ECONOMIC ANALYSIS OF LITHIUM-ION BATTERY ENERGY STORAGE SYSTEMS

A Thesis by

Daniel Gilchrist

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The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

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Visvakumar Aravinthan, Committee Chair

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Chengzong Pang, Committee Member

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Mehmet Bayram Yildirim, Committee Member

DEDICATION

To my wife and my parents.

ACKNOWLEDGEMENTS

I am grateful to my committee chair, and advisor, Dr. Visvakumar Aravinthan for all the encouragement and support throughout my undergraduate and graduate education. His mentorship was instrumental in where I am today. I would like to thank Dr. Chengzong Pang for his expertise and the education he has provided. His dedication to students has been critical to my development. I would also like to thank committee member Dr. Mehmet Bayram Yildirim for his support. My gratitude is also extended to the Department of Electrical Engineering & Computer Science at Wichita State University for all it has provided.

Most of all, I would like to thank my family for always being there for me and always being supportive of my pursuits.

ABSTRACT

Shifts in consumer behaviors in the power sector coupled with social and environmental policies have created a higher demand for reliable power and a desire to generate that power from less reliable sources. To bridge the gap in reliability between the power that is generated and the power that is consumed, it is up to the utility to deploy new strategies to face these challenges that have been created. One technology that can aid utilities in facing these challenges is a lithium-ion battery energy storage system (BESS). This thesis will present four common applications for BESS use in the power system which include load shifting, voltage support, back-up power supply, and frequency regulation. The economic feasibility of the use of this system will be presented by comparing the costs of traditional solutions to the cost of a lithium-ion BESS to satisfy the needs of the different applications. The cost comparison shows the potential benefits of deploying this technology. Market trends for lithium-ion battery costs will also be presented to demonstrate the increased potential benefit of the technology.

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LIST OF ABBREVIATIONS

BESS	Battery Energy Storage System
DoD	Depth of Discharge
EV	Electric Vehicle
kW	Kilowatt
kWh	Kilowatt Hour
LMP	Locational Marginal Price
LTC	Load Tap Changer
M	Million
MW	Megawatt
MWh	Megawatt Hour
O&M	Operation and Maintenance
PV	Photovoltaics
R&D	Research and Development
RTO	Regional Transmission Organization
UPS	Uninterruptible Power Supply

LIST OF SYMBOLS

$	U.S. Dollars
%	Percent

CHAPTER 1

INTRODUCTION

1.1 Introduction and Background

Technological advances in recent years have been invoking changes in the way people use power that have never been seen before. Not only do customers want more reliable power, they are more sensitive to any fluctuations in the systems due to the increase of electronic loads. These higher electronic loads make it more difficult for the utility to improve their power quality. In addition to this, social and environmental influence to reduce global carbon emissions have in recent years ramped up the implementation of renewable energy resources tied into the power system. These renewable sources include solar and wind energy ranging in size from residential use to utility scale installations.

The traditional power system has relied on centralized generation for many decades. This process involves a centralized station that generates bulk electric power for the power system. This power is typically supplied by a steam turbine which utilizes heat from burning fossil fuels such as coal or gas, and from nuclear boilers. In addition to hydro power, where geographically viable, these types of facilities have provided most of power supplied to the power system. This power is then transmitted long distances to surrounding load centers where it is then distributed to the end user for consumption. The underlying principle of the electric power system is that the electricity that is generated is being consumed nearly instantly. The only way to ensure the power system functions properly is to ensure that the electricity generated is equal to the electricity consumed by the end user while considering any losses on the system. To do this, the energy must be stored until it is needed. The energy is traditionally stored in the form of the fuel. Energy in the form of fuel such as coal or natural gas can be stored until it can be converted into electrical energy as it is needed. Once the electrical energy is generated it is consumed. This control over the energy in its fuel state has allowed operators the ability to maintain the system at a high rate of reliability as compared to the needs of the end user.

With the recent increases in deployment of renewable energy, one problem has become inherently clear. Which is the fact that renewable energy cannot be controlled. Whereas with traditional means, the fuel can be controlled. With renewable energy there is no way to control the fuel. With solar, we know when the sun is going to come up, and when the sun is going to go down. However, there is no way to control when a cloud will come by and prevent the sunlight from reaching the PV array. There is even less predictability with wind. For example, if the wind is not blowing, there will be no power from the wind turbines. This volatility in generation output has far reaching effects on the power system. With significant penetration of renewable energy on the power system there is an ever-increasing need for the ability to be able to store the energy harnessed from renewable sources.

Early attempts at storing electrical energy after it has been generated came in the form of pumped hydro. This process involves using the electric energy to pump water to a higher elevation which stores the potential energy to later let gravity do the work to convert the energy back to electrical energy using hydro generators. While this is a clever solution to utilize any excess electrical energy that has been generated, there are still limitations due to inefficiencies in the process [1]. While this technology pre-dates the recent push for renewable generation, the need for storage has always existed and newer technologies have made significant improvements in efficiencies for storage.

Battery technology is the latest storage technology to be implemented at the utility scale. Batteries can store electrical energy using a chemical process which differs based on the type of battery used. While there are many types of batteries that have been tested on the power system, lithium-ion batteries will be the focus in this thesis, due to the maturity of the technology and proven utilization on the power system. Battery technology has been around for many years but has only recently been adopted for use as a large-scale system benefiting the power system [2]. Restrictions in the technology itself has prevented the use at this scale. However, the technology has matured to the level of implementation. The most prevalent restriction to the widespread adaptation of the use of this technology comes down to economics.

This thesis will present the economic viability of this technology as a solution to existing challenges faced on the power system. Proven applications of the technology will be presented, along with the associated costs of the existing methods to overcome these challenges compared to the associated cost of implementing the BESS. The purpose of this thesis is to provide a high-level approach to the viability of a lithium-ion BESS as a competitive option for a utility to use to solve certain issues that may be presented.

1.2 Scope of Thesis

The scope of this thesis is to perform a benefit cost analysis to determine the viability of a lithium-ion BESS for utility use. This will be done by analyzing and comparing the costs and benefits generated by deploying this type of system compared to traditional alternatives in specified applications. The costs will be specified by tangible assets procured by the utility. The benefits will be specified by the potential revenue associated with this type of system. The social and environmental costs or benefits will not be included in the scope of this thesis.

1.3 Organization of Thesis

This thesis consists of five chapters. Chapter 1 introduces the background of the thesis. Chapter two is the literature review of market trends and levelized cost of storage. Chapter 3 presents BESS applications. Chapter 4 covers potential scenarios and the results for each of the BESS applications presented. Chapter 5 will include the results, and Chapter 6 is the conclusion and future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Market Trend

The use of battery storage on the power system has been around for a short time when compared to the amount of time that major power systems have been in use. Power systems became more prominent in the last part of the 19th century. However, it wasn't until a century later that the first BESS was used on the power system in 1987. Up until 2009 there were only a handful of large scale BESS projects. Most of these projects utilized lead-acid batteries, one utilized a Nickel-based battery, and five used a Sodium-based battery [3] [4].

It wasn't until 2009 that the first lithium-ion battery was used. After 2009 the use of BESS systems took off, with multiple different types of technologies being tested. The cost of the battery systems was still prohibitive through this period, but public financing and government incentives were able to offset some of those costs which proved to be beneficial to the testing of the different types of technologies. During this time the lithium-ion battery technology proved to be the best suited technology for multiple power system applications due to its efficient power and energy density. Efficiency in charging and low self-discharge rate are also advantageous for lithium-ion batteries [4].

After 2015, most new BESS installations were lithium-ion systems. Many of these installations were intended for use in PJM's frequency regulation market where the characteristics of the BESS became the best design to take advantage of the revenue streams available in this market. This is a great example of how the industry has been able to take advantage of this new technology for the benefit of the power system [4].

Another driving force behind the shift to lithium-ion batteries was thanks to factors in other markets, namely the automotive market. The demand for batteries for use in EV's has increased significantly in recent years which had helped to increase the demand for the batteries themselves, and a demand for an increase in R&D to improve the technology and manufacturing processes for lithium-ion batteries. This demand has helped to lower the market price for these batteries year over year to the point they are now. This trend is projected to continue until battery prices drop to less than $100/kWh [5]. This downward trend can be seen in Figure 1.

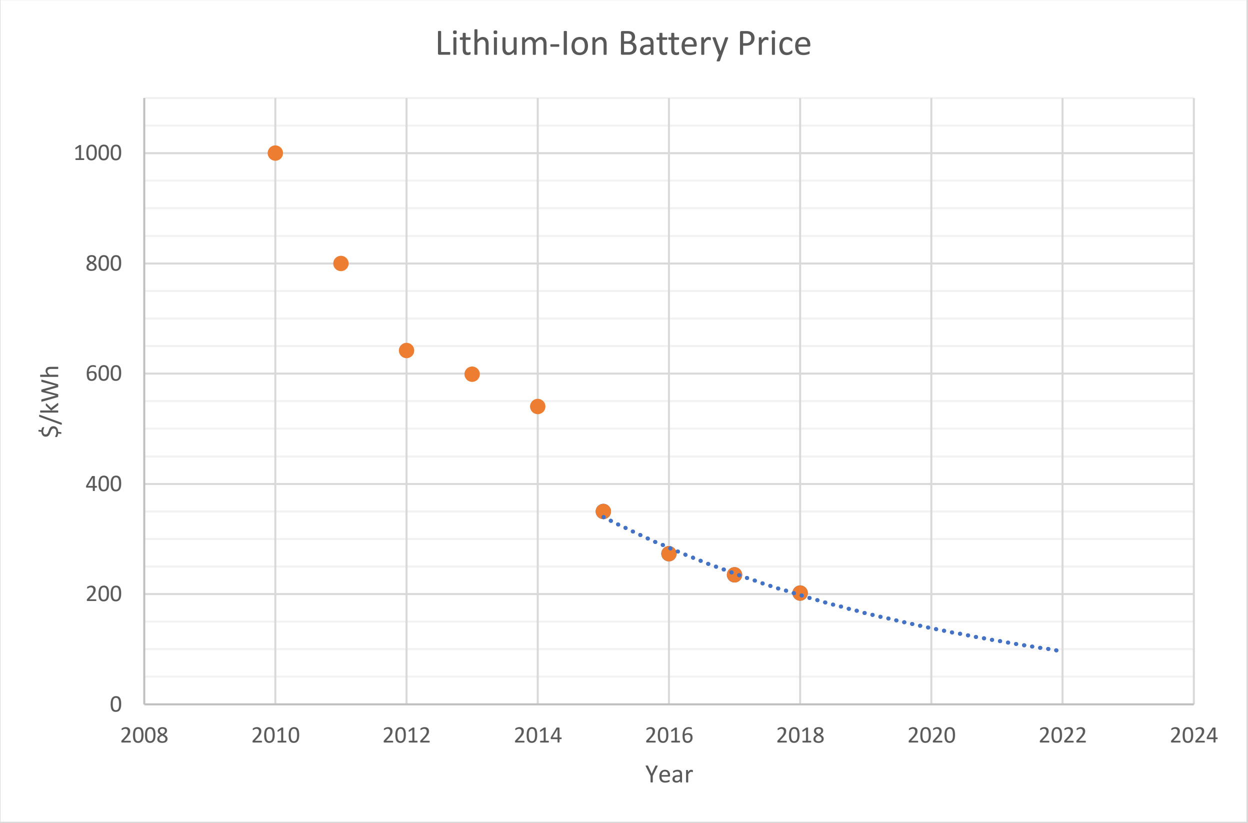

Figure 1: Lithium-Ion Battery Price Trends

2.2 Levelized Cost of Storage

A levelized cost of storage has been proposed by Lazard to analyze the levelized costs of different storage technologies compared to a base traditional alternative solution. The study analyzes two main categories of applications which include applications before and after the meter. Applications before the meter include topics such as transmission and frequency regulation, and after the meter includes microgrid and commercial applications [7].

Even in the unsubsidized section of the study there were storage applications that were competitive with the base alternative levelized costs. The study was done in 2015 and even with the cost at that time, lithium-ion storage applications in frequency regulation were shown as competitive alternatives to the traditional options. The only other storage technology that was competitive with the lithium-ion technology across most of the applications was Zinc storage. However, it was noted that this technology was not matured and had little industry deployment. The lack of data on this technology may have added to the lower cost [7].

The study also included a five-year projected cost based on a cost decline. This projection showed the lithium-ion technology declining at a much higher rate compared to other technologies. This rapid decline is likely due to the external driving forces discussed earlier. With the five-year projection considered, the lithium-ion technology outpaced the zinc technology to become the most economically viable storage option available. This projection also shows the lithium-ion storage solution to be competitive in most applications when compared to the base traditional case [7].

In this thesis we will look at four common storage applications on an individual basis and look more in depth at the comparative traditional solutions. By avoiding a base case scenario and comparing the alternatives individually we can get a more precise look at the economic viability of lithium-ion storage solutions at current market prices. We will only take into consideration the applications that are ahead of the meter to see how the technology can be of benefit to the utility. It is the goal of the utility to find the most economically beneficial solution to keep customer rates low and to maximize their return. The goal here is to show that lithium-ion storage technology can be a beneficial solution to challenges that utilities face.

CHAPTER 3

BATTERY ENERGY STORAGE SYSTEM APPLICATIONS

3.1 Load Shifting

One application for BESS is load shifting. With load shifting energy can be stored during valley periods when load and/or pricing is lower, then the energy can be supplied as the loads increase or as the price of generating the energy becomes higher. This application can be applied strictly to demand to reduce the magnitude of the peaks on a circuit, which can alleviate capacity concerns. It can also be applied to renewable generation. As we know, renewable generation is at the will of nature and cannot be dispatched according to demand. A BESS helps to control renewable generation by storing the energy when renewable generation is at its peak and exceeds the demand, then supply the energy when generation is lowest and does not quite meet the given load. This type of load shifting application can also be applied directly to the cost of generation to be able to store the most amount of energy at the lowest cost and supply it later to avoid having to use alternate forms of generation at a higher cost.

3.2 Voltage Support

Another application for BESS is voltage support. A BESS can be used in conjunction with renewable generation to maintain a steady supply of power from the utility source. Renewable generation is very sporadic. Output from a solar array can change significantly due to passing clouds which can block direct sunlight for a short duration multiple times a day. A decent sized solar installation can cause a large fluctuation in utility demand, and with that change in load comes a change in voltage supplied to any nearby customers. Wind generation also has the same issue due to varying wind speeds. This change in voltage is compensated for using LTCs and voltage regulators in substations and out on the line. LTCs and voltage regulators have a finite amount of tap changes they can make in their lifetime and once that limit is reached the unit needs to be replaced [7]. Due to the rapid changes in load inherent with renewable generation, the lifetime of the voltage regulation equipment is significantly reduced.

3.3 Back-up Power Supply

Back-up power supply is also a common application for a BESS. This type of application has traditionally been used at a smaller scale as a UPS to supply power to critical loads on the customer’s side of the meter. However, this can be scaled up to supply power to critical loads during the event of an outage. This is typically set up to supply power for a shorter duration of time, as outages lasting for hours are typically very rare. If they do occur it is most often related to an emergency event such as extreme weather. This type of system can last longer than other types of applications as the batteries do not cycle as often as other types of applications due to the infrequency of utility outages. This type of system may be more useful in areas where a redundant or backup utility feed may be cost prohibitive to construct.

3.4 Frequency Regulation

One other common application for a BESS is frequency regulation. It is very important to maintain frequency in a power system. If the frequency is not properly maintained the effects could be catastrophic resulting in major system wide blackouts. Traditionally frequency has been maintained by the ramping of generation to meet the given demand [8]. This process could take several minutes to reach a desired output. One distinct advantage a BESS has is that it can respond to changes in the demand in a matter of milliseconds. This results in a much more time efficient manner of regulating frequency versus traditional practices.

CHAPTER 4

BESS APPLICATION SCENARIOS

4.1 Load Shifting Scenario

TABLE 1

LINE LIMITS FOR FIGURES 2 AND 3

Line	Limit
13	20 MW
23	10 MW

TABLE 2

L1 LOADS FOR FIGURES 2, 3, AND 4

Time	Load (L1)
10p-7a	10 MW
7a-5p	15 MW
5p-10p	25 MW

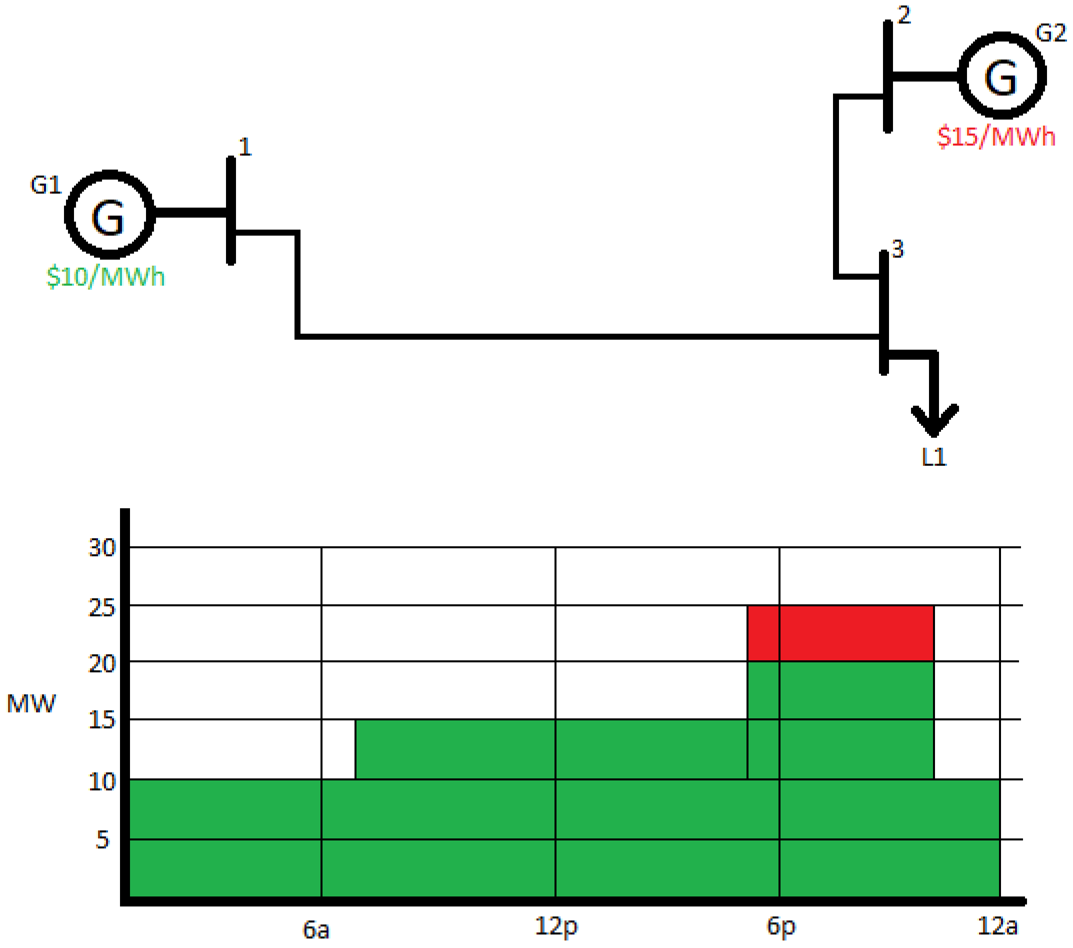

Figure 2: Load Shifting with Second Generator and No BESS

In this example, shown in Figure 2, using LMP techniques we can see that the preferred generator to supply the load would be from G1. The cost per kWh is lower on G1 than it is on G2 by $5 per kWh. The preferred method would be to always supply the full load from G1. However, due to the limit on the line from bus one to bus three being 20 MW we need to be able to supply the additional 5 MW from G2 from 5p to 10p. This extra 5 MW from G2 comes at a higher cost per kWh to be able to supply the load.

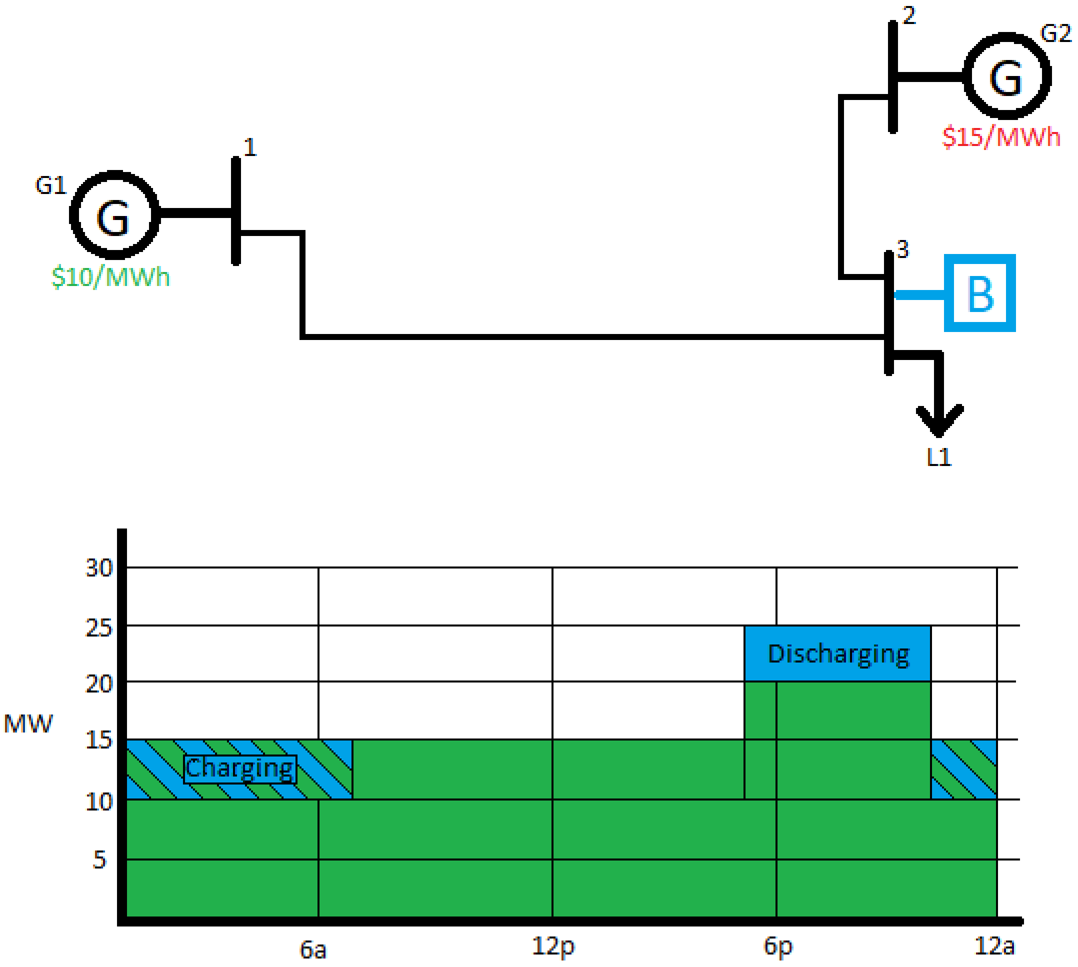

Figure 3: Load Shifting with Second Generator and BESS

In Figure 3, we see how the installation of a BESS can be applied to shift the load by storing energy when the load is lower, and supply energy during peak time to avoid needing to use the higher cost generator. In this figure we can see that the battery is consuming 5 MW of power from 10p to 7a. During this time the power being supplied to the load and the battery is only at a combined 15 MW which is still below the 20 MW limit on the line between bus one and bus three. Between the hours of 5p and 10p the BESS supplies 5 MW of power to alleviate overloading on the line and to avoid the need of using the higher cost generation during this time. Since the BESS was charged using the lower cost generation, a difference of $5 per MWh was saved.

This BESS would need to be a 5 MW/25 MWh system. A system this size on average costs around $340 per kWh [9]. This puts the total cost of the system around $8.5M. With a cost savings of $5 per MWh it would not be economically feasible to install a BESS in this scenario. However, if G2, bus 2, and the line between bus 2 and bus 3 were excluded from this scenario as shown in Figure 4, the economics of installing a BESS would be much more appealing.

TABLE 3

LINE LIMITS FOR FIGURE 4

Line	Limit
13	20 MW

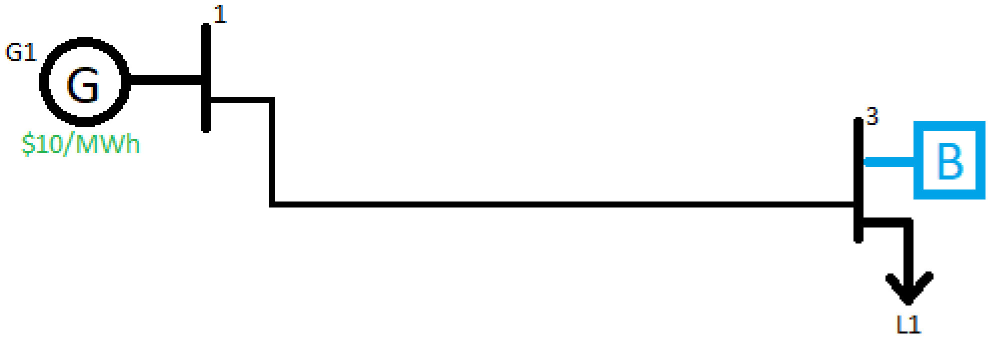

Figure 4: Load Shifting with BESS and No Second Generator

In this scenario, the only options for serving the load would be to install a new generator, upgrade the line, or install the BESS and apply load shifting techniques to serve the load while still staying within the line limits. The costs of installing a new generating facility are significantly higher than installing a BESS [9]. Additionally, the costs of upgrading a transmission line typically runs around $1M per mile. In this scenario the transmission line would need to be 9 or more miles in length to make the BESS the most economically viable option when comparing initial costs. One thing to keep in mind is the lifetime of the BESS. The cycling rate and DoD influence the overall life of the battery packs used in a BESS [10]. The battery packs make up approximately 60% of the overall costs of a BESS. At current rates this puts the cost of a battery pack right around $200/kWh [11]. If the battery pack needs replaced after 10 years it would be an additional $5M every 10 years that would need to be taken into consideration when determining the cost benefits of each available option.

4.2 Voltage Support Scenario

In Figure 5 a real-world example is shown of the output from a utility owned solar installation along with the utility feed from the circuit this installation is connected to. The load that the solar and utility source is feeding is also shown in Figure 5. The abrupt drop in solar output is due to cloud coverage on this given day. As clouds pass over the solar panel it blocks the sunlight from reaching the panel, thus resulting in a loss of power from solar generation. The load still needs to be supplied when the solar generation is lost, which must then be supplied by the utility source. With less load on the utility system there is less voltage drop which must be compensated for by the regulators on the