called GridSTAR at the Philadelphia Navy Yard in Philadelphia. The Philadelphia Industrial Development Corporation (PIDC) owns the Navy Yard and the GridSTAR is a model for residential scale PV-storage grid interaction. It was built using state-of-the-art green building technology and materials that have a minimal carbon footprint, and it generates its own electricity because of solar panels, due to which it can be called a net-zero home. The GridSTAR has been built to act as an immersive learning experience center for regional stakeholders and act as a collaborative empowering tool for smart grid technologies. It brings together utilities, grid operators, equipment manufacturers, policy makers, energy researchers, students and builders under one highly energy efficient roof. The mission of the GridSTAR Center Initiative is to integrate energy storage and system controls along with distributed generation to study its impact on the U.S. electrical transmission and distribution network. It is also to be used as a hands-on experimental, educational infrastructure tool for multiple audiences.

Figure 4-1: The GridSTAR home

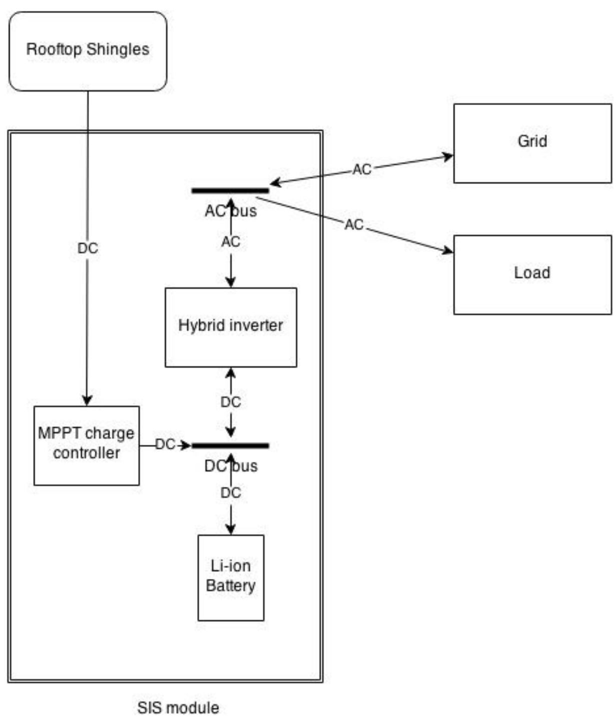


Figure 4-2: Block diagram of the GridSTAR system

PV Solar Shingles

The GridSTAR system has a PV integrated solar rooftop consisting of Apollo II roofing shingles that are manufactured by CertainTeed. There are a total of 77 modules. The array is wired in 5 parallel strings of 13 modules each, and a separate wiring of 3 parallel strings with 4 modules each. The 5 strings in parallel are connected to the Solar Integration System Module while the remaining 3 strings are connected to a DC hub, which is used for some of the electrical components of the home.

Figure 4-3: Solar shingles at the GridSTAR

Each module contains 14 high efficiency mono-crystalline silicon solar cells with a max power of 54 W. The shingles have unique benefits of being lightweight, high wind resistance, improved water handling and wire management, and also has a greater aesthetic appeal compared to rack mounted rooftop panels. The system specifications are shown in table 1.

Table 1: PV specifications

Module Max Power (Pmax)	54 W
Module Max Power Voltage (Vmp)	6.78 V
Module Max Power Current (Imp)	8.02 A
Arrangement	13 modules in series x 5 parallel strings
System Voltage	6.78*13 = 88.14 V
System Current	8.02*5 = 40.1 A
System Max Power	3534 W

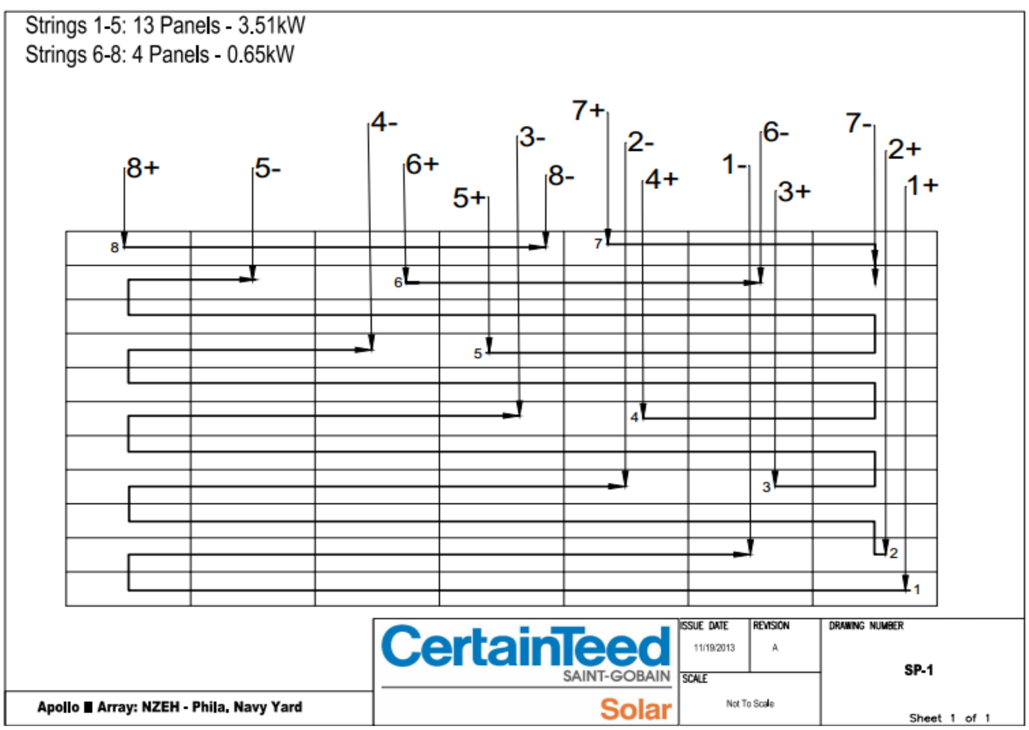


Figure 4-4: Wiring diagram of the rooftop shingles. (Source: CertainTeed)

Although the PV system is currently up and running, real time data is not being used in this research due to lack of solar output for every month of the year. The system started generating data in the beginning of January 2014 and currently has only 6 months of data. So instead, TRNSYS has been used to model the solar output. The solar irradiance data has been downloaded from the TMY3 database for the Philadelphia Airport region (NSRDB update - TMY3: Alphabetical List by State and City. (n.d.)). The PV shingle and inverter characteristics were inputs in the TRNSYS model to get an output hourly power profile in alternating current units.

Solar Integration System Module

The SIS (Solar Integration System) module is an energy management system that is used to capture energy and store it in the battery for future usage. The module consists of four major system components:

1. Inverter: Hybrid, grid-tied inverter for power conversion and grid interconnection
2. Gateway Computer: Computer to coordinate system operation locally and to communicate to the cloud via the Internet
3. Solar Charger: Maximum Power Point Tracking (MPPT) charger to control PV power
4. Lithium-ion battery

In the GridSTAR system, energy can be stored in the battery either from the rooftop solar shingles or from the grid. The battery is charged and discharged by Direct Current (DC) power, while power supplied by the grid is Alternating Current (AC). This is why an inverter needs to be used to charge/ discharge the battery. The solar power output is controlled by the MPPT controller and fed into the inverter, which can either use that power to charge the battery or convert to AC power for supply to the load or sold to the grid.

Figure 4-5: The SIS module consisting of the MPPT, battery and inverter.

MPPT Charger

The MPPT installed at the GridSTAR is the Xantrex^{TM} XW Solar Charge Controller. A MPPT charger is an electronic DC-to-DC converter that adjusts the solar array voltage to match the battery bank voltage. It takes the DC input from the PV array, converts it to high frequency AC and converts it back down to match the battery DC voltage. The battery operating voltage is between 42 to 58 Vdc while its nominal voltage is 48 Vdc. On the other hand, the maximum output voltage of the PV arrays is around 88 Vdc. The MPPT charger decreases this PV voltage to 48 Vdc by increasing the current while keeping the maximum power constant by following the maximum power point curve (figure 4-6).

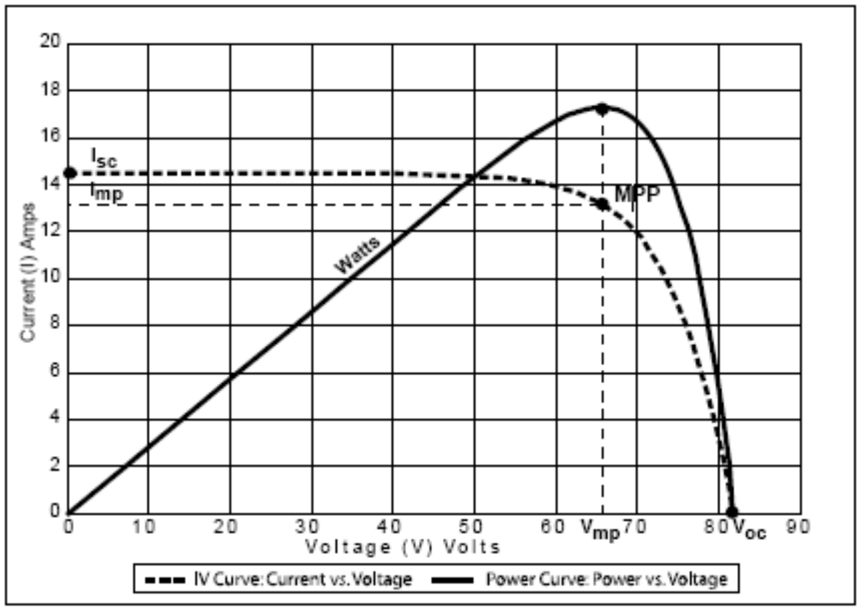


Figure 4-6: Maximum Power Point Curve

A solar module is a constant current device. For any amount of sunlight, the current remains the same while the voltage increases or decreases. With more sunlight, we get a greater voltage and greater power and lesser power output with less solar energy. But for solar modules connected to a battery, the battery voltage cannot change much. If the solar output voltage is greater than 58 Vdc, there will be a loss in power as the battery will only pull current at a maximum of 58V.

Table 2: Electrical specifications of the MPPT controller. (Source: Schneider Electric XW SCC spec sheet)

Max PV operating voltage	140 Vdc
Battery Voltage operating range	10 Vdc to 80 Vdc
Maximum Output Current	60 A
Maximum Output Power	3500 W
Efficiency	98% (nominal 48V)

Battery

The battery is an 11.7 kWh Lithium ion battery. The battery chemistry was not obtainable from the manufacturer as they claim it to be proprietary information. But an electrical specification sheet about the running conditions of the battery was obtained. These are enlisted in table 3. A nominal operating voltage of 48Vdc is being used throughout the framework of this research. The life cycle used is an average between the estimated values given by the manufacturer of 3000 to 5000 cycles. This comes to 4000 cycles at 80% depth of discharge. This value plays a role in a later part of the research where the battery degradation cost has been introduced.

