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ENGINEERING & TECHNOLOGY MANAGEMENT

Research Project: Current and Emerging Trends in Battery Technology

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Table of contents

1. History of Energy Storage

On October 23, 2015, there was a massive natural gas leak at Aliso Canyon, near Los Angeles, California. The leak lasted for nearly five months until mid-February 2016. According to the Environmental Defense Fund, during this time, 109,000 metric tons of methane were released into the atmosphere—the largest leak in U.S history [1]. Not only were people who lived nearby the Canyon faced with impacts from air pollution, but there were also economic losses. The amount of leaked methane was equal to over one billion gallons of gasoline, or over 21 million U.S dollars [2]. These economic resources were wasted within just a few months. In addition, due to the leak, there was the longer-term concern of not having enough fuel supply for natural gas-fired electric generation in Southern California until Summer 2017 since most of natural gas used in the region relied on Aliso Canyon storage.

While the state legislature was seeking solutions, the California Public Utilities Commission approved plans to build a total of 104.5 MW of lithium-ion battery-based energy storage system in the Los Angeles Metropolitan Area. The plan was a collaboration of Southern California Edison and San Diego Gas and Electric. The system can provide electricity for 2,500 houses for a day, or 15,000 houses for four hours [3]. Additionalyy, in critical facilities, the utilities also installed a 2.4 MW lithium-ion battery, which can provide electricity for the whole building for an hour and a half [4]. The system was online by the end of February 2017, ensuring the stability of electric grid in the region. The battery system built in the Los Angeles Metropolitan Area is just one of many systems were built and are being built around the US.

In another approach, which targets on smaller customers, Green Mountain Power partnered with Tesla to install the Tesla Powerwall 2 in its customers' houses in the state of Vermont. The Powerwall 2 batteries help customers to reduce electric cost by storing energy during off-peak hours which has a lower rate, and discharge during high-peak hours. In addition, with the capacity of 13.5 kWh the battery system will also provide electricity to customers if power shortage happens, and increase stability. After two years of implementing the program, Green Mountain Power was able to reduce the cost of each battery to $15 per month, which was more than half of its price of $37.5 per month in 2015. An evaluation of the program shows that energy storage reduced demand for electricity up to 10 megawatts during peak hour, which is equivalent to taking 7,500 homes off the grid [5].

In addition to stabilize electricity supply, there are other reasons why electrical energy should be stored. First, energy storage is important to any modern appliances, human activities, and industries. Modern human lives rely heavily on energy in many aspects, such as technology, transportation, and food processing. It has been estimated that there are about $80 billion lost due to power outage annually in the US [6]. To prevent this, facilities, or areas that are heavily dependent on electricity, usually build their own energy storage or generation systems. Second, with the growth of renewable energy, the need for energy storage also increases. Due to the nature of renewable energy, it is not possible to control when generation occurs and whether it be aligned with high peak demands. In some cases, a significant amounts of electricity are generated during low peak hours that cannot be stored or reused. This creates financial losses to the energy industry. Increasing stability and easing high demand is the third reason. In some remote locations, an energy battery system also helps to serve occasional high peak demand by connecting batteries to the grid. Last, an energy storage system serves as a management tool for distributed generation and offers standby power generation [7].

In the 1900s, to supply energy during peak hour, there were different methods used. One of them was the pumped hydroelectric storage (PHS), which was built around the world, mostly in Europe and the U.S. The system was built on the idea of a dam. During high-peak hours, water in a high elevation reservoir is released, passes through power houses generating electricity, and gets discharged into a lower reservoir. During off-peak hours, water is pumped back from the lower elevation reservoir into the high elevation reservoir. The capacity of the PHS depends on how much water is stored, as well as pressure, and elevation of the two reservoirs. The size of PHS plants varies from 1 MW to 3000 MW. The capacity of PHS plants around the world is about 127-129 GW in 2012 [8]. The disadvantages of PHS are long construction time and high capital investment.

With new breakthroughs in technology, rechargeable battery technology has been widely used because it can alleviate the disadvantages of PHS system. Battery Energy Storage (BES) takes a relatively short construction time (12 months), and is more flexible on installation location [8]. There are three main types of batteries that are being used to store energy.

Lead-acid batteries are the most widely used for rechargeable batteries, UPS system, back-up power, and some hybrid car models. Its cathode is made of lead dioxide (PbO_2), and the anode is made of lead. The electrolyte is sulfuric acid. Lead-acid batteries have fast response time, small daily self-discharge rate (less than 0.3 percent), high cycle efficiency, and low cost ($50-600 per kWh). However, for a large-scale utility battery system, lead-acid batteries are not suitable due to low cycling time and poor performance at low temperatures [8]. Therefore, the system usually needs a thermal management system, which are costly in large-scale projects.

A sodium-sulfur (NaS) battery is made from molten sodium and molten sulfur as its two electrodes, and beta alumina as its solid electrolyte. A sodium-sulfur battery is considered a promising solution for high power BES system. This is due to technology advantages, such as high energy density, high power capacity, zero daily self-discharge, and is made from non-toxic as well as inexpensive materials. However, NaS battery also works best at a certain temperature range, and has high operating costs [8]. Researchers in Japan have been investigating and implementing NaS batteries into large scale project.

Nickel-Cadmium (NiCd) battery is another type of battery that uses nickel hydroxide and metallic cadmium for its two electrodes and an aqueous alkali solution for its electrolyte. Nickel-Cadmium battery systems are highly reliable, requires low maintenance, and have fast delivery time. However, the battery system uses high toxic materials, and suffers with memory effect, a decrease in capacity if the battery is repeatedly recharged after being partially discharged [8]. Due to environmental concerns and limited technology, nickel-cadmium batteries are not widely installed for large-scale utility battery system.

Another battery technology that is widely used is Lithium-ion (Li-ion), which uses lithium metal oxide as the cathode, graphitic carbon as the anode, and a non-aqueous organic liquid containing dissolved lithium salts for the electrolyte. Li-ion battery has high cycle efficiency, fast response time, and is relatively lightweight compared to other technologies. However, its disadvantage is that the lifetime of li-ion battery can be affected by the cycle depth-of-discharge, and as other technology, an on-board computer is required to manage its operation, which increases its cost [8]. Due to its advantages and safety, Li-ion batteries are largely deployed in utility-scale BES systems, and in hybrid and EV cars.

2. **Technology**

There are many types of battery used in residential and small commercial. However, today, the most common one is primarily based on the Li-ion chemistry.

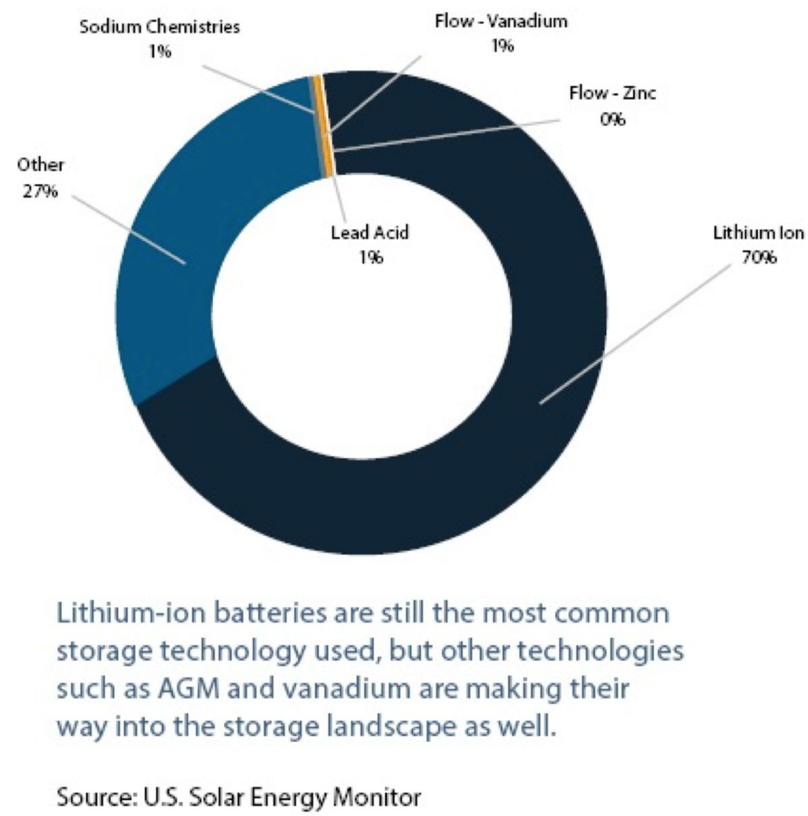

Figure A1: Percentage of Li-ion batteries used among the other types of battery technologies [9]

Focusing on the Li-ion battery, some technical challenges are found in technology of the battery itself and some challenges are associated with deployment. Challenges related to technology can be viewed in six aspects: cost, safety, performance (peak power at low temperatures, state-of-charge measurement, and thermal management), specific energy (how much energy battery can store per kilogram of weight), specific power (how much power battery can store per kilogram of mass), and lifespan (measured in term of both number of charge and discharge cycles and overall battery age) [10]. While the term "lithium-ion" refers not to a single electrochemical couple but to a wide array of different chemistries, those six aspects are economically related to each other differently depending on the different chemical substances used in the Li-ion battery technologies. Here is an example of tradeoff among the five principal Li-ion battery technologies.

