

STUDY OF BATTERY STORAGE TO DELAY INFRASTRUCTURE UPGRADE IN  
THE ELECTRICAL GRID

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Master of Science

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by

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The undersigned, appointed by the Dean of the Graduate School,  
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STUDY OF BATTERY STORAGE TO DELAY INFRASTRUCTURE UPGRADE IN  
THE ELECTRICAL GRID

Presented by Jackson J. Herbst

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

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## ABSTRACT

As energy consumption continues to rise in the United States, there exists a need to increase energy production, through either existing methods or the development of new methods. Environmental concerns encourage the use of technologies such as wind and solar power, yet the sporadic nature of these energy sources limits practical implementation on a large scale. In this study, batteries are proposed as a means of storing electrical grid energy during periods of low demand, to be used during periods of high demand. A systematic method of determining material costs was developed for both lead acid and lithium ion batteries, which was then applied to three locations in need of energy supplementation. Battery storage was shown to not be affordable at any of the three locations, with traditional infrastructure upgrades remaining the least expensive option. While battery material costs are potentially less expensive, other costs associated with the battery systems are too high at the present time.

# **Chapter 1: Introduction**

## **1.1 General Description**

The goal was to determine the cost of implementing battery storage at each of the three locations considered for analysis. These costs were then compared with the cost of traditional infrastructure upgrades to determine which of the locations could be suitable candidates for battery storage. The project motivation is explained alongside general terminology to provide the necessary background information. Basic battery operation is also discussed to highlight the advantages and disadvantages of various battery types. Utility data are then used to determine the amount of battery capacity required to supplement each location. A rough estimate of battery costs are given, and then later a systematic approach is developed to more closely optimize battery material costs.

## **1.2 Summary of Chapters**

### Chapter 2

Battery operation, chemistries, and terminology are explained in this chapter to provide an introduction to concepts further discussed in later chapters. Battery types are chosen for analysis and characterized by general advantages and disadvantages. The project motivation is explained in addition to the benefits of battery storage.

### Chapter 3

This chapter discusses the analysis of data supplied by the utility company. The goal of the chapter was to find the required energy of a battery storage system for each of the three locations being considered, and additionally to determine the number of cycles that the batteries would need to undergo during their lifetime. This information is then used to quantify the amount of battery capacity, and thus total material cost.

### Chapter 4

This chapter describes the method of analysis used to minimize material costs. The goal of the chapter was to find a way to optimize battery capacity when accounting for capacity decay, while building upon the conclusions reached in chapter 3. While a simple cost analysis was conducted in chapter 3, this chapter discusses a more thorough approach.

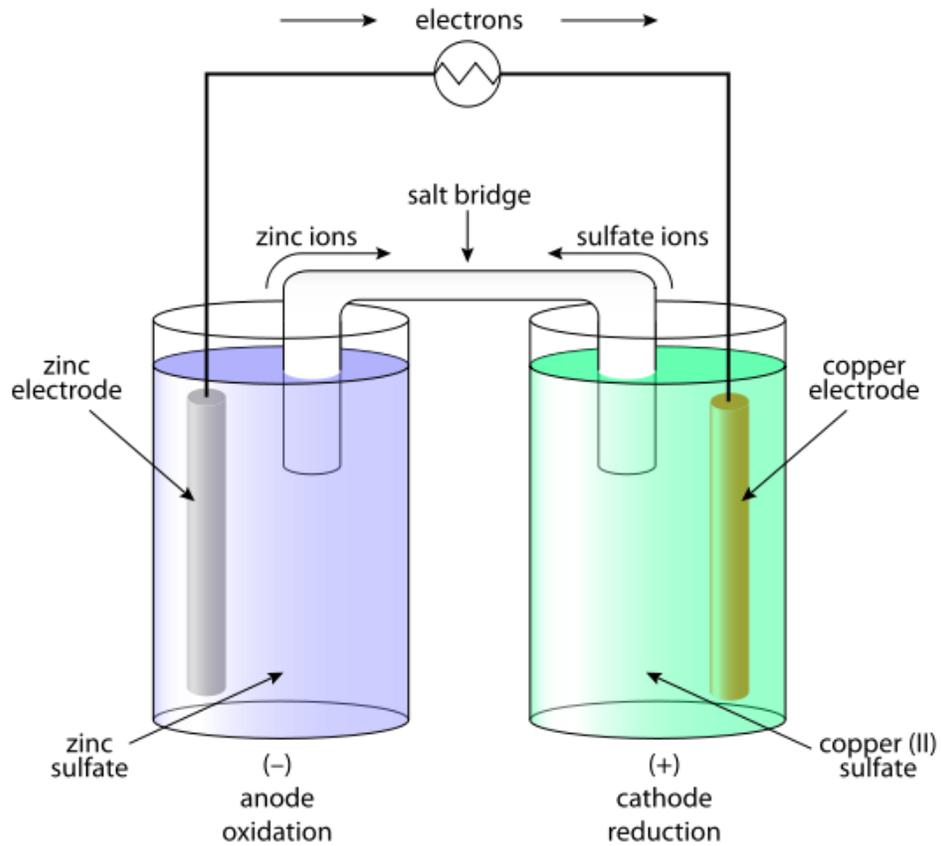
## **Chapter 2: Background**

Battery chemistries, technologies, and operation are essential knowledge to preface the discussion presented in this study, as well as finding suitable solutions. Introducing battery terminology and various battery chemistries will provide a thorough understanding of the concepts being discussed.

### **2.1 Battery Operation**

A battery is a device that stores chemical energy for the purposes of supplying electrical energy on demand. This is achieved through the use of two electrodes that are connected by an electrolyte [1]. This electrolyte needs to be a good ionic conductor to allow the flow of ions between electrodes, but also a poor electrical conductor to prevent short circuiting the battery. A diagram of basic battery operation can be seen in Figure 2.1. The salt bridge is a commonly used electrolyte that allows the passage of ions, but prevents the flow of electrons. The purpose of the electrolyte is to allow neutralization of the positive and negative ions that are produced by the reaction that would otherwise interfere with the continuation of the reaction. In Figure 1, zinc is at the negative electrode, or anode, and is the source of electrons for the reaction. The copper in the reaction starts as a solution of copper sulfate. The zinc rests in a solution of zinc sulfate, which provides an electrically neutral medium for the conduction of zinc ions from the anode to the salt bridge. When electrons from the anode reaction flow toward the cathode, they combine with copper ions in solution to form neutral copper atoms that accumulate on the cathode. This process results in excess zinc and sulfate ions at the anode and cathode, respectively. These oppositely charged ions flow toward one another

through the salt bridge, thus removing them from solution. This is important for the reaction, as a buildup of ions would prevent the reaction from taking place. The anode solution would become positively charged and the cathode solution would become negatively charged, preventing the flow of electrons.



**Fig. 2.1. Zn - Cu Voltaic Cell**

When discussing battery operation, it is common to refer to the cell. A cell is the fundamental unit of operation, which can be connected together in series or parallel to form a battery. Either may be chosen depending on the desired discharge characteristics of the battery. If connected in series, the operating voltage will be higher, and if connected in parallel, the operating current will be higher. The cell has a particular voltage named the cell voltage, which is unique to each particular battery chemistry, and

is determined by the electrochemical potentials of the materials that comprise the electrodes.

The chemical energy in the cell is supplied by an oxidation-reduction, or redox, reaction [2]. The cell should have an electrode that is a good oxidizing agent, and an electrode that is a good reducing agent. The energy content of the battery is equal to the voltage multiplied by the battery capacity, so both of these parameters are important to assess battery performance. Capacity is a measure the total charge of the battery, or the number of electrons available for current flow. This quantity is typically expressed in Coulombs, but is also shown with units of amp hours (Ah) and other units depending on the context. Voltage is the operating voltage of the battery, which is dependent on the cell voltage of the battery chemistry. Voltage can be increased by combining batteries together in series, but operating voltages of battery clusters are discrete by nature of being multiples of the cell voltage. Both voltage and capacity decay with time and use, so energy content of a battery is not constant. This is an important concept when designing battery systems, as initial capacity must be greater than what is required in the present. This ensures sufficient energy is delivered throughout the battery lifetime.

## **2.2 Project Motivation**

Batteries have historically had many uses in mobile, low power applications and devices. As the cost of batteries reduces, they are showing continuing promise for energy storage at fixed locations. This is especially useful for utility companies, where the demand for energy from their customers is often uncertain. This uncertainty has been growing worse in recent years due to the sporadic nature of increasingly popular

alternative energy sources such as wind farms and solar cells. Utility companies must find a way to supply the appropriate amount of power at a given time, and this becomes more difficult as unpredictability of non-grid power sources continues to rise. Battery storage would allow the storage of excess grid energy to be used during periods of low demand, which could be used to supplement the grid during periods of high demand. The ultimate goal of this work was to estimate the minimum cost of a suitable battery storage system, one that could delay the need for infrastructure upgrade. If the cost of the storage is less than the infrastructure upgrade, then the storage is an economically viable alternative to the traditional upgrade methods.

Determining the appropriate amount of energy storage for a particular application is perhaps the most difficult design problem when engineering a storage system. There is a certain amount of guaranteed energy that a battery should be able to supply at any point during the lifetime of the battery. Additional capacity must be included in the battery to account for natural decay over the course of its lifetime. This is an especially important consideration for long use applications, as well as quickly decaying batteries such as lead acid. Lithium ion batteries decay more slowly and so don't require as much extra capacity to compensate for battery decay. These two types of batteries, lead acid and lithium ion, are the two types of batteries being compared in this analysis, as they are the most commonly used and supply the most energy per unit cost. These technologies are well-developed and there is a large amount of pre-existing information on their performance characteristics.

## 2.3 Lead Acid Batteries

The two most common types of lead acid batteries are flooded and sealed. Car batteries are manufactured using the flooded design, so they are most familiar in common applications. The electrolyte of the battery is easily accessible to allow the addition of water as the battery dries out, which makes them suitable for such applications where user interaction may be required. On the contrary, sealed batteries do not have accessible internal components and are most commonly found in two varieties; VRLA and AGM [3]. AGM is an acronym for Absorbed Glass Matte, whose construction allows for more efficient charges and discharges [4]. The downside is that they tend to have a shorter life due to higher acid content, which makes them a poor choice when a long lifetime is necessary. VRLA is an acronym for Valve Regulated Lead Acid and uses a valve to safely control the emission of hydrogen and oxygen gases [5]. The buildup of these gases is extremely dangerous due to the risk of combustion, and the reaction is notably exothermic. The valves reduce the need for ventilation when many batteries are used in a small space, although some ventilation is still required to remove the gases from the battery enclosure [6]. There is also little to no maintenance required; a convenient characteristic for large battery systems where individual batteries would otherwise need to be checked on a regular basis. VRLA sealed batteries may be considered for safety concerns alone, but the low maintenance is an added benefit. The choice between VRLA and flooded lead acid batteries is ultimately dependent on the application. VRLA will have a slightly shorter lifetime compared to flooded lead acid, but will have lower costs associated with maintenance, safety, and ventilation. The flooded lead acid batteries are likely to be used in a system where longer battery lifetime is preferred above all else.

VRLA would be a good choice for a low maintenance system and still a cost effective choice when shorter lifetime is accounted for. When all is considered, it is a widely used battery chemistry in existing storage systems that compromises between lifetime and maintenance.

## **2.4 Lithium Ion Batteries**

The two most common types of lithium ion batteries are lithium cobalt oxide ( $\text{LiCoO}_2$ ) and lithium iron phosphate ( $\text{LiFePO}_4$ ) [7]. Most commonly used in electronics is  $\text{LiCoO}_2$  due to its greater energy density, although there are safety concerns associated with overheating, igniting, and exploding. Since these batteries are used in electronics, they are typically small in size and dissipate heat quickly, and so these safety concerns are of lesser relevance. Safety is more of an issue with larger batteries, which makes  $\text{LiCoO}_2$  less practical for storage applications. This issue is magnified when considering a storage application with many batteries in close proximity. Temperature regulation is of paramount importance to ensure battery safety in addition to battery performance. Temperature regulation may introduce new costs in the storage system depending on location. Alternatively,  $\text{LiFePO}_4$  batteries are less prone to overheating and are much safer to use [8]. They are commonly used in storage applications because of this, despite having a lower energy density. They are the industry standard lithium ion battery chemistry due to their greater safety, especially when considering that space is usually not a significant design constraint for utility storage.

Airplanes are an example of an application where both safety and space may be compromised, which led to the failure of the Boeing 787 battery system in 2013 [9]. The

engineers chose the  $\text{LiCoO}_2$  chemistry for its energy density and greater availability, which likely contributed to the instances of thermal runaway despite the official cause of the failures being unknown. Such instances have encouraged the use and further development of  $\text{LiFePO}_4$ , which has become universally used in large storage applications.

## 2.5 Battery Comparison

In summary, the two most practical batteries to use for storage are VRLA and  $\text{LiFePO}_4$ . For purposes of general comparison, they can be referred to as lead acid and lithium ion. Table 2.1 summarizes the general advantages and disadvantage of the two battery types.