Table 3: Electrical specifications of the battery. (Source: Sunverge datasheet)

Battery capacity	11.7 kWh, 225Ah
Battery voltage	42 to 58 Vdc operating range
Max Charge Rate	60 A from SCC; 90A from 4.5 kW inverter
Max Discharge Rate	90A to the 4.5kW inverter
Cycle Life (80% DoD)	3000-5000 cycles (temp & usage dependent)
Efficiency	97%

Inverter

The inverter being used is the Schneider Xantrex XW4548 hybrid inverter/ charger. It can convert DC solar power to output AC, discharge DC power from the battery and convert to AC output to grid/load, and convert input AC power from the grid to DC power for battery charging. It also contains a temperature sensor to measure the battery temperature in order to adjust charging for maintaining homeostasis.

Table 4: Inverter characteristics. (Source: Schneider XW datasheet)

Continuous Output Power	4500 W
Nominal Frequency	58.5-60.5 Hz
CEC Weighted Efficiency	93%
AC Voltage	120/ 240 Vac split-phase

Load

The load data from the GridSTAR was deemed inappropriate to be used in my model due to a couple of reasons. Firstly, similar to the rooftop PV, there is currently insufficient data for a year's load profile. Secondly, the house is not being used as a residential space. It is being used as an immersive classroom and research center to monitor the systems. This load profile does not reflect the average residential load profile, so instead, regional hourly load data is used which was obtained from the Open EI website that has documented residential load data based off the Building America House Simulation Protocols for all TMY3 locations in the United States. (OpenEI residential load profiles, (n.d.)). The Residential Energy Consumption Survey (RECS) by the EIA was used for statistical references of building types by location. To ensure uniformity in data sources, both load and solar irradiance data have been taken for the Philadelphia International Airport region. The Philadelphia region is classified under 'Mixed humid' according to the Building America Climate Zone Map which is then used to decide the fuel source for space heating, air conditioning and water heating.

There are three hourly energy profiles available on the Open EI directory- low, base and high. The low profile has an average monthly usage of 550 kWh; the base profile uses 1050 kWh, while the high profile averages to 1500 kWh per month. Taking into consideration that the GridSTAR is a highly energy efficient construction, the 'low' load profile is used in my model. The monthly electricity consumption data can be seen in figure 4-8. According to the datasheet, heating and cooking is powered by natural gas, while cooling, HVAC, electrical appliances, lighting and the water heater are all powered by electricity. The GridSTAR is powered by unique systems and has a different energy consumption pattern compared to an 'average' energy efficient home. For example, it uses a photo thermal absorption system for hot water heating, instead of the electric water boiler that is used in the data.

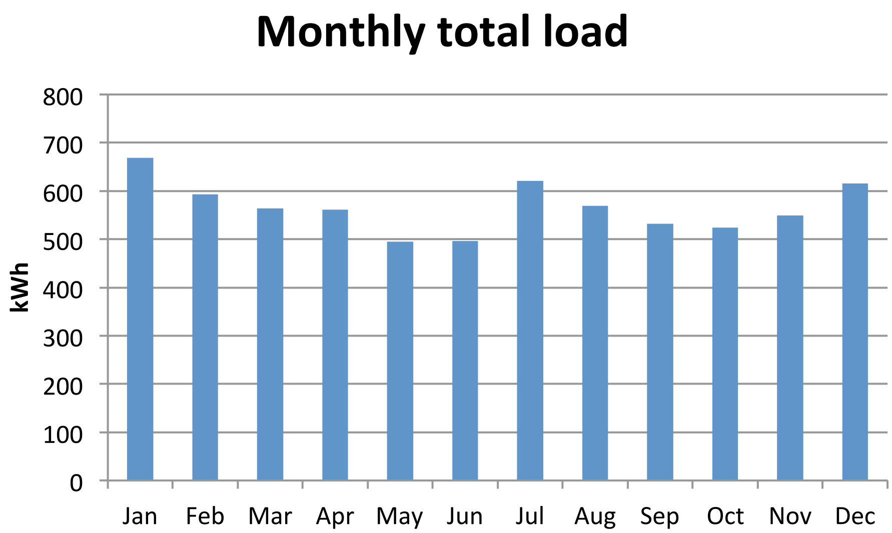


Figure 4-7: Monthly trend of the load in kWh (Source: OpenEI, Philadelphia region)

Chapter 5

Methodology

A linear optimization has been set up in MATLAB to maximize revenues of the entire system. The system power flows are all controlled by the algorithm based on their price signals. The time frame for each power flow is an hour and the system is optimized for 24 hours starting from midnight. The initial battery state of charge is user defined and the battery SOC at t_{24} for day 1 is constrained to be SOC at t_1 for the next day. The optimization is run for 365 days.

The revenues of the system depend on two extrinsic parameters that are used by the model – price of grid purchased electricity and the cost of the battery. An intrinsic parameter that also determines revenues is the percentage of battery capacity allocated to emergency backup power. Grid purchased electricity is categorized into off-peak hours and on-peak hours. Four different off-peak hours are chosen – 5, 7, 9 and 11 cents/kWh. The price difference between off and on-peak electricity is being varied for each simulation run and the corresponding revenues are noted. This is determined at a particular battery price. The battery price is further varied for each simulation from 200$/kWh to 600$/kWh. Each of the above mentioned simulations are run for different levels of battery capacity allocated to emergency backup ranging from 0 to 75% of total battery capacity. Finally, we get revenue outputs as a function of battery price and difference between off and on-peak electricity price for different battery emergency backup capacities.

Electricity Pricing Structure

Residential units across the country now have the freedom to choose their electricity provider according to rate plans that best fit the owner's electricity needs. The GridSTAR system under consideration is a residential unit and presently, residential owners are not given the choice of paying for their electricity according to Location Marginal Pricing (LMP). The system is located at the Navy Yard, Philadelphia and the utility under consideration is PECO (Philadelphia Electric Company). As a PECO customer, residential units have an option of paying according to two price structures – a fixed price or a time of day price. Using a battery for energy arbitrage savings makes sense only when the unit is on a time of day pricing. PECO Smart Time Pricing will be used as the pricing structure (PECO Smart Time Pricing, (n.d.)). The on-peak hours are from 2pm to 6pm every day and are priced higher than the off-peak hours.

The difference between off and on-peak price is being varied from 4 to 20 cents a kWh. To further analyze the effect of grid electricity, the base level off peak prices are varied from 5 to 11 cents a kWh. This gives an analysis of a wide range of pricing structures throughout the country. For simplicity's sake, the model assumes that the price of buying electricity from is the grid is equal to the price of selling PV and battery power to the grid at any particular time. This is a hybrid mixture of feed-in-tariff and net metering.

Battery degradation cost

This research pays a particular emphasis on the battery factor called battery degradation cost. The battery degradation cost is a simplistic assumption of the dollar value of every kWh that the battery is worth given the operating conditions by the manufacturer. As the battery has a high capital investment, there needs to be an economic justification for the battery usage for its revenue generating services. It does not make financial sense if the battery is generating short term revenues by continuous cycling and having to be replaced before the capital has been recovered by the generated revenues. Simply put, the battery degradation cost takes into account various battery parameters as shown in equation (1) and attaches a dollar amount to every kWh of usable battery capacity.

This dollar value acts like a trigger mechanism for the battery to charge or discharge. If the potential revenue is greater than the degradation cost, the optimization setup allows the battery to participate in market services. If the degradation cost is greater than the price signal, the battery will not operate and lie dormant. The battery degradation cost, X_{bat}, is a value which the optimization model uses to allow the battery to vary its state of charge.

$$X_{bat}\ (\$/kWh) = (bat_{cost})/(DoD * n * Cb * cycles) \qquad (1)$$

Where,

bat_{cost} – cost of the battery pack

DoD – depth of discharge

n – battery round-trip efficiency

Cb – battery capacity

cycles – the number of total cycles the battery can undergo in its lifetime.

Since the number of total cycles depends on factors like charge-discharge rate, depth of discharge, and temperature conditions, there will always be a given range of total cycles. In my model, I have assumed a mean value of 4000 total cycles based on the manufacturers' specification sheet which gives a range of 3000 to 5000 cycles. The battery cost in the optimization model is varied from 200 to 600 $/kWh to reflect different battery costs available in the market in the present and the future, to analyze how the revenues are a function of battery cost. An 80% manufacturer recommended depth of discharge is used, with a roundtrip efficiency of 93%.

Table 5: Battery degradation costs for different values of battery costs

Battery cost ($/kWh)	Battery degradation cost ($/kWh)
200	0.067
250	0.084
300	0.101
350	0.118
400	0.134
450	0.151
500	0.168
550	0.185
600	0.202

Linear optimization in MATLAB

The linear programming function in MATLAB is called linprog and it is used to find the minimum solution to an objective function that is bound by equality and inequality equations. The minimization problem can be stated as -

Min $f^T x$ such that $A.x \leq B$ (*Inequality equations)*

$Aeq.x = beq$ (*Equality equations)*

$lb \leq x \leq ub$ (*Upper and lower bounds)*

f, x, B, beq, lb and ub are all vectors while A and Aeq are matrices. Since our problem is a maximization problem, the signs in the objective function $f^T x$, are reversed and the final solution of the optimization is multiplied by -1.

Objective function

The objective of the optimization is to maximize the revenues of the PV-battery-grid system. The sources of revenues are from the sale of excess PV and battery power to the grid. To account for regulation profits, two additional parameters are added - battery capacity allocated for regulation up and regulation down. The costs incurred are for buying grid power for load as well as for the battery. Note that the battery degradation cost, X_{bat} plays a part in the objective function every time the battery is being charged or discharged. To calculate arbitrage profits, the last two terms of $Batt_{regup}$ and $Batt_{regdown}$ are set to zero.

To maximize –

$$\left[D_{pv_{grid}} * P_{grid_{sell}}\right] + \left[D_{batt_{grid}} * \left(P_{grid_{sell}} - \frac{X_{bat}}{n_{dchg}}\right)\right] - \left[D_{grid_{load}} * P_{grid_{pur}}\right]$$

$$- \left[D_{grid_{batt}} * \left(P_{grid_{pur}} + n_{chg} * X_{bat}\right)\right] - \left[D_{pv_{batt}} * n_{chg} * X_{bat}\right] - \left[D_{batt_{load}} * \frac{X_{bat}}{n_{dchg}}\right]$$

$$+ \left[\left(Batt_{reg_{up}}\right) * \left(P_{cap} + c * \left(P_{per} - X_{bat} * n_{chg}\right)\right)\right]$$

$$+ \left[\left(Batt_{reg_{down}}\right) * \left(P_{cap} + c * \left(P_{per} - \frac{X_{bat}}{n_{dchg}}\right)\right)\right]$$

Decision variables

The decision variables are all the power flows of the system and also the state of charge of the battery. The battery can be charged from the grid and/or the PV shingles. It can be discharged to the grid and/or the load. Load can be satisfied from PV, battery and/or the grid.