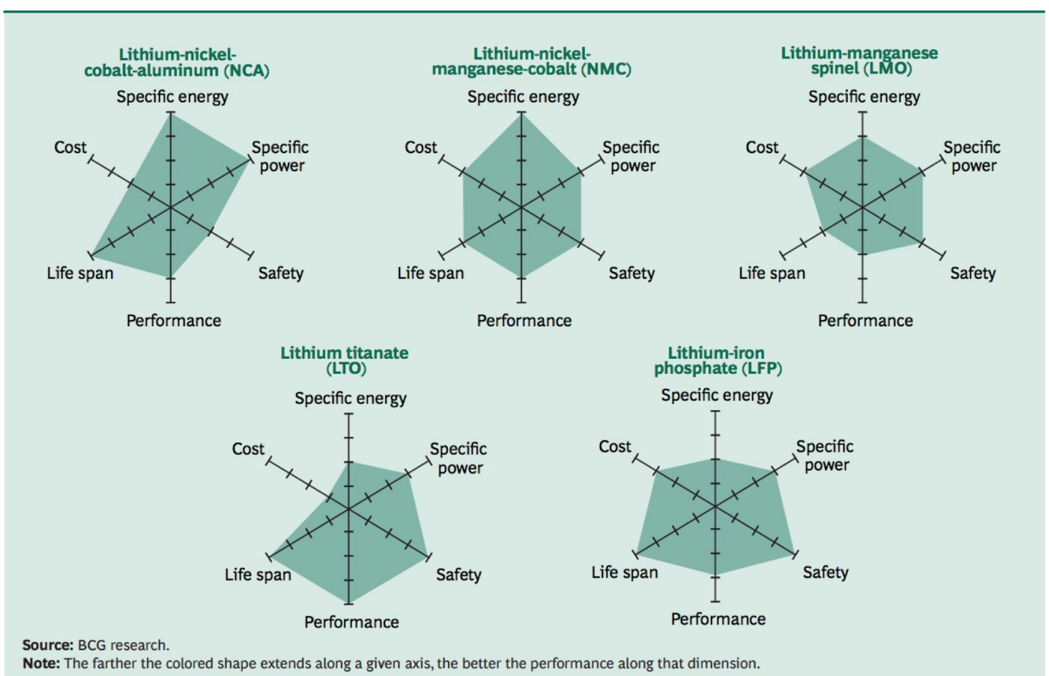

Figure A2: Tradeoff among the five principal Li-ion battery technology. [9]

In terms of safety, Li-ion is an inherently unstable chemistry [11]. The example of Li-ion battery fires that recently happened are the one in Samsung Galaxy Note 7 and the other in stationary storage of Pacific Northwest in July 2013. The only way to address these situations is to implement fire mitigation technologies which are costly and complex. In terms of the cost, based on the Advanced Automotive Batteries group, the analysis on battery pack pricing with the input from 16 major battery producers and over 20 automotive producers, it is clear that the future pricing of Li-ion battery packs seems not as optimistic as the values quoted by many battery manufacturers [11]. According to Advanced Automotive Batteries' 2010 report, the projected average cell pricing in 2020 is about $325/kWh for long range EV's (and much higher for high power cells), and that the pack-level balance of systems will take the total pricing of the units to above $400/kWh. Moreover, in terms of performance and lifespan, the cycle life and thermal performance appear to fall short in cheap Li-ion alternatives which typically have thicker electrode structures. The thin electrode structure and costly electrolyte blends would enhance well thermal performance and cycle life, but this would also raise the price per unit of energy [11].

Other challenges associated with deploying battery are installation, control system, and inverter issues. Today, modern smart inverters typically have overcharge or overdischarge cut-off sensor to ensure that the batteries are not unduly over-charged or discharged. However, users need to be aware that some batteries are still not equipped with this technology [12]. Batteries must not be over-charged or discharged. In-fact, batteries are not expected to be discharged below 0.5 per cell, *i.e.*, for a 12V battery, minimum voltage to discharge the battery must be around 10.8V. If it is discharged below this level, the intelligent inverter would possibly shut the system down in order to prevent damage to the battery. The typical problems related to inverters are over-load and wiring circuit and cable sizing. When calculating the loads to be connected to the inverter, the total demand load must not exceed the rating of the inverter otherwise this could cause shut downs or burning. Moreover, the calculation also involves cable sizing. The wrong wire or cable size could cause fire.

3. **Perspectives**

Having reviewed some of the history and technical capabilities and limitations of energy storage in general and battery storage in particular, it is useful to step back and survey the environment—the energy landscape—in which battery technology is operating and developing. By considering this landscape from the perspective of different actors in the space—consumers, utilities, government and regulators, and the energy storage industry along with enabling technologies—it becomes readily apparent how complex the interactions of players can be, how difficult it is to predict future states, but also how critical engagement must become. David Owens, Edison Electric Institute's Executive Vice President for Business Operations Group and Regulatory Affairs notes that to realize the promise of cleaner, more reliable, and affordable energy requires an integrated approach with greater collaboration and dialogue between all of these players with their various roles, responsibilities, and attributes [13].

A recent publication by the Deloitte Center for Energy Solutions highlighted the increasing options available to energy consumers [14]. Historically, electric utilities have been viewed as natural monopolies and consumers have traditionally been passive and captive energy takers. While some jurisdictions have experimented with different levels of and approaches to customer choice—particularly during the 1990s—North American electricity consumers still typically have an electricity provider or distributor that operates under some form of a traditional utility regulatory model that involves a regulatory compact ensuring that a utility has an opportunity to earn a reasonable return in exchange for providing non-discriminatory service to all at reasonable rates.

With rapidly advancing technology and expectations, energy consumers are increasingly more able to become more active participants in the energy market. This participation can come in simple forms such as choosing the resources in their energy supply mix, selecting alternative rate structures like time-of-use (TOU), or participating in individual and aggregated forms of distributed energy like solar photovoltaic systems that can reduce variable energy costs. Many of these changes result from increasing availability and adoption of variable energy resources (VERs) and distributed energy resources (DERs) largely due to falling costs. In addition, investment in upgrading underlying grid technology allow for smarter two-way connectivity. This movement of more data resulting from this increasing connectivity points to the potential for consumers, through smart infrastructure, to respond to prices and market conditions in a concept known as transactive energy. While there are limited trials of this concept, there remain many technical challenges including concerns by utilities that transactive energy structures could create reliability problems on the complex distribution system if utilities were to relinquish some of their current system control to market forces [3].

While widespread changes to the current regulated market model may be understandably delayed because of technical challenges, a common understanding of basic definitions and concepts among players is also a hurdle. Batteries (and other forms of energy storage) have the distinct characteristic of being at times a load (*consuming* electricity while charging) and also a generator (*providing* electricity while discharging). This duality makes consideration difficult using any traditional conceptual framework like that underlying regulation. As a starting point for this discussion, it is useful to consider batteries as a DER consistent with a definition presented by the National Association of Regulatory Utility Commissioners (NARUC) [15].

> A DER is a resource sited close to customers that can provide all or some of their immediate power needs and can also be used by the system to either reduce demand (such as energy efficiency) or increase supply to satisfy the energy or ancillary service needs of the distribution grid. The resources, if providing electricity or thermal energy, are small in scale, connected to the distribution system, and close to load. […]

In addition to facilitating common terminology, NARUC also outlines some of the challenged to regulators brought by DERs like battery storage:

- Potential costs that DERs impose on the grid
- Recovery of grid costs from DER customers and cost shifts to other customers
- Proper accounting of and compensation for benefits DERs provide
- Physical and technological challenges to the grid

- Ownership and control issues

Facilitating greater growth and integration of battery storage (and other DERs and VERs) onto the grid will require greater investment in transformational infrastructure upgrades. While the end result of such investments can lead to potential benefits like renewable generation closer to load, deferred infrastructure transmission and distribution infrastructure investments, temporary solutions for regional and local capacity shortages, local transmission and distribution congestion relief, and greater consumer choice, some group will have to pay for these benefits. Ratemaking is more art than science and utility regulators vary in their ability and willingness to use rate-setting authority to advance social policies because of inevitable cost shifts and cross subsidization. NARUC notes that it is important to consider the public interest in addition to any direction from executive and legislative bodies and it is worth noting that research and development funding also falls into this area [16].

Technology moves faster than bureaucracy, but these policy matters affect the battery industry in addition to utilities and consumers. As with any rapidly evolving technology industry, research and development involve high costs along with great uncertainty and risk. Policy (in various forms including direct regulation, subsidies, and standards promulgation) can help emerging technologies advance from concept or early adoption to mainstream acceptance. This achievement of critical mass was named “crossing the chasm” by Geoffrey Moore. Indeed, the role of government policy and utility partnerships should not be discounted. In an interview with *EPRI Journal*, Emily Reichert, CEO of a Massachusetts-based incubator for energy technology start-up firms noted that utilities have an opportunity to provide demonstration facilities for new technologies while “what the grid looks like 10 years from now will depend on how the federal government prioritizes infrastructure upgrades. Investing nationally in grid infrastructure could be a great opportunity for a much smarter grid that enables more renewable and distributed energy at a larger scale.” [17]

The greater consumer options and evolving preferences affect other players in the energy landscape who must adjust their strategies and models or try to shape the new emerging paradigm. Utilities, many slow to adapt, are facing select consumers bypassing part of their network and shifting costs to remaining customers that create issues of equity. Many regulatory and government bodies have also been slow to recognize transformations. New York’s “Reforming the Energy Vision” Strategy serves as one example of a more comprehensive strategy (looking even beyond electricity) to explore energy evolution [18]. With so many more interactions possible among even the limited payers identified here, any attempt to model development of the battery industry would require multiple models at macro and micro levels. As an example, The Electric Power Research Institute (EPRI) identified some of the challenges of modeling energy storage benefits paraphrased here [19]:

- Understanding performance characteristics, cost, expected service life, and relative technological maturity
- Defining the technical requirements including hardware, software, and user interfaces
- Understanding the possible impact on transmission and distribution system planning, construction, and operations

- Assessing value and cost break-even points
- Understanding the effects of policy and regulation on the adoption and cost-effectiveness
- Understanding potential environmental impacts

This scope of the model in this project is necessarily more limited. The next section contains a financial payback analysis of consumer batteries using specific assumptions about battery attributes (technology, cost, and service life) along with current utility costs and rate structure.