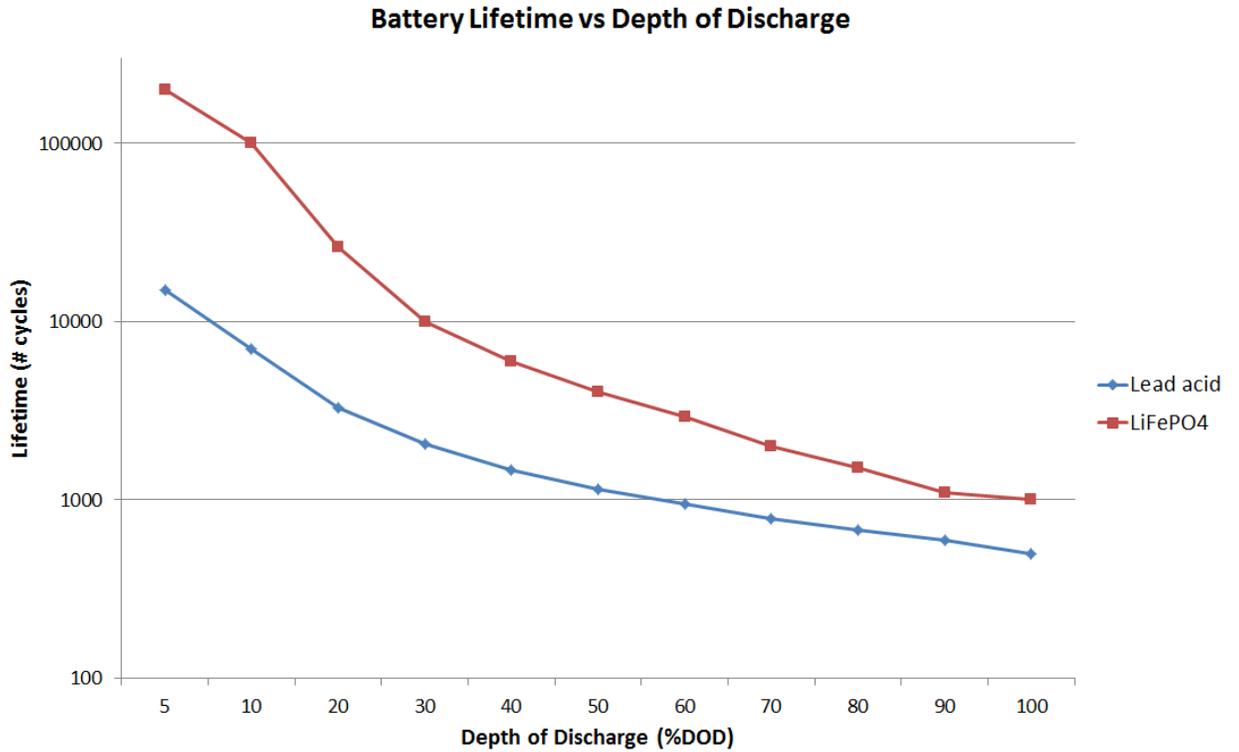
**Table 2.1. Comparison of battery types**

<b>Lead Acid</b>	<b>Lithium Ion</b>
Heavy due to lead	Lightweight
Low energy density	High energy density
Hazards associated with sulfuric acid	Hazards associated with fire
Shorter lifetime	Longer lifetime
Lower cost	Higher cost

Overall, lithium ion is a high performing battery at higher cost, while lead acid is a lower performing battery with low cost [10]. The most cost-effective choice is dependent on the application, and is influenced by factors such as storage method, environmental conditions, lifetime of storage, and required capacity [11]. As will be discussed later, these factors are often difficult to quantify and can impact each other.

A battery's lifetime is described by the number of cycles, or charges and discharges, that a battery is expected to undergo until it reaches the end of its life. The end of life is defined as the point in a battery's lifetime where the capacity retention is considered to be no longer acceptable. For lead acid, this value is defined as 50% capacity retention, and for lithium ion it is 80% capacity retention [12], [13]. These numbers are arbitrary, but they are industry standards. Lithium ion batteries do not decay as rapidly, so they can afford to have a defined end of life at a higher percentage. Since lead acid batteries decay more quickly, their end of life is defined at a lower percentage. As soon as capacity retention of the battery drops below the corresponding amount, it is considered to have reached the end of its life. It is important to note that capacity is defined as the amount of charge that can be stored within the battery. As a battery undergoes cycles of charges and discharges, it holds continually less charge upon each subsequent cycle due to unavoidable decay of the battery.

Another important parameter to consider is depth of discharge (DOD). This is defined as the percent amount of capacity that is used during a given cycle. For instance, 70% DOD describes a battery that uses 70% of its available capacity. This is a simple parameter to understand and control, and greatly affects battery lifetime, so it is convenient to use as a starting point for battery comparison.



**Fig.2.2. Depth of discharge vs. lifetime for lead acid and lithium ion [14]**

Plotting battery lifetime together with DOD is useful for assessing the performance of a battery, which can be seen in Figure 2.2. This graph shows the relation of lifetime to DOD for a generic lead acid and lithium ion battery. In the graph, battery lifetime is logarithmic, so lithium ion has a longer lifetime relative to that of lead acid as DOD is reduced. Lithium ion batteries are rated for 1000 cycles at 100% DOD and 200,000 cycles at 5% DOD. In a theoretical scenario where 20 times the necessary capacity is used in the battery system, the system will discharge 5%, and according to the graph will have 200 times as many cycles in its lifetime relative to that of full discharge. If the system is needed for a very large number of cycles, total cost of batteries over the desired lifetime can be reduced by a factor of 200 by increasing initial investment by a

factor of 20. The result is an overall reduction in cost by a factor of 10, and is a consequence of the logarithmic dependency of DOD on lifetime. Similarly, for lead acid batteries the cost is reduced by a factor of 1.25, so this sort of consideration is much more relevant when using lithium ion batteries. This is an extreme example, but shows the impact that DOD and initial investment have on total cost.

A parameter called C-rate is useful for describing the charge and discharge rates of batteries. The C-rate number is effectively the inverse of the amount of time the discharge takes place. For instance, a battery discharging at 1C will completely discharge in 1 hour, whereas the same battery will discharge in 0.5 hours at 2C [15]. The concept of C-rate can be confusing, but it is easier to understand when visualized in this way.

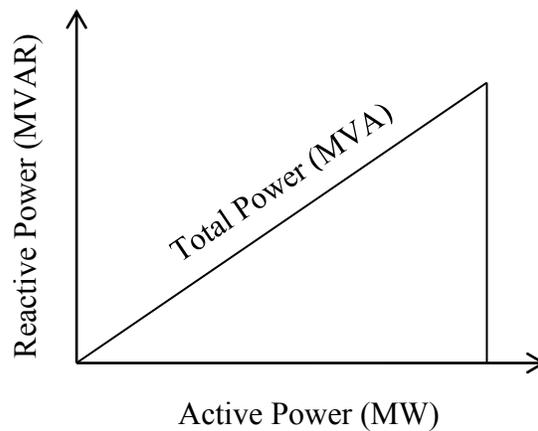
## **Chapter 3: Data Analysis**

Three locations were selected for analysis by the utility company. The first is a feeder named Price Feeder 009, and the second is a substation named Pershing. Both of the locations provide electricity for distribution. The two locations showed periods of overload, where the grid demand exceeded the rated capacity of the feeder and substation. This was most common during winter and summer months when air conditioning and heating were used more heavily. The third location, a voltage line named Clark-72, was in need of voltage regulation. The intent was to use batteries to store energy during voltage peaks, and use that energy during voltage troughs.

### **3.1 Method of Analysis**

The utility company provided yearly data for each of these locations that included hourly load data for every day during the year. If usage was below the maximum rated capacity of the location, then the value was deleted. This eliminated all data that was not relevant to the analysis. If usage was above the maximum capacity, then the value was kept. This was done for the entire year, which left only the data that was relevant to overload. When plotted, the total required battery usage to meet demand was determined. For Pershing and Price locations, megawatts (MW) and megavolt amps (MVA) can be used interchangeably, as there is effectively no reactive power being produced at these locations. The distinction is important for Clark, however. Reactive power is produced at Clark as a consequence of inductance in the transformers, but this does not apply to Pershing and Price where mostly active power is supplied through a load that can be

considered purely resistive. In reality, there will always be some amount of reactive power, but it is very small at these locations. Reactive power is defined as having a  $90^\circ$  phase separation between voltage and current waveforms, whereas active power waveforms are in phase with each other [16]. The active component is the only valuable power metric for determining delivered power, however, reactive power still exists in the voltage line despite no energy being delivered to the load. These two power components are often represented as a complex number with real and imaginary parts. For this analysis however, phase information is of no importance and so the reactive and active power can be related through a right triangle as magnitudes to find the resultant total power. Figure 3.1 shows how these types of power are related. The total power for the Clark-72 voltage line can be calculated from the reactive and active power data using the Pythagorean Theorem.



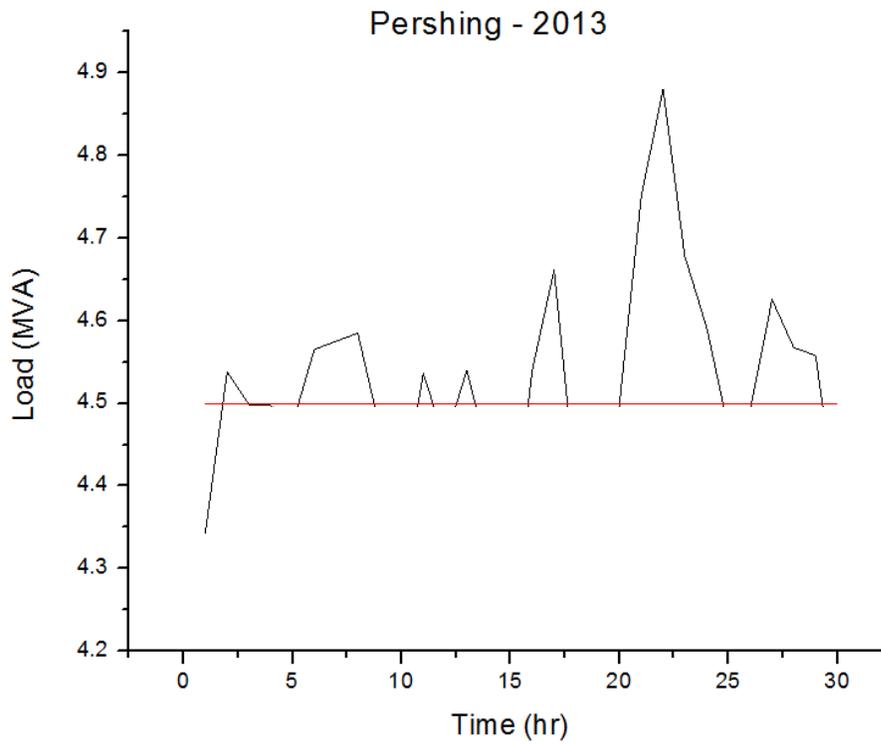
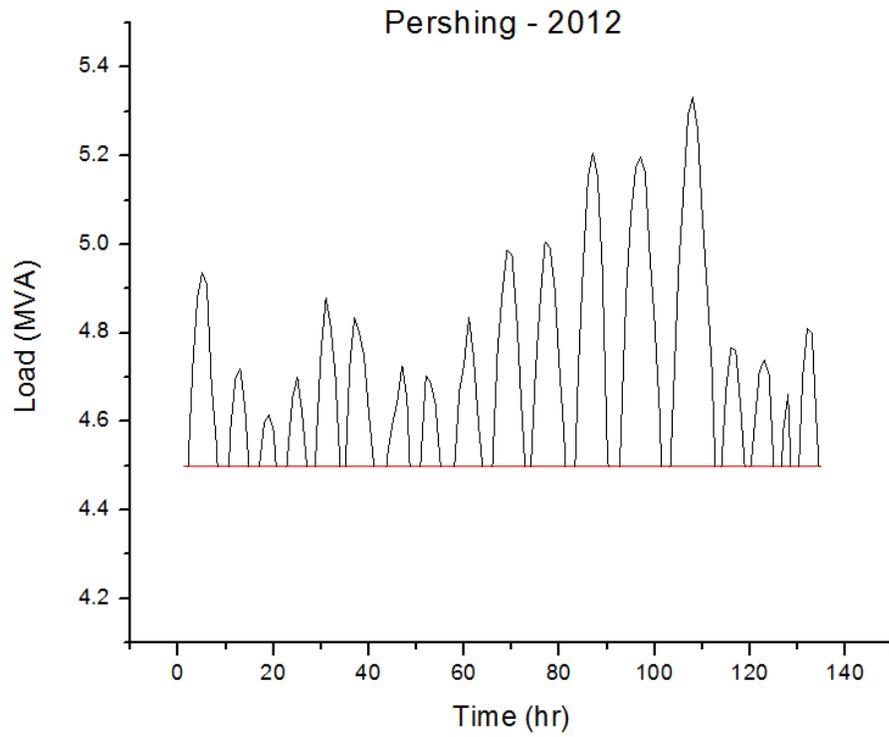
**Fig. 3.1. Reactive, active, and total power**

### 3.2 Pershing

For analysis of the load data from the Pershing substation, all values less than peak load were removed, leaving only load data relevant to battery discharge. This ignores time between discharges, and thus time required for battery charging, but is convenient to assess the necessary storage capacity and number of cycles throughout a given year. Data from 2012, 2013, 2014, and up through May 31<sup>st</sup> of 2015 were analyzed on a yearly basis, with graphs made to display battery usage throughout the year. These data are shown in Figure 3.2. Time on the graphs is displayed as cumulative hours of battery usage over the course of the year. The load line is also displayed on the graphs, and represents the power output where battery usage becomes necessary to meet demand. This value is 4.5 MW during the summer and 5 MW during the winter. There is no data for Pershing directly, so it is important note that the data are from a larger substation called Brookfield that supplies Pershing and another substation. Pershing uses 50% of the Brookfield capacity in summer and 57% of capacity in winter, so the overage at Brookfield that corresponds to Pershing can be determined. This equates to 9 MW during summer and 8.77 MW during winter. If the Brookfield data exceed these values, the amount of excess power can be used to find the required capacity of the battery system.

It is important to acknowledge the gaps between cycles on the graphs. They correspond to regions where the load dips below the load line, but they are a consequence of the discrete nature of the load data and do not represent meaningful information for the purposes of this analysis. These regions have been removed from the plots, thus leaving a gap between cycles. These gaps were left in the plots to make it easier to see the individual cycles. The total time for each plot is thus lengthened by approximately two

hours per cycle compared to the amount of time the batteries would actually spend in discharge.