Constraints

There are three equality constraints used:

The power flow from the PV shingles -

$$D_{pv_{load}} + D_{pv_{batt}} + D_{pv_{grid}} = D_{pv} \tag{1}$$

The power flow to the load -

$$D_{pv_{load}} + D_{grid_{load}} + D_{batt_{load}} = D \tag{2}$$

To ensure continuous battery SoC in between time periods, the SoC at time *t+1* is determined by SoC at time *t* and the net charging or discharging of the battery -

$$Cb_{soc(t)} + \left(D_{pv_{batt}} + D_{grid_{batt}}\right) * n_{chg} - \left(D_{batt_{load}} + D_{batt_{grid}}\right) * n_{dchg} = Cb_{soc(t+1)} \tag{3}$$

The battery is constrained by a maximum charge and discharge rate every hour. To ensure unidirectional flow of power via charging or discharging, an additional constraint must be added which says that the sum of the charge and discharge power must be less than the charge/discharge rate every hour. A 10% upper and 10% lower limit buffer is kept on the SoC as the manufacturer recommended depth of discharge is 80%.

The inequality constraints used are:

Battery capacity allocation –

$$Batt_{reg_{up}} + Batt_{reg_{down}} + Cb_{soc} \leq Cb \tag{1}$$

The maximum battery charge rate -

$$\left(D_{pv_{batt}} + D_{grid_{batt}} + Batt_{reg_{up}} * c\right) * n_{chg} \leq max\ battery\ charge\ rate \tag{2}$$

The maximum battery discharge rate -

$$\frac{D_{batt_{load}} + D_{batt_{grid}} + \left(Batt_{reg_{down}} * c\right)}{n_{dchg}} \leq max\ battery\ discharge\ rate \tag{3}$$

To ensure the unidirectional charging and discharging of the battery -

$$\left(D_{pv_{batt}} + D_{grid_{batt}} + \left(Batt_{reg_{up}} * c\right)\right) * n_{chg} + \frac{\left(D_{batt_{load}} + D_{batt_{grid}} + \left(Batt_{reg_{down}} * c\right)\right)}{n_{dchg}} \leq Charge\ rate \tag{4}$$

For the energy arbitrage case, the Batt_reg_up and Batt_reg_down are set to zero. The battery capacity and the capacity allocated to emergency backup figure in the upper and lower limits for battery state of charge.

Chapter 6

Results

1. Base case without PV

This is the base case scenario where the annual energy bill of the residence on time-of-use electricity pricing without solar PV is analyzed.

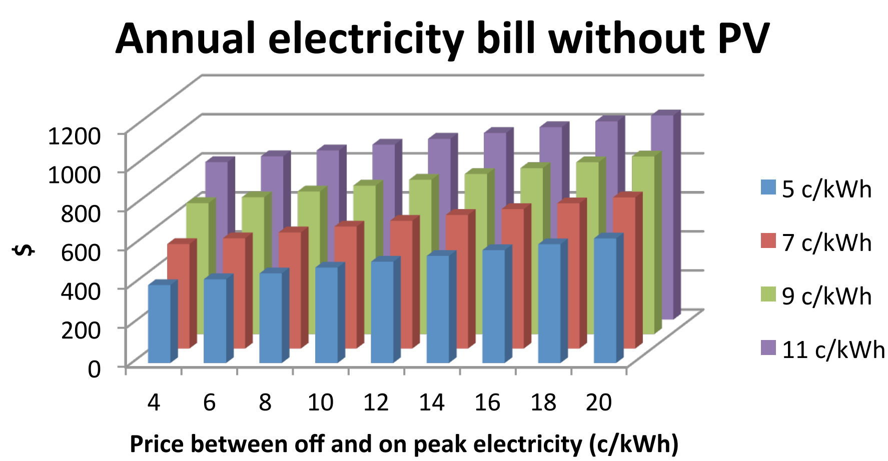


Figure 6-1: Annual electricity bill at for different on and off peak prices

As the off-peak price of electricity increases, the annual electricity bill increases. Also, as the difference between on and off-peak price increases, the annual electricity bill increases. This is assuming that the homeowner’s electricity consumption is not price sensitive.

2. Case with only PV System

The second case of the optimization model includes the installation of rooftop PV shingles in the system. Because of zero marginal costs of PV energy, the system will supply the loads by PV power and if PV power is not available or if it is insufficient, then grid electricity will be purchased. Excess PV will be sold to the grid instantaneously. We are assuming a sunken capital cost of PV shingles and not an LCOE of solar power.

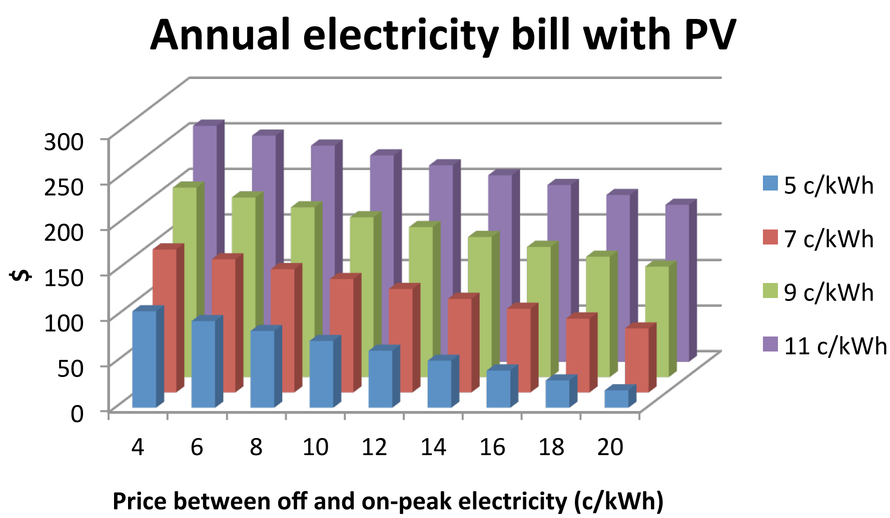


Figure 6-2: Annual electricity bill with PV at different electricity pricing.

The period of excess PV production coincides with the on-peak electricity timings and as the price of buying power is the same as the price of selling it, it comes as no surprise that as the peak price difference increases, the electricity bill falls. The net savings with the PV system increase as both the off peak price increases as well as the price difference increases (figure 6-3).

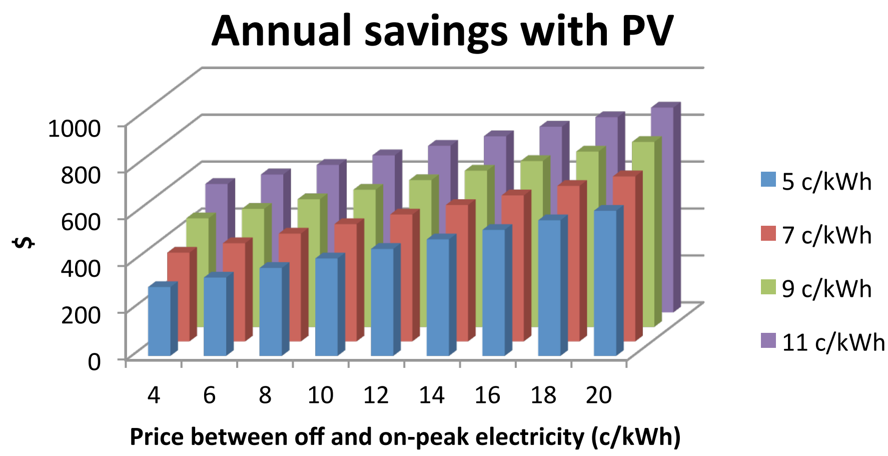


Figure 6-3: Annual savings with PV

As the price of electricity is varied, the revenue of the system changes and is used for determining the additional value that the battery can provide.

3. Case with Energy Arbitrage

Now, the battery is included in the system and it is allowed to participate in energy arbitrage. At current PECO rates of electricity and battery prices, it is not profitable for the battery to perform energy arbitrage. This is because the battery degradation cost is greater than the market prices of purchasing stored battery power. We are varying the battery cost as well as the peak price of electricity to get the revenues for each set of changing parameters in order to determine at what set of conditions the battery earns revenues. To find the net benefit of energy arbitrage with only the battery system, we subtract the base case PV revenues from the ones we obtain in this simulation. This gives us the net revenue stream due to the battery participating in energy arbitrage. Simulations are run for the different off-peak prices as well.

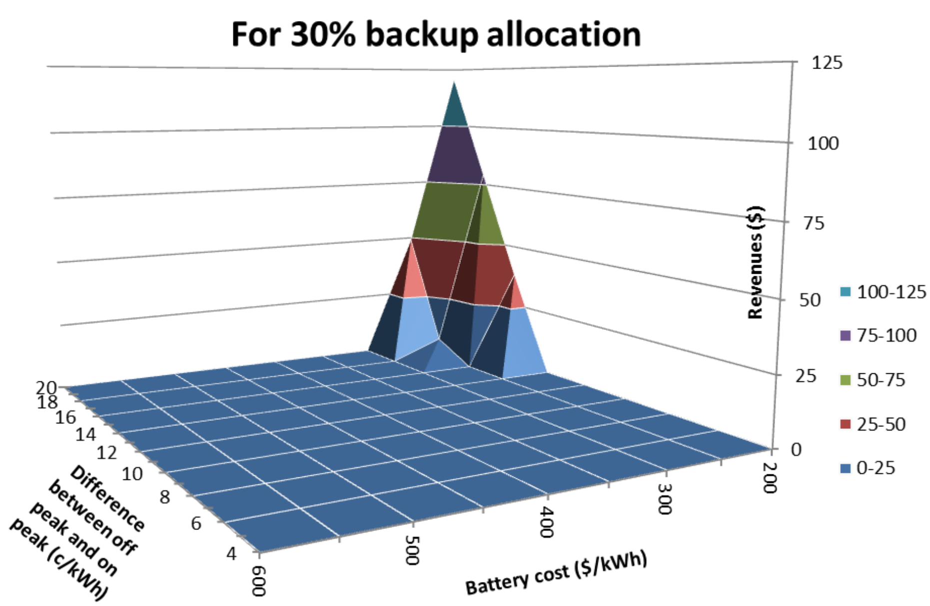


Figure 6-4: Revenues for off-peak price of 5c/kWh.