4. **Modeling the Use of residential and small scale commercial batteries**

Battery technology is being increasingly used on a small scale. But on an aggregate level, small scale batteries (< 100 kWh) have yet to see wide scale adoption. The rate of adoption is likely to be driven first by those with electric consumption models that are best aligned with storage battery technology. That is, allow for charging late at night when power is the cheapest.

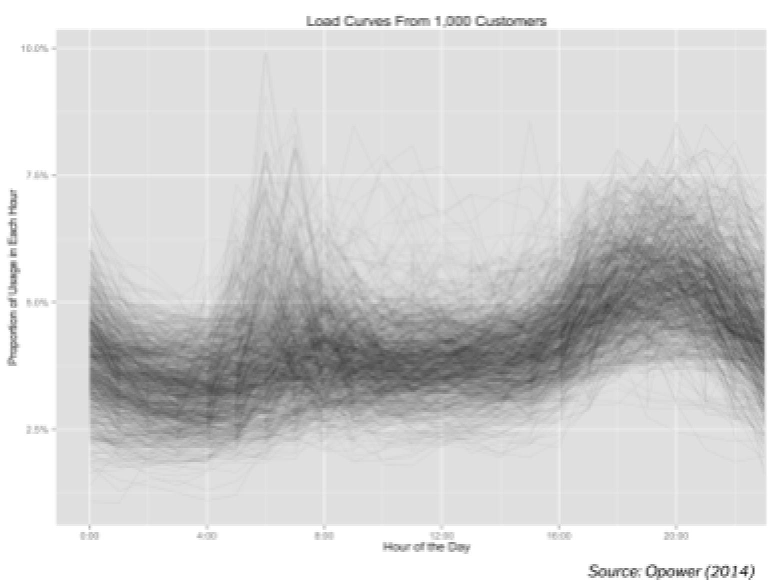

Figure B1: Load Curves from 1,000 customers

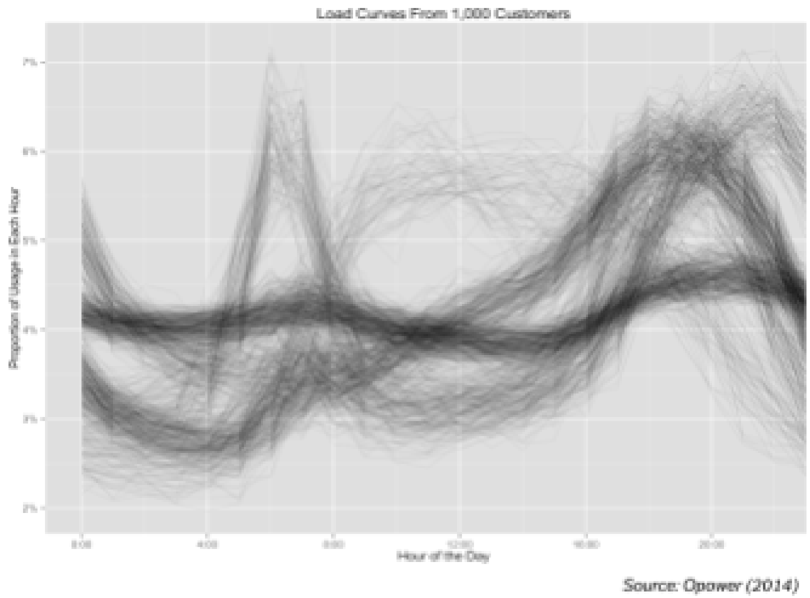

Figure B2: Grouped load curves from 812,000 datasets

To determine which markets might first adopt battery technology is a broad scale it is first necessary to understand how different market segments demand electricity. Figure B1 illustrates load curves for 1000 customers from data collected by Opower [20]. While the data indicates some late evening peaking and along with some early morning peaks, discerning recognizable patterns can prove difficult. The article goes on to present refined data collections from over 812,000 customers into "load archetypes" of which five begin to emerge as shown in figure B2. Recognizing that each consumption curve is levelized by plotting as a proportion of usage throughout the day and coloring the five trend lines, the results are seen in figure B3. Focusing on two of the curves, the dark green curve has an early spike commensurate with families waking up and leaving for work and school and later coming home and starting to use electricity again in the evening. Another, magenta colored is representative of commercial daytime companies that begin using power as employees show up for work and then trails off in the evening as employees head home and business winds down. We'll refer to these two trends as typical 'Residential' and 'Commercial load curves.

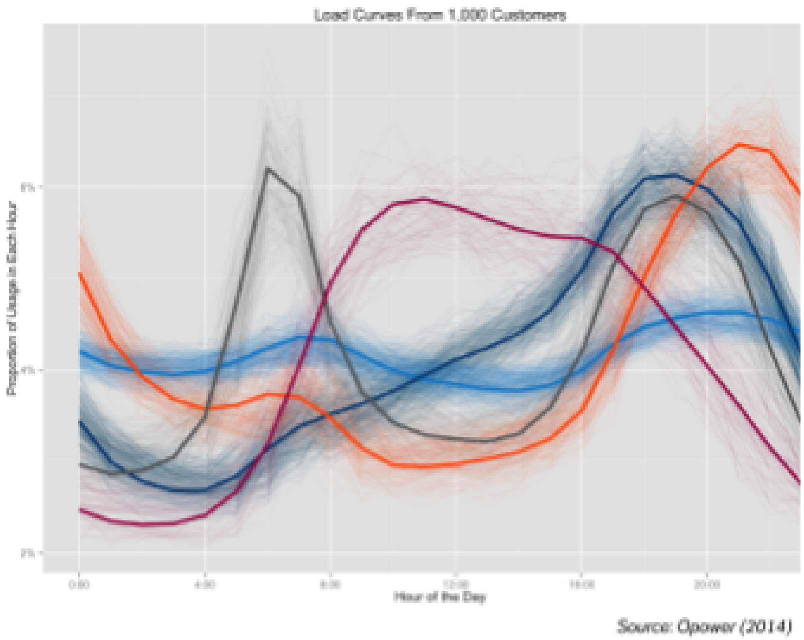

Figure B3 Colored Market segments for each grouping

They average residential household in the west region of the United States uses 12570 kWh of electricity per year [21]. Based on 34 and average of 34 kWh per day, and the data from Figure B3 we can generate a typical residential demand profile as shown in Figure B4. We see a low of about one kWh during the night and midday when people are not at home and peaks of twice that, 2 kWh during the early morning and evening.

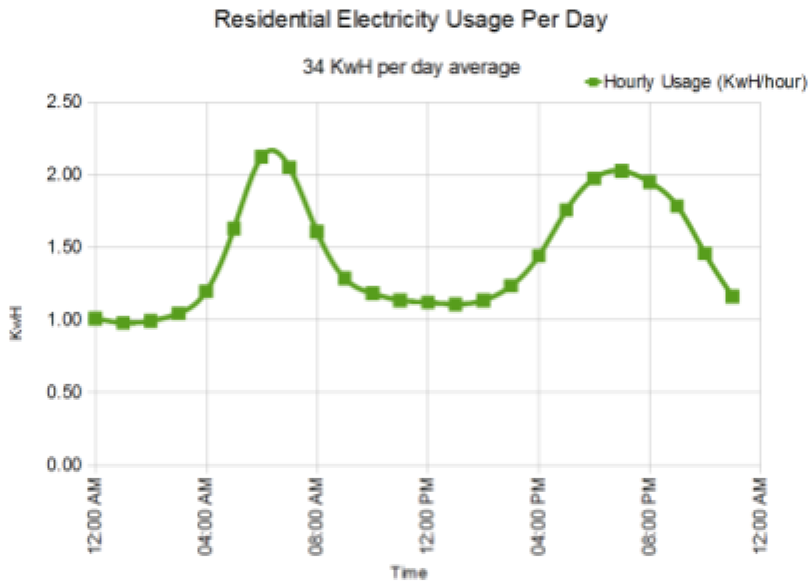

Figure B4: Typical Residential electricity usage based on a daily average

What would happen if this family were to add a small battery, charging the battery in the late night hours and discharging the battery at during the day as needed? Based on a 34 kWh usage a 40 kWh battery would be required and the resulting activity shown in Figure B5. We see the electric grid supplying about 10 kw of electricity for four hour during the night and the state of charge raising to 35 kWh as the family begins to wake up and use more electricity. During the day, the battery discharges and begins the cycle again the next night.

