

PEAK SHAVING USING ENERGY STORAGE AT THE RESIDENTIAL LEVEL

Interactive Qualifying Project Report completed in partial fulfillment
of the Bachelor of Science degree at
Worcester Polytechnic Institute, Worcester, MA

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Abstract

Electricity demand is not constant throughout the day. This forces energy suppliers to use less efficient generators which can be easily turned on and off to match demand. By storing electricity when demand is low and expending this electricity when demand is high electricity demand can be flattened, allowing for the use of more efficient generators. This study investigates whether or not this can be economically viable at a residential level.

This study found that for none of the storage technologies or pricing schemes studied was this application economically viable. It was found that the initial cost and the replacement costs were the bulk of the costs, and that efficiency is the most important factor to the amount of revenue generated by the system.

Executive Summary

Generators of electricity would like to produce as much electricity as possible from all of their power plants. Doing this allows them to maximize their profits and avoid waste from having some of their plants not operating. However, electricity usage is not constant; it varies in predictable patterns over the course of a day and a year. In order to meet this changing demand they must turn their generators on and off as demand changes, leaving good power plants off or running at less than full capacity during off hours and operating less efficient plants during peak hours to meet high demand. Storing energy during off-peak hours and using that energy during peak hours can reduce these peaks and valleys. Doing this at a residential level would allow the investment required to be spread out among many people.

This study looked at four different storage technologies and three different pricing structures. The technologies studied were lead-acid, NiCd, ZnBr, and Li-Ion batteries. The parameters of these technologies are given below in Table 1. The pricing structures investigated were time of use pricing plans from WE Energy, Baltimore Gas

and Electric (BGE), and Massachusetts Electric Company (MECO). A summary of the aspects of these pricing structures that are used in the model are given in Table 2. The technologies were chosen to be low maintenance and to be appropriate for small scale applications. The pricing plans were chosen to vary in the length of the peak period and consequently the difference between the minimum and maximum price, because lower number of hours of peak price meant that the peak price was much higher than the off-peak price.

	Battery Cost (\$/kWh)	Power Conversion System Cost (\$/kW)	Balance of Plant (\$/kW)	Operation and Maintenance (\$/kW/Year)	Replacement Cost (\$/kWh)	Replacement Period (yrs.)	Efficiency (AC to AC)
Lead-Acid	200	175	50	5	200	5	0.75
Ni/Cd	600	175	50	25	600	10	0.65
Zn/Br	400	175	0	20	100	8	0.60
Li-ion	500	175	0	25	500	10	0.85

Table 1: Storage Technology Parameters

	Summer Minimum (\$/kWh)	Summer Maximum (\$/kWh)	Winter Minimum (\$/kWh)	Winter Maximum (\$/kWh)	Peak Period Length (Hrs)
WE	0.05	0.38	0.05	0.27	4
BGE	0.07998	0.1417	0.07509	0.10442	6
MECO	0.04157	0.10219	0.04157	0.10219	12

Table 2: Pricing Structure Parameters

In order to measure the economic viability of this application, a model was created which attempts to measure the return on investment (ROI) of this system after a number of years; it is given below in Equations 1 and 2.

$$\begin{aligned}
P(t, E_{sto}) = & \sum_{i=1}^t \text{PV} (eE_{sto}(d_s p_{sMax} + d_w p_{wMax}), i) \\
& - ((C_{bat} * E_{sto}) + C_{pcs} * (E_{sto}/T_p) + C_{BoP} * (E_{sto}/T_p)) \\
& - \sum_{i=1}^t \text{PV} (E_{sto}(d_s p_{sMin} + d_w p_{wMin}), i) \\
& - \sum_{i=1}^t \text{PV} (C_{O\&M}(E_{sto}/T_p), i) \\
& - \sum_{i=1}^t \text{PV} (C_{repl}(E_{sto}), \lceil i/T_r \rceil) / T_r
\end{aligned} \tag{1}$$

$$ROI = (P(t, E_{sto}) / C_i(E_{sto})) * 100 \tag{2}$$

Where E_{sto} is the energy stored by the system, t is the number of years the system has been operating, $P(t, E_{sto})$ is the profit of the system, e is the efficiency of the system, d_s is the number of days in the summer period, d_w is the number of days in the winter period, p_{sMax} and p_{sMin} are the maximum and minimum energy prices in the summer, p_{wMax} and p_{wMin} are the maximum and minimum energy prices in the winter, C_{bat} is the cost of buying the initial batteries in \$/kWh, C_{pcs} is the price of buying the power conversion system in \$/kW, C_{BoP} is the cost of balance of plant in \$/kW, T_p is the peak period length in hours, $C_{O\&M}$ is the yearly operation and maintenance cost in \$/kW/Year, C_{repl} is the replacement cost in \$/kWh, T_r is the replacement period in years, and C_i is the initial cost of the system.

The model takes into account the initial cost of the system and then yearly costs and revenues associated with buying and selling energy, maintenance, and replacements. These were all adjusted for present value and inflation.

Using this model it was determined that no combination of the technologies and pricing plans looked at was economically viable, only three of the combinations gained

money every year and none of these made up for the initial investment after 20 years. All the other combinations lost money each year and therefore only became worse investments over time. The effects of changing parameters in the model were then studied to determine they're effect on the profitability of this application. Figure 1 displays the breakdown of costs in the model after 10 years, showing that the initial cost and the replacement costs form the majority of the total cost, which makes them important targets for cost reduction when attempting to make this application economically viable. It was also found that efficiency has a large effect on the amount of revenue the system generates and because of this is also an important factor.

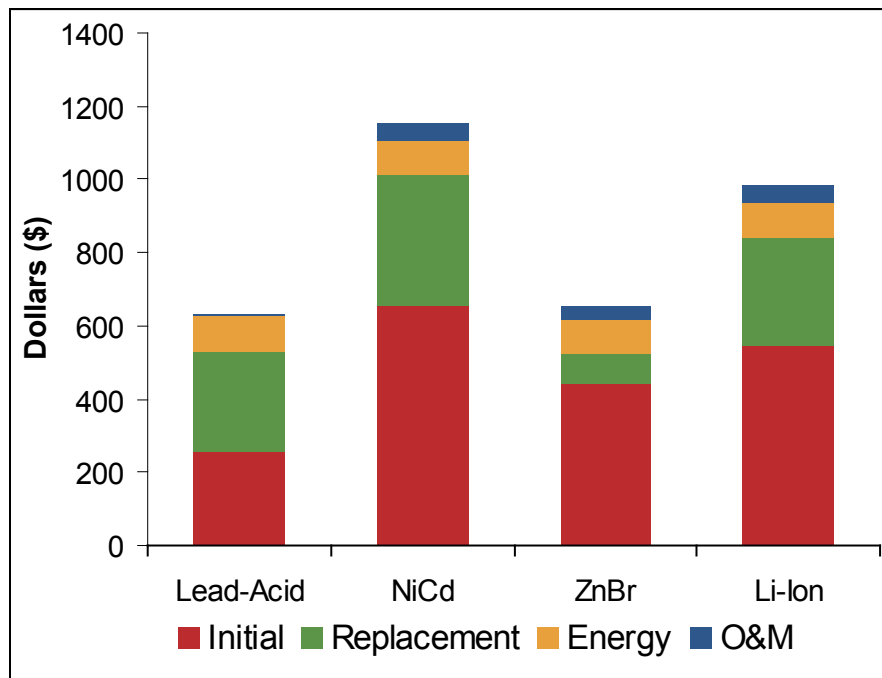


Figure 1: Cost Breakdown By Technology

Introduction

The electrical grid supplies consumers by connecting them to generators of electricity, such as coal, nuclear, and hydro-electric power plants. This system suffers from power consumption not being constant, while many systems supplying them are best operated at a constant rate [31][14]. Continuous operation can be necessary either because the plant takes a long time to start and stop or because the economics of the power plant dictates that it must operate around the clock to justify its large construction cost [3]. Some of the suppliers who do not run continuously cannot provide power at times of maximum demand. Wind and solar farms are good examples of generators whose output are not consistent and may not correspond with times of peak demand [4]. These non-continuous systems still suffer from the problem that their output does not necessarily match the demand [23]. Typically, continuous sources can be operated more inexpensively, while less efficient sources need to be used to meet peak demands. Historically natural gas turbines have been used for peaking because they involve less capital costs and are easily brought on and off line. The more expensive peaking power sources lead to the price of generating energy increasing dramatically when demand peaks. There is a natural desire to lessen peak demands to save money.

These peaks occur at consistent and predictable times throughout the day. There are three main characteristics of electricity usage throughout a day: morning ramp, peak demand, and hourly and five minute peaks. The morning ramp is a rapid increase in load in the morning, normally between 5:00 and 7:00 AM. Peak demand is a period of time, normally in the early evening, where demand is at its highest throughout the day. Hourly and five minute peaks are brief peaks that happen within an

hour. While relatively small peaks the short period of time in which they occur can be problematic. Overall, power usage ramps up in the morning and stays relatively high until the evening at which point it begins to decline and stays low until the next morning, as shown in Figure 2 [2]. Demand for electricity also varies seasonally, being higher in the winter and summer than in spring and fall [2].

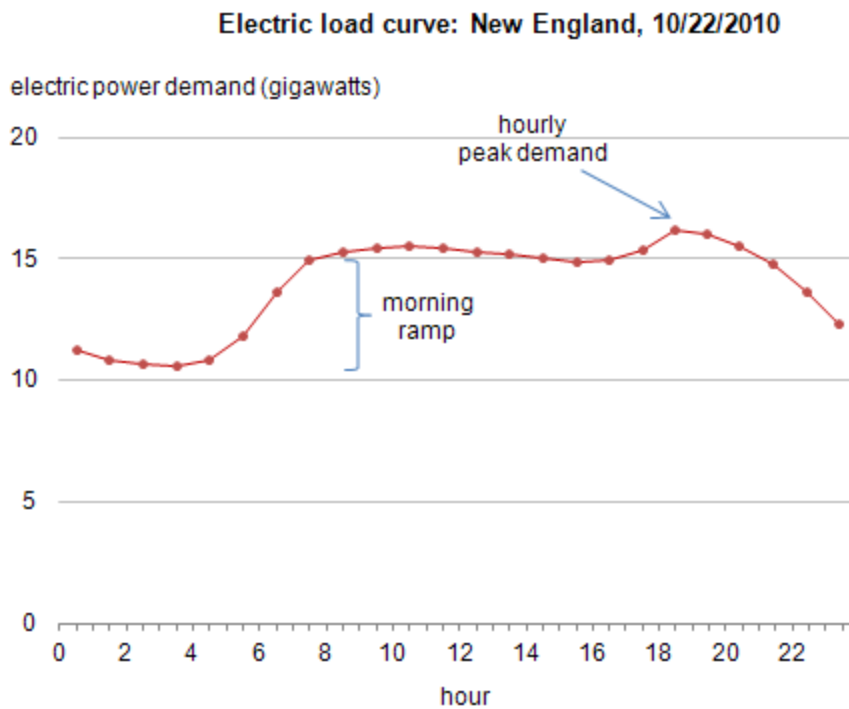


Figure 2: Daily Electricity Demand[2]

Attempting to moderate demand and reduce peaks is called peak shaving or load leveling. This is often done by storing energy during low demand hours and using the stored energy during high demand hours. This reduces the price to generate the energy by preventing the use of less efficient power generation. Peak shaving is normally done at a large scale by power companies to save money and is sometimes

done by commercial companies to make money by buying cheap power during low demand and selling expensive power during high demand [4][19].

This paper seeks to determine if peak shaving can be done at the level of a non-commercial residential customer in order to reduce energy costs by allowing power generation to be done with more efficient systems. The analysis of energy storage technologies will be done by measuring the cost of such a system over time and comparing this to the money that the consumer will save, to determine if there is incentive for residential customers to implement an energy storage system.

Energy Storage Technologies

There is a wide range of energy storage technologies that are at various levels of development and practicality for residential use. The following sections describe technologies that may have utility at the residential scale. The costs must be manageable, the size of the equipment must be suitable for home use, and efficiencies must be sufficient to achieve economic performance. Residential demand patterns have a strong impact on the requirements for energy storage systems. Energy usage is high during waking hours and low during sleeping hours. There are other usage trends that can impact storage technologies. However, the diurnal use of energy dictates that storage technologies work well on the time scale of 12 hours.

Flywheels

Flywheels are energy storage devices that store kinetic energy in a spinning mass called a rotor. The input energy is used to spin the rotor and output energy is generated using electromechanical machines (i.e. electrical generators) [18]. However,

friction acts on the flywheel to cause it to slow down, thereby losing energy. Friction between the rotor and its support and the air are the causes of energy loss. In order to minimize friction losses the rotor is often enclosed in a vacuum or a low-viscosity fluid. The lost energy is in the form of heat, which must be managed to maintain the flywheel within the operating temperature range of the parts. Heat control is accomplished by minimizing the friction and by using cooling systems to move the heat away from the flywheel [1].

Due to the fact that flywheels lose energy over time to friction, and because they have high charge and discharge rates, flywheels are generally used for low duration storage such as over seconds to a few hours [29]. This is applicable situations where energy generation fluctuates, but constant output is required, such as in wind energy, where gusts and lulls in the wind create inconsistent output, or solar energy where a passing cloud may reduce output [5]. While some flywheels may be able to be used for storing energy over the duration that is required for this study, it is on the very edge of what is reasonable for flywheels. As a result, flywheels will not be considered in this report. As technology improves, the storage duration of flywheels may increase and their usage in this application should be studied.

Batteries

A battery is a system that converts chemical energy held within the battery into electric energy, and in rechargeable batteries this process can also be reversed to turn electric energy into chemical energy to later be discharged. Batteries are split into two classifications based on this ability. Primary batteries cannot be recharged, while

secondary batteries can be recharged. A battery consists of one or more connected cells, each of which contains three main components: the anode, the cathode, and the electrolyte. The anode is the negative electrode; it gives up electrons to the circuit to which the battery is providing power. The electrode chemically oxidizes during the reaction to provide electrons. The cathode is the positive electrode and it accepts electrons from the external circuit which causes the cathode to be chemically reduced in the reaction. The electrolyte provides the medium of transfer for the charge between the anode and the cathode. The charge is transferred as ions and so the electrolyte is also known as the ionic conductor. Electrolytes are commonly liquids with salts, acids, or alkalis dissolved in them in order to grant ionic conductivity, however sometimes solid electrolytes can be used if they are ionic conductors at the operating temperature of the battery [6] A diagram showing a battery and the flow of ions through the electrolyte and electrons through the circuit is given in Figure 3.

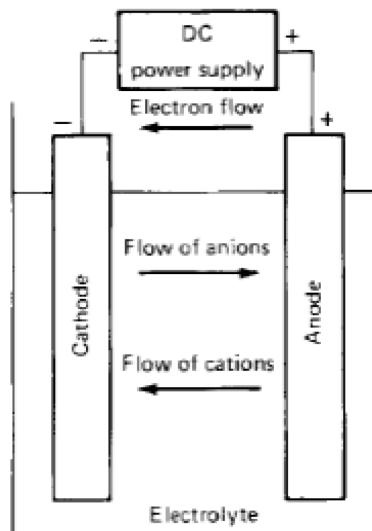


Figure 3: Cell Diagram [6]

This study will look at secondary batteries exclusively, because the capability to recharge is necessary for this application. Secondary batteries are recharged by passing current through them in the opposite direction from discharge. This capability to be recharged makes secondary batteries storage devices for electric energy. Batteries are commonly used in systems where they are located between an energy source and a load. They are charged at a constant rate and discharge to the load as it requires electricity. This is how hybrid cars operate [6]. They are a natural choice for this application due to their reliability, simplicity, and modularity [17].

Lead-acid Batteries

Lead-acid batteries use lead for both the cathode and anode and a solution of sulfuric acid for the electrolyte. Lead-acid batteries have been in use for a long time and are a well developed battery technology. Lead-acid batteries are used in cars and trucks to provide power for starting internal combustion engines. They tend to be inexpensive and readily available, which makes them a common choice for new applications [16]. However, they have lower cycle life, high maintenance requirements, and low specific energy [29]. A common variant of Lead-acid batteries is the Valve Regulated Lead-Acid battery (VRLA). In VRLA's there is much less electrolyte in order to reduce issues with leakage and the battery is sealed with a valve to regulate the movement of gas in and out of the cell. This technology has very low maintenance requirements and is less expensive. However, it has a lower cycle life than traditional Lead-acid batteries. Valve Regulated Lead-Acid batteries have been chosen for this study because low maintenance is extremely valuable in a residential setting [1].

Ni/Cd Batteries

Nickel-Cadmium batteries use nickel for its cathode, cadmium for its anode, and an alkaline electrolyte. Nickel-cadmium batteries are sealed and require no maintenance and have a long cycle life, which makes them a good choice for this application. However, they are more expensive than lead-acid batteries and have a lower specific energy than many other batteries. In addition, the use of cadmium is an environmental concern as cadmium is a heavy metal and should not be disposed of by normal means [6]. This requires the end-user to be aware and take special action to dispose of the batteries when they need to be replaced [26].

Zn/Br Batteries

Zinc-bromine batteries are flow batteries, which are a type of battery in which at least one of the active materials is in solution with the electrolyte at all times [29]. In this case the bromine is always dissolved in the electrolyte, while the zinc is dissolved while the battery is discharged and plated onto the negative electrode when charged [1]. Zinc-bromine batteries have good specific energy, good energy efficiency, and are made of low-cost materials, but require extra systems to ensure proper operation and safety [6]. Because bromine is hazardous, especially when inhaled, the possibility of bromine escaping the system is the most prominent safety concern. This is mitigated by the fact that bromine is more common in the complex poly-bromide state rather than free bromine, but any spill or leak of the electrolyte will cause the slow release of bromine vapors, and the user must be prepared to handle it [1].

Li-ion Batteries

In lithium-ion batteries lithium ions move between the cathode and the anode to charge and discharge the battery. Because of the back and forth movement of the lithium-ions these batteries are sometimes referred to as rocking-chair batteries. This type of battery is also sealed and therefore requires no maintenance and has a long cycle life, in addition to having high charge and discharge rate and a high specific energy. However, they have no chemical mechanism to prevent overcharging. As such, they require circuitry or mechanical devices to prevent over-charge [6].

Technology Parameters

Performance

There are three main categories of performance characteristics that will be discussed in this study: Capacity, efficiency, and charge/discharge rate. Capacity mainly concerns the given capacity of the battery in ampere-hours, the nominal voltage of the battery, and how to find the capacity in watt-hours which will be used in the calculations. The metrics of efficiency that will be used are round-trip efficiency and self-discharge rate. Charge and discharge rates are important characteristics of the battery which affect the other performance characteristics and choosing them appropriately to charge and discharge within the necessary timeframes while maximizing capacity is vital.

Capacity

The capacity of a battery is normally given in ampere-hours at a given discharge rate. This rate is given in C-units, which are relative to the capacity of the battery. One C-unit is equal to the current it takes to discharge the batteries nominal capacity in one hour, so for a 100Ah battery 1C would be 100A. For this study, however, it is more useful to give the capacity in watt-hours. In order to convert ampere-hours to watt-hours we need to integrate the capacity in ampere-hours multiplied by the voltage of the battery over the discharge time, as shown in Equation 3.

$$E = \int_0^{T_d} Q * V(t) dt \quad (3)$$

Where E is energy stored by the battery in watt-hours, Q is the capacity of the battery given in ampere-hours, and V(t) is the voltage of the battery as a function of time.

The capacity in watt-hours can also be more easily approximated using the battery's nominal voltage, given for each technology in Table 4, in which case converting from ampere-hours to watt-hours is done by simply multiplying the capacity in ampere-hours by the nominal voltage, as shown in Equation 4

$$E = Q * V_N \quad (4)$$

Where V_N is the nominal voltage of the system.

A battery's specific energy and energy density are also related to its capacity. Specific energy is the capacity in watt-hours per unit of mass (Wh/kg), and energy density is the capacity in watt-hours per unit of volume (Wh/L). These metrics are

useful in determining the space the battery will take up, as well as how heavy the setup will be. While these metrics are given in Table 3, they will not be used in the model and are only provided in order to allow the size and weight of the system to be determined and used as another factor with which to make decisions on which technology to use.

	Specific Energy (Wh/kg)	Energy Density (Wh/L)
Lead-Acid	30	90
Ni/Cd	30	90
Zn/Br	70	65
Li-ion	125	350

Table 3: Specific Energy and Energy Density By Technology[6]

Efficiency

The main metric of efficiency of a battery is its round-trip efficiency, this is the percentage of the input energy which is discharged. This metric assumes that there is no time between charging and discharging, so this metric gives the best case efficiency. The round-trip efficiency used in this study and given in Table 4 is the AC to AC round-trip efficiency, which is the efficiency from the grid to the grid, which includes the efficiency of both the storage technology itself and the conversion from alternating current to direct current and back. The efficiencies of technologies in this study vary from .6, for Zn/Br, to .85, for Li-Ion.

There is also another source of energy loss, which is called self-discharge or parasitic loss. This is the energy the battery loses over time in which it is not being either charged or discharged, it is normally given as the percentage of stored energy lost during unit of time (%/hour). The significance of this loss varies by technology and

in this study the batteries are not being left unused with energy in them for long periods of time. The highest rate of parasitic loss in this study is Zn/Br and Li-Ion with .01%/hour, because this is such a small amount, even if the batteries were left charged over the weekends when they are unused, the amount lost would still be insignificant, so self-discharge is not factored into the model. Table 4 gives the values for round trip efficiency and self-discharge rate for each storage technology.

	Nominal Voltage (V)	Round Trip Efficiency	Self-Discharge Rate
Lead-Acid	1.75	0.75	.1%/day
Ni/Cd	1.2	0.65	0 ¹
Zn/Br	1.8	0.60	.01%/hr
Li-ion	3.2	0.85	.01%/hr

Table 4: Voltage and Efficiency Parameters by Technology[8]

Charge/Discharge Rates

Choosing appropriate charge/discharge rates is important due to its impact on the battery's capacity. For both charging and discharging, lower rates increase the efficiency of the battery by decreasing the input energy required for slower charging and by increasing the capacity for slower discharges. Therefore, in order to maximize the batteries efficiency charge and discharge rates should be chosen such that they are as low as possible while still fully charging and discharging within the given period and keeping them within the allowed limits of the battery.

In this study rates will be assumed to be as low as is possible in order to fully charge the batteries during off-peak periods and fully discharge the batteries during peak hours. The rate will be kept within acceptable ranges for the technology and the

¹ Self-Discharge Rate is Insignificant

cost will be for the standard rates given by the manufacturer, which will be kept to when possible.

Technology Parameters (Cost)

The cost of the system is described by three main categories of costs: initial costs, maintenance costs, and replacement costs. The initial cost is the initial cost to build the system; including the cost of the batteries, the cost of support systems for the battery, and the cost of systems for converting between alternating current from the grid and direct current used by the batteries. The maintenance costs are the costs to keep the system running properly and are expressed as a yearly cost. The replacement cost is the cost to replace the battery system at the end of their lifespan, how often this is depends on the technology and varies from 5-10 years [25]. The values for all of the technology cost parameters are given in Table 5.

The initial cost of the system is made up of the cost of the batteries, the cost of the power conversion system (PCS), and the cost of balance of plant. The cost of the batteries scales with the amount of energy that they need to store. The power conversion system converts alternating current from the grid to direct current that the batteries use. This cost scales with the power that it is required to handle. Balance of plant costs are the costs of any support systems required by the batteries or PCS. These costs will typically be cooling for the system, control systems for preventing the battery from over or under charging, and systems which monitor for failures within the system [9].

The cost of maintenance is given in dollars per kilowatt per year. This is the upkeep cost of the system either from operation, such as electricity consumed by equipment supporting the batteries, or from maintenance of the system. Because part of the criteria for picking battery technologies for this study was being low maintenance, the cost of operation and maintenance will be low for many of the technologies, and mostly be in the form of passive costs such as electricity for the support systems, rather than in the more active form of replacements for failed parts [7].

The replacement costs are the costs incurred whenever the batteries in the system need to be replaced. For many of the technologies in this study this value is the same as the original cost of the battery because the battery systems are sealed and the whole system must be bought again. This is because sealed systems are much lower maintenance and require the operator to interact with the system the least. The frequency with which this cost must be paid is dependent on the technology's replacement period. The replacement period is based on the technologies cycle life and certain assumptions about the systems use [8].

Cycle life is a measure of how many times the battery can be fully charged and discharged during its lifespan. In this study the batteries undergo one cycle per weekday, so the cycle life can easily be converted to real-time between replacements. A battery's cycle life can vary based on how it is used, the charge and discharge rates, how often it is fully charge and discharged, and how often and in what state it sits idle can all affect the cycle life. In this study the average cycle life is given as a flat amount and the usage and settings of the battery will be kept in recommended ranges so that this value is accurate.

	Battery Cost (\$/kWh)	PCS Cost (\$/kW)	BoP (\$/kW)	O&M (\$/kW)	Replacement Cost (\$/kWh)	Replacement Period (yrs.)
Lead-Acid	200	175	50	5	200	5
Ni/Cd	600	175	50	25	600	10
Zn/Br	400	175	0	20	100	8
Li-ion	500	175	0	25	500	10

Table 5: Technology Price Parameters [8]

Electricity Pricing

The reason that storing energy during off hours and using it during peak hours can be economically viable at the residential level is a pricing structure for residential energy use called time of use pricing. Time of use pricing is when energy use at different times of the day cost different amounts of money, this is used by energy companies to provide incentive for users to reduce peak demand and increase off-peak demand [20][22][24]. This is shown in Figure 4, which shows the energy usage of customers on standard plans and customers on time-of-use plans. The exact implementation of this kind of system varies from company to company based on demand in that area and how the company would like to affect it [21][22][28].

Tables 1-3 provide example implementations of time of use pricing by Massachusetts Electric Company (MECO), Baltimore Gas and Electric (BGE) and We Energies (WE). BGE and WE employ a three tier structure, with a mid-peak period which is in the transitions to and from off-peak and peak, and prices differ in the summer and winter due to different energy demands in each period of the year [10][11]. However, MECO uses a simpler two tier system that is constant throughout the year. In all cases weekends are always considered off-peak, as well as some holidays [12].

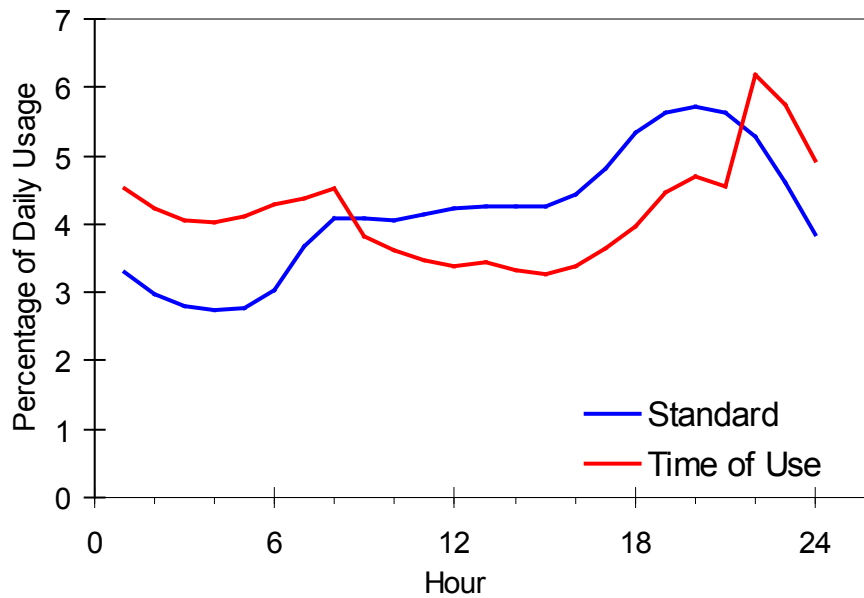


Figure 4: Usage by Time-of-Use and Standard Pricing Models [15]

These pricing structures were chosen because they are from states with approximately average energy prices and provide a system with a small difference in price but long peak hours (MECO), a system with a high variation in price but short peak hours, and a system between the two (BGE) [11][12]. Variations in the implementations of a time of use pricing system will have a large effect on the results of this study; however the methods used can easily be adapted to other time-of-use pricing structures.

Period	Rate (\$/kWh)	Hours Per Day
Peak ²	0.10219	13
Off-Peak ³	0.04157	11

Table 6: MECO Time of Use Pricing [12]

² MECO Peak Period: 8am-9pm

³ MECO Off-Peak Period: 9pm-8am

Period	Rate (\$/kWh)	Hours per Day
June-Sept Peak ⁴	0.1417	10
June-Sept Inter-Peak ⁴	0.09092	6
June-Sept Off-Peak ⁴	0.07998	8
Oct-May Peak ⁵	0.10442	8
Oct-May Inter-peak ⁵	0.09616	6
Oct-May Off-Peak ⁵	0.07509	10

Table 7: BGE Time of Use Pricing [11]

Period	Rate (\$/kWh)	Hours per Day
Oct-May Peak ⁶	0.27	4
Oct-May Mid-Peak ⁶	0.21	8
Oct-May Off-Peak ⁶	0.05	12
June-Sept Peak ⁶	0.38	4
June-Sept Mid-Peak ⁶	0.27	8
June-Sept Off-Peak ⁶	0.05	12

Table 8: WE (Wisconsin) Time of Use Pricing [10]

Electricity Usage

Electricity usage follows predictable patterns over time. This pattern is in general a morning ramp followed by a period of relatively stable usage, a peak in the late afternoon and evening, and a significant drop in usage in the late evening [2]. This pattern can vary, however, between the summer and winter, which is why time of use pricing structures often give different prices and even different times of peak and off-peak periods in the winter and summer. Figure 5 shows average electricity usage in the summer period, June-September, and the winter period, October-May. The winter follows the same approximate shape as the overall average, while the summer has

⁴ BGE Summer Peak: 10am-8pm, Inter-Peak: 7am-10am 8pm-11pm, Off-Peak 11pm-7am

⁵ BGE Winter Peak: 11am-5pm, Inter-Peak: 7-11am 5-9pm, Off-Peak 9pm-7am

⁶ WE Peak: 2-6pm, Mid-Peak: 8am-2pm 6-8pm, Off-Peak: 8pm-8am

higher usage during mid-day. This is mostly due to increased use of air conditioning during the day to keep the house cooled [13][27][30].

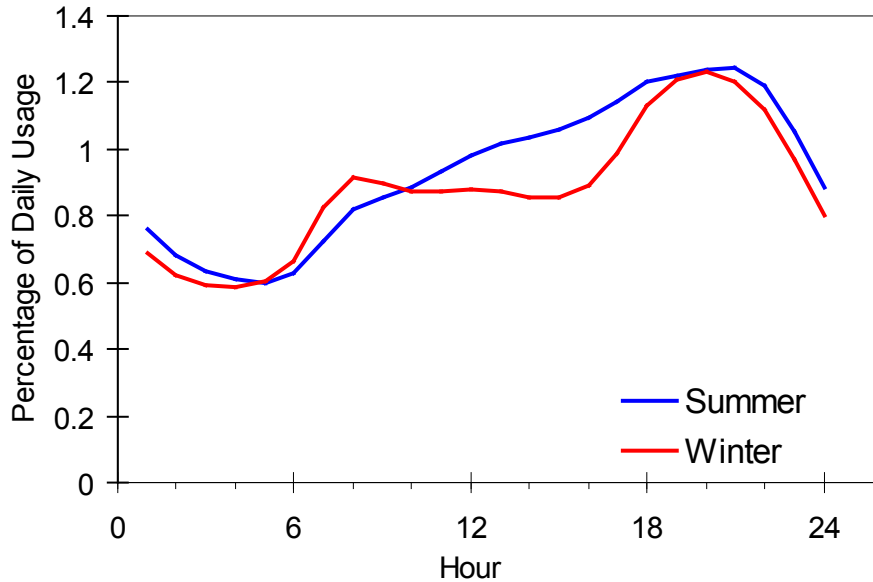


Figure 5: Electricity Usage in Summer and Winter [15]

The sources of electricity would prefer that electricity demand was a constant however, because they would like to be run all day. Figure 6 shows the difference between actual usage and a constant amount of usage all day. Because the demand varies, some must be turned on and off depending on the time of day, which hurts the profits of the power plants as well as forcing them to use less efficient methods that deal with being turned on and off over the course of a day better. Complicating this varied demand further are sources of electricity that do not produce electricity at constant rates and vary not only throughout the day, but also from day to day, such as wind and solar energy [3].

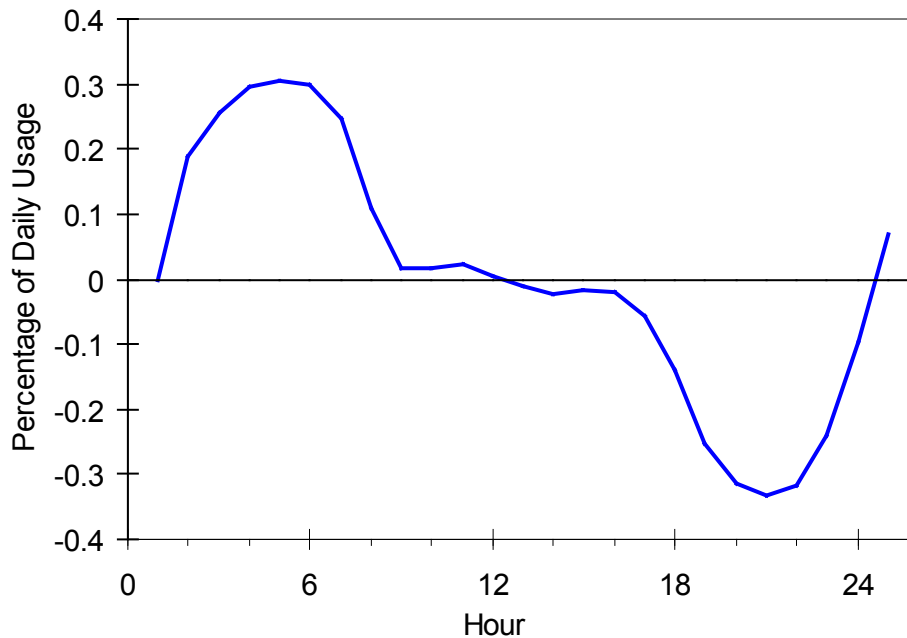


Figure 6: Difference Between Actual and Constant Usage [15]

Model

Assumptions

This model makes certain assumptions about the batteries used and the behavior of the system. It assumes that if the battery can be discharged during the peak period, then it can be charged during the off-peak period. In regards to the cost of the power conversion system (PCS), this makes sense because while less energy comes out of the system during discharge due to the efficiency of the storage technology, the off-peak periods are always at least twice the peak periods and no efficiency is less than 50%, so they PCS supports enough power to charge the battery during off-peak. When it comes to the batteries themselves, however, this can be assumed because, while some standard charge times are longer than any of the off-

peak periods, the technologies that have these long standard charge times also have a quicker charge time that is within all the off-peak times.

This model also assumes that the batteries are fully charged and fully discharged during each cycle and that the batteries do not lose capacity over time. This can be assumed because the batteries used in this study do not lose capacity quickly if the battery is operated correctly, which is done by fully charging and discharging the battery every cycle.

The system in this model is also assumed to be directly connected to the grid, rather than having the outputted energy be used by the inhabitants of the residence. This means that the output power of the system can be greater than the usage of the house without issue. This is assumed because a system which can output to either and takes the usage of the house into account would be significantly more expensive. This does not change the positive effect of the system on the grid because the net effect on the grid is simply the normal usage of the house plus the usage and output of the system.

The system is assumed to only operate on non-holiday weekdays because in all time of use pricing structures the weekend and approximately ten holidays are off-peak times all day.

Cost

The cost of the storage system is given in four components: the initial cost, yearly cost, replacement cost, and energy cost. The initial cost is the cost to buy the batteries and support systems to manage the battery and connect to the grid, and depends on

the kilowatt-hours stored and the power required, which is dependent on the kilowatt-hours stored and the duration of the peak period. The yearly costs are operation and maintenance costs for the storage system and depend upon the power of the system. The replacement costs are the costs to replace failed batteries and depend upon the kilowatt-hours stored and the replacement period, which varies by technology. Energy cost is the cost of charging the batteries everyday during the off-peak period, it depends on both the number of kilowatt-hours stored and the pricing structure being used [9].

$$C(t, E_{sto}) = C_i(E_{sto}) + C_y(t, E_{sto}) + C_r(t, E_{sto}) + C_e(t, E_{sto}) \quad (5)$$

Where t is the number of years the system has been running, E_{sto} is the amount of energy the system stores, C is the total cost of the system as a function of t and E_{sto} , C_i is the initial cost, C_y is the yearly cost, C_r is the replacement cost, and C_e is the cost of buying energy.

Initial Cost

The initial cost is also made up of three subcomponents: the cost of the batteries themselves, the cost of the power conversion system (PCS) which converts between the grid and the storage system, and the balance of plant costs which are any support systems needed to manage the batteries. The cost of the batteries is dependent on the number of kilowatt-hours stored by the system, while the cost of the PCS and balance of plant costs are dependent on the power needed [8].

$$C_i(E_{sto}) = (C_{bat} * E_{sto}) + (C_{pcs} * (E_{sto}/T_p)) + (C_{BoP} * (E_{sto}/T_p)) \quad (6)$$

Where C_{bat} is the cost of the initial purchase of batteries in \$/kWh, C_{pcs} is the initial cost of the power conversion system in \$/kW, C_{BoP} is the cost of balance of plant in \$/kW, and T_p is the length of the peak period in hours.

Yearly

The yearly costs of the storage system are the costs of operation and maintenance of the system which depends on the power of the system. The present value of this cost must also be taken because it is incurred over time. The present value of each of these costs must be taken separately as the costs occur every year [8].

$$C_y(E_{sto}) = C_{O\&M}(E_{sto}/T_p)$$

$$C_y(t, E_{sto}) = \sum_{i=1}^t PV(C_{O\&M}(E_{sto}/T_p), i) \quad (7)$$

Where $C_{O\&M}$ is the yearly cost of operation and maintenance in \$/kW/Year, and $PV(C, i)$ is the present value of some amount of money C after i years.

Replacement

The replacement cost is incurred at the end of every replacement period, which varies by technology. This cost depends on the number of kilowatt-hours the system can store and must be adjusted for present value in the same way as the yearly cost [8]. This value is annualized by finding how much will be paid at the time of replacement and dividing that amount by the number of years between replacement.

$$C_r = C_{repl}(E_{sto})/T_r$$

$$C_r(t, E_{sto}) = \sum_{i=1}^t PV(C_{repl}(E_{sto}), [i/T_r]) / T_r \quad (8)$$

Where C_{repl} is the replacement cost of the system in \$/kWh and T_r is the replacement period of the system in years.

Energy

The cost of charging batteries for one day is dependent only on the minimum price of energy and the number of kilowatt-hours to store. The batteries are fully charged at the minimum price everyday.

$$C_{eDay}(E_{sto}) = E_{sto} P_{min} \quad (9)$$

Where C_{eDay} is the cost of buying energy for one day, and p_{min} is the minimum price of energy.

Revenue

The revenue of the system over a day is dependent on the efficiency of the system and the maximum price of energy. The energy is sold at the maximum price, however the efficiency of the system affects how much can be sold. The revenue from one day is given below in Equation 10.

$$R_{day}(E_{sto}) = E_{sto} p_{max} e \quad (10)$$

Where R_{day} is the revenue from one day, p_{max} is the maximum price of energy, and e is the efficiency of the system.

All Year

When energy prices do not vary between the summer and winter periods the energy cost and revenue from a year is simply the number of days in a year multiplied by the revenue for one day.

$$\begin{aligned} C_e(E_{sto}) &= dE_{sto} p_{min} \\ R(E_{sto}) &= deE_{sto} p_{max} \end{aligned} \quad (11)$$

Where C_e is the cost of energy, R is the revenue, and d is the number of days in a year,

When calculating the energy cost and revenue after a number of years, the present value for each year must be calculated separately, this makes the equations:

$$\begin{aligned} C_e(t, E_{sto}) &= \sum_{i=1}^t PV(dE_{sto} p_{min}, i) \\ R(t, E_{sto}) &= \sum_{i=1}^t PV(deE_{sto} p_{max}, i) \end{aligned} \quad (12)$$

Summer/Winter

In many time of use pricing schemes, however, prices vary between the summer and winter periods due to changes in energy use. In this case to calculate the energy cost and revenue in a year the revenue of a single day in the summer and winter periods is found.

$$\begin{aligned}
R_{sDay}(E_{sto}) &= eE_{sto} p_{sMax} & R_{wDay}(E_{sto}) &= eE_{sto} p_{wMax} \\
C_{eS}(E_{sto}) &= E_{sto} p_{sMin} & C_{eW}(E_{sto}) &= E_{sto} p_{wMin}
\end{aligned} \tag{13}$$

Where R_{sDay} and C_{eS} is the revenue and energy cost from one day in the summer, R_{wDay} and C_{eW} is the revenue and energy cost from one day in the winter, p_{sMax} and p_{sMin} are the maximum and minimum energy prices in the summer, and p_{wMax} and p_{wMin} are the maximum and minimum energy prices in the winter.

Then each is multiplied by the number of days in its period and the two values are combined to yield the revenue and energy cost of a full year. After applying present value the energy cost and revenue of the system after some number of years is found.

$$\begin{aligned}
R(E_{sto}) &= eE_{sto}(d_s p_{sMax} + d_w p_{wMax}) \\
R(t, E_{sto}) &= \sum_{i=1}^t PV(eE_{sto}(d_s p_{sMax} + d_w p_{wMax}), i) \\
C_e(E_{sto}) &= E_{sto}(d_s p_{sMin} + d_w p_{wMin}) \\
C_e(t, E_{sto}) &= \sum_{i=1}^t PV(E_{sto}(d_s p_{sMin} + d_w p_{wMin}), i)
\end{aligned} \tag{14}$$

Where d_s is the number of days in the summer period and d_w is the number of days in the winter period.

Profit

Combining the cost and revenue functions, the profit for the system after x years and storing y kilowatt-hours is found.

$$\begin{aligned}
P(t, E_{sto}) = & \sum_{i=1}^t \text{PV} (eE_{sto} (d_s p_{sMax} + d_w p_{wMax}), i) \\
& - ((C_{bat} * E_{sto}) + C_{pcs} * (E_{sto}/t_{peak}) + C_{BoP} * (E_{sto}/T_p)) \\
& - \sum_{i=1}^t \text{PV} (E_{sto} (d_s p_{sMin} + d_w p_{wMin}), i) \\
& - \sum_{i=1}^t \text{PV} (C_{O\&M}(E_{sto}/T_p), i) \\
& - \sum_{i=1}^t \text{PV} (C_{repl}(E_{sto}), \lceil i/T_r \rceil) / T_r
\end{aligned} \tag{15}$$

Return on Investment

In order to adjust for the different initial investments for different technologies, pricing schemes, and amounts of energy stored, profit is normalized into return on investment (ROI). This metric allows for the profitability of different setups to be compared despite varying levels of initial investment. ROI is calculated by dividing the profit by the initial cost of the system, this gives a percentage of the initial investment gained or lost; it is given in the equation below.

$$ROI = (P(t, E_{sto}) / C_i(E_{sto})) * 100 \tag{16}$$

Analysis

Economic Viability

After calculating ROI for different amounts of energy stored for each pricing/storage technology combination it became clear that when considering ROI the number of kilowatt-hours stored does not make a difference. This makes sense when considering the formula because all costs and revenues scale off of the number of kilowatt-hours stored, either directly or indirectly through power, which is assumed to be

number of kilowatt-hours stored divided by the length of the peak period in hours, so when it is normalized, the number of kilowatt-hours stored no longer makes a difference. For this reason, unless otherwise stated the amount of energy stored has been assumed to be one kilowatt-hour.

Figures 7, 8, and 9 give the ROI over 20 years for each technology under the WE Energy, BGE, and MECO pricing schemes respectively. These graphs clearly show that under current conditions there are no combinations of technology and pricing scheme for which this process is economically viable. None of the combinations have a ROI over -49% after 20 years or over -65% after 10 years. Only three combinations even have ROI's above the starting amount of -100% after the initial cost is incurred. This means that for all other pairs, there is no period of time at which they operate at a profit, the annual cost of O&M, annualized replacement, and energy costs are always greater than the annual revenue of reselling the energy.

All three of these combinations which have ROI's above -100% have the same pricing scheme, WE Energy's. This makes WE Energy's pricing scheme far and away the best of the three for this application. The defining characteristics of this pricing scheme are a large difference between peak and off-peak prices and a short peak period length. The large difference between peak and off-peak prices means more money is made during each daily cycle of buying and selling energy. The very short peak period length, only four hours, means that the system must be able to support high power levels in comparison with other pricing schemes to discharge all of its energy during the peak period, this increases the initial cost of the power conversion system and balance of plant, and increases the cost of yearly O&M. Because WE Energy's

pricing scheme is by far the best of the three it will be the assumed values of pricing for later analysis.

Of the four storage technologies, ZnBr batteries had the best performance for all three pricing structures. ZnBr batteries have relative low efficiency and moderate cost, but no balance of plant costs and relatively high replacement period. ZnBr batteries are also unique in that they are the only technology of the four that has a different replacement cost than its initial battery cost. While the initial cost for ZnBr is \$400/kWh, the replacement cost is only \$100/kWh, over the long term this can make a very large difference.

Of the other three storage technologies, Li-Ion was consistently worse than ZnBr and NiCd was worse than Li-Ion, however the ranking of Lead-Acid varied between pricing structures. For BGE and MECO's pricing schemes Lead-Acid was the worst technology by far, but for WE Energy's Lead-Acid was the second best behind ZnBr. Because efficiency is the only parameter of the storage technology that is affected by minimum and maximum energy price, this must be because of the very short peak period length. This means that the Lead-Acid batteries cost was much less affected by the requirement of high power. The cost is affected by power in two instances, the initial cost of the power conversion system and balance of plant, and the yearly O&M cost. The cost of the power conversion system is constant among all storage technologies and Lead-Acid has the same balance of plant costs as NiCd at \$50/kW and more than Li-Ion and ZnBr who both have no balance of plant costs. However, Lead-Acid has significantly less yearly O&M costs than the other three at \$5/kW/year compared to ZnBr's \$20/kW/year and Li-Ion and NiCd's \$25/kW/year. This difference is

enough to make up for Lead-Acid's higher initial costs due to high power, and due to the fact that O&M costs are yearly this will only become more pronounced.

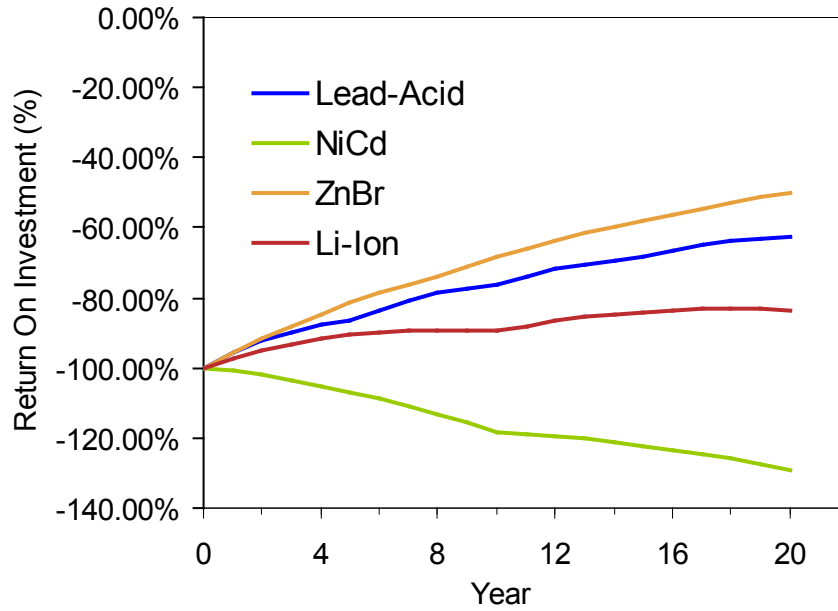


Figure 7: ROI vs. Time for WE Energy

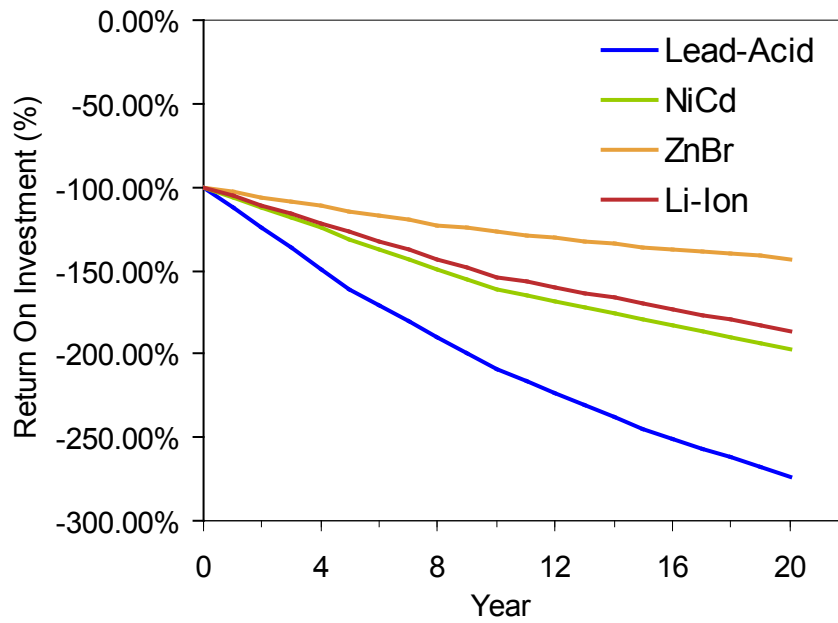


Figure 8: ROI vs. Time for BGE

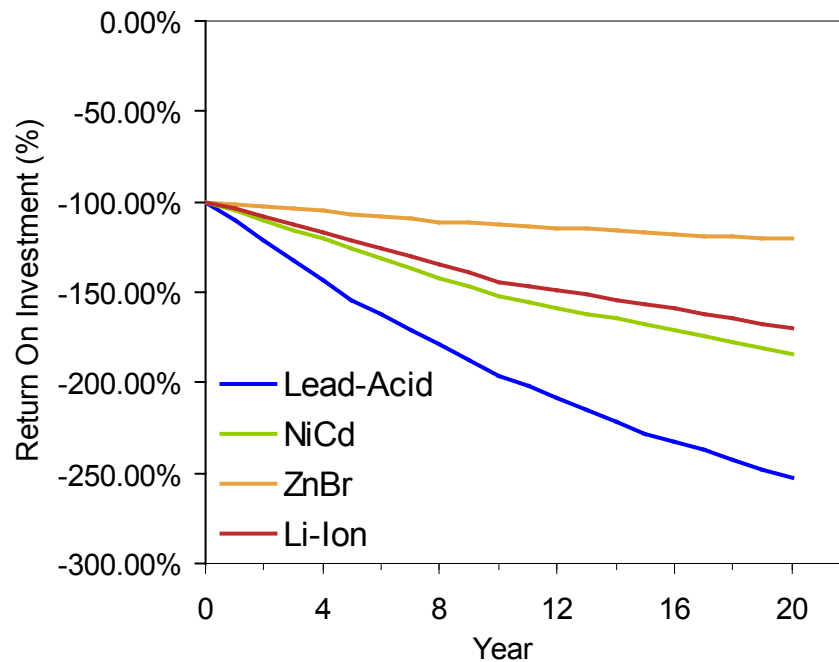


Figure 9: ROI vs. Time for MECO

Sensitivity Analysis

Having determined that under current circumstances this process is not economically viable the question of what parameters can change and how them being changed will affect the economic viability of this application. There are two main categories of these parameters, pricing structure and storage technology. Changes to pricing structure would need to be implemented by energy companies or enforced by government policy, while changes in storage technologies can be affected by advances in the technologies, the manufacturers, or subsidized by the government.

Pricing Structure

The aspects of pricing structure that can be modified to affect the economic viability of this application are the duration of the peak period, the minimum energy

price, and the difference between minimum and maximum energy price. Both the minimum price and the difference in prices are required because the efficiency of the system is below 100%, meaning that some of the energy bought at minimum price is not resold at the highest price, so the profit of a daily cycle can not be written purely in terms of the difference in price. Equation 17, below, gives the profit of a daily cycle per kilowatt-hour and the simplified version if efficiency could be 100%.

$$\begin{aligned} \text{Profit} &= p_{\min} - ep_{\max} \\ \text{Profit} &= p_{\min} - p_{\min} = \Delta p \end{aligned} \tag{17}$$

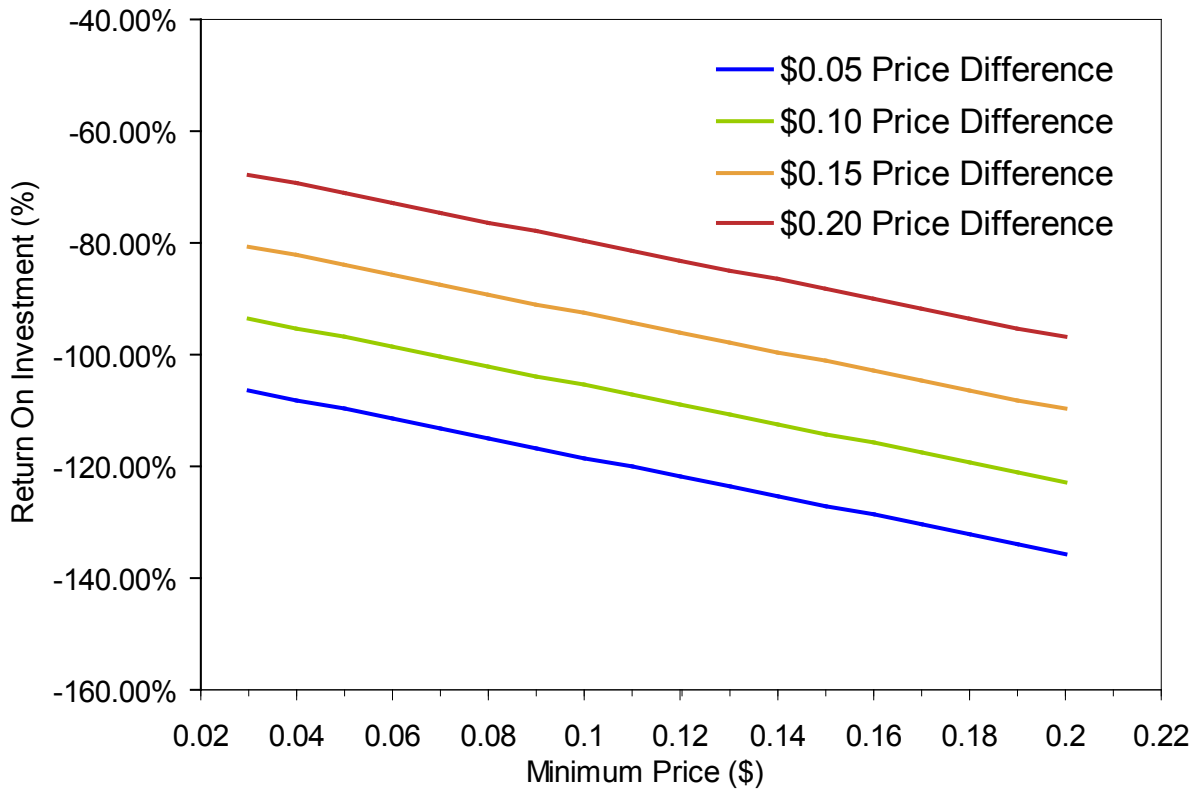


Figure 10: Minimum Price and Return on Investment for Selected Price Differences

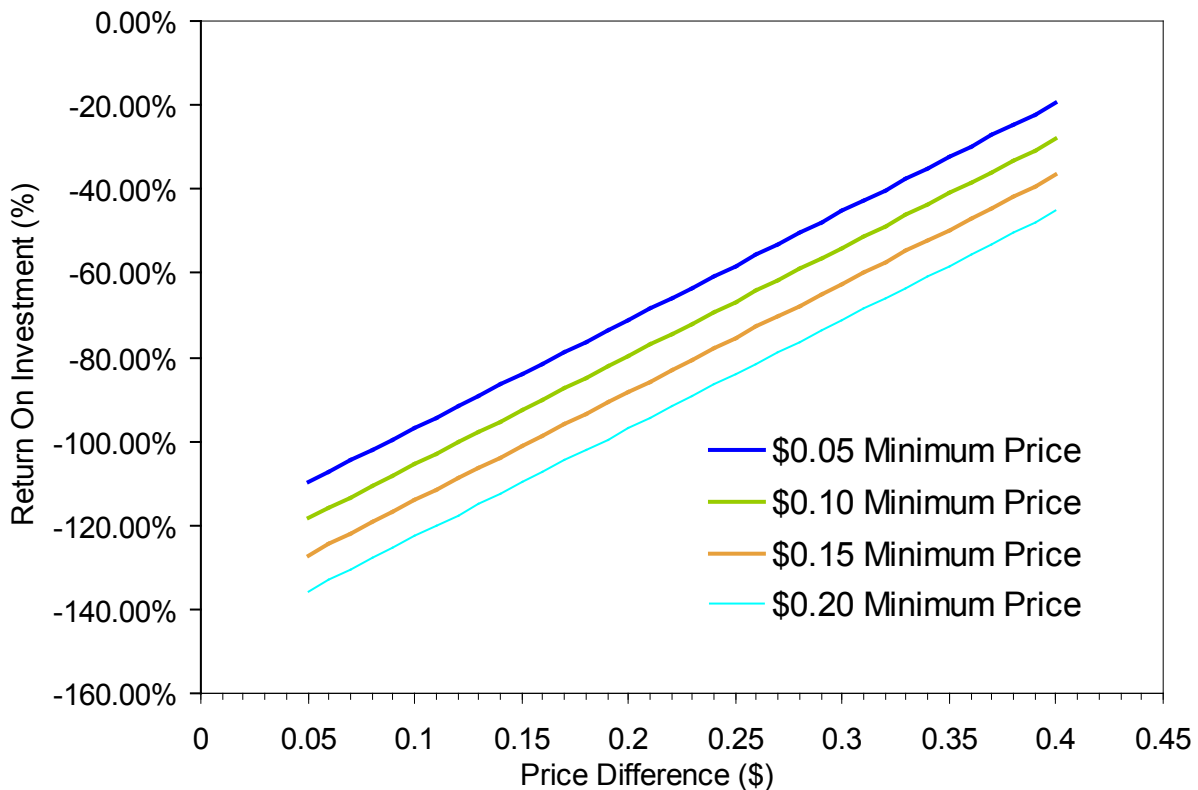


Figure 11: Price Difference and Return on Investment for Selected Minimum Prices

Figure 10 shows minimum price at selected price differences versus ROI after 10 years. This figure assumes that one set of prices is used all year, the length of the peak period is four hours, and ZnBr batteries are used. This shows that increasing the minimum price negatively affects the ROI of the system; this is because this increases the amount of money wasted by the fact that the system does not have 100% efficiency as this wasted energy is bought at the minimum price. The figure also shows that the effect of changing the minimum price is not affected by the size of the difference in prices.

Figure 11 shows price difference at selected minimum prices versus ROI after 10 years with the same setup as Figure 10. Increasing the difference in prices increases the ROI of the system, this is clear through inspection of both the figure above and the

model, because a larger difference in prices means more profit in the daily cycle in which energy is bought and sold. The figure also shows that minimum price does not affect the scaling of the difference in prices.

The length of the peak period affects the system in one way, the power the system needs to handle, decreasing the peak period length increases the power needed to discharge the entire battery during that time. Because decreasing the length of the peak period only increases costs by increasing power requirements, longer peak periods are better, up to the point where the model's assumption that the battery can be charged during off-peak times is no longer true, at 12 hours. Figure 12 shows the effect of changing peak period lengths between 4 and 12 hours on ROI of the system after 10 years using WE Energy prices. The values of ROI have been normalized to the value at a peak period length of four hours in order to facilitate comparisons between the technologies. The figure shows that while ROI increases with increasing peak period length, there are diminishing returns as it approaches 12 hours. It also shows that ZnBr batteries scale the best with decreased power; this is because ZnBr batteries have no balance of plant costs and the second lowest yearly O&M costs. NiCd on the other hand scale the worst because they have balance of plant costs and are tied for highest O&M costs. As the ROI is considered over longer periods of time, the scaling of Lead-Acid batteries will improve, because while they have balance of plant costs, their yearly O&M costs are extremely low compared to the others, which will make more of an impact as time goes on.

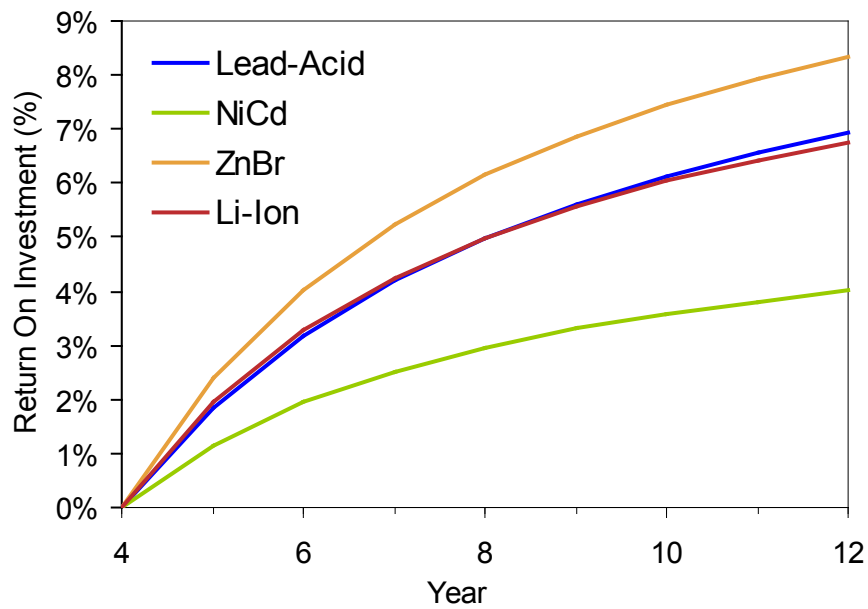


Figure 12: Peak Period Length and ROI for each Technology

Technologies

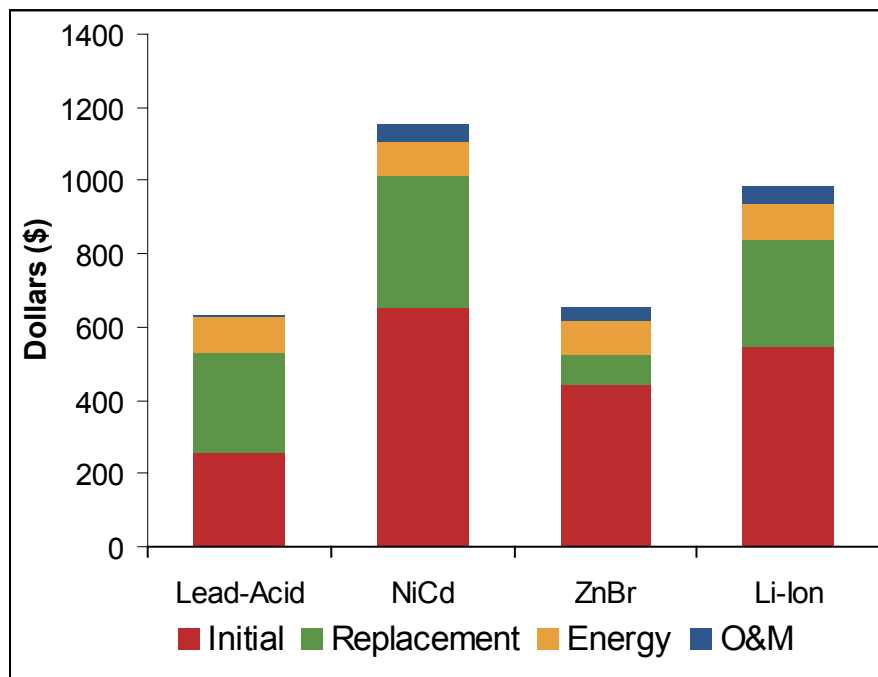


Figure 13: Cost Breakdown By Technology

Figure 13, above, details the cost breakdown of the four storage technologies after 10 years, this can be used to help determine which aspects of a technologies cost are the best the focus on reducing. It is important to keep in mind while considering these figures that initial cost is a one time payment and the other types of cost are recurring, meaning that over time they will increase while initial cost will shrink.

It is clear from the figure above that initial cost has a large impact on the overall costs of the system, even after 10 years have passed. This makes sense because initial cost is not subject to discount rate, because it happens at the beginning, and at 10 years replacement costs have only been incurred between one and two times. Because of initial cost's large impact on total cost it is a natural place to look to reduce costs and increase the economic viability of this application. Initial cost can be reduced by improvements in technology reducing the cost of materials or finding cheaper methods of production. It can also be reduced by the government subsidizing purchases of batteries for this purpose if the government wants to provide incentives for people to do this in order to help the grid provide energy more efficiently. Table 9, below, gives the amount the initial cost would have to be reduced per kilowatt-hour to make this process break even after 10 years.

	Lead-Acid	NiCd	ZnBr	Li-Ion
WE	-\$195.96	-\$775.88	-\$303.26	-\$487.19
BGE	-\$495.89	-\$1027.00	-\$543.65	-\$814.76
MECO	-\$428.39	-\$944.02	-\$466.58	-\$741.60

Table 9: Profit after 10 Years by Technology/Pricing Structure

It is important to note when considering the above table that of the 12 combinations only three of them are making money over time: Lead-Acid/WE, ZnBr/WE,

and Li-Ion/WE. These will have negative ROI until 10 years when they break even and start generating money, while the others will be have positive ROI until 10 years when they become even and start losing money. Of the three profitable combinations, Lead-Acid requires the least improvement in initial cost, followed by ZnBr and then Li-Ion, this is because Lead-Acid has the lowest initial cost, followed by ZnBr and Li-Ion.

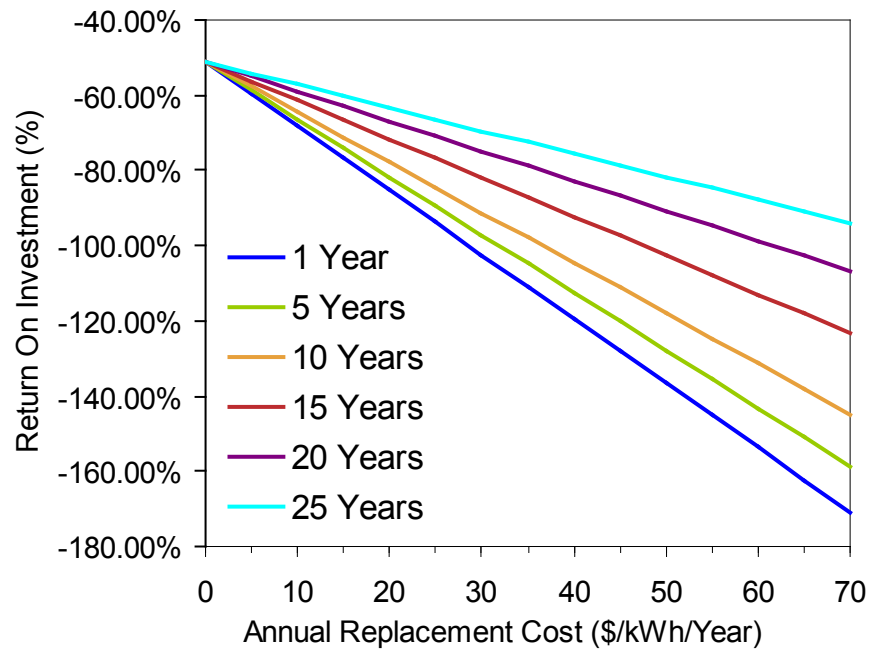


Figure 14: Annual Replacement Cost and ROI

Figure 14, above, shows the effect of the annual replacement cost on ROI after 10 years, where annual replacement cost is the cost of a replacement divided by how often the system needs to be replaced. This assumes ZnBr parameters other than replacement cost and replacement period and WE Energy parameters for pricing. The figure also shows additional effect that modifying the replacement period has beyond the change it makes on annual replacement cost. This additional effect is due to the discount rate applied when calculating present value, because the replacement cost is paid after a longer amount of time, the replacement cost is lower in real dollars.

O&M costs have a linear effect on ROI, halving the O&M costs reduces the total costs by half of O&M's cost, the effect on ROI then becomes clear when looking at the cost breakdowns. Because this depends on the total cost of O&M, increasing the cost of O&M increases the effect of lowering the rate. O&M costs scale off of the power required by the system, so increasing the power requirement makes the O&M rate more important, because of this short peak period length pricing structures, which increase the power requirement of the system, make O&M costs more of a factor. O&M costs are also a yearly cost, so they will become more important as time goes on and the initial costs become less and less relevant, as shown in Figure 15 below.

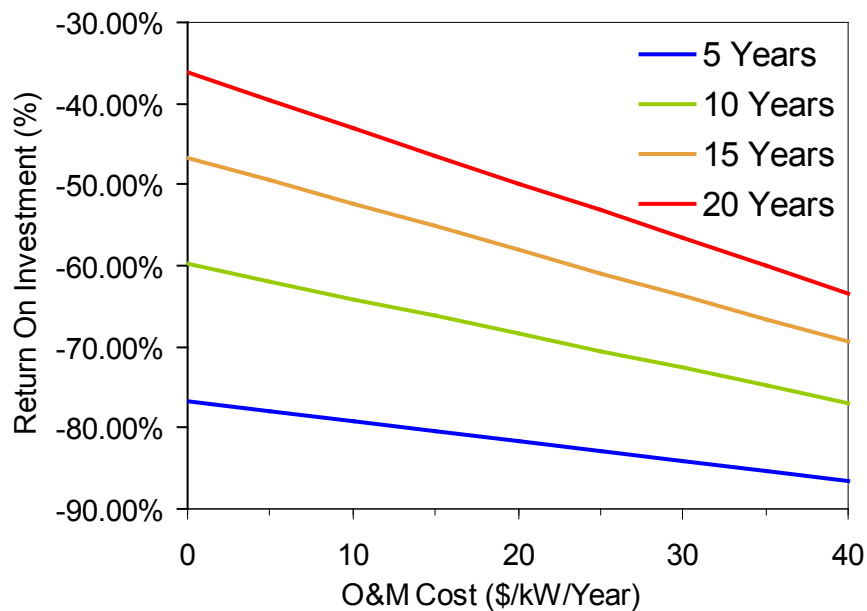


Figure 15: O&M Cost and ROI

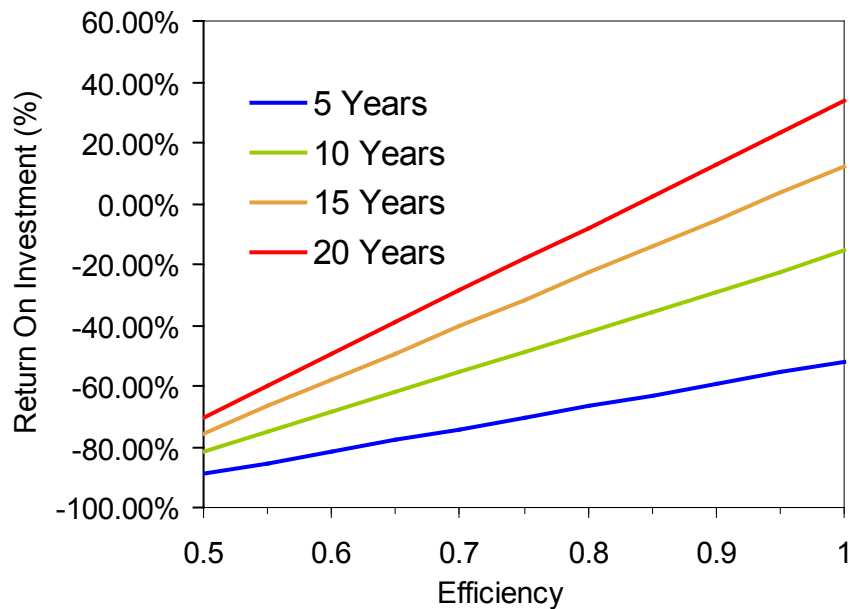


Figure 16: Efficiency and ROI

The efficiency of the system has a direct effect on the revenue generated by the system. Increasing the efficiency therefore increases the revenue, by increasing the percentage of the stored energy that can then be resold at maximum price. Increases in efficiency have a large effect on the system because rather than affect a portion of the costs, as many of the previous parameters have, efficiency effects the entire revenue, increasing the efficiency by 10% increases the revenue of the entire system by 10%. As this affects the yearly profit of the system, the effect of changing the efficiency increases over time; this is shown in Figure 16.

Conclusion

A model was created to measure the economic viability of storing energy during off-peak times and using that energy during peak-times, at the residential level. The model used the initial cost of the system as a function of energy stored and power

required, yearly O&M costs, replacement costs, the cost of buying energy, and the revenue generated by then reselling it to the grid. Four technologies were looked at in this study: Lead-acid, NiCd, ZnBr, and Li-Ion batteries. In addition, three time of use pricing schemes were used, from WE Energy, BGE, and MECO. It was found that for none of these technologies or pricing schemes was this process economically viable. Three combinations, Lead-Acid/WE, ZnBr/WE, Li-Ion, were profitable on a yearly basis, but never offset the initial investment.

The effect of changing parameters was also investigated, it was found that even after 10 years the initial investment was a large portion of total costs, with replacement costs also accounting for much of the total cost. The efficiency of the system was also found to be a large factor in the profitability of the system, due to its effect on the systems total revenue. Further research could be conducted into more technologies and pricing schemes, as well as research into specific batteries instead of an approximation of the technology as a whole, allowing the study to use more specific numbers for the battery's performance. In addition, further research could be conducted into generating a model which takes into account daily fluctuations in residential energy use and systems in which energy stored can be used by the residence, instead of simply reselling it to the grid.

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