The graph above tells us that the battery does not cycle for most battery prices and price differences between on and off-peak electricity. Only on the top right corner of the graph, we do notice that revenues are generated. The battery price has to be lesser than 300$/kWh and the on-peak electricity price should be at least 16 cents more than the off-peak price.

The following graphs show the revenues of energy arbitrage for different electricity pricing levels and each graph shows the revenue at different levels of battery allocated towards emergency backup. The X axis has the varied battery cost ($/kWh) from 200 to 600 for each of the levels of battery backup.

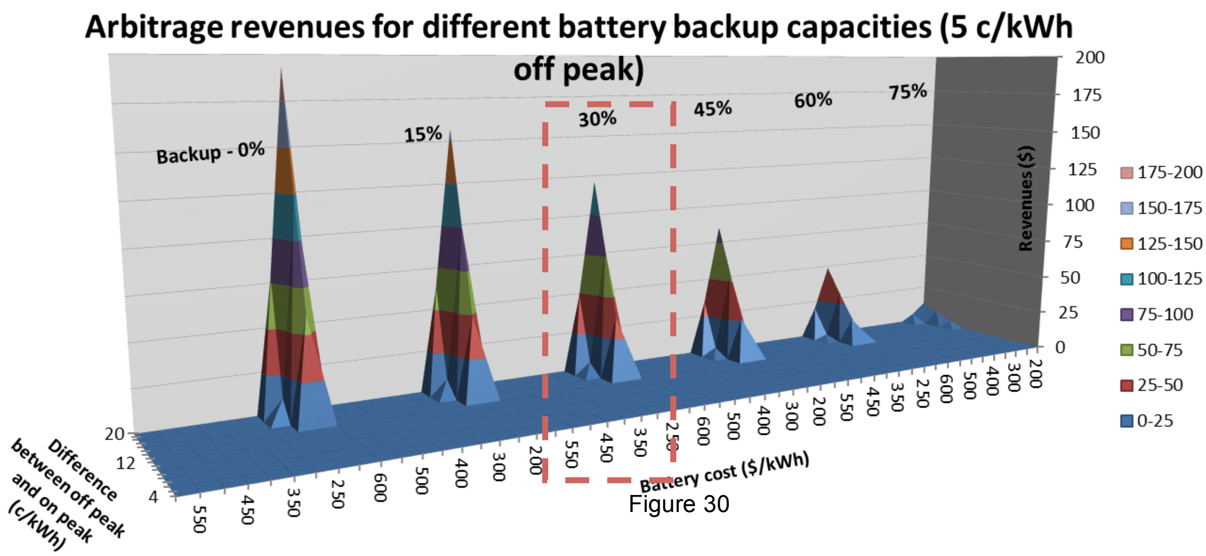


Figure 6-5: Arbitrage revenues at different backup levels. Off-peak price 5 c/kWh

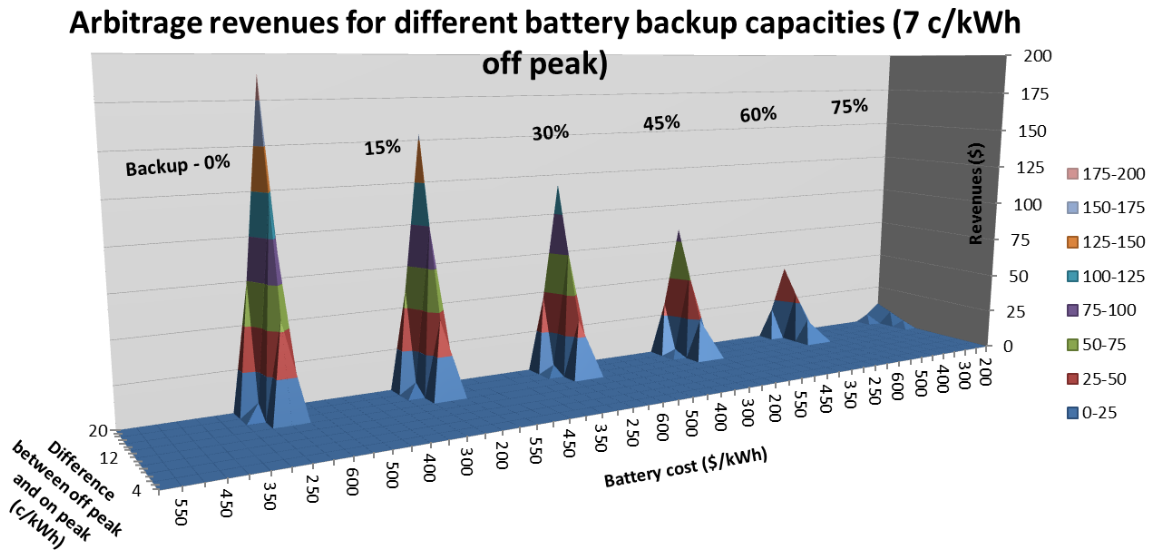


Figure 6-6: Arbitrage revenues at different backup levels. Off-peak price 7 c/kWh

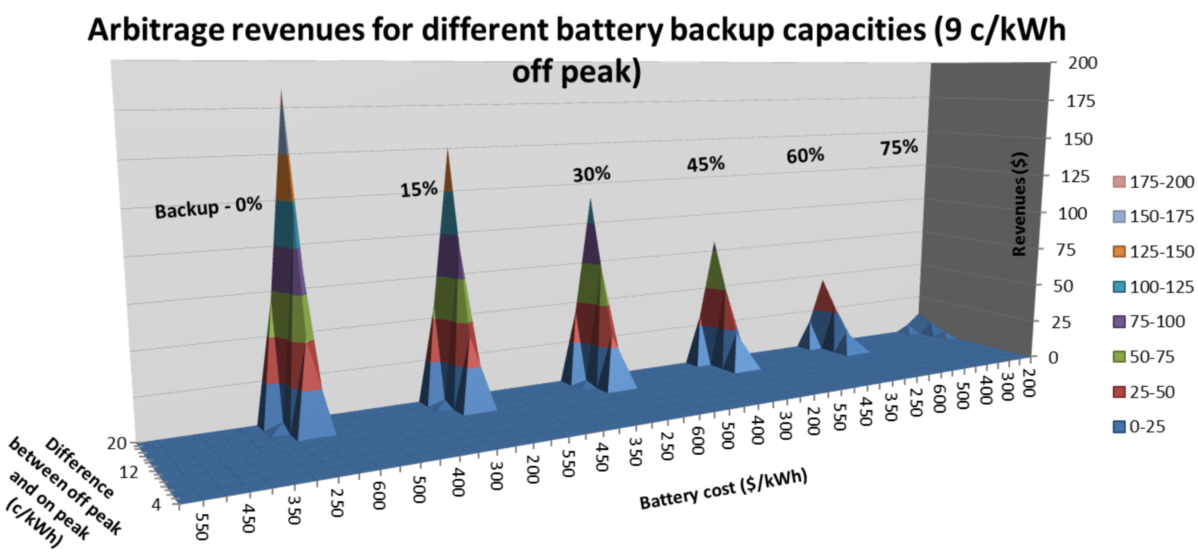


Figure 6-7: Arbitrage revenues at different backup levels. Off-peak price 9 c/kWh

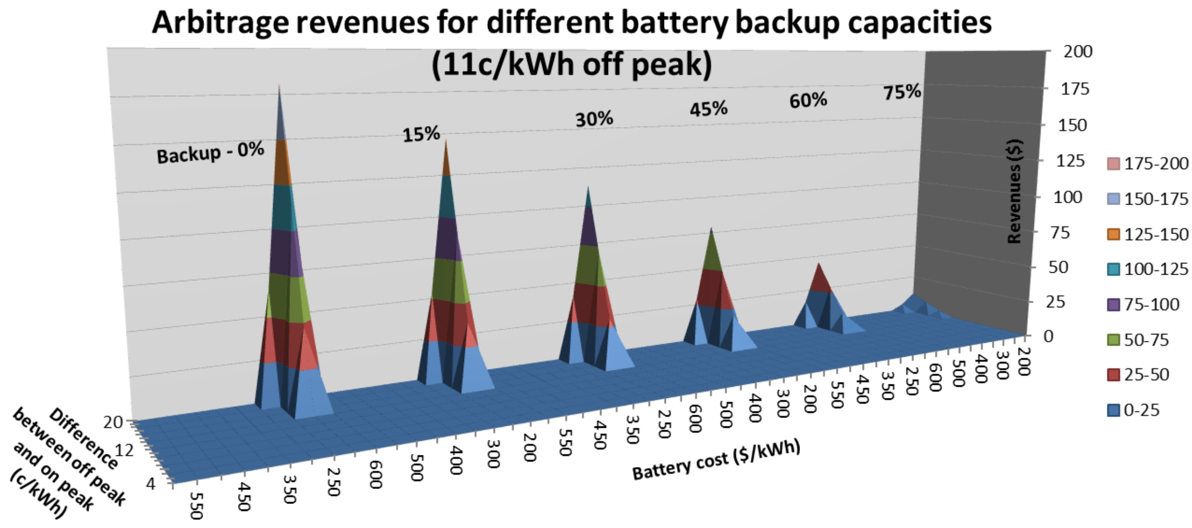


Figure 6-8: Arbitrage revenues at different backup levels. Off-peak price 11 c/kWh

When all of the battery capacity is allocated towards arbitrage, we get annual revenue of $193 at a battery price of 200$/kWh and electricity price difference of 20 c/kWh. Increasing the battery backup to 75%, the revenue falls to $12.

The trends observed are –

1. There are threshold values of battery cost and difference between off and on-peak electricity prices that dictate battery cycling for participation in the arbitrage market. As the battery price increases, the cycling falls to zero. As the price difference decreases, the cycling falls to zero. These threshold values are
   a. Battery price ≤ 200$/kWh and price difference ≥ 16c/kWh
   b. Battery price ≤ 250$/kWh and price difference ≥ 18c/kWh
2. The revenues have a positive linear dependency on the amount of battery allocated for arbitrage services.

3. As the off-peak price of electricity increases, the revenues decrease but not by a very large amount. For every cent/kWh increase in off-peak price, the annual revenues decrease by $2.

4. When the battery does cycle, all the battery capacity allocated towards regulation is used on a daily basis. The battery cycles only once every day.

Figure 6-9 and 6-10 show the battery state of charge during energy arbitrage. The battery gets charged at night and discharges during the day. The same pattern is observed every day. The state of charge lower limit is set up such that it ensures there is always battery capacity allocated towards emergency backup. The only difference between the two charts is the depth of discharge of the battery. For a case where higher capacity is allocated towards backup, the battery discharges lesser and vice versa.