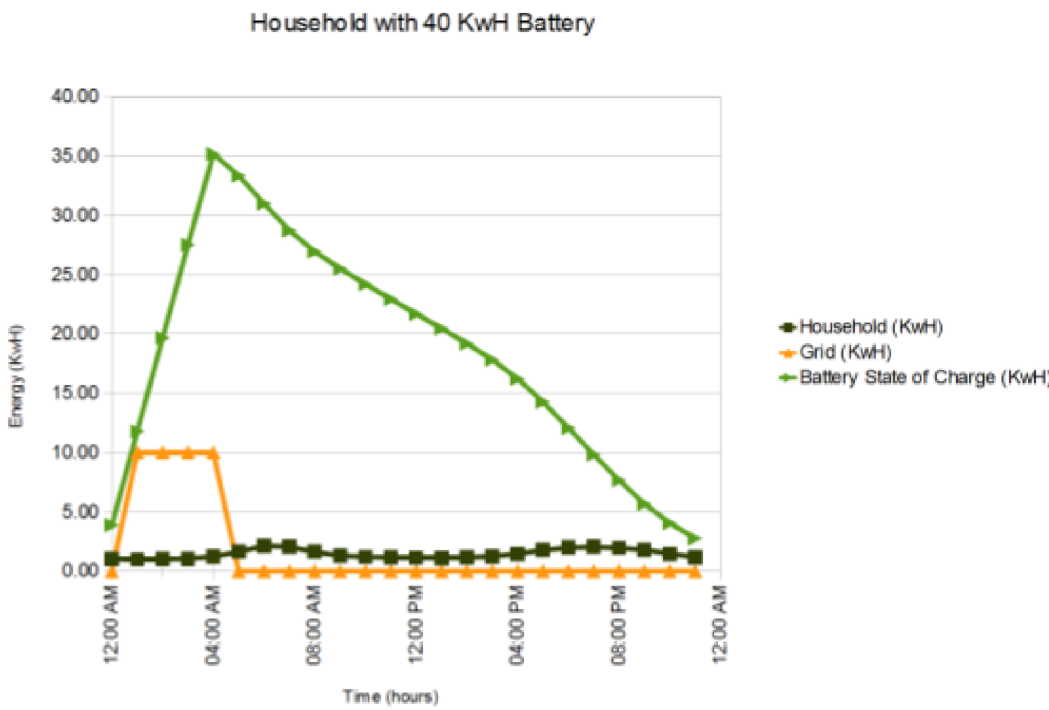

Figure B5: Residential with 40 kWh battery storage

Based on time of use charging that discounts Off-peak electricity from \$0.094/kWh to \$0.044/kWh, the daily electric bill would decrease from \$3.23 per day down to \$1.76 – saving \$1.47 per day or about \$537 per year. A typical 40 kWh battery may cost about \$18,600 plus installation which results in a payback period of over 30 years – well beyond the threshold for the financially minded consumers. But what if solar or wind energy is added to the mix?

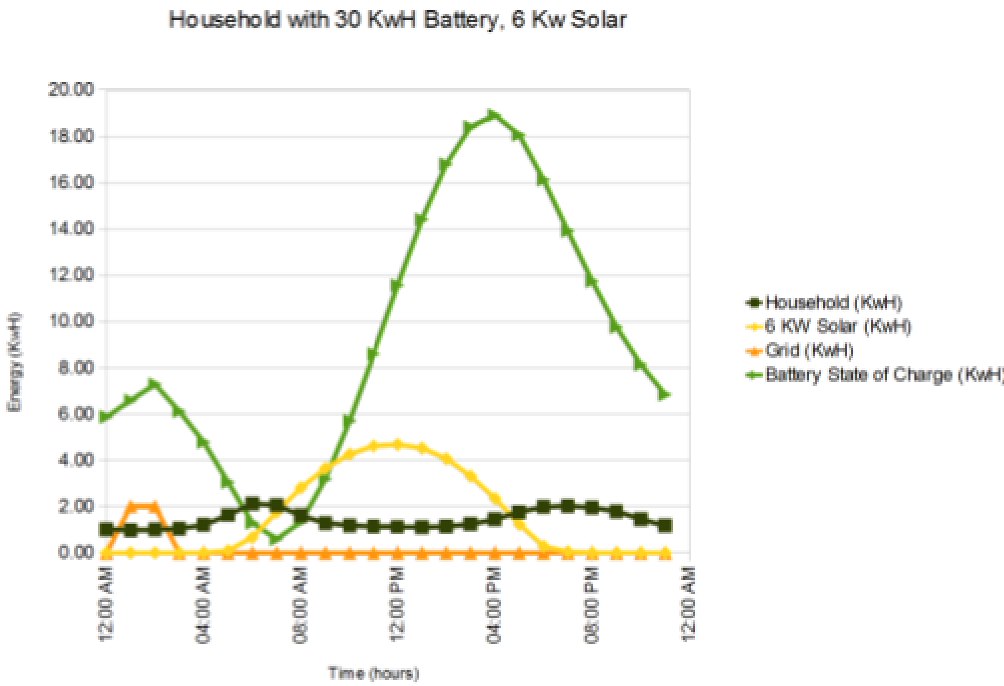

Figure B6: Residential Household with 30 kWh battery and 6 kW solar array

Solar is more cost competitive today than ever before. A 6 kW array with summer sun in the Portland area would provide about 38.3 kwh of electricity each day [22]. The resulting daily activity is shown in Figure B6. Solar production peaks out at about 5 kW at mid-day. During this time the battery is charged however, during the day, there is insufficient energy to compensate for conversion and storage losses (estimated at 10% each way). Thus 4 kWh is still necessary during the night to provide sufficient energy before the sun shines again the next day. During this day, the total cost to the customer would be $0.18 per day or a savings of $3.05. Further notice the battery is no longer need to be sized at 40 kWh; 20 kWh appears to be sufficient. But why 30 kWh?

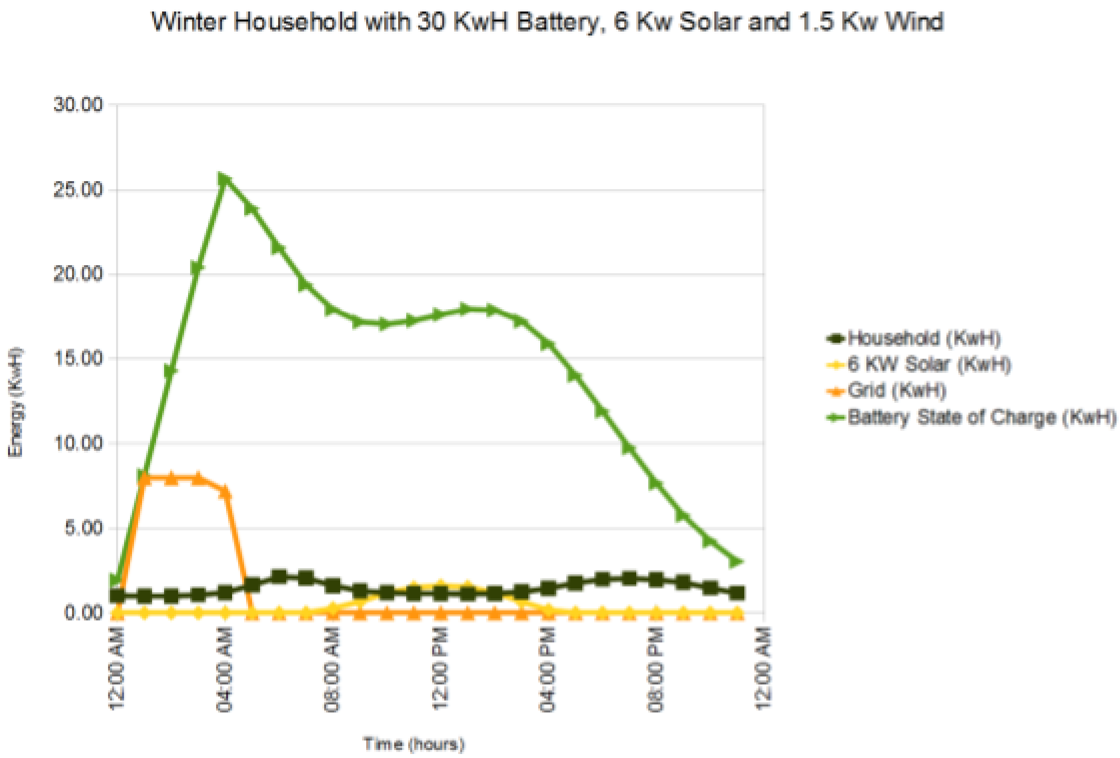

Figure B7: Winter household residential with 6 kW solar and battery

During the winter, the same 6 kWh array will only average 8.7 kWh production for the day. And some days even less. The typical winter day is shown in Figure B7. Due to reduced solar production, 31.2 kW of grid capacity is required bringing the total cost to $1.37 per day. Some would suggest a small wind turbine may help offset lower solar production. NREL data suggests that average winter wind speeds are 4.6 m/s (10.3 mph) in Portland as compared to 2.9 m/s (6.4 mpg) in the summer. Modeling the wind production performanced based on a Pika T701 1.5 kW wind turbine suggests daily summer production would be limited to just 0.3 kWh per day and winter production of 2.6 kWh per day during the winter. A plot of the winter energy requirements with a wind turbine is shown in figure B8. In summary, based on NREL data, Portland Oregon is simply not a suitable location to generate energy from a small wind turbine. Analysis in another location with an average annual wind speed of 6 m/s (13.4 mph) would certainly provide different results. Further inspection recognizes that the battery would need to be sized at 30 kWh to meet the necessary daily demand.