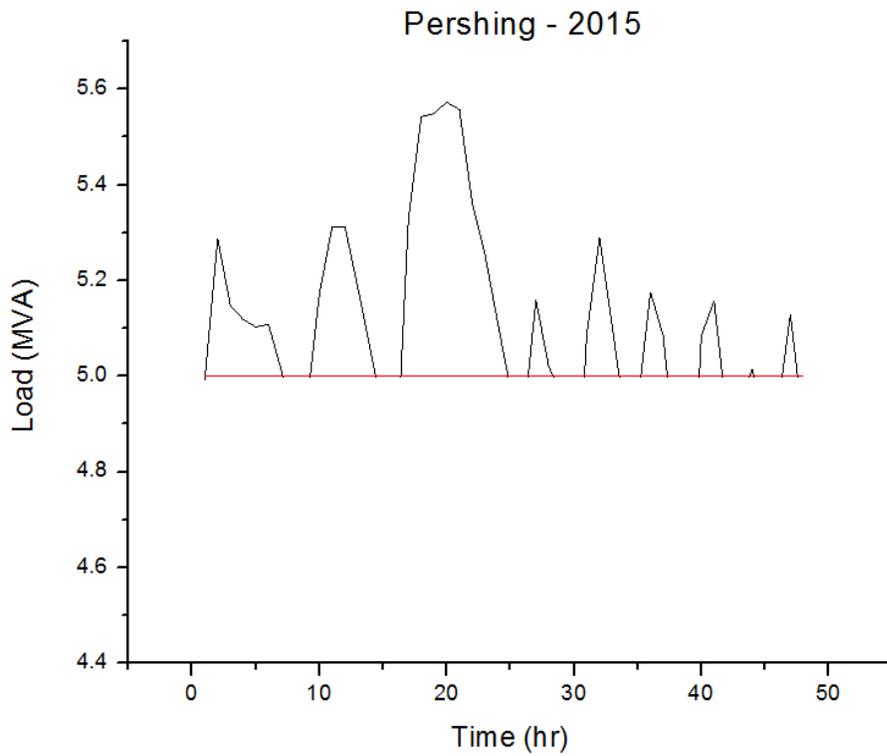
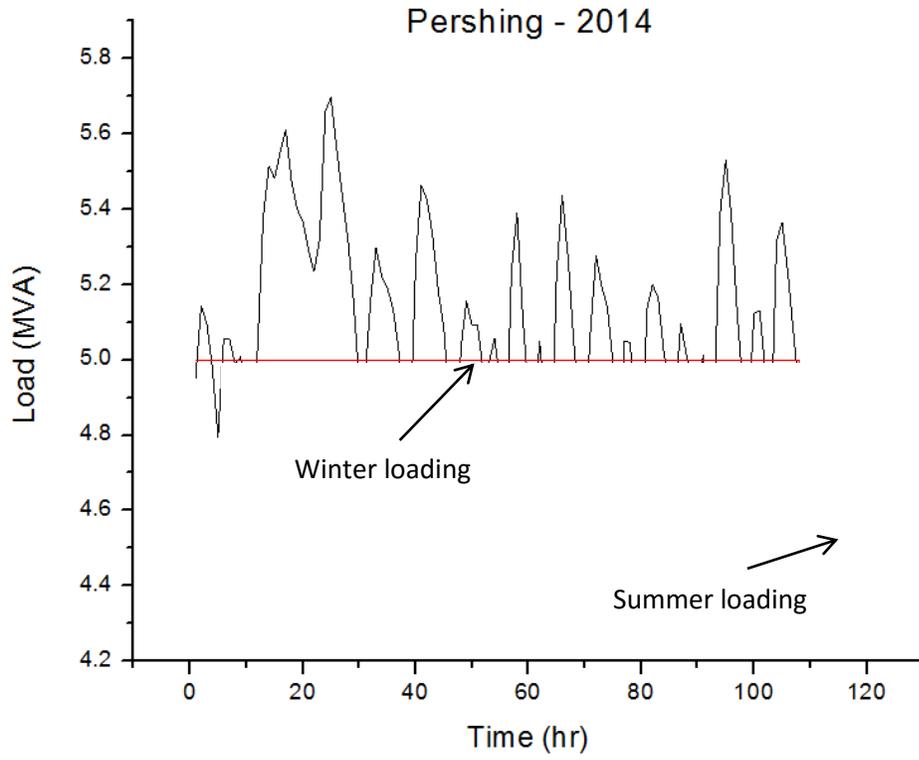


Fig. 3.2. Four plots showing annual load data for Pershing

Data from 2012 and 2013 show excess loading exclusively during the summer, with winter loading remaining beneath capacity, as is evident from the 4.5 MW load line. Data from 2014 show excess load primarily during winter, with only one battery cycle required during summer months. In 2015, capacity is only exceeded during winter months. The following table shows the number of cycles that correspond to each year.

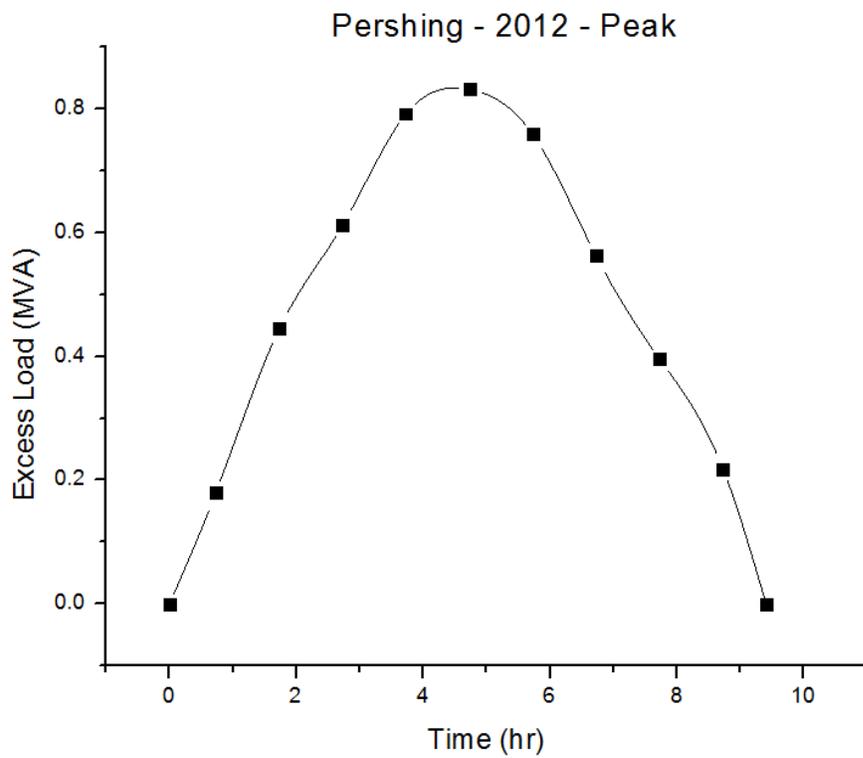
**Table 3.1. Cycle count for each corresponding year**

2012	2013	2014	2015	<b>Average</b>
18	7	18	8	<b>15.5</b>

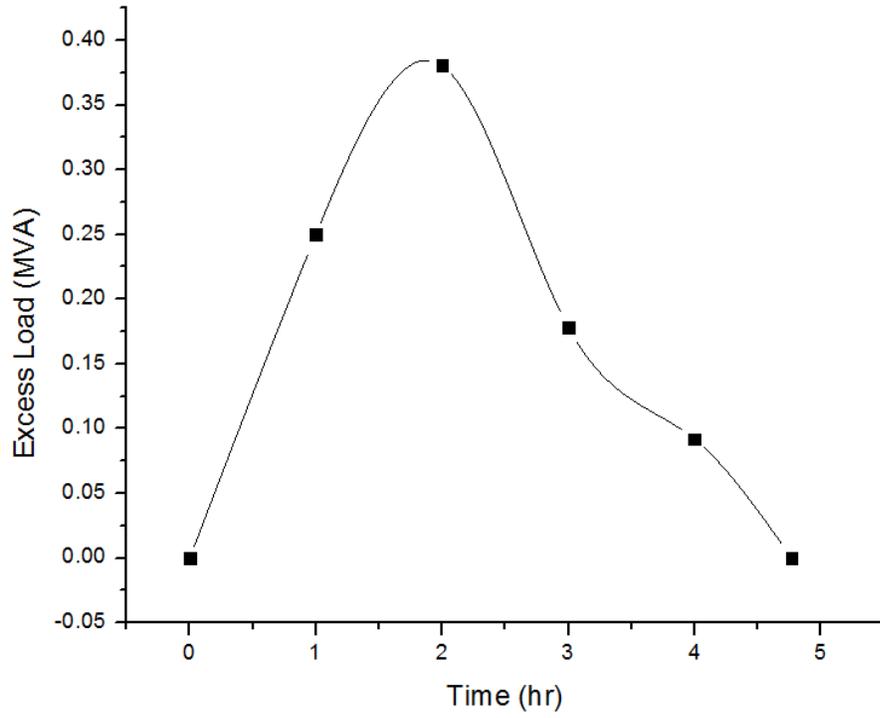
Since 2015 had only 5 months of recorded data, the cycle number of 8 was extrapolated across the entire year and was found to be 19.2. This value, along with the values for the other three years, was used to calculate the average listed in the table. It is worth noting that a linear extrapolation is not ideal, but is the best option if the year 2015 is to be included in the average. The value of 19.2 is probably a generous estimate, because the cycle count is unlikely to remain consistent over the course of the entire year. If 2015 is excluded, the resulting average is 14.3, so it is safe to assume based on these data that an average of 14-16 cycles per year can be expected. This means that over the course of the 30 year desired lifetime of the battery system, the batteries would undergo a total of 465 cycles using the 15.5 cycle per year average. The number of cycles is low enough to allow for a full depth of discharge of the batteries, even for lead acid batteries which have shorter lifetimes. A high allowable DOD would result in a lower initial investment, so this is advantageous to lowering cost. The end of life of a lead acid battery at full

discharge occurs at roughly 500 cycles, so it is convenient to design the battery system so that it lasts for 500 cycles given that it is slightly in excess of the 465 cycle estimate.

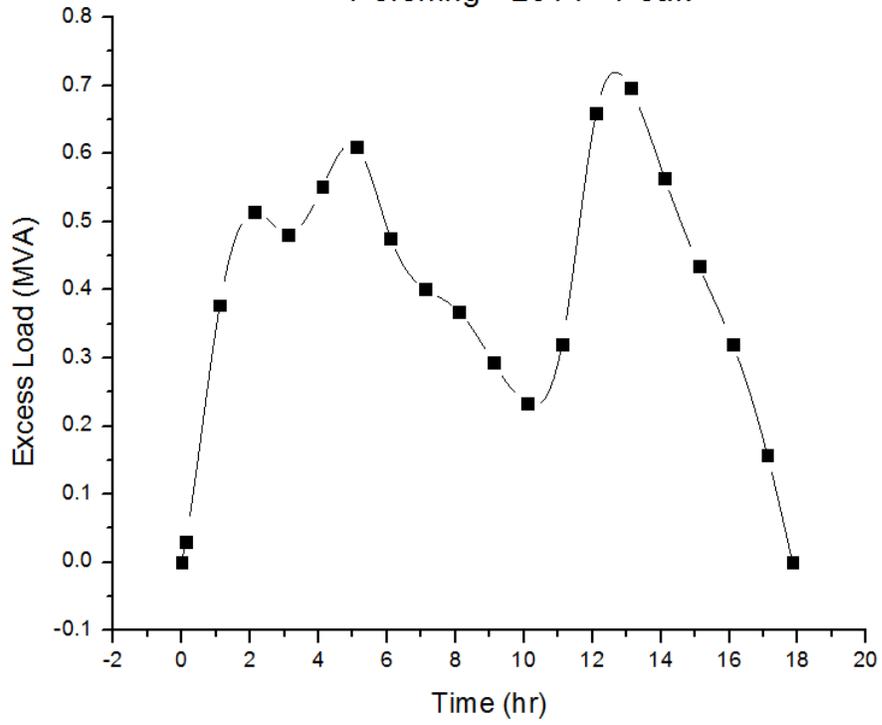
The largest peak from each year was selected for analysis individually to determine the amount of battery storage that would be necessary to supply energy for that peak, and would thus be sufficient for the entire year. The following figures show these peaks.

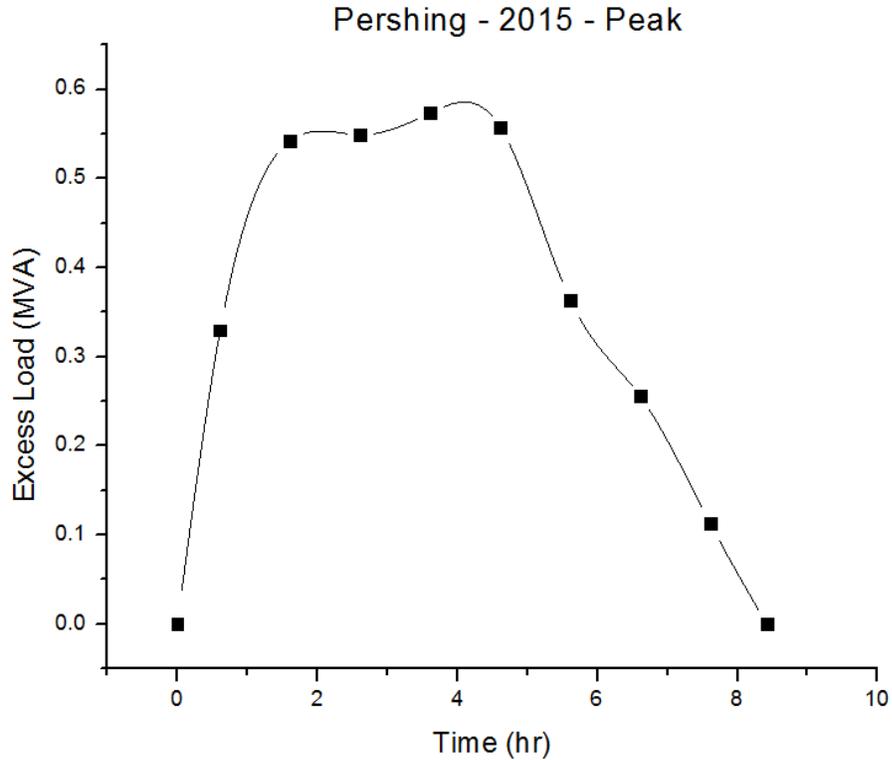


Pershing - 2013 - Peak



Pershing - 2014 - Peak





**Fig. 3.3. Four plots showing load data corresponding to the largest peak from each year**

These data points were connected using a spline feature for a more accurate battery usage trajectory. The values of the peaks were determined to find the highest power output that the batteries would have to supply at any given time, and the curves were integrated to find the largest amount of total energy that the batteries would need to supply during any given cycle. Table 3.2 shows these results. While the data vary widely, a 15 MWh battery system would be expected to meet this demand at a typical DOD. The actual system could be as low as 8 MWh at full discharge however, due to the low number of cycles over the course of the battery lifetime. The amount of energy of the system will require ultimately depends on the battery type and its decay characteristics.