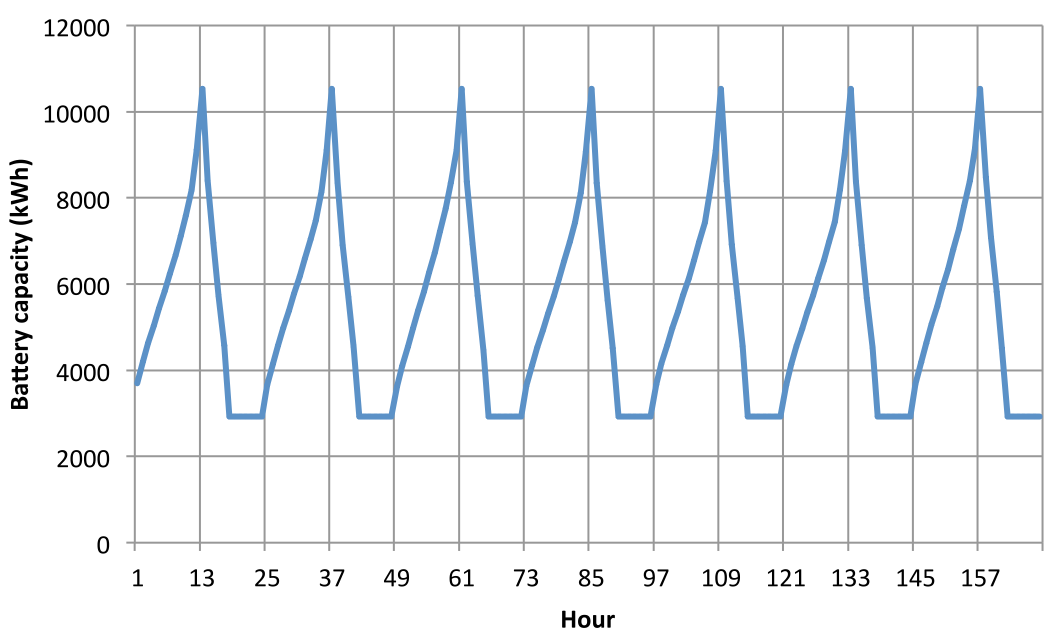


Figure 6-9: Battery SoC trend at battery price of 200$/kWh; Off-peak - 5c/kWh; On-peak - 25c/kWh; 15% backup (Jan Week 1)

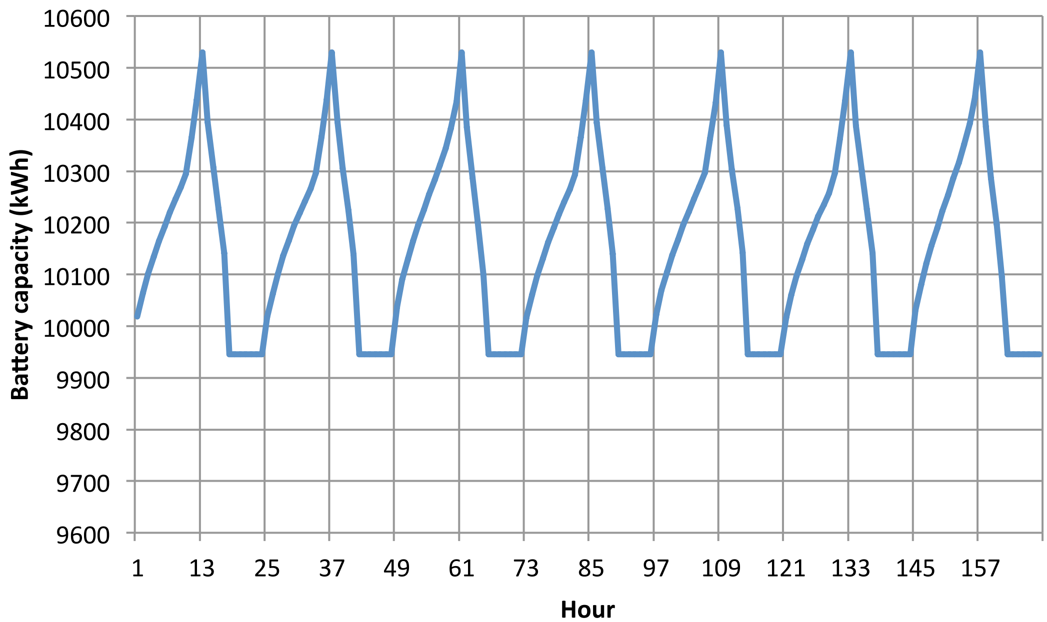


Figure 6-10: Battery SoC trend at battery price of 200$/kWh; Off-peak - 5c/kWh; On-peak - 25c/kWh; 75% backup (Jan Week 1)

This daily cycling of the battery directly affects the life of battery operation in terms of number of years. Manufacturers do not attach a lifespan (number of years) for batteries as battery life is determined by the number of total cycles. Since this optimization calculates the total energy (kWh) that the battery charges/discharges over the entire year, we can effectively determine the number of years the battery would last. It gives a general idea about the usage pattern of the battery. The battery years is calculated by the dividing the total available battery capacity by the capacity used every year.

$$Total\ Battery\ Capacity\ =\ DoD * Cb * n * cycles =\ 34819.2\ kWh$$

$$Battery\ years\ = Total\ Battery\ Capacity /\ Capacity\ used\ annually$$

Figure 6-11 shows the projected life span of the battery for each backup scenario. For conditions where arbitrage is profitable, we observe that the battery lifespan increases exponentially for higher levels of backup. A shorter life span will require more frequent battery changes. A longer lifespan on the other hand brings with it an uncertainty since we don't yet know the performance characteristics of ageing batteries. Battery operators have to ensure an optimal balance between storage offered and projected lifespan of the battery.

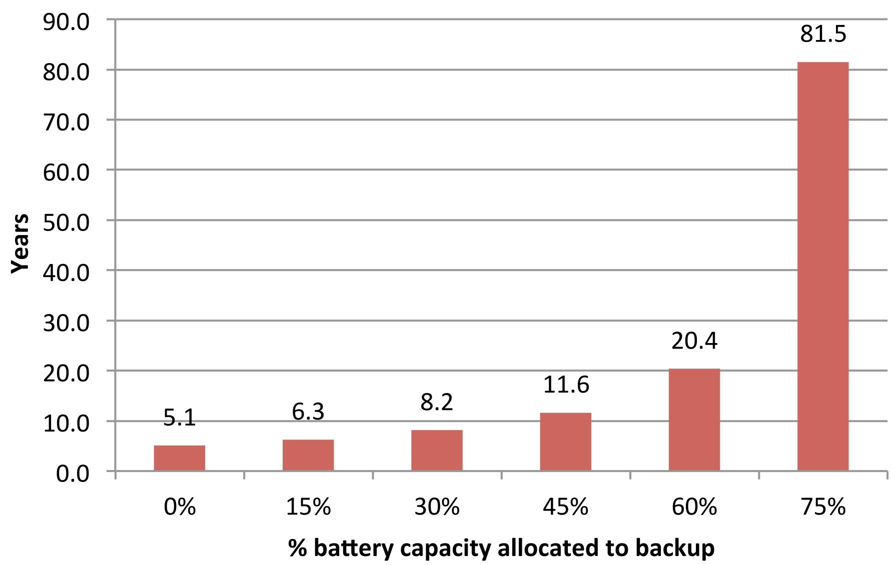


Figure 6-11: Battery usage according to capacity allocated to backup. (For conditions where energy arbitrage is profitable)

4. Case with frequency regulation

In this case, the available battery capacity is allowed to bid into the ancillary service market to participate in frequency regulation. A similar approach is taken as in the energy arbitrage case – the battery capacity not allocated to backup is used to participate in frequency regulation. An equality is introduced which ensures that the regulation up capacity bid is equal to the regulation down capacity.

In the real world, the battery capacity is bid into the day ahead market, but in our simulation we are using previous years capacity and performance price data and letting the optimization model decide whether it is feasible or not to bid into regulation at any particular hour. A contract to dispatch ratio of 0.5 is used. Regulation capacity and performance prices are taken from PJM's website for the year 2013. It is observed that the capacity prices are significantly higher than the performance prices. The mean of capacity price was 24.02$/MW with a maximum value of 756.05$/MW while for the performance it was only 4.12$/MW with a maximum value of 29.14$/MW.

After running the simulations, it is observed that regulation is always profitable regardless of the price of battery and price difference between off and on peak electricity. The following graphs show a contour of the revenues at two backup levels – 75% and 15%.

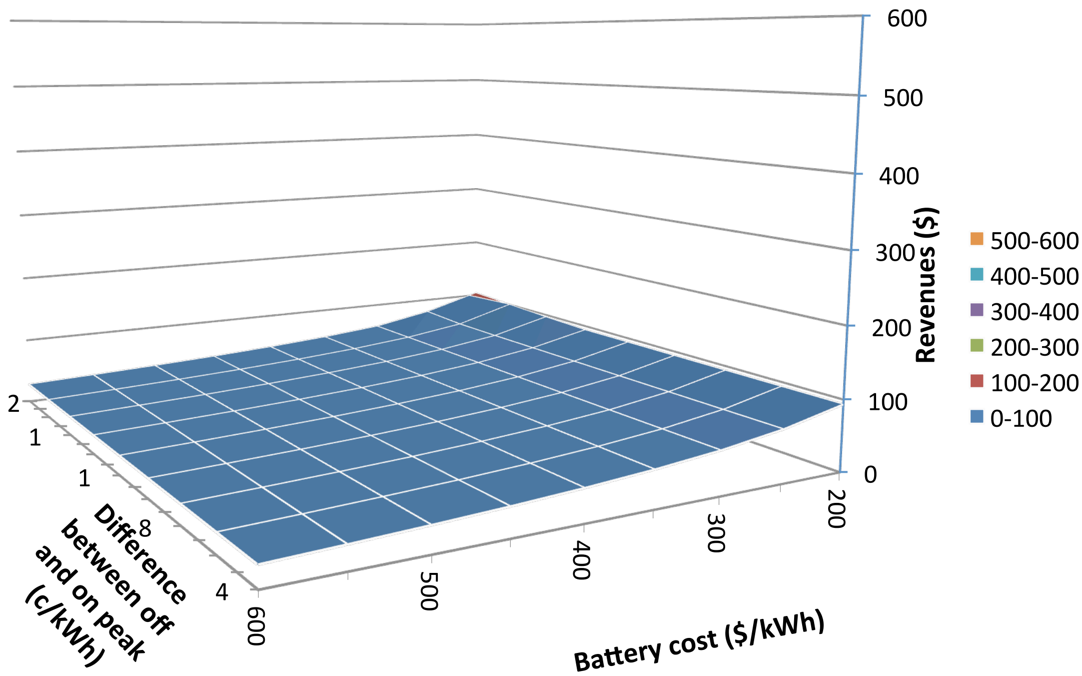


Figure 6-12: Revenues at 75% backup. Off-peak price 7 c/kWh

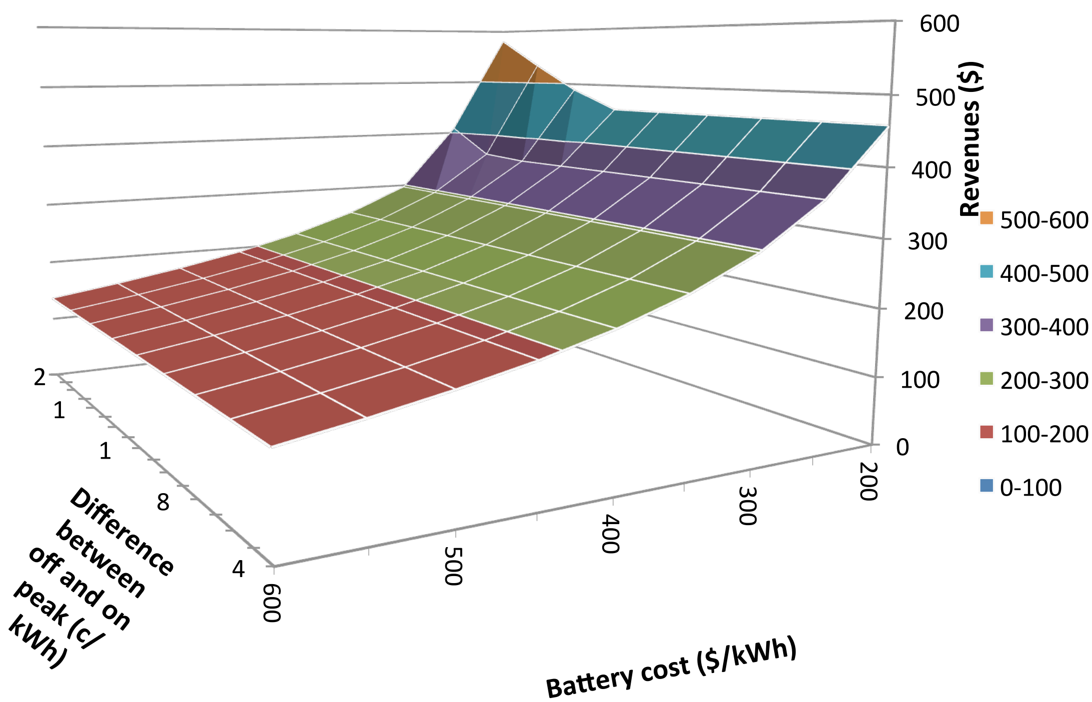


Figure 6-13: Revenues at 15% backup. Off-peak price 7 c/kWh

It is observed that the revenues are not dependent on the price difference between off and on-peak electricity, but they increase as the battery price decreases. As the price conditions surpass the threshold where arbitrage becomes profitable, a significant rise in revenues is seen in the top right corner of the graphs. In this portion, the battery participates in both energy arbitrage as well as frequency regulation.

Once we have determined the trend of revenues with respect to battery cost, electricity price difference at a fixed battery backup %, the next analysis is to see the trend of the revenues as the capacity allocated towards backup is varied. The following sets of graphs show the trend of revenues vs backup % and battery cost.

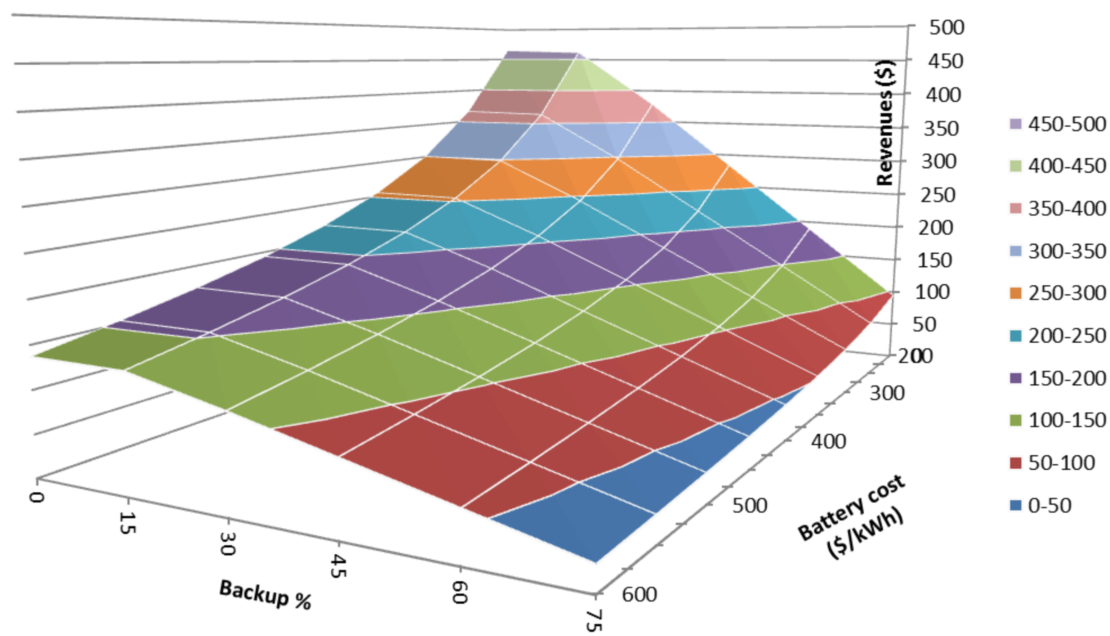
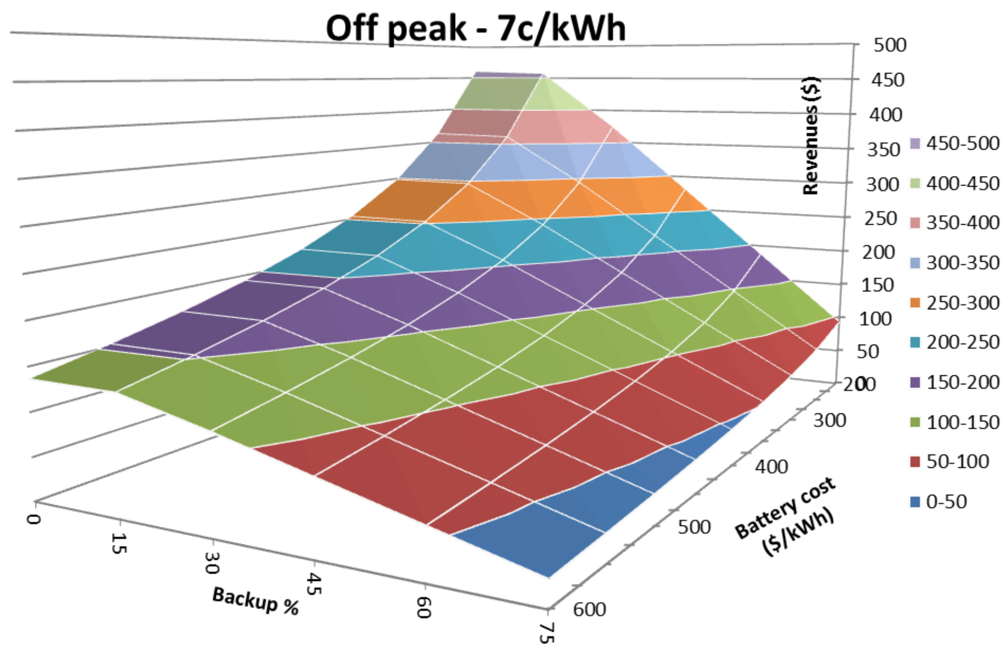


Figure 6-14: Revenues for different battery backup percentages at different battery costs. Off-peak price of 5c/kWh electricity and peak price difference of 6c/kWh.

The same curvature of the above contour graph is observed for different off-peak prices of 7, 9 and 11 c/kWh (figure 6-15 (a,b,c)). As the battery price increases, the slope of the revenues for different backup levels decreases.



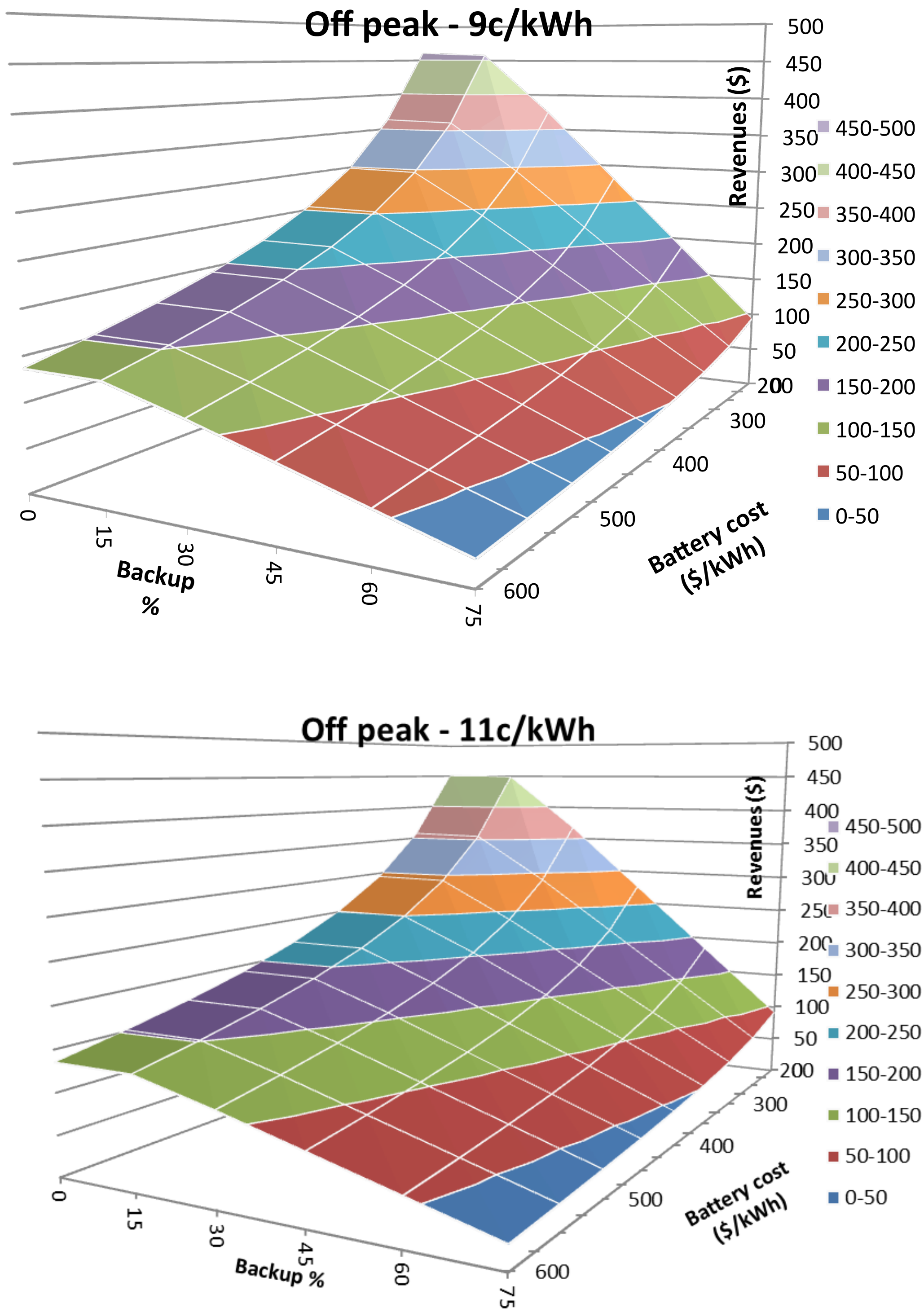


Figure 6-15 (a) (b) (c): Revenues for different battery backup percentages at different battery costs. Peak price difference of 6c/kWh.

A similar plot is made for revenues vs backup % and peak electricity price (figure 6-16). The revenues of regulation do not depend on the price difference between on peak and off-peak electricity, which is an intuitive result since regulation profits are based on capacity and performance prices set by PJM.

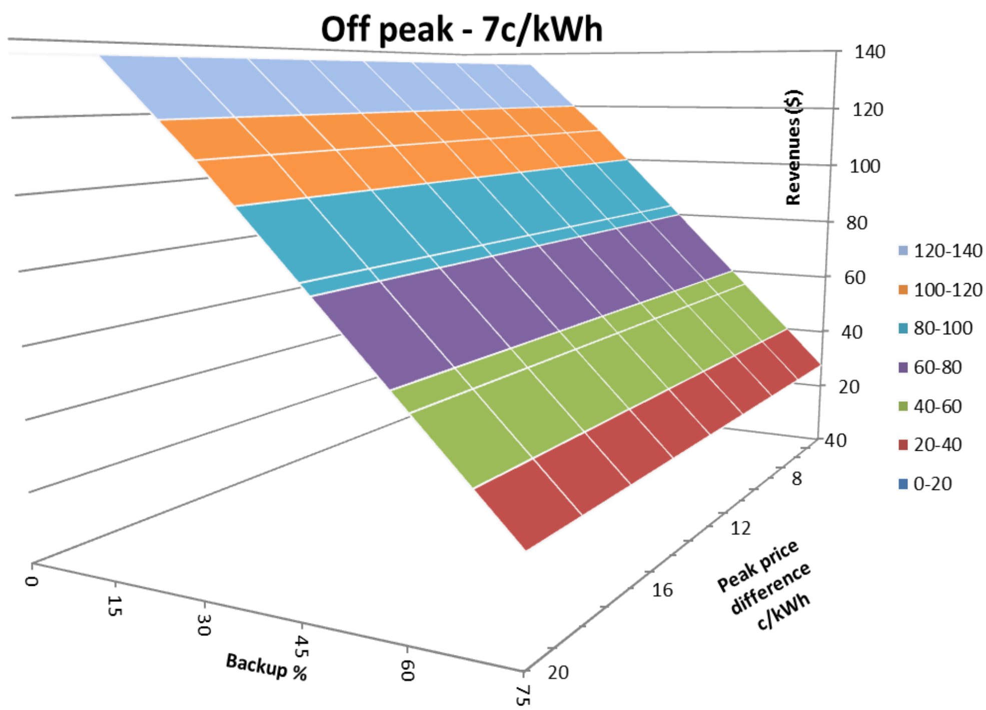


Figure 6-16: Revenues for different battery backup percentages at different peak price differences. Battery cost of 600 $/kWh.

The developed optimization model selects which hours to participate in regulation based on regulation price signals based on PJM. The number of hours bid changes according to the battery price. For the 200 $/kWh battery, it is observed that regulation bids are for about 1600 hours, or about 1/5th of the year. On the other hand, for battery prices of 600$/kWh, regulation bids are made for only 200 hours during the entire year, ten times lesser than the previous case. This selective participation of battery use for regulation leads to different life spans on the batteries.

Figure 6-17 shows us the usage life of the battery for different battery prices. Battery life in years is calculated in the same way as in the arbitrage case. The cheaper battery bids into the regulation market more often and gains more revenue compared to the more expensive battery. It is being used more frequently and hence the battery life is shorter. For batteries priced at 600 $/kWh, at very high backup levels, the battery life exceeds over a 100 years and is not shown in the graph due to scale limitations. The batteries priced at 200 $/kWh would have to be replaced every 5 years if most of the capacity is used for regulation.

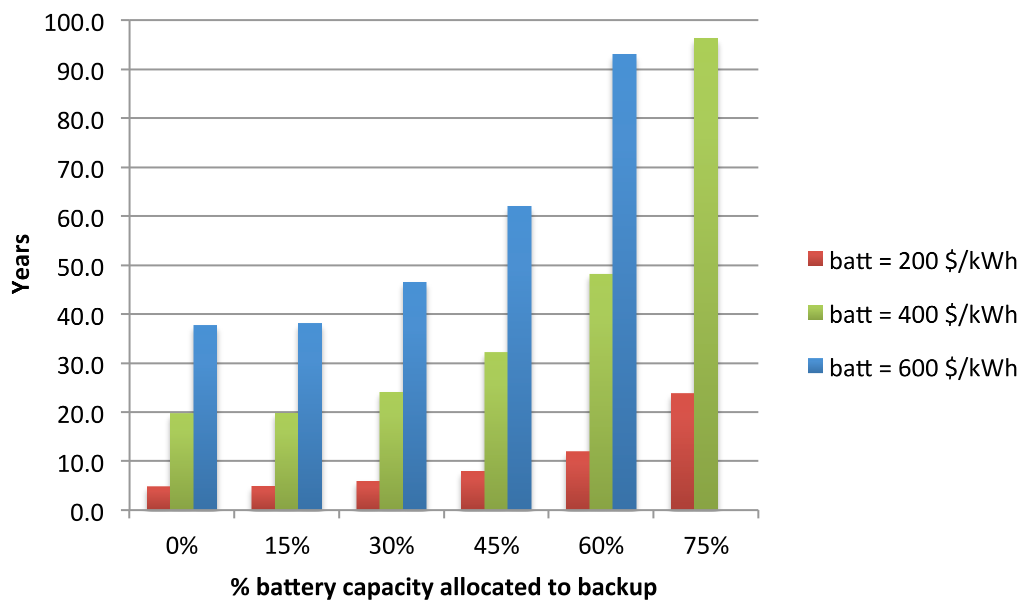


Figure 6-17: Usage of the battery according to capacity allocated to backup.

Now that we have characterized the trends of revenue with respect to battery backup %, battery cost and grid electricity price, this research seeks to answer an important question – what is the cost of 1kWh of emergency storage? This research has identified a profitable revenue stream for the battery, i.e. regulation. Given current market conditions, the frequency regulation market is the most profitable use of a battery storage device. The revenues calculated in this research account for the capital cost as well. To simplify matters, we can say that a unit of battery capacity can either bid into regulation or otherwise provide emergency backup power. Thus, every kWh not bid into the regulation market is associated with a lost opportunity cost.

We have calculated a cost of backup in $/kWh of capacity for different backup capacities ranging from 1.755 kWh to 8.755 kWh. That corresponds to 15% to 75% of the total battery capacity respectively. These costs are illustrated in the following graphs. The homeowner has a yearly cost of battery backup which can be availed at any time based on the homeowners needs. To account for the battery degradation for running the battery for emergency purposes, an additional cost of X_{bat} will be charged per kWh of usage.

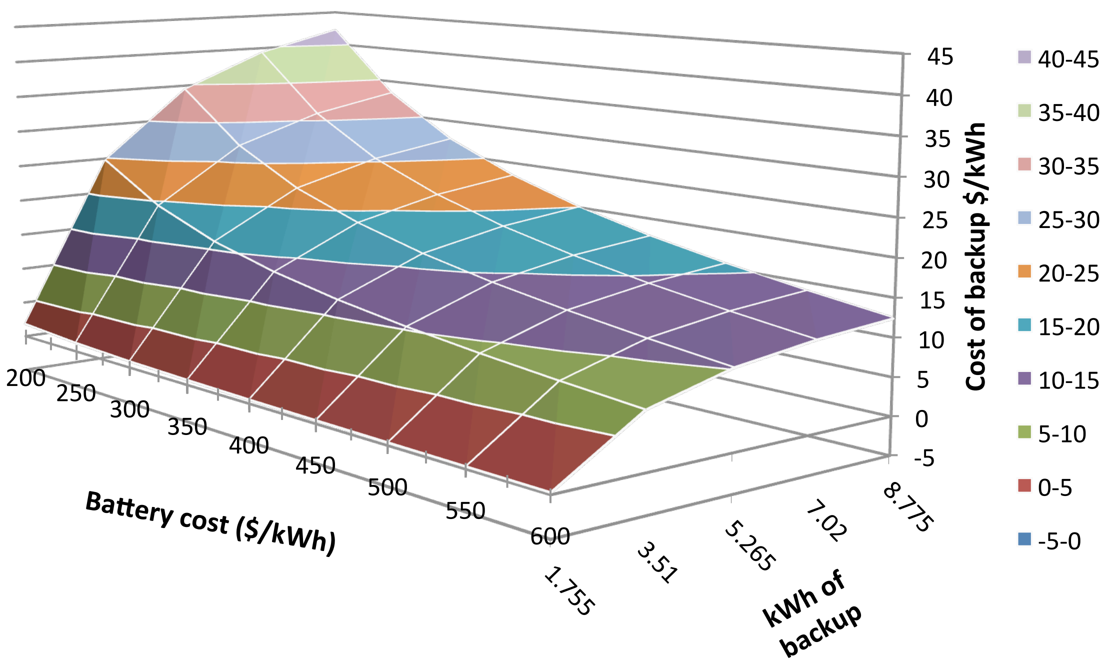
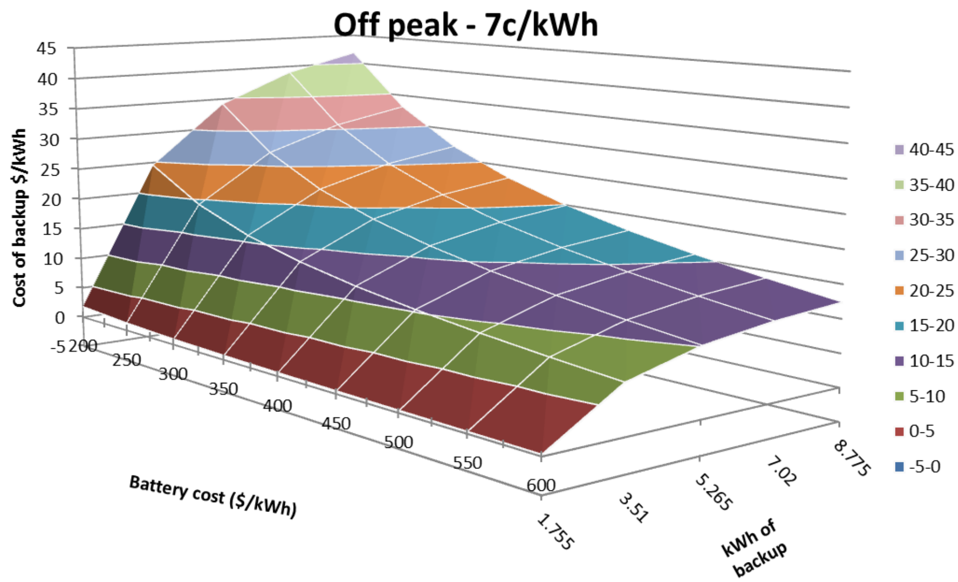
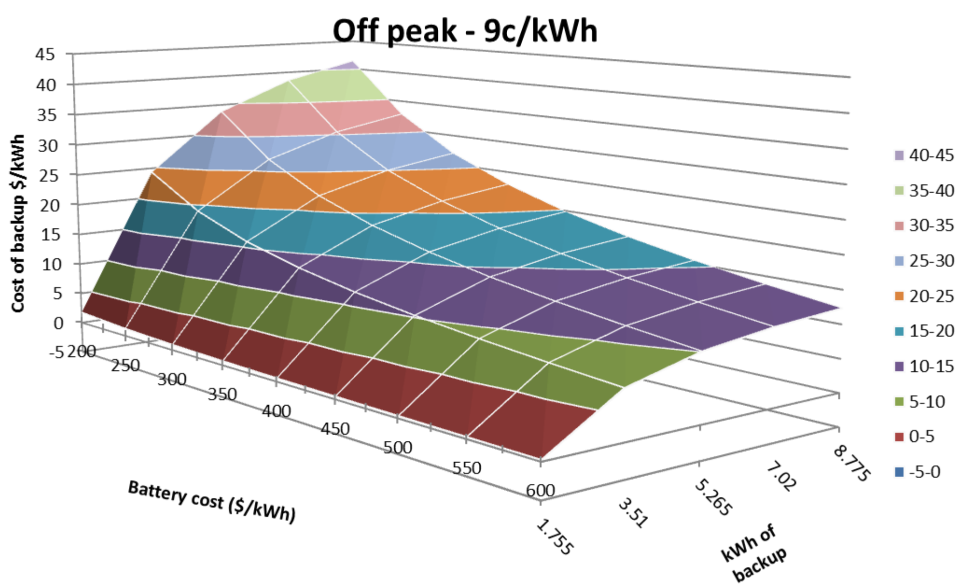


Figure 6-18: Backup cost ($/kWh) for different levels of backup capacity at varied battery costs. Off-peak price of 5c/kWh electricity and peak price difference of 6c/kWh.


Off peak - 7c/kWh
45
40
35
30
25
20
15
10
5
0
-5
Cost of backup $/kWh
200
250
300
350
400
450
500
550
600
Battery cost ($/kWh)
1.755
3.51
5.265
7.02
8.775
kWh of backup
40-45
35-40
30-35
25-30
20-25
15-20
10-15
5-10
0-5
-5-0


Off peak - 9c/kWh
45
40
35
30
25
20
15
10
5
0
-5
Cost of backup $/kWh
200
250
300
350
400
450
500
550
600
Battery cost ($/kWh)
1.755
3.51
5.265
7.02
8.775
kWh of backup
40-45
35-40
30-35
25-30
20-25
15-20
10-15
5-10
0-5
-5-0

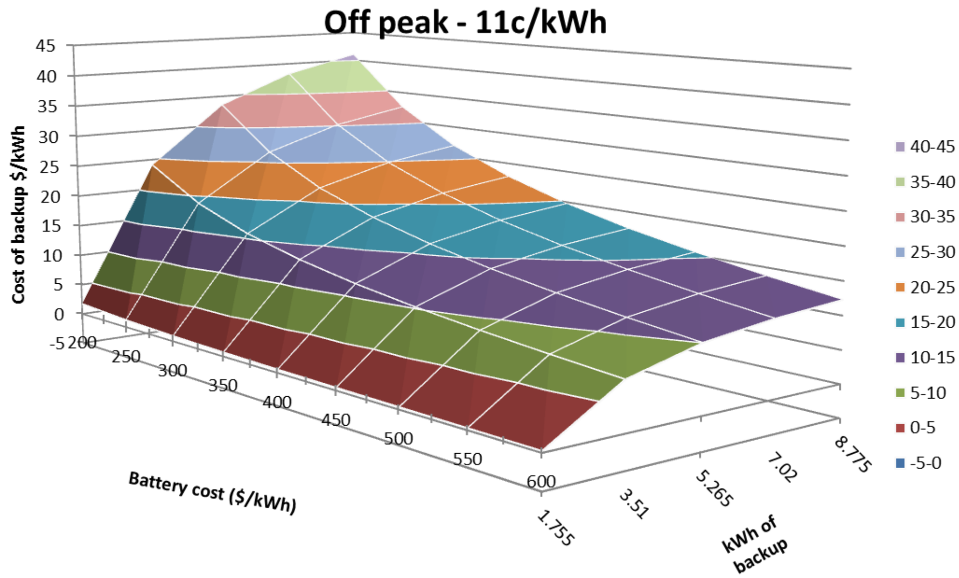


Figure 6-19 (a) (b) (c): Backup cost ($/kWh) for different levels of backup capacity at varied battery costs. Peak price difference of 6c/kWh.

Comparing figure 6-18 and 6-19 (a,b,c), it is observed that the price per kWh of storage does not change according to the off-peak price of electricity. At lower battery prices, the lost opportunity cost of backup increases as compared to higher battery prices. Within the same battery price, we see a much greater increase in backup cost for more capacity, than compared with a higher battery price. But since there will be an additional cost of charging/discharging the battery during emergencies (battery degradation cost), the total cost of running the battery during emergencies will be according to both the fixed cost of storage plus the running costs.

To determine the cost of a specific backup quantity at a certain battery cost, we need to simply look up the value from the graph ($/kWh) and multiply it by the backup quantity. For example, for a battery that costs 600$/kWh and a 7 kWh emergency backup capacity, the price from the graph is around 11.5 $/kWh. The fixed cost of emergency backup is $7 * 11.5 = \$80.5$ a year plus a running cost of 0.20$/kWh (from table 5). On the other hand, a 300$/kWh battery for 7kWh backup will cost $175 a year with a running cost of 0.10$/kWh, half of that as compared with the more expensive battery.

These numbers obtained is terms of the lost opportunity cost of the battery and not the value of backup per-say that will be charged to a customer. A high lost opportunity cost at lower battery price only indicates that the cheaper battery can make greater profits when not used for backup. For a third party financer, these lost opportunity costs can be a metric to charge the customer for backup power according to the customers kWh requirements.

Chapter 7

Conclusions

At current prices of lithium ion batteries, i.e. around 600$/kWh, it is not feasible to perform energy arbitrage, but frequency regulation is shown to be a profitable option as a revenue stream for these batteries. At current battery prices, the maximum profits that can be gained from the battery is about $150 annually, if all the available capacity of the 11.7 kWh battery is allocated towards regulation. Of course, this is the maximized revenue assuming full knowledge of the regulation clearance prices for selective, optimized participation by the battery. We may see different values when using price uncertainties associated with the clearance prices since the battery operator will bid into the market using different control strategies.

Apart from providing grid stabilization services, regulation is a good way to add value to the quantity of battery allocated towards backup. Taking an average duration of a blackout to be for 120 minutes as previously mentioned in the introduction, and the regular modelled load profile of the GridSTAR, the maximum energy demanded would be 3.6kWh. Since the battery has 11.7 kWh capacity, about a quarter of it will lie unused for such average blackout events and can be utilized for regulation services with an assurance that at least 7.2 kWh of backup will be available for unpredicted power outages. The capacity allocated to backup can vary depending on the homeowner's wish and in case of a predictable weather event, the battery can be kept at full charge for situations when a blackout event could be predicted, for example an approaching thunderstorm.

When a unit of battery capacity is used for backup services, it is losing out on regulation revenues, which can be considered as a lost opportunity cost for backup power and a dollar value can be attached to a kWh of emergency backup. This can provide financial institutions and battery owners with a good metric to price customers for emergency battery backup power. A third party owned battery could charge the customer the lost opportunity cost of regulation every year, while the remaining battery capacity can be bid into the market for regulation services. Both parties can benefit from this model – the homeowner gets backup without paying for the high capital cost of the battery, and the battery operator gains a return on investment.

This research does not aim to compare between generators and batteries as backup sources. Generators have their own advantages and disadvantages as mentioned in the background section and it is up to the homeowner to make an informed decision on what technology best suits his/ her needs. But generators do not have the option of participating in revenue generating services, while batteries do. The results have shown that lithium ion batteries can be an economical option for residential storage if allowed participation in PJM's regulation service for generating revenue to offset the high capital cost. At lower emergency load demands (lesser than 4 kW), the expensive lithium ion battery has a potential to be cost competitive with even the cheapest gas powered portable generators that have bad efficiencies at lower ratings. Further research needs to be done to compare the LCOE (levelized cost of energy) of generators and batteries.

The battery degradation cost is an important parameter in this thesis and it is dependent on the total energy that the battery can cycle. This research uses a very simplistic value of battery life of 4000 deep discharge cycles that is estimated based on the manufacturer specification sheet. It would be beneficial if more accurate values of battery cycles could be determined based on shallow cycling of the battery since regulation is a service that requires shallow cycling of the battery. If the battery chemistry favors shallow cycling over deep cycling, we will observe a much greater life span of the battery, which in turn would lower that battery degradation cost.

While this research deals with the economics of the system, further research needs to be done on the power systems engineering aspect of integrating aggregated batteries in community systems. For participation in the PJM market, these smaller batteries need to be interconnected via smart controllers to provide the minimum requirements of 0.1 MW. Interconnecting these batteries in a microgrid community can present quite a few engineering challenges that need to be identified and addressed in future research. With this being said, there certainly is a big scope in the present energy scenario for residential scale, aggregated storage community homes.

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