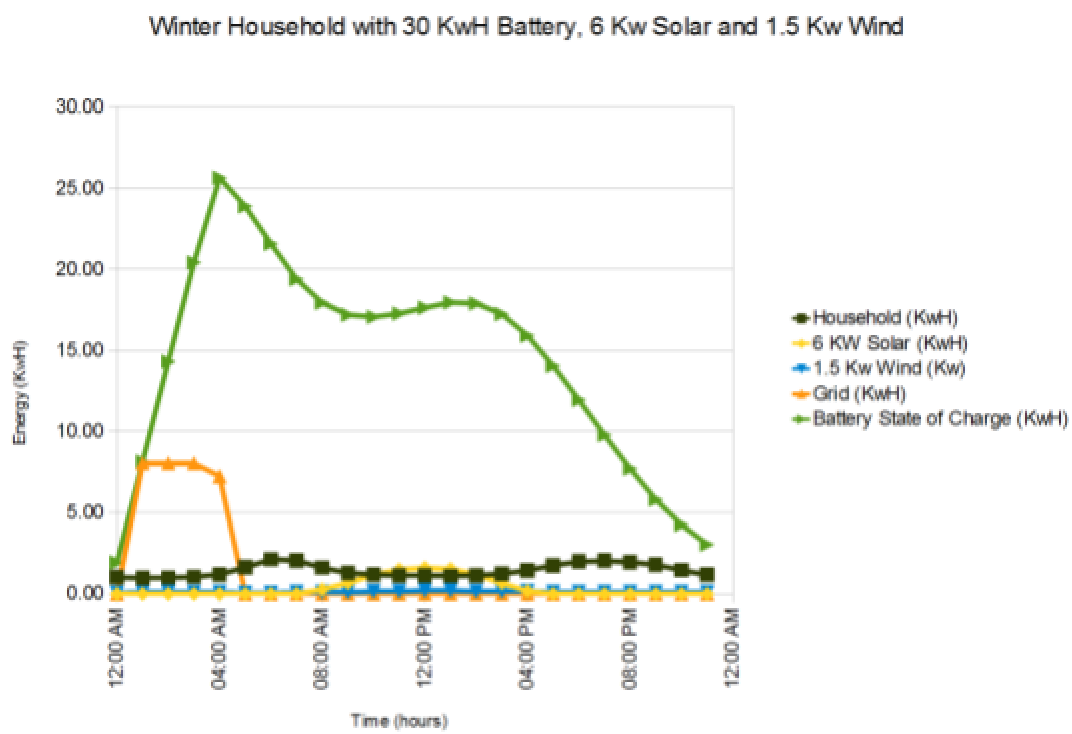

Figure B8: Household residential energy with solar, wind and battery

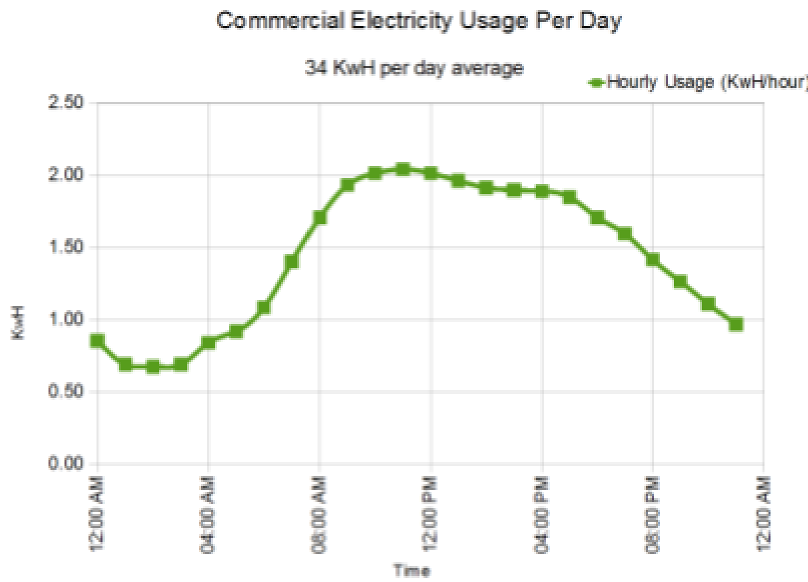

Figure B9: Commercial Electricity Usage per day

From a commercial perspective things are a little different. The daily peak in electricity consumption more closely mirrors solar capacity. Based on a commercial business with 945 square feet, an average consumption of 13.3 kWh we have an annual electrical consumption of 12,568 kWh per year [21]. See figure B9 for the average daily power curve. Figure B10 and B11 show the typical summer and winter energy use. Again we see that a 20 kWh battery is sufficiently sized during the summer, but a 30 kWh battery is necessary during the winter.

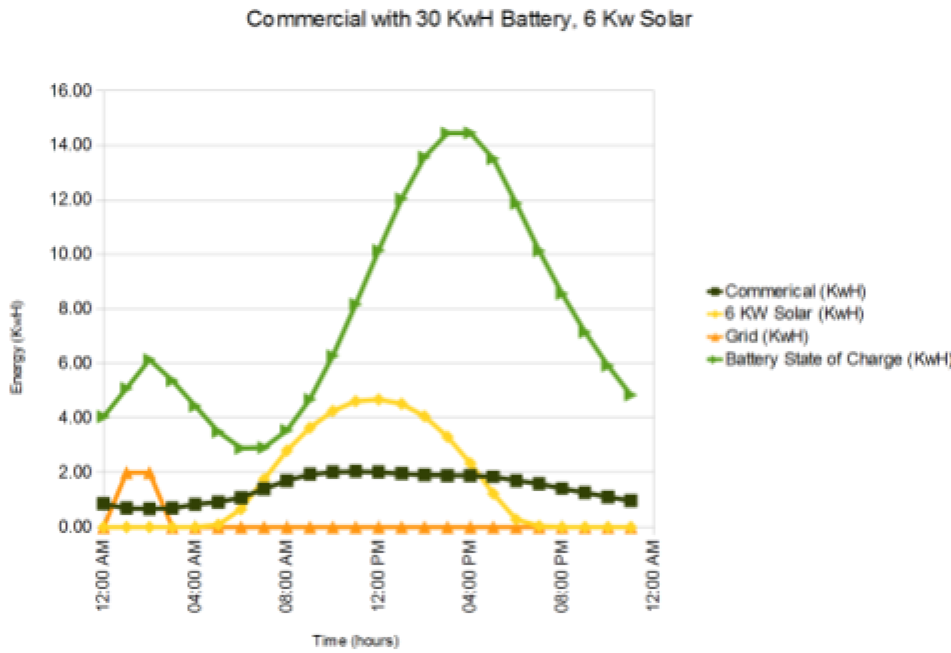

Figure B10: Commercial energy profile with 30 kWh battery, 6 kW solar and 1.5 kW wind

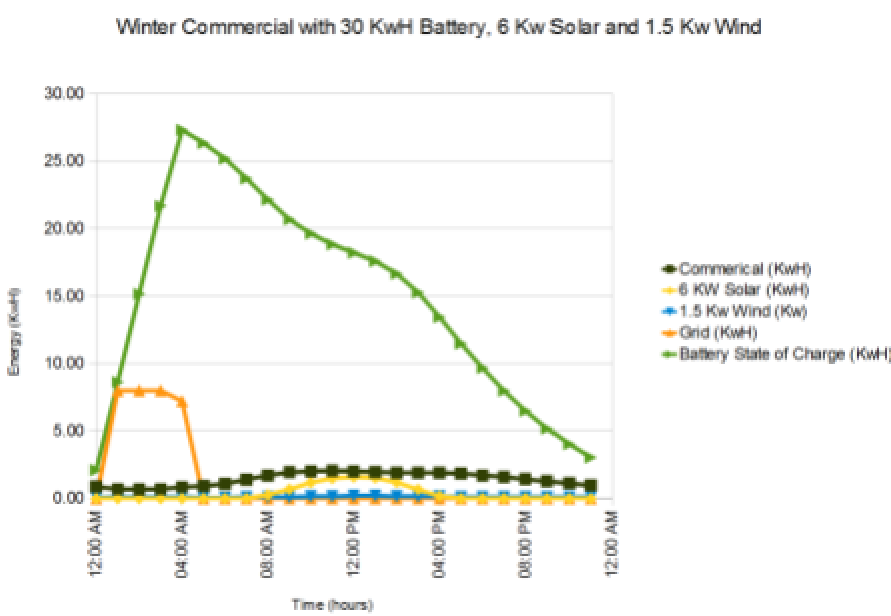

Figure B11: Winter Commercial

Concluding remarks on battery use models.

From both the residential and commercial model we see that without a solar installation a 40 kWh battery in necessary to support needs. The additional of solar photo voltaic can easily decrease the requirement down to 30 kWh.

A 28 kWh battery installation would cost about $14,400 (2X $6,200 per 15 kWh powerwall battery plus $2000 installation) [23]. From a strict financial perspective the numbers don't make sense yet, but the price of battery technology is dropping rapidly. Other markets will have different rate structures.

Of further note, one must wonder at what point will electric car batteries be useful for providing power. In many ways electrical consumption follows people. When they go to work, they use electricity at work. When they go home, they use electricity at home. Does it make sense to let our cars provide our energy. A Nissan Leaf has a 30 kWh battery, provided a limited driving and an opportunity to fast charge at rates above 6 kW at night, it might work. However, what remains to be seen is life cycle cost. Batteries degrade with use. And while 300 charge cycles used to be considered good, newer technology appears to be approaching 1000 cycles and with some companies claiming 3000-4000 cycles. Any detailed life cycle cost analysis would need to consider battery life cycle, but little validated data is available on the topic – but what limited data is available suggests batteries with appropriate usage profiles and temperature controls are lasting longer than anticipated.

5. Conclusion and Summary

In the 1900s, engineers used pumped hydroelectric energy storage. During peak hours, water is released to generate electricity and supply the grid. The disadvantages of this system are long construction time, high capital investment, and high maintenance costs. With new breakthrough in technology, battery energy storage is introduced, and is slowly becoming a dominant energy storage. There are different types of batteries that are being used, but Lithium-ion battery is the most common one due to many advantages comparing to the other types of batteries such as sodium-sulfur (NaS), nickel-cadmium (NiCd), and lead-acid batteries. However, there are still of limitations of the battery technology that encourage researchers and producers to innovate in areas such as thermal management, peak power at low temperature, and lifespan. There are complex interactions of actors in today's energy landscape. Consumers, utilities, regulators and battery technology firms all have stakes in the development of consumer-scale battery technology. Despite—or perhaps because of the fast pace of technological advances, many of these players have been slow to respond to industry transformation.

To demonstrate how certain markets might first adopt battery technology, we built a model using data collected from 1000 customers using Opower. We find that having a 40 kWh battery would decrease the daily electric bill from $3.23 per day to $1.76 per day, or about $537 per year, for residential customers, during the summer time. With an installation of 6 kW solar array, during the summer time, the total cost would be $0.18 per day. Also, the battery size appears to be sufficient at 20 kWh. During the winter time, with solar, the total cost would be $1.37 per day. In addition, Portland (Oregon) is not suitable for wind power, so energy generated from wind turbine is too low for energy use. For a commercial business with 945 square feet and 13.3 kWh average usage, a 20 kWh battery is sufficiently sized during the summer, but a 30 kWh battery is necessary during the winter. The cost of a typical 40 kWh battery is about $18,600 plus installation, and payback period of over 30 years. Therefore, at this moment, it would not be a good option financially for customers. Actions from policymakers and utilities, such as giving incentives, or financial help could drive greater adoption. For future research, electric car batteries might also be useful for providing power within more integrated consumer energy systems.

Reference:

[1] Page, Samantha. "The Scariest Part Of California'S Gas Leak Wasn'T Rashes And Bloody Noses. It'S What Happens Next.". *ThinkProgress*. N.p., 2017. Web. 13 June 2017.

[2] "Aliso Canyon Leak Sheds Light On National Problem". *Environmental Defense Fund*. N.p., 2017. Web. 13 June 2017.

[3] Wagman, David. "Energy Storage Rose From California Crisis". *IEEE Spectrum: Technology, Engineering, and Science News*. N.p., 2017. Web. 14 June 2017.

[4] "Energy Storage | Edison International". *Edison.com*. N.p., 2017. Web. 14 June 2017.

[5] Carlson, Kristin. "GMP Launches New Comprehensive Energy Home Solution From Tesla To Lower Costs For Customers - Green Mountain Power". *Green Mountain Power*. N.p., 2017. Web. 14 June 2017

[6] Chen, Allan. "Berkeley Lab Study Estimates $80 Billion Annual Cost Of Power Interruptions | Berkeley Lab". *News Center*. N.p., 2017. Web. 14 June 2017

[7] Whittingham, M. S. "History, Evolution, And Future Status Of Energy Storage". *Proceedings of the IEEE* 100.Special Centennial Issue (2012): 1518-1534. Web.

[8] Luo, Xing et al. "Overview Of Current Development In Electrical Energy Storage Technologies And The Application Potential In Power System Operation". *Applied Energy* 137 (2015): 511-536. Web.

[9] "What is the best type of battery for solar storage?," *Solar Power World*, 02-Jun-2017. [Online]. Available: http://www.solarpowerworldonline.com/2015/08/what-is-the-best-type-of-battery-for-solar-storage/. [Accessed: 13-Jun-2017].

[10] “Batteries for Electric Cars – Challenges, Opportunities ...” [Online]. Available: https://www.bing.com/cr?IG=0D4E351D335C441B95B0510D886DAC78&CID=3DD0089110AE68E111E8023111A86922&rd=1&h=ZhyxEjZf94lPJmpxYnY1L05v9oVstzq4SB48wH4JP7g&v=1&r=https%3a%2f%2fwww.bcg.com%2fdocuments%2ffile36615.pdf&p=DevEx,5062.1. [Accessed: 13-Jun-2017].

[11] P. J. Whitacre, “Aquion,” *3 Challenges: Lithium Ion Battery Safety, Cost, and Performance*. [Online]. Available: http://blog.aquionenergy.com/lithium-ion-battery-safety-cost-and-performance-challenges. [Accessed: 13-Jun-2017].

[12] S. P. Adegoke, “COMMON INVERTER PROBLEMS & SOLUTIONS | LinkedIn.” [Online]. Available: https://www.bing.com/cr?IG=569B8300B52D46B88F258C596EB0DC32&CID=234C2C506CA06955225126F06DA668D0&rd=1&h=l7tu6EfgtGmRPtX5g3hq7yg9nhTHVKsKyfsloQxAfG0&v=1&r=https%3a%2f%2fwww.linkedin.com%2fpulse%2fcommon-inverter-problems-solutions-shola-peters-adegoke-itil-&p=DevEx,5063.1. [Accessed: 13-Jun-2017].

[13] Electric Power Research Institute, "The Integrated Energy Network: It's Right on Point," *EPRI Journal,* 9 May 2017. Available: http://eprijournal.com/the-integrated-energy-network-its-right-on-point/

[14] Deloitte Center for Energy Solutions, "Choose, aggregate, transact: Increasing options for electricity customers," May 2017. Available: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-energy-and-resources-increasing-options-for-electricity-customers.pdf. [Accessed May 2017].

[15] G. Bade, "DistribuTECH 2017: Why utilities are skeptical about transactive energy," 17 February 2017. [Online]. Available: http://www.utilitydive.com/news/distributech-2017-why-utilities-are-skeptical-about-transactive-energy/436047/. [Accessed May 2017].

[16] The National Association of Regulatory Utility Commissioners Staff Subcommittee on Rate Design, "NARUC Manual on Distributed Energy Resources Rate Design and Compensation," The National Association of Regulatory Utility Commissioners, Washington, D.C., 2016. Available: http://pubs.naruc.org/pub/19FDF48B-AA57-5160-DBA1-BE2E9C2F7EA0

[17] New York State, "Reforming the Energy Vision," [Online]. Available: https://rev.ny.gov/. [Accessed May 2017].

[18] Electric Power Research Institute, "The 'Matchmaker' for Launching Energy Technologies," *EPRI Journal,* 9 May 2017. Available: http://eprijournal.com/the-matchmaker-for-launching-energy-technologies/

[19] Electric Power Research Institute, "Overview: Program 94 - Energy Storage and Distributed Generation," June 2016. [Online]. Available: http://www2.epri.com/Our-Portfolio/Pages/Portfolio.aspx?program=053125. [Accessed May 2017].

[20] Fischer, Barry. "We Plotted 812,000 Energy Usage Curves On Top Of Each Other. This Is The Powerful Insight We Discovered.". *Blogs.oracle.com*. N.p., 2017. Web. 14 June 2017.

[21] U.S. Energy Information Administration, Table C14 Electricity consumption and expenditure intensities, 2012 [Online] Available: www.eia.gov

[22] "Pvwatts Calculator". *Pvwatts.nrel.gov*. N.p., 2017. Web. 14 June 2017.

[23] "Tesla Powerwall". *Tesla.com*. N.p., 2017. Web. 14 June 2017.

Appendix
Supporting Calculations

Residential-BaseCase

Residential Model				Base Rate:	0.0939	$/kWh			
No Battery – Constant Electricity Pricing									
Time	Household (KwH)						Rate ($/KwH)	Energy Cost ($)	
12:00 AM	1.01					Base Rate	$0.09	$0.10	
1:00 AM	0.98					Base Rate	$0.09	$0.09	
2:00 AM	0.99					Base Rate	$0.09	$0.09	
3:00 AM	1.05					Base Rate	$0.09	$0.10	
4:00 AM	1.2					Base Rate	$0.09	$0.11	
5:00 AM	1.63					Base Rate	$0.09	$0.15	
6:00 AM	2.12					Base Rate	$0.09	$0.20	
7:00 AM	2.05					Base Rate	$0.09	$0.19	
8:00 AM	1.61					Base Rate	$0.09	$0.15	
9:00 AM	1.29					Base Rate	$0.09	$0.12	
10:00 AM	1.18					Base Rate	$0.09	$0.11	
11:00 AM	1.14					Base Rate	$0.09	$0.11	
12:00 PM	1.12					Base Rate	$0.09	$0.11	
1:00 PM	1.11					Base Rate	$0.09	$0.10	
2:00 PM	1.14					Base Rate	$0.09	$0.11	
3:00 PM	1.24					Base Rate	$0.09	$0.12	
4:00 PM	1.44					Base Rate	$0.09	$0.14	
5:00 PM	1.76					Base Rate	$0.09	$0.17	
6:00 PM	1.98					Base Rate	$0.09	$0.19	
7:00 PM	2.03					Base Rate	$0.09	$0.19	
8:00 PM	1.95					Base Rate	$0.09	$0.18	
9:00 PM	1.79					Base Rate	$0.09	$0.17	
10:00 PM	1.46					Base Rate	$0.09	$0.14	
11:00 PM	1.16					Base Rate	$0.09	$0.11	
								$3.23	**per day**

Residential-TimeOfUse

Residential Model			Winter Rates	$/KwH	
No Battery – Time of Use Charging			Off-peak	0.04399	
			Mid-peak	0.07572	
			On-Peak	0.13197	
Time	Household (KwH)		Rate ($/KwH)	Energy Cost ($)	
12:00 AM	1.01	Off-peak	$0.04	$0.04	
1:00 AM	0.98	Off-peak	$0.04	$0.04	
2:00 AM	0.99	Off-peak	$0.04	$0.04	
3:00 AM	1.05	Off-peak	$0.04	$0.05	
4:00 AM	1.2	Off-peak	$0.04	$0.05	
5:00 AM	1.63	Off-peak	$0.04	$0.07	
6:00 AM	2.12	On-Peak	$0.13	$0.28	
7:00 AM	2.05	On-Peak	$0.13	$0.27	
8:00 AM	1.61	On-Peak	$0.13	$0.21	
9:00 AM	1.29	On-Peak	$0.13	$0.17	
10:00 AM	1.18	Mid-peak	$0.08	$0.09	
11:00 AM	1.14	Mid-peak	$0.08	$0.09	
12:00 PM	1.12	Mid-peak	$0.08	$0.08	
1:00 PM	1.11	Mid-peak	$0.08	$0.08	
2:00 PM	1.14	Mid-peak	$0.08	$0.09	
3:00 PM	1.24	Mid-peak	$0.08	$0.09	
4:00 PM	1.44	Mid-peak	$0.08	$0.11	
5:00 PM	1.76	On-Peak	$0.13	$0.23	
6:00 PM	1.98	On-Peak	$0.13	$0.26	
7:00 PM	2.03	On-Peak	$0.13	$0.27	
8:00 PM	1.95	Mid-peak	$0.08	$0.15	
9:00 PM	1.79	Mid-peak	$0.08	$0.14	
10:00 PM	1.46	Off-peak	$0.04	$0.06	
11:00 PM	1.16	Off-peak	$0.04	$0.05	
				$3.03	**per day**

Residentail-Final-Summer

Residentail							Winter Rates	$/KwH	
Summer, Solar, Battery and Wind							Off-peak	0.04399	
					Previous End of Day		Mid-peak	0.07572	
					15		On-Peak	0.13197	
				Grid Battery Cha	Battery charging				
					Battery				
Time	Household (KwH	6 KW Solar (KwH	1.5 Kw Wind (Kw	Grid (KwH)	Battery State of Charge (KwH)		Rate ($/KwH)	Energy Cost ($)	
12:00 AM	1.01	0	0		13.87	Off-peak	$0.04	$0.00	
1:00 AM	0.98	0	-0.01	2	14.58	Off-peak	$0.04	$0.09	
2:00 AM	0.99	0	-0.01	2	15.26	Off-peak	$0.04	$0.09	
3:00 AM	1.05	0	-0.01		14.09	Off-peak	$0.04	$0.00	
4:00 AM	1.2	0	-0.01		12.76	Off-peak	$0.04	$0.00	
5:00 AM	1.63	0.09	-0.01		11.02	Off-peak	$0.04	$0.00	
6:00 AM	2.12	0.66	-0.01		9.25	Mid-peak	$0.08	$0.00	
7:00 AM	2.05	1.76	-0.01		8.54	Mid-peak	$0.08	$0.00	
8:00 AM	1.61	2.81	-0.01		9.28	Mid-peak	$0.08	$0.00	
9:00 AM	1.29	3.65	0		11.13	Mid-peak	$0.08	$0.00	
10:00 AM	1.18	4.26	0		13.64	Mid-peak	$0.08	$0.00	
11:00 AM	1.14	4.62	0		16.53	Mid-peak	$0.08	$0.00	
12:00 PM	1.12	4.68	0.01		19.5	Mid-peak	$0.08	$0.00	
1:00 PM	1.11	4.52	0.01		22.35	Mid-peak	$0.08	$0.00	
2:00 PM	1.14	4.06	0.03		24.77	Mid-peak	$0.08	$0.00	
3:00 PM	1.24	3.31	0.03		26.4	On-peak	$0.13	$0.00	
4:00 PM	1.44	2.35	0.06		26.96	On-peak	$0.13	$0.00	
5:00 PM	1.76	1.23	0.09		26.2	On-peak	$0.13	$0.00	
6:00 PM	1.98	0.28	0.09		24.34	On-peak	$0.13	$0.00	
7:00 PM	2.03	0.04	0.06		22.18	On-peak	$0.13	$0.00	
8:00 PM	1.95	0	0.03		20.03	Mid-peak	$0.08	$0.00	
9:00 PM	1.79	0	0.01		18.05	Mid-peak	$0.08	$0.00	
10:00 PM	1.46	0	0.01		16.44	Off-peak	$0.04	$0.00	
11:00 PM	1.16	0	0		15.14	Off-peak	$0.04	$0.00	
								$0.18	**per day**

Residential-Final-Winter

Residential							Winter Rates	$/KwH	
Winter, Solar, Battery and Wind							Off-peak	0.04399	
					Previous End of Day		Mid-peak	0.07572	
					3		On-Peak	0.13197	
				Grid Battery Cha	Battery charging				
					Battery				
Time	Household (KwH	6 KW Solar (KwH	1.5 Kw Wind (Kw	Grid (KwH)	Battery State of Charge (KwH)		Rate ($/KwH)	Energy Cost ($)	
12:00 AM	1.01	0	0.06		1.93	Off-peak	$0.04	$0.00	
1:00 AM	0.98	0	0.09	8	8.12	Off-peak	$0.04	$0.35	
2:00 AM	0.99	0	0.09	8	14.3	Off-peak	$0.04	$0.35	
3:00 AM	1.05	0	0.09	8	20.42	Off-peak	$0.04	$0.35	
4:00 AM	1.2	0	0.09	7.2	25.66	Off-peak	$0.04	$0.32	
5:00 AM	1.63	0	0.06		23.9	Off-peak	$0.04	$0.00	
6:00 AM	2.12	0	0.06		21.59	On-Peak	$0.13	$0.00	
7:00 AM	2.05	0	0.09		19.4	On-Peak	$0.13	$0.00	
8:00 AM	1.61	0.26	0.09		17.94	On-Peak	$0.13	$0.00	
9:00 AM	1.29	0.66	0.09		17.19	On-Peak	$0.13	$0.00	
10:00 AM	1.18	1.18	0.14		17.06	Mid-peak	$0.08	$0.00	
11:00 AM	1.14	1.49	0.14		17.27	Mid-peak	$0.08	$0.00	
12:00 PM	1.12	1.59	0.2		17.63	Mid-peak	$0.08	$0.00	
1:00 PM	1.11	1.53	0.2		17.96	Mid-peak	$0.08	$0.00	
2:00 PM	1.14	1.19	0.14		17.89	Mid-peak	$0.08	$0.00	
3:00 PM	1.24	0.66	0.14		17.23	Mid-peak	$0.08	$0.00	
4:00 PM	1.44	0.17	0.14		15.91	Mid-peak	$0.08	$0.00	
5:00 PM	1.76	0	0.09		14.04	On-Peak	$0.13	$0.00	
6:00 PM	1.98	0	0.09		11.93	On-Peak	$0.13	$0.00	
7:00 PM	2.03	0	0.09		9.76	On-Peak	$0.13	$0.00	
8:00 PM	1.95	0	0.09		7.68	Mid-peak	$0.08	$0.00	
9:00 PM	1.79	0	0.09		5.78	Mid-peak	$0.08	$0.00	
10:00 PM	1.46	0	0.09		4.24	Off-peak	$0.04	$0.00	
11:00 PM	1.16	0	0.09		3.03	Off-peak	$0.04	$0.00	
								$1.37	**per day**

Commercial-BaseCase

Commercial									
No Battery – Constant Electricity Pricing							Base Rate:	0.0939	$/kWh
Time	Commercial (kWh)						Rate ($/KwH)	Energy Cost ($)	
12:00 AM	0.85					Base rate	$0.09	$0.08	
1:00 AM	0.69					Base rate	$0.09	$0.06	
2:00 AM	0.67					Base rate	$0.09	$0.06	
3:00 AM	0.69					Base rate	$0.09	$0.06	
4:00 AM	0.84					Base rate	$0.09	$0.08	
5:00 AM	0.92					Base rate	$0.09	$0.09	
6:00 AM	1.08					Base rate	$0.09	$0.10	
7:00 AM	1.4					Base rate	$0.09	$0.13	
8:00 AM	1.71					Base rate	$0.09	$0.16	
9:00 AM	1.93					Base rate	$0.09	$0.18	
10:00 AM	2.01					Base rate	$0.09	$0.19	
11:00 AM	2.04					Base rate	$0.09	$0.19	
12:00 PM	2.01					Base rate	$0.09	$0.19	
1:00 PM	1.96					Base rate	$0.09	$0.18	
2:00 PM	1.91					Base rate	$0.09	$0.18	
3:00 PM	1.9					Base rate	$0.09	$0.18	
4:00 PM	1.89					Base rate	$0.09	$0.18	
5:00 PM	1.85					Base rate	$0.09	$0.17	
6:00 PM	1.71					Base rate	$0.09	$0.16	
7:00 PM	1.59					Base rate	$0.09	$0.15	
8:00 PM	1.41					Base rate	$0.09	$0.13	
9:00 PM	1.26					Base rate	$0.09	$0.12	
10:00 PM	1.11					Base rate	$0.09	$0.10	
11:00 PM	0.97					Base rate	$0.09	$0.09	
								$3.23	**per day**

Commercial-TimeOfUse

Commercial							Winter Rates	$/KwH	
No Battery – Time of Use Charging							Off-peak	0.04399	
							Mid-peak	0.07572	
							On-Peak	0.13197	
Time	Commercial (KwH)						Rate ($/KwH)	Energy Cost ($)	
12:00 AM	0.85					Off-peak	$0.04	$0.04	
1:00 AM	0.69					Off-peak	$0.04	$0.03	
2:00 AM	0.67					Off-peak	$0.04	$0.03	
3:00 AM	0.69					Off-peak	$0.04	$0.03	
4:00 AM	0.84					Off-peak	$0.04	$0.04	
5:00 AM	0.92					Off-peak	$0.04	$0.04	
6:00 AM	1.08					On-Peak	$0.13	$0.14	
7:00 AM	1.4					On-Peak	$0.13	$0.18	
8:00 AM	1.71					On-Peak	$0.13	$0.23	
9:00 AM	1.93					On-Peak	$0.13	$0.25	
10:00 AM	2.01					Mid-peak	$0.08	$0.15	
11:00 AM	2.04					Mid-peak	$0.08	$0.15	
12:00 PM	2.01					Mid-peak	$0.08	$0.15	
1:00 PM	1.96					Mid-peak	$0.08	$0.15	
2:00 PM	1.91					Mid-peak	$0.08	$0.14	
3:00 PM	1.9					Mid-peak	$0.08	$0.14	
4:00 PM	1.89					Mid-peak	$0.08	$0.14	
5:00 PM	1.85					On-Peak	$0.13	$0.24	
6:00 PM	1.71					On-Peak	$0.13	$0.23	
7:00 PM	1.59					On-Peak	$0.13	$0.21	
8:00 PM	1.41					Mid-peak	$0.08	$0.11	
9:00 PM	1.26					Mid-peak	$0.08	$0.10	
10:00 PM	1.11					Off-peak	$0.04	$0.05	
11:00 PM	0.97					Off-peak	$0.04	$0.04	
								$3.03	**per day**

Commercial-Final-Winter

Commercial							Winter Rates	$/KwH	
Winter, Solar, Battery and Wind							Off-peak	0.04399	
					Previous End of Day		Mid-peak	0.07572	
					3		On-Peak	0.13197	
				Grid Battery Cha	Battery charging				
					Battery				
Time	Commerical (Kw	6 KW Solar (KwH	1.5 Kw Wind (Kw	Grid (KwH)	Battery State of Charge (KwH)		Rate ($/KwH)	Energy Cost ($)	
12:00 AM	0.85	0	0.06		2.1	Off-peak	$0.04	$0.00	
1:00 AM	0.69	0	0.09	8	8.62	Off-peak	$0.04	$0.35	
2:00 AM	0.67	0	0.09	8	15.16	Off-peak	$0.04	$0.35	
3:00 AM	0.69	0	0.09	8	21.68	Off-peak	$0.04	$0.35	
4:00 AM	0.84	0	0.09	7.2	27.31	Off-peak	$0.04	$0.32	
5:00 AM	0.92	0	0.06		26.34	Off-peak	$0.04	$0.00	
6:00 AM	1.08	0	0.06		25.19	On-Peak	$0.13	$0.00	
7:00 AM	1.4	0	0.09		23.72	On-Peak	$0.13	$0.00	
8:00 AM	1.71	0.26	0.09		22.15	On-Peak	$0.13	$0.00	
9:00 AM	1.93	0.66	0.09		20.68	On-Peak	$0.13	$0.00	
10:00 AM	2.01	1.18	0.14		19.64	Mid-peak	$0.08	$0.00	
11:00 AM	2.04	1.49	0.14		18.83	Mid-peak	$0.08	$0.00	
12:00 PM	2.01	1.59	0.2		18.21	Mid-peak	$0.08	$0.00	
1:00 PM	1.96	1.53	0.2		17.59	Mid-peak	$0.08	$0.00	
2:00 PM	1.91	1.19	0.14		16.66	Mid-peak	$0.08	$0.00	
3:00 PM	1.9	0.66	0.14		15.27	Mid-peak	$0.08	$0.00	
4:00 PM	1.89	0.17	0.14		13.45	Mid-peak	$0.08	$0.00	
5:00 PM	1.85	0	0.09		11.48	On-Peak	$0.13	$0.00	
6:00 PM	1.71	0	0.09		9.67	On-Peak	$0.13	$0.00	
7:00 PM	1.59	0	0.09		7.98	On-Peak	$0.13	$0.00	
8:00 PM	1.41	0	0.09		6.49	Mid-peak	$0.08	$0.00	
9:00 PM	1.26	0	0.09		5.17	Mid-peak	$0.08	$0.00	
10:00 PM	1.11	0	0.09		4.03	Off-peak	$0.04	$0.00	
11:00 PM	0.97	0	0.09		3.04	Off-peak	$0.04	$0.00	
								$1.37	**per day**

Commercial-Final-Summer

Commercial							Winter Rates	$/KwH	
Summer, Solar, Battery and Wind							Off-peak	0.04399	
					Previous End of Day		Mid-peak	0.07572	
					4		On-Peak	0.13197	
				Grid Battery Cha	Battery charging				
					Battery				
Time	Commerical (Kw	6 KW Solar (KwH	1.5 Kw Wind (Kw	Grid (KwH)	Battery State of Charge (KwH)		Rate ($/KwH)	Energy Cost ($)	
12:00 AM	0.85	0	0		3.05	Off-peak	$0.04	$0.00	
1:00 AM	0.69	0	-0.01	2	4.08	Off-peak	$0.04	$0.09	
2:00 AM	0.67	0	-0.01	2	5.12	Off-peak	$0.04	$0.09	
3:00 AM	0.69	0	-0.01		4.35	Off-peak	$0.04	$0.00	
4:00 AM	0.84	0	-0.01		3.41	Off-peak	$0.04	$0.00	
5:00 AM	0.92	0.09	-0.01		2.46	Off-peak	$0.04	$0.00	
6:00 AM	1.08	0.66	-0.01		1.85	Mid-peak	$0.08	$0.00	
7:00 AM	1.4	1.76	-0.01		1.87	Mid-peak	$0.08	$0.00	
8:00 AM	1.71	2.81	-0.01		2.49	Mid-peak	$0.08	$0.00	
9:00 AM	1.93	3.65	0		3.63	Mid-peak	$0.08	$0.00	
10:00 AM	2.01	4.26	0		5.22	Mid-peak	$0.08	$0.00	
11:00 AM	2.04	4.62	0		7.1	Mid-peak	$0.08	$0.00	
12:00 PM	2.01	4.68	0.01		9.08	Mid-peak	$0.08	$0.00	
1:00 PM	1.96	4.52	0.01		10.98	Mid-peak	$0.08	$0.00	
2:00 PM	1.91	4.06	0.03		12.54	Mid-peak	$0.08	$0.00	
3:00 PM	1.9	3.31	0.03		13.44	On-peak	$0.13	$0.00	
4:00 PM	1.89	2.35	0.06		13.5	On-peak	$0.13	$0.00	
5:00 PM	1.85	1.23	0.09		12.64	On-peak	$0.13	$0.00	
6:00 PM	1.71	0.28	0.09		11.08	On-peak	$0.13	$0.00	
7:00 PM	1.59	0.04	0.06		9.39	On-peak	$0.13	$0.00	
8:00 PM	1.41	0	0.03		7.85	Mid-peak	$0.08	$0.00	
9:00 PM	1.26	0	0.01		6.45	Mid-peak	$0.08	$0.00	
10:00 PM	1.11	0	0.01		5.23	Off-peak	$0.04	$0.00	
11:00 PM	0.97	0	0		4.15	Off-peak	$0.04	$0.00	
								$0.18	**per day**

PaybackModel

Pack Back Calculation					
Average Base C(	3.23	per day		$1,179.76	Per Year
Average cost with 6 KW solar & Battery					
	Winter	1.37	per day		
	Summer	0.18	per day		
	Average	0.775	per day	$283.07	Per Year
Annual Projected Savings				$896.69	Per Year
Cost of System	28 KwH Battery		$14,400.00		(Two Tesla 14 KwH PowerWalls)
	6 KW Solar		$18,000.00		($3 per watt pricing model)
	Total Cost		$32,400.00		
	Payback Period		**36.1**	**Years**	
	(Zero cost of capital, zero incentive)				