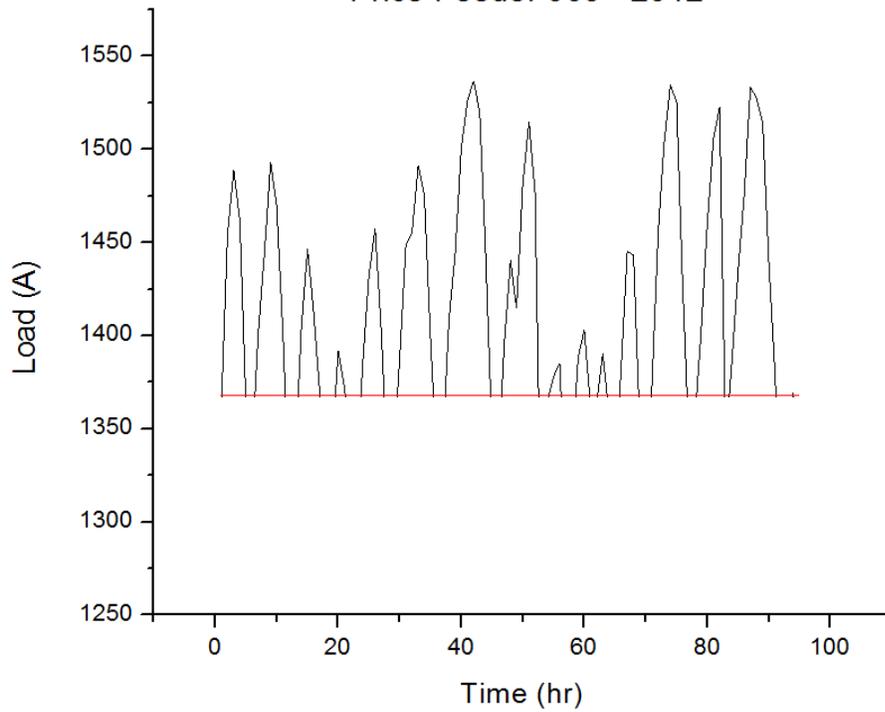
**Table 3.2. Peak Power and energy required for a battery system to deliver for each year**

Year	Max Peak (MVA)	Discharge Time (h)	Total Energy (MVAh)
2012	0.83	9.43	4.74
2013	0.38	4.75	0.89
2014	0.72	17.8	7.45
2015	0.59	8.25	3.21

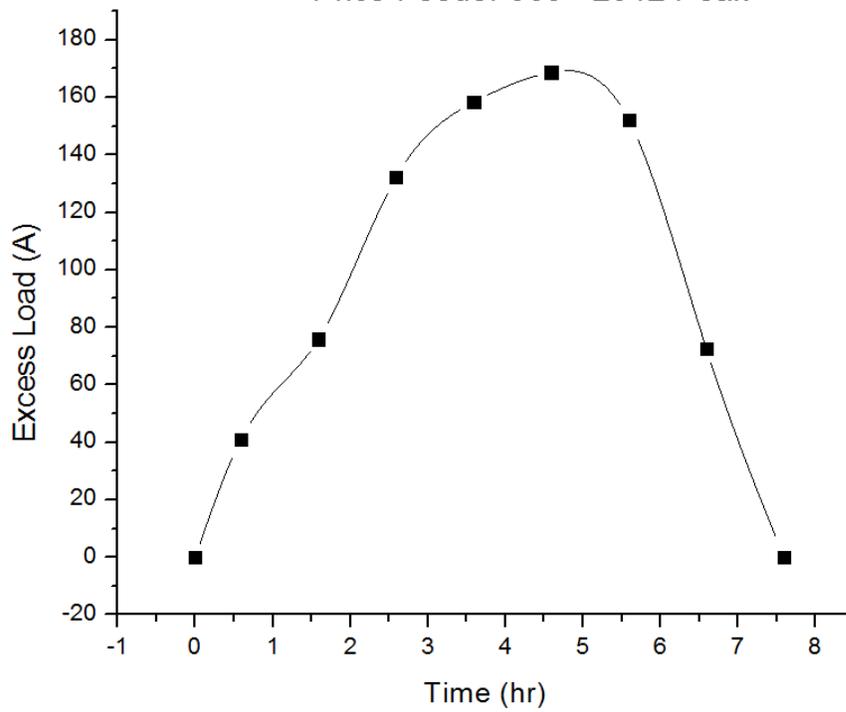
### **3.3 Price**

The method of analysis for Price was the same as Pershing. While Price is technically a feeder and not a substation, they can be treated as identical for this analysis since they both generate power for the purpose of delivery and distribution. The portions of the load data that exceeded the maximum allowable load were selected for analysis and the rest were discarded. Figure 3.4 shows these graphs. Once again, the space between cycles on the graph represents the natural space that results from selecting the load data, and their time on the graph is roughly two hours per cycle. The plot of the peak for each cycle has been included after each subsequent year. There was no load data for 2015, so only 2012 – 2014 were analyzed.

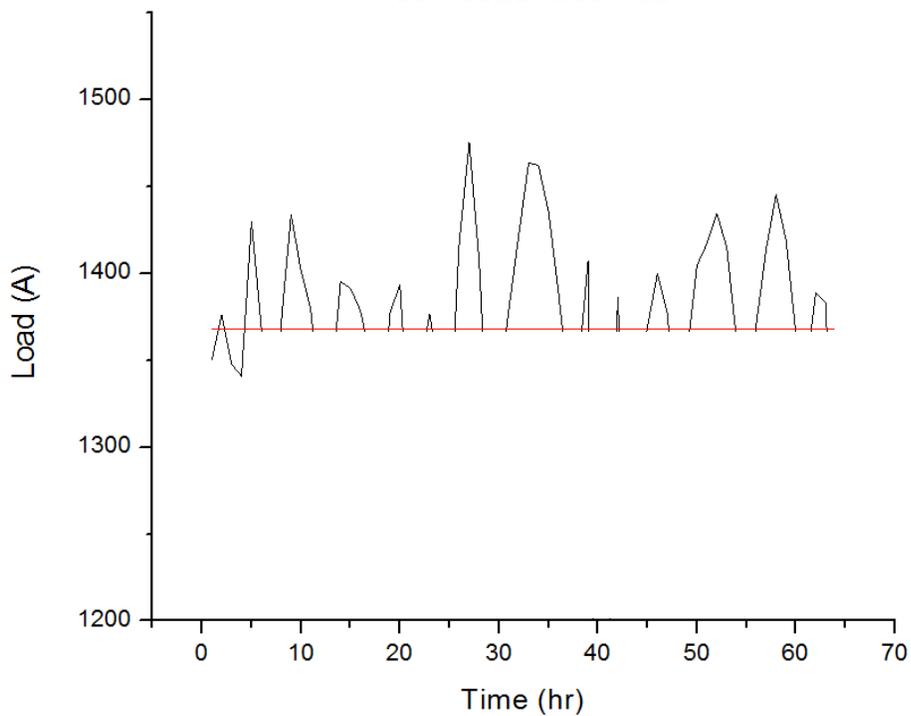
Price Feeder 009 - 2012



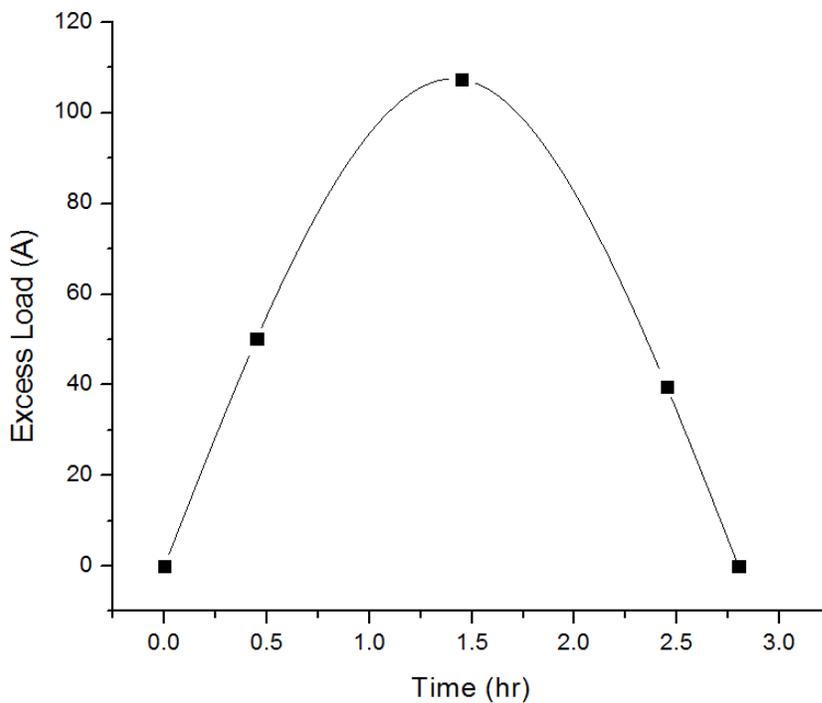
Price Feeder 009 - 2012 Peak

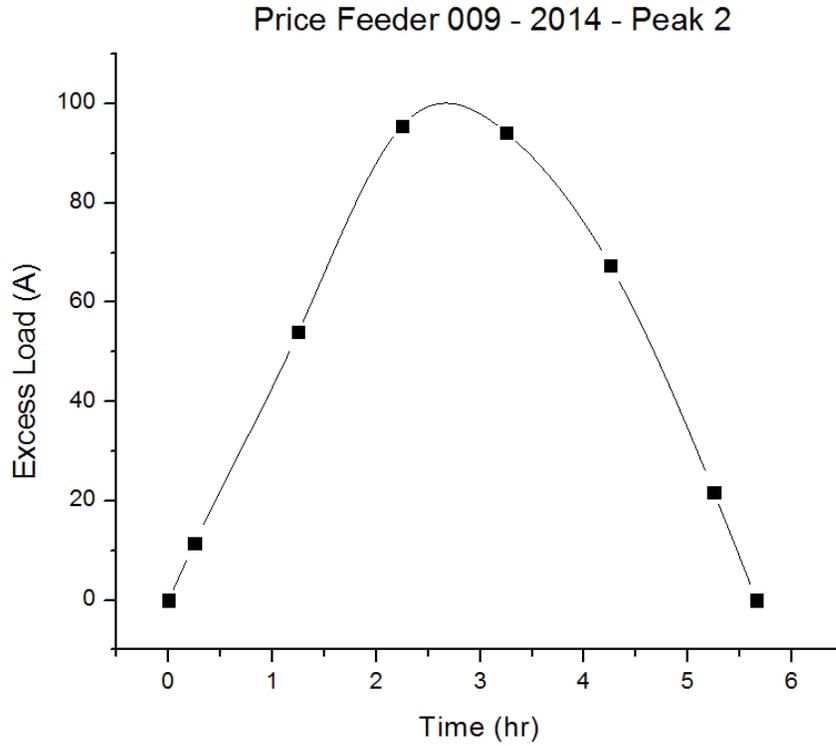


Price Feeder 009 - 2014



Price Feeder 009 - 2014 - Peak 1





**Fig. 3.4. Five plots showing annual load data and corresponding peaks for Price**

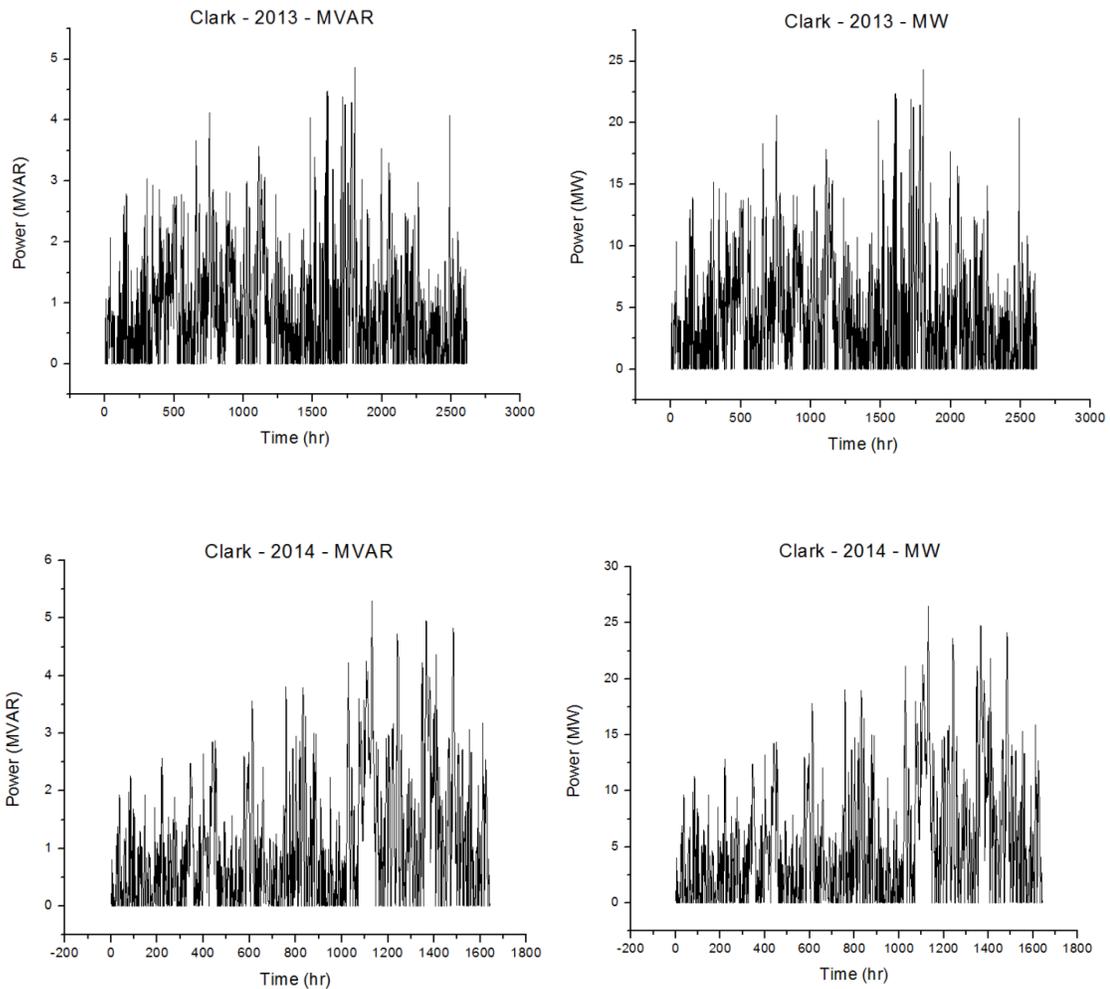
The year 2012 showed excessive loading during summer only, as opposed to both summer and winter for 2014. Two peaks were chosen for 2014 because there was not a clear maximum. There was no excess loading in 2013, so this year is excluded. Table 3.3 compares peak values for both years. There were 15 cycles for 2012 and 14 cycles for 2014, making for an average of 14.5. This is similar to Pershing and would allow for high discharge depths.

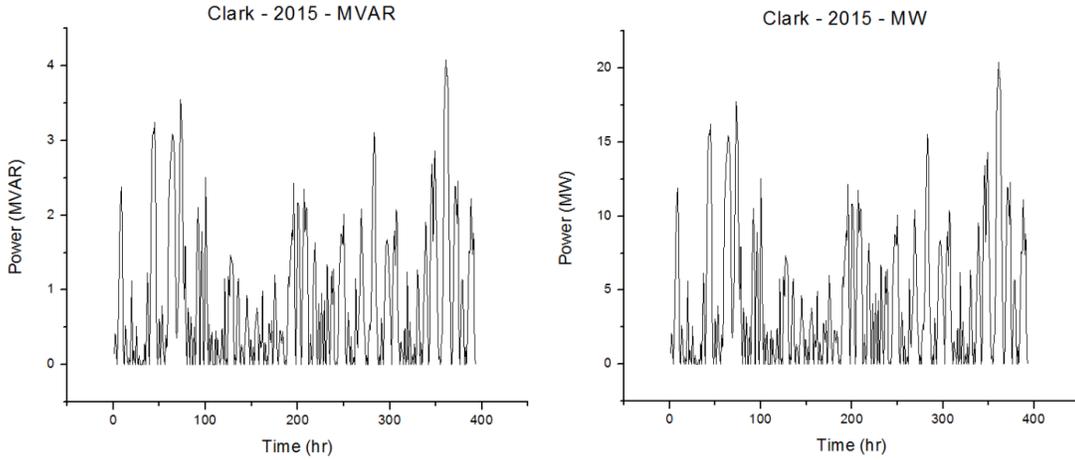
**Table 3.3. Maximum power and energy for Price**

Year	Max Peak (MVA)	Discharge Time (hr)	Total Energy (MVAh)
2012	0.68	7.6	3.17
2014	0.43	5.7	1.33

### 3.4 Clark

Load data from the Clark substation was analyzed to determine energy storage necessary to prevent the need for a voltage regulator installation. Data were used from the years 2013, 2014, and through May 31<sup>st</sup> of 2015. The data show the MW and MVAR power requirements on an hourly basis, and for the purposes of this analysis, excess time periods of zero power were removed. The MW data represent active power, and MVAR data represent reactive power. The resulting data were graphed and can be seen below in Figure 3.5.

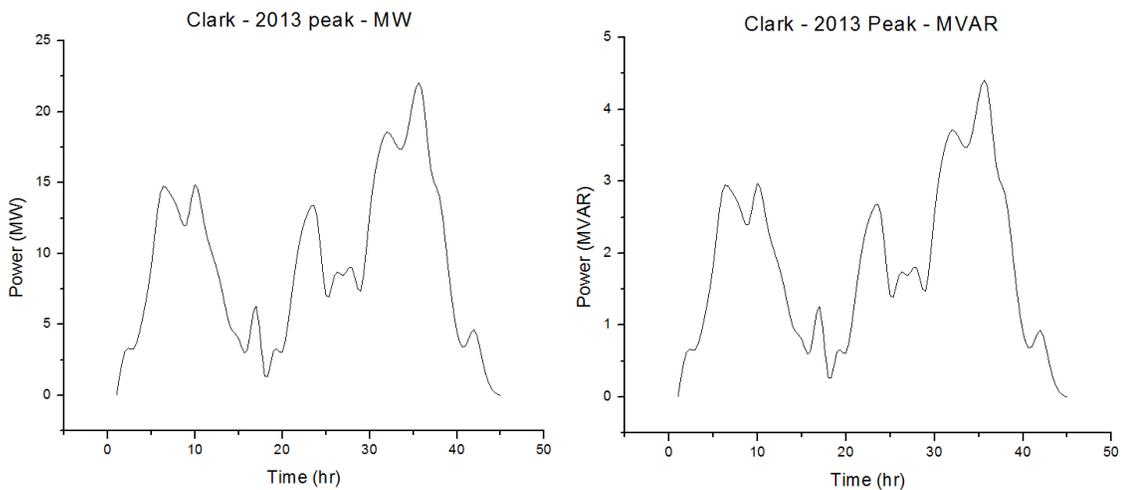


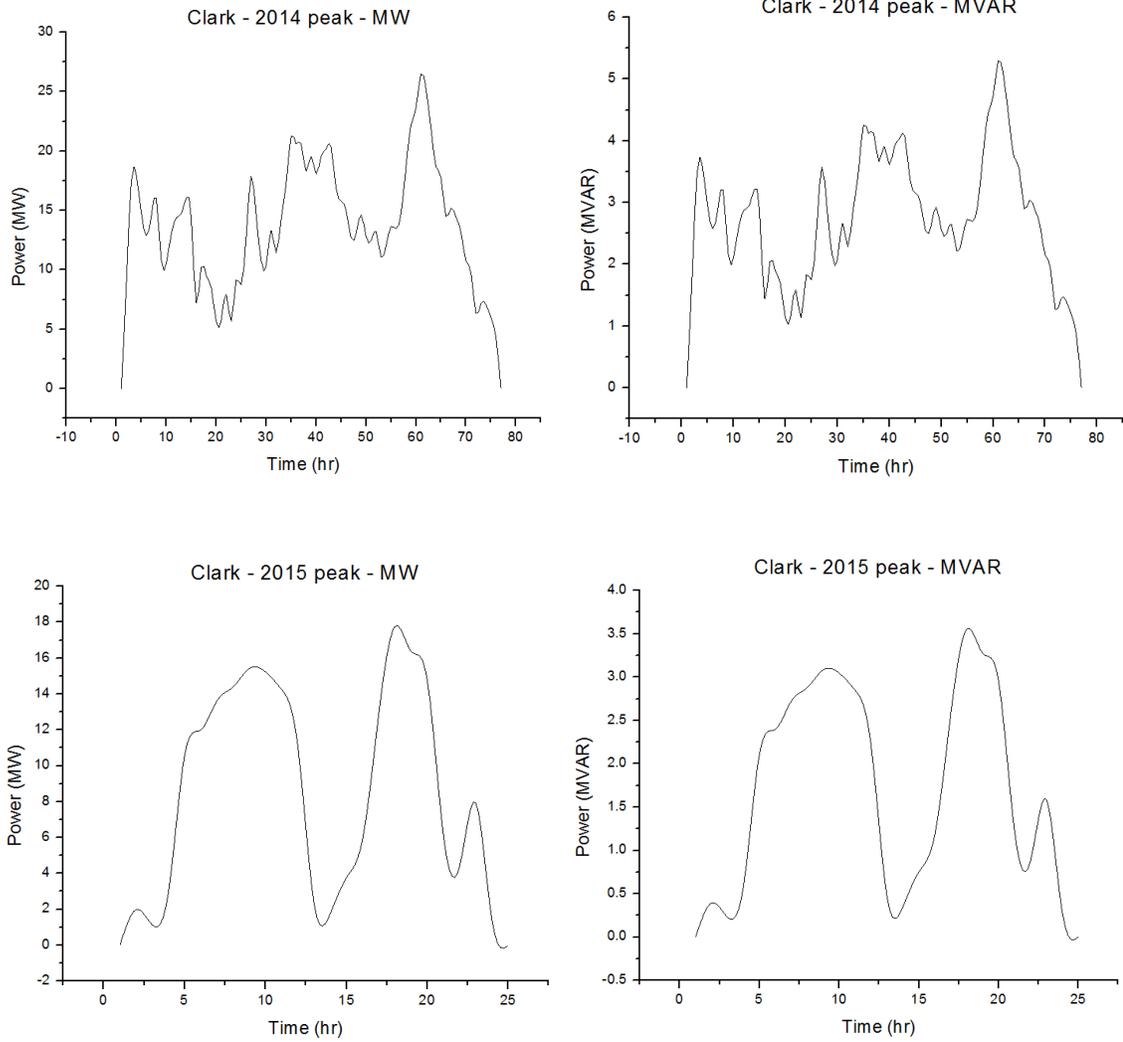


**Fig. 3.5. Active and reactive load data for Clark**

The plots for MVAR and MW are identical for a given year, with the exception that the MW values are 5 times greater. The listed time in hours is an accurate representation of the amount of time that energy storage would be utilized throughout the year.

The largest cycles for these years are difficult to see, and had to be zoomed in to find them. The largest peaks for each year, for both MVAR and MW, are shown below in Figure 3.6.





**Fig. 3.6. Peak cycles from Clark data**

It is interesting to note the wide variation in these curves and the general unpredictability of power and how it changes with time. Such rapid discharge fluctuations are not ideal for battery use, and would likely shorten the lifetime of a battery system. Table 3.4 shows the relevant energy and peak data from these graphs after combining active and reactive power into total power. This was accomplished by the method explained in section 3.1.

**Table 3.4. Energy and peak for largest cycles from Clark data**

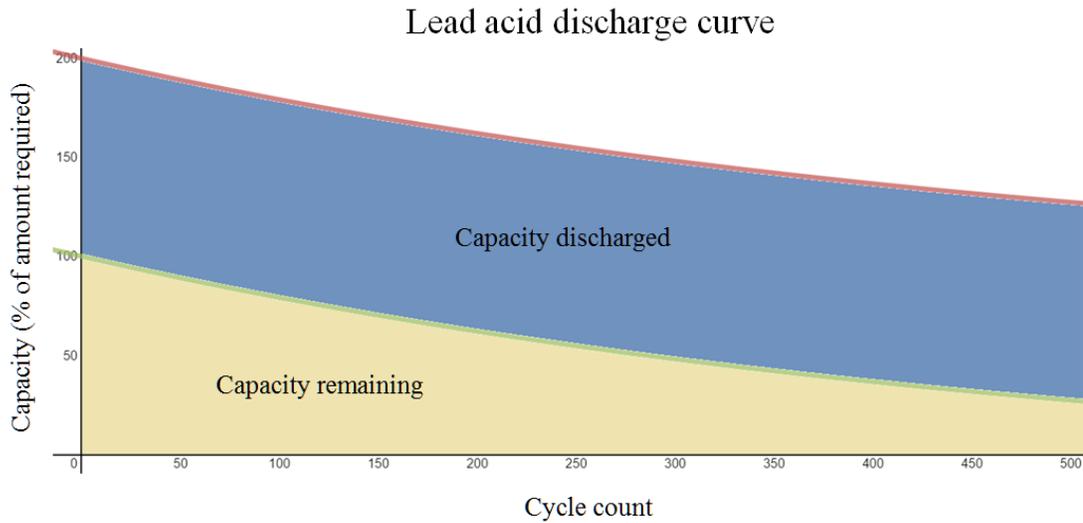
Year	Duration Time (h)	Max Peak (MVA)	Total Energy (MVAh)
2013	43	24.4	417
2014	76	27.5	1072
2015	24	20.4	212

Based on these data, it does not appear that a battery storage system will not be economically feasible, even for a best case scenario of 212 MVAh. This would require an enormous battery system, among the largest in the world [17]. Coupling this with the fact that the discharge times of these cycles are regularly over 40 hours in duration makes battery storage impractical. Little time for recharging between cycles makes the problem even worse. It appears that battery storage is simply not a good option for supplementing voltage lines.

### **3.5 Initial Estimate**

The total capacity of a battery reduces with cycle count [18]. Consider a scenario where a lead acid battery is discharged at 100% DOD and can be used for 500 cycles, at which point it has reached the end of its lifetime. This is typical of lead acid batteries, and would be ideal for a utility energy storage application. The problem arises from the definition of “end of lifetime”. The industry standard for lead acid batteries is to define end of life at 50% capacity retention. This would mean at the end of 500 cycles, the battery would only be able to supply 50% of the energy requirement. The obvious solution would be doubling the initial capacity, with the intent of providing the exact

required energy at the end of the lifetime. The problem is that this reduces DOD over the lifetime of the battery, allowing it to last for more cycles. This is illustrated in Figure 3.7, which shows a general discharge curve for lead acid batteries.



**Fig. 3.7. Example of lead acid discharge when starting at 50% DOD**

As seen in Figure 3.7, there is still a substantial portion of the capacity remaining after 500 cycles. This means the capacity increase would be larger than necessary, and that the optimum capacity increase lies somewhere between 1 and 2 times the required capacity for lead acid batteries. Pinpointing this exact amount is difficult, and there is no universal method of optimizing capacity. When the batteries cost millions of dollars for large systems it is important that capacity is optimized as closely as possible.

**Table 3.5. Total estimated battery material cost**

Battery Type	Required Energy (MWh)	Required Initial Energy (MWh)	Location	Cost (million \$)
Lead Acid	7.45	14.9	Pershing	2.24
Li Ion	7.45	8.27	Pershing	4.55
Lead Acid	3.17	6.34	Price	0.95
Li Ion	3.17	3.52	Price	1.94

In the Table 3.5, the Required Energy (RE) is the amount of energy needed to be able to prevent overload at any time based on the utility data that were provided. The Required Initial Energy (RIE) is the amount of energy that must be initially available to ensure the RE will be available at any point throughout the lifetime of the battery. For lead acid, the RIE is doubled, and for lithium ion the RIE is 1.11 times greater than the RE. This is not optimal as previously discussed, but was a simple way of initially estimating the material costs. The reason the RIE for lithium ion batteries is 1.11 times greater than the RE is due to overall lesser degradation when compared to lead acid batteries. Lithium ion batteries last for approximately 1000 cycles at 100% DOD, at which point they will possess 80% of their original capacity due to industry standard. Since this system is being designed for 500 cycles, it will need to need to retain 90% of its initial capacity if linear degradation is assumed. It can be found from here that 1 is 90% of 1.11, so RIE must be equal to this amount greater than RE. This information was used to find the values in Table 3.5 in conjunction with current battery costs. These material battery costs are \$150/kWh for lead acid, and \$550/kWh for lithium ion [19], [20]. It is interesting that while lead acid requires more initial capacity to account for higher degradation, the cost is still lower due to the much higher material cost of lithium

ion. In chapter 4, a more in-depth analysis was developed to further optimize material costs.

## Chapter 4: Economic Analysis

A method was developed to more closely optimize material costs, which builds upon the estimation described in chapter 3. The goal was to focus on material costs and develop a means of systematically accounting for battery degradation throughout the lifetime of the battery system. It is essential for this application that the battery systems would be able to deliver a certain guaranteed amount of energy throughout the lifetime of the system. There are many applications where this is not important, but if the battery system is to be a suitable replacement for traditional infrastructure upgrade, it is necessary to design the system to deliver a specific amount of energy throughout its entire lifetime.

### 4.1 Material Costs

It is important to consider capacity loss of the batteries, also called degradation, which occurs naturally as a function of time. A percentage of the battery capacity is non-recoverable over time due to resting capacity loss, and can be approximated over long periods of time by considering the annual resting capacity loss. Lead acid batteries generally lose 1.5% of their remaining capacity per year, and lithium ion batteries lose 1% per year. The general resting capacity loss as a function of time can thus be described by the following equation.

$$C = C_0(1 - k)^n \quad (4.1)$$

The initial capacity is shown as  $C_0$ , the degradation per year is  $k$ , the time in years is  $n$ , and the final capacity after degradation is  $C$ . While this process is continuous, it is convenient to measure capacity loss in annual terms, and is a good approximation over long periods of time. Degradation due to resting capacity loss will accumulate and become significant over years of use. For instance, a battery system will lose about one-third of its capacity over 30 years. Table 4.1 shows this resting capacity loss for both lead acid and lithium ion batteries at various relevant intervals.

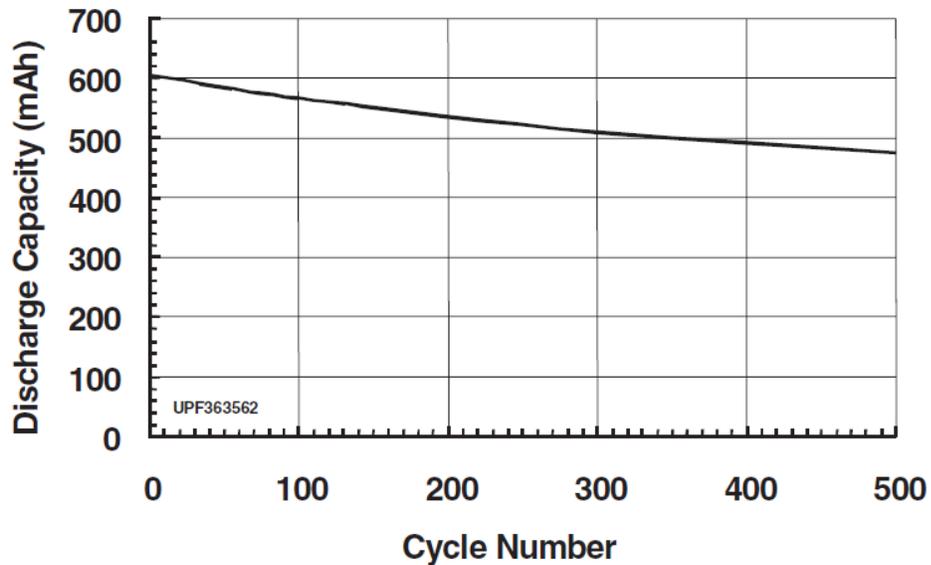
**Table 4.1. Comparison of resting battery capacity loss over various intervals**

Time (years)	Lead Acid (% Remaining)	Lithium Ion (% Remaining)
5	92.7	95.1
10	86.0	90.4
15	79.7	86.0
30	63.5	74.0

It is apparent that the seemingly innocuous 1.5% and 1% decay rates result in drastic reductions in capacity when given enough time. This is especially important to consider for applications where few cycles are used over a long time period. If the cycle count of the batteries were to be high over a short time period, this resting degradation would be a lesser concern.

In addition to resting capacity loss, the discharge capacity loss as a function of cycle life must be considered as the second form of battery degradation. If the number of cycles over a given time is known, then this battery degradation is also a function of time. This is ideal, as it allows for these two forms of degradation to be combined into a single

equation. The resting capacity loss equation has been previously defined, and so it is necessary to define the discharge capacity loss. It can be assumed that the capacity of the battery follows an exponential decay as a function of cycle life, as seen in the following Figure 4.1.



**Fig. 4.1. Lithium ion capacity as a function of cycle number [21]**

This plot represents the degradation behavior of a standard lithium ion battery, and the same principle holds true for lead acid batteries. This is a good approximation when the batteries undergo less than 500 cycles, such as the utility application being considered. It should be noted, however, that as cycle count increases, batteries tend to not follow this exponential decay as closely. The general formula for exponential decay is shown in equation 4.2:

$$C = C_0 e^{-\alpha n} \tag{4.2}$$

Once again, the initial capacity is  $C_0$ , the time in years is  $n$ , and the final capacity after degradation is  $C$ . The decay constant  $\alpha$  is dependent on the degradation characteristics of the battery, which are a function of battery chemistry and depth of discharge. This parameter can be found for each battery chemistry by knowing the ratio of final to initial capacity, as well as the number of years being considered.

### **Lead Acid**

From Figure 2.2, it can be seen that the lead acid battery end of life is reached after approximately 500 cycles. Industry standard defines this end of life to occur after 50% capacity loss. Since the battery system should be designed to undergo 500 cycles during its 30 year life expectancy, the exponential decay constant  $\alpha$  can be solved from (4.2) as follows:

$$\begin{aligned}0.5C_0 &= C_0e^{-30\alpha} \\ \ln 0.5 &= -30\alpha \\ \alpha &= -\frac{\ln 0.5}{30} = 2.31 \times 10^{-2}\end{aligned}$$

This value can now be used in future calculations for this system, because it describes the rate of lead acid battery degradation at full discharge.

The two types of battery degradation have been defined, and can now be unified into a single equation. The resting capacity loss can be multiplied by the discharge capacity loss to achieve total battery capacity loss. The following equation shows the fraction of final capacity to initial capacity, which varies on a scale of 0 to 1.

$$\frac{C}{C_0} = e^{-\alpha n}(1 - k)^n \quad (4.3)$$

This equation can be rearranged to give the amount of initial capacity,  $C_0$ , that would be needed such that the required capacity,  $C_r$ , would be deliverable at the end of life. In equation (4.4), the variable  $C_r$  has replaced  $C$ , because the final capacity should be designed to equal the required capacity.

$$C_0 = \frac{e^{\alpha n}}{(1 - k)^n} C_r \quad (4.4)$$

The amount of capacity for a 30 year battery system can be determined by a single 30 year system, by 2 installments of 15 year systems, or even more installments of lower lifetime systems. While the system could last for 30 years, it may be more economically feasible to design a shorter lifetime system to be replaced at specific intervals. Table 4.2 compares single-use lead acid battery systems at various lifetimes and installment frequencies.

**Table 4.2. Comparison of lifetime, initial capacity, number of installments, and total lifetime capacity**

System lifetime (years)	$C_0$ (multiples of $C_r$ )	Number of installments	$C_T$ (multiples of $C_r$ )
5	1.21	6	7.26
10	1.47	3	4.41
15	1.77	2	3.54
30	3.15	1	3.15

The parameter  $C_T$  is the total lifetime capacity, and is the number of installments multiplied by  $C_0$ . The cheapest overall system is the single 30 year system, however it

may be desirable to implement two 15 year systems, as the initial investment is nearly reduced by half. The total cost in comparison is higher, but not by a significant margin. This would be entirely dependent on the budget of the specific application, as either option is a sound economic choice. The 5 and 10 year systems result in a much higher overall cost with less initial savings, and so appear to be worse options. The reason is that due to the low cycle count, the batteries are being wasted to some extent by not being put to full use. The obvious solution would be to add more batteries to the existing system instead of replacing it entirely. This would ultimately prove to lower both total and initial costs by supplementing the initial battery system with capacity installments at regular intervals, as opposed to wasting capacity by prematurely retiring each system.

Consider the scenario where the initial capacity,  $C_0$ , is set to be equal to the required capacity,  $C_r$ , with the intent of implementing yearly capacity installments to account for degradation on an annual basis. At first glance, this problem seems difficult solve, since each new installment would have a different rate of decay relative to the decay rate of the other installments at that point in time. However, the percent rate of decay on an annual basis does not change, meaning that each installment reduces by the same percentage every year. This means that there is a consistent amount of capacity required for each installment. This installment capacity,  $C_i$ , can be found as a fraction of initial capacity by subtracting (4.3) from 1, as shown in (4.5). This equation states that the installment capacity is equal to one minus the fraction amount of capacity remaining.

$$C_i = 1 - e^{-\alpha n}(1 - k)^n \quad (4.5)$$

Using (4.5) for an example where  $n = 1$ , this value is found to be  $0.037C_r$ . If this amount is summed over 29 installments, and added to the initial capacity  $C_0 = C_r$ , the resulting final capacity  $C_T$  is equal to  $2.07C_r$ . This is a large savings compared to what was seen in Table 4.2. Overall, this result can be systematically found over any number of installments in a given time as described by the following equation.

$$C_T = [1 + (m - 1)(1 - e^{-\alpha^n/m}(1 - k)^{n/m})]C_r \quad (4.6)$$

Here,  $m$  is equal to the number of total installments over the lifetime of the system, including the initial battery system. It is important to note that this equation does not compensate for battery degradation that occurs between installments. Because  $C_0$  is set to  $C_r$ ,  $C_r$  is not guaranteed to be deliverable as the battery degrades. To account for this,  $C_0$  must be increased by the amount that degrades over the course of an installment. This will ensure that exactly  $C_r$  will be left remaining at the end of each installment period. This can be accomplished by multiplying (4.6) by a factor shown in (4.7).

$$f(C_r - C_i) = C_r \quad (4.7)$$

In (4.7), the ending capacity  $C_r - C_i$  is redefined to be equal to  $C_r$  by introducing a coefficient  $f$  on the left side of the equation. Since  $C_r$  is defined to be equal to 1, it can be substituted for 1 in the factor. Rearranging (4.7) gives:

$$f = \frac{1}{1 - C_i} \quad (4.8)$$

This factor is then multiplied by (4.6) to yield a more accurate value for total capacity.

$$C_T = [1 + (m - 1)(1 - e^{-\alpha n/m}(1 - k)^{n/m})] \frac{1}{1 - C_i} C_r \quad (4.9)$$

This equation can be simplified using (4.5):

$$\begin{aligned} \frac{C_T}{C_r} &= [1 + (m - 1)(1 - e^{-\alpha n/m}(1 - k)^{n/m})] \frac{1}{1 - (1 - e^{-\alpha n/m}(1 - k)^{n/m})} \\ &= [1 + (m - 1)(1 - e^{-\alpha n/m}(1 - k)^{n/m})] e^{\alpha n/m}(1 - k)^{-n/m} \\ &= e^{\alpha n/m}(1 - k)^{-n/m} + (m - 1)e^{\alpha n/m}(1 - k)^{-n/m} - (m - 1) \\ &= e^{\alpha n/m}(1 - k)^{-n/m}(1 + m - 1) - m + 1 \\ &= me^{\alpha n/m}(1 - k)^{-n/m} - m + 1 \end{aligned}$$

$$C_T = [m(e^{\alpha n/m}(1 - k)^{-n/m} - 1) + 1]C_r \quad (4.10)$$

Initial capacity is defined as:

$$C_0 = (1 + C_i)C_r \quad (4.11)$$

Using these equations, the same parameters can be calculated as before. The difference is that these values correspond to the use of capacity installments as opposed to a replacement of the entire battery system. These values are shown in Table 4.3.

**Table 4.3. Comparison of initial and total capacities with installment implementation**

Installment time (years)	$C_0$ (multiples of $C_r$ )	Number of Installments	$C_T$ (multiples of $C_r$ )
6	1.20	5	2.29
3	1.11	10	2.21
2	1.07	15	2.19
1	1.04	30	2.17

This shows a substantial reduction in the amount of capacity necessary to guarantee  $C_T$ . Interestingly, both  $C_0$  and  $C_T$  reduces with number of installments as opposed to the values in the previous table, which makes intuitive sense.  $C_0$  approaches 1 as the number of installments approaches infinity. Overall, it is apparent that installments are the most practical method of maintaining a certain amount of capacity in a battery system. Refer to Figure 4.3 for a plot comparing total capacity to number of installments.

Total capacity has been found in terms of required capacity, but voltage drop must be introduced before assessing the true cost of the battery materials. The following equation relates energy, capacity, and voltage.

$$E = CV \tag{4.12}$$

Equation (4.12) is the definition of voltage, and describes the total energy that can be delivered by the battery. Since energy is the parameter of interest when designing for implementation with the utility grid, voltage drops that occur within a given cycle must be accounted for. The following graph shows the dependency of discharge time on cell voltage.

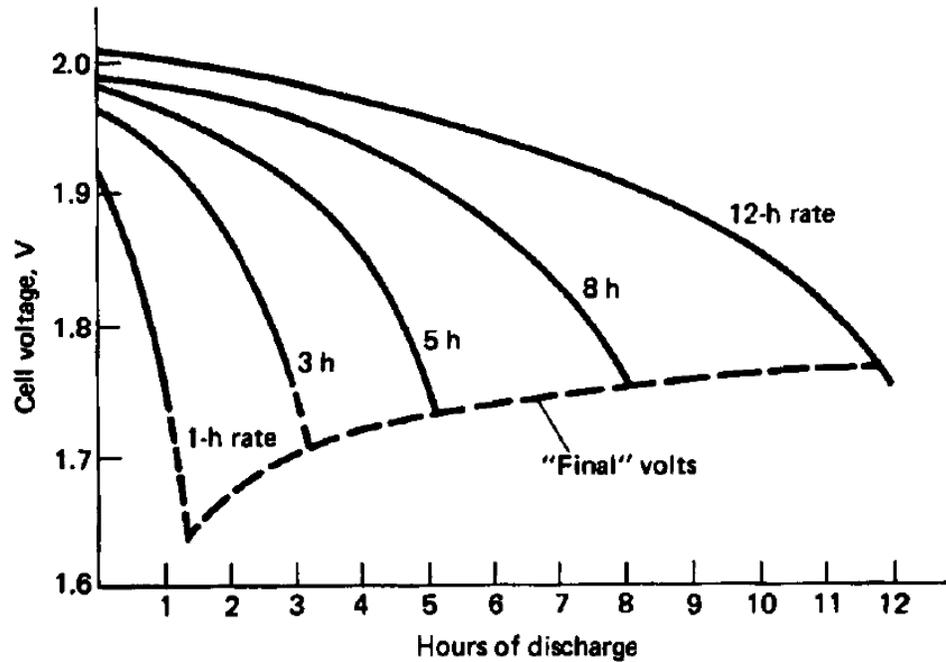


Fig. 4.2. Cell voltage as a function of discharge duration for lead acid batteries [21]

While voltage drops are larger at high discharge rates, the utility data have shown that maximum energy usage occurs during cycles with the longest discharge times. This means that for the purposes of calculating the energy deliverable by the battery, the cell voltage can be set equal to the time-average voltage value corresponding to the longest estimated discharge time. To find the average voltage, it is most practical to assume a linear voltage drop, which appears to be a good approximation based on the above graph. Given a cell voltage of 2.0 V, the average cell voltages can be calculated by adding the corresponding voltages and dividing by discharge duration. Below is Table 4.4 that compares maximum discharge duration for the locations being considered, along with the average cell voltage throughout those durations.

**Table 4.4. Discharge duration and voltage comparison for Pershing and Price locations**

Location	Longest duration (hours)	Average voltage (V)
Pershing	17.8	1.89
Price	7.6	1.87

Since the longest Pershing duration exceeds the values in the graph, the 12-hour discharge voltage was conservatively chosen as the minimum voltage. Assuming this average voltage remains constant throughout the lifetime of the battery, an equation based on (4.12) can be found that relates initial energy ( $E_0$ ) to required energy ( $E_r$ ), initial capacity ( $C_0$ ), and required capacity ( $C_r$ ).

$$\begin{aligned} E_r &= C_r V \\ E_0 &= C_0 V \\ &\downarrow \\ E_0 &= \frac{V_{cell} C_0}{V_{avg} C_r} E_r \end{aligned} \quad (4.13)$$

The factor of  $V_{cell}/V_{avg}$  was included in the equation to compensate for the voltage loss. With this equation, the total amount of energy necessary for initial investment can be calculated. Using a cost of \$150/kWh for lead acid batteries, the total initial battery cost can also be calculated, as shown in Table 4.5. The required energy was selected from Tables 3.2 and 3.3.

**Table 4.5. Comparison of initial battery material cost for Pershing and Price locations, assuming a 6 year installment frequency**

Location	Required energy (kWh)	Initial energy (kWh)	Initial cost (thousand \$)
Pershing	7450	9460	1419
Price	3170	4070	611

The initial energy was calculated using the  $C_0/C_r$  factor corresponding to 6 year installment periods, as this is probably more realistic than the use of more frequent installments. The initial cost would be higher with less frequent installments, and lower with more frequent installments.

### **Lithium Ion**

As opposed to the 50% standard for lead acid batteries, the industry standard for end of life of lithium ion batteries is 80% retention of initial capacity. A lithium ion battery reaches its end of life after 1000 cycles at full discharge, at which point the battery capacity will be 80% of its original capacity. The battery system should be designed to accommodate 500 cycles over the 30 year system lifetime, so a time period of 60 years should be used for the purposes of finding the exponential decay constant. This constant can be found using (4.2).

$$0.8C_0 = C_0 e^{-60\alpha}$$

$$\ln 0.8 = -60\alpha$$

$$\alpha = -\frac{\ln 0.8}{60} = 3.72 \times 10^{-3}$$

This is nearly an order of magnitude less than the decay constant for lead acid batteries, which is reflective of its generally longer lifetimes. Equation (4.4) can once again be used to determine the initial and total capacities of replaceable installments.

**Table 4.6. Comparison of lifetime, initial capacity, number of installments, and total lifetime capacity**

System lifetime (years)	$C_0$ (multiples of $C_r$ )	Number of installments	$C_T$ (multiples of $C_r$ )
5	1.07	6	6.42
10	1.11	3	3.33
15	1.23	2	2.46
30	1.51	1	1.51

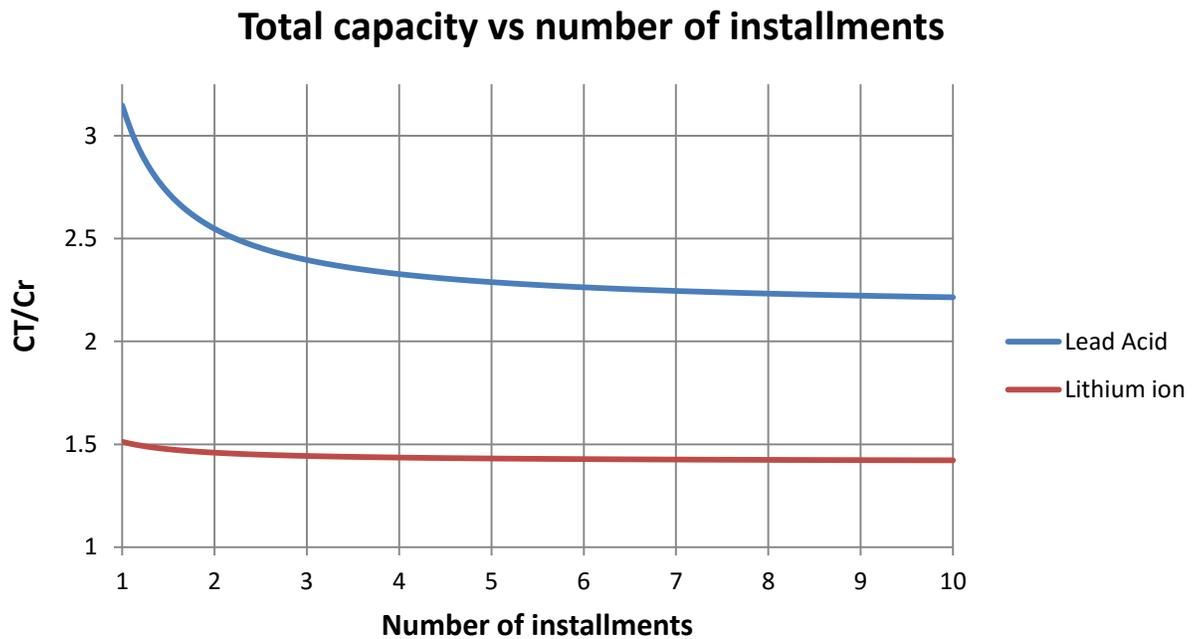
Compared to Table 4.2, Table 4.6 shows an enormous improvement of capacity retention over the lead acid system. As with lead acid, the 15 year lifetime system appears to be the best value, and provides a reasonable balance between initial and total capacity costs.

Using the method developed for lead acid batteries, the capacity required for the use of installments is shown in Table 4.7. This provides the economic advantage of adding to existing battery storage as opposed to replacing it entirely.

**Table 4.7. Comparison of initial and total capacities with installment implementation**

Installment time (years)	$C_0$ (multiples of $C_r$ )	Number of Installments	$C_T$ (multiples of $C_r$ )
6	1.079	5	1.431
3	1.040	10	1.422
2	1.027	15	1.419
1	1.014	30	1.416

As expected, both initial and total capacity reduces as installment frequency increases. It is apparent that installments are the more economical approach to battery storage, the same as lead acid previously. Both initial and total costs are represented by a less varied range of values when compared to lead acid batteries. This is due to the lower decay constant, which yields a closer range of capacity values over a given period of time.



**Fig. 4.3. Total capacity relative to required capacity as a function of installment number up to 10 installments**

In Figure 4.3, equation (4.10) is plotted for both lead acid and lithium ion batteries to show the effect of installment frequency on total capacity, and thus total cost. Ideally, the total capacity should be as close to 1 as possible. It should be noted that the value for a single installment using (4.10) where  $m = 1$  is equivalent to that of using (4.4) for one thirty year system, which shows the consistency between the single-use and installment analysis methods. This can be approximately seen in Figure 4.3 when

comparing with the tables for single-use systems. It is apparent from the plot that increasing installment frequency has diminishing returns on reducing total capacity, especially for lithium ion batteries. Taking into account the inconvenience of more frequent installments, it is likely not practical to implement installments more frequently than once per year.

To determine the total cost of the batteries, the voltage characteristics must be accounted for. As seen with lead acid batteries, discharge rate affects the cell voltage, and thus total energy that can be delivered by the battery. This same principle applies to lithium ion batteries as well. Figure 4.4 shows the discharge characteristics of a standard 7 Ah lithium ion cell that had been previously charged at a rate of 1 A to the maximum cell voltage of 4.2 V.

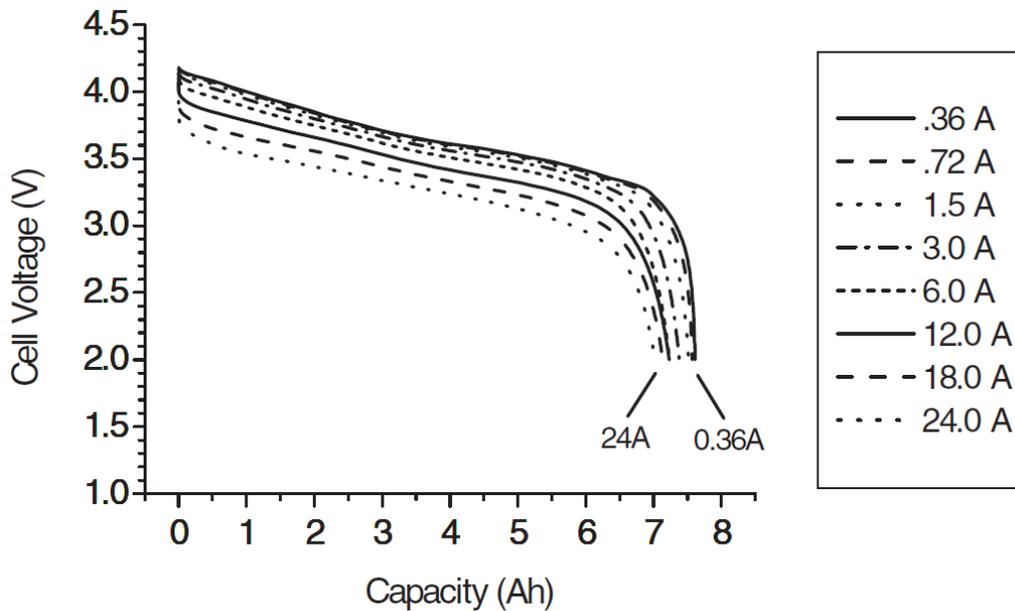


Fig. 4.4. Cell voltage vs. discharged capacity for 7 Ah lithium ion cell [21]

These data are noteworthy because it shows the change in both discharged capacity and voltage with respect to discharge rate. It is difficult to discern specific numbers from the figure, so relevant data has been compiled in Table 4.8.

**Table 4.8. Capacity and energy delivered by a standard 7 Ah lithium ion cell [21]**

Discharge rate (A)	Duration (h)	Capacity (Ah)	Energy (J)	Avg. voltage (V)
0.36	21	7.60	27.63	3.64
3.0	2.5	7.38	26.36	3.57
6.0	1.2	7.23	25.55	3.53

The reference for these data did not include the 0.72 and 1.5 A discharge rates, presumably due to their extremely similar discharge characteristics as seen in Figure 4.4. This exemplifies one of the main advantages of lithium ion batteries, namely their ability to deliver consistent energy throughout a wide range of discharge rates. As seen in Table 4.4, the maximum discharge duration varies from 7.6 to 17.8 hours depending on location. This is much longer than the 2.5 hour duration shown in Table 4.8, which itself shows nearly the same energy delivered as the 21 hour discharge duration. The bottom line here is that the energy delivered by the batteries would be approximately the same regardless of discharge rate for the utility applications being considered.

**Table 4.9. Comparison of initial lithium ion battery cost for Pershing and Price locations, assuming a 6 year installment frequency**

Location	Required energy (kWh)	Initial energy (kWh)	Initial cost (thousand \$)
Pershing	7450	9301	5116
Price	3170	3991	2195

Table 4.9 compares the lithium ion battery cost at Pershing and Price locations, using voltages found by linearly interpolating between the 2.5 and 21 hour values seen in Table 4.8. These values were found to be 3.63 and 3.60 V for Pershing and Price, respectively. The cost of lithium ion batteries is nearly quadruples the cost of lead acid batteries. There are two reasons for this. First, the material cost is much greater. Second, the cell voltage drop is higher for lithium ion. The voltage drop remains fairly constant regardless of discharge duration, but the drop is quite substantial considering an initial cell voltage of 4.2 V. This means that more initial energy must be available to compensate, and thus a higher initial cost. Lead acid batteries are certainly the better option to minimize material costs, and will be the battery chemistry used to calculate final costs later on in the chapter.

## **4.2 Additional Costs**

So far, material costs have been the focus of analysis. Before estimating total battery system costs, additional costs must be introduced. They will not be used for calculations, but rather will explain the nature of overall system costs. For the total system cost, a price per kilowatt-hour will be used that corresponds to battery system costs at Eagle Picher, a local battery system manufacturer.

## **Lead Acid**

In addition to material costs, there are a number of other costs that must be considered, primarily storage and protection, temperature regulation, and control systems [22]. These costs are variable depending on the environment, application, and battery system provider. For example, a storage system located in a region with a moderate, stable climate would require less shielding relative to a harsher climate. This would reduce the cost heating and air conditioning, as well as well as the battery housing unit. These cost savings are applicable regardless of location, but if a less robust storage system is utilized in a harsher climate, battery life will suffer. It is first important to define exactly what is meant by a harsh climate.

Battery life is affected by a number of environmental factors, predominantly temperature, but humidity and general moisture have an effect as well, particularly for lead acid batteries. The effect that temperature has on battery performance is complicated and dependent on a number of factors, such as depth of discharge, C-rate, and discharge duration. Because of this, it is difficult to use existing data to assess the effect of temperature on a specific application. It is still a useful tool in approximating battery performance, and comparing different batteries.

Lead acid batteries are generally robust and have good performance at normal ambient temperatures and slightly below ambient. This makes them suitable for use in temperature-controlled applications where they will be used without exposure to hot summers and cold winters. Figure 4.5 shows the dependency of voltage on discharge time for various temperatures.

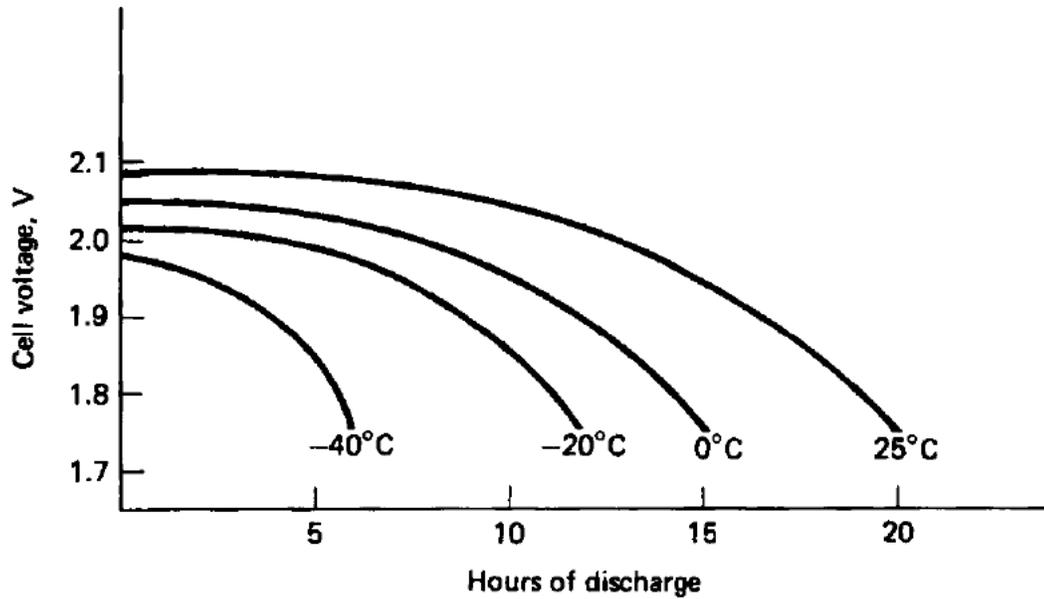


Fig. 4.5. Cell voltage vs. discharge duration as various temperatures [21]

The discharge rate is  $C/20$ , but the same principle holds true regardless of discharge rate: low temperature reduces performance. It should be noted that while  $C/20$  would typically be considered a long discharge duration, it is similar to the expected rate in the utility application being considered. While some drop in voltage is unavoidable, keeping the battery at a normal, indoor temperature allows the battery to be fully discharged while still maintaining a usable cell voltage.

### Lithium Ion

Lithium ion batteries tend to fare better under extreme temperatures than lead acid, but they still need to be stored at room temperature for optimal performance. For example, if a battery is stored at  $60^{\circ}\text{C}$ , it will lose approximately 80% of its charge due to resting capacity loss as opposed to the 25% expected at room temperature. This may or

may not be acceptable depending on the application, but it certainly means that the batteries would need to be constantly connected to a power source to maintain full charge. Lithium ion batteries are more resistant to extreme temperatures than lead acid, both hot and cold [23]. If the storage system would be exposed to very hot and cold temperatures, then lithium ion would be the better choice. Ideally, if the temperatures vary widely enough to render lead acid useless, then temperature controlled housing should be used regardless.

As discussed earlier, voltage is equally as important as capacity when the quantity of energy stored is a constraint. The major question of cost is whether the heating and housing of the batteries is more cost effective than simply adding additional batteries to offset the drop in voltage. This would be heavily dependent on location, and because heating, insulation, and battery quantity are all affected by the temperature of the environment, it is difficult to make a generalized analysis. Now that the necessary battery system energy is known, it is instead best to use the total cost per kilowatt-hour from Eagle Picher to determine the total cost.

### **4.3 Results**

The total battery system costs can be found using the total required energy from Table 4.5. Eagle Picher lead acid battery systems are \$600/kWh [12], and is the value used to calculate the total system costs shown in Table 4.10. Material costs are also shown in the table as a point of comparison, which were also found previously in Table

4.5. The Pershing substation and Price feeder locations are compared alongside their corresponding infrastructure upgrade costs.

**Table 4.10. Lead acid battery material and total system costs compared to infrastructure upgrade costs for Pershing and Price locations [24]**

Location	Initial system cost (\$x10 <sup>3</sup> )	Total system cost (\$x10 <sup>3</sup> )	Infrastructure cost (\$x10 <sup>3</sup> )
Pershing	5676	10832	2700
Price	2442	4658	150

The use of batteries does not appear to be economical for either Pershing or Price. The wide disparity in infrastructure costs is due to the nature of the upgrade requirements for each location. For Price, a feeder exit cable is the limiting component, which is relatively inexpensive. Pershing is limited by its transformers, and so the traditional approach would be to upgrade either the transformers or the entire substation. Material cost at Pershing is substantially less expensive than infrastructure cost, so if total system cost can be reduced then battery storage may be a viable option at the Pershing substation.

Otherwise, battery systems are still too expensive to warrant use as a replacement of traditional upgrade methods. The battery costs themselves are not necessarily the limiting factor, however. The majority of the costs of these systems are unrelated to the battery materials, and so much improvement will need to be made in reducing other costs associated with these systems before they become a viable alternative.

It is important to note that an even further detailed analysis would account for the time value of money, in addition to the steadily decreasing costs of lead acid and lithium ion batteries. It is difficult to predict the future cost of these batteries, so the assumption

was made to use present costs regardless of when the battery system or installment would be purchased. In addition, it is difficult to predict how the decrease in material cost would affect overall system cost. A future analysis could take this into consideration if accurate predictions could be made.

In conclusion, three locations were selected as potential candidates for battery storage, namely the Clark voltage line, Price feeder, and Pershing substation. Battery storage was shown to be too expensive at all locations, and is not acceptable as an alternative to traditional infrastructure upgrades considering current battery prices. A method of material cost optimization was developed for lead acid and lithium ion batteries, which could be useful in future work related to battery cost analysis. As battery costs continue to decrease, battery storage will likely become a viable option in the future.

## References

- [1] Lower, Stephen. "Chem1 Electrochemistry: Cells and Electrodes." *Chem1 Electrochemistry: Cells and Electrodes*. N.p., 2005. Web. 19 Feb. 2016.
- [2] Cao, Jian, Nigel Schofield, and Ali Emadi. "Battery Balancing Methods: A Comprehensive Review." *2008 IEEE Vehicle Power and Propulsion Conference* (2008).
- [3] Chieh, Chung. "Chemistry of Batteries." *Chemistry of Batteries*. University of Waterloo, n.d. Web. 19 Feb. 2016.
- [4] Green Batteries. "Glossary of Battery Terms." *Glossary of Battery Terms*. N.p., 2016. Web. 12 Feb. 2016.
- [5] Cowie, Ivan. "All About Batteries, Part 3: Lead-Acid Batteries | EE Times." *EETimes*. N.p., n.d. Web. 13 Jan. 2014.
- [6] "Handbook for Stationary Lead-acid Batteries." (n.d.): n. pag. Feb. 2012. Web.
- [7] Scrosati, Bruno, and Jürgen Garche. "Lithium Batteries: Status, Prospects and Future." *Journal of Power Sources* 195.9 (2010): 2419-430.
- [8] Ritchie, Andrew, and Wilmont Howard. "Recent Developments and Likely Advances in Lithium-ion Batteries." *Journal of Power Sources* 162.2 (2006): 809-12.
- [9] BBC. "Dreamliner: Boeing 787 Planes Grounded on Safety Fears." *BBC News*. N.p., 17 Jan. 2013. Web. 3 Mar. 2016.
- [10] Bode, Hans. *Lead-acid Batteries*. New York: Wiley, 1977.
- [11] Scrosati, Bruno. "Recent Advances in Lithium Ion Battery Materials." *Electrochimica Acta* 45.15-16 (2000): 2461-466.
- [12] Bond, James. Eagle Picher. Aug. 2015.
- [13] Saxena, Samveg, Caroline Le Floch, Jason Macdonald, and Scott Moura. "Quantifying EV Battery End-of-life through Analysis of Travel Needs with Vehicle Powertrain Models." *Journal of Power Sources* 282 (2015): 265-76.
- [14] Fox, Stuar. "How Does Depth of Discharge Factor into Grid Connected Battery Systems?" *How Does Depth of Discharge Factor into Grid Connected Battery Systems?* N.p., 20 Aug. 2013. Web. 19 Feb. 2016.
- [15] MIT Electric Vehicle Team. "A Guide to Understanding Battery Specifications." (n.d.): n. pag. Dec. 2008. Web. 6 Apr. 2016.
- [16] Miller, T. J. E. *Reactive Power Control in Electric Systems*. New York: Wiley, 1982.

- [17] Rodriguez, George D., William C. Spindler, and D.s. Carr. "Operating the World's Largest Lead/acid Battery Energy Storage System." *Journal of Power Sources* 31.1-4 (1990): 311-20.
- [18] Pascoe, P.e., and A.h. Anbuky. "VRLA Battery Discharge Reserve Time Estimation." *IEEE Transactions on Power Electronics IEEE Trans. Power Electron.* 19.6 (2004): 1515-522.
- [19] Albright, Greg. "A Comparison of Lead Acid to Lithium-ion in Stationary Storage Applications." (n.d.): n. pag. AllCell Technologies LLC, Mar. 2012. Web.
- [20] Hensley, Russell. "Battery Technology Charges Ahead." *McKinsey & Company*. N.p., July 2012. Web. 24 Jan. 2016.
- [21] Linden, David, and Thomas B. Reddy. *Handbook of Batteries*. New York: McGraw-Hill, 2002. Print.
- [22] Berera, Geetha P. "Lead-Acid Storage Cell." (n.d.): n. pag. MIT 3.014 Materials Laboratory, 13 Nov. 2006. Web.
- [23] Santhanagopalan, Shriram, Kandler Smith, and Jeremy Neubauer. *Design and Analysis of Large Lithium-ion Battery Systems*. N.p.: Artech House, 2015. 29.
- [24] Rudy Probst, Jackson Herbst, and Randy Schlake. *Grid of the Future Technical Team Battery Energy Storage to Address System Overload and Voltage Concerns*. Ameren. Sep. 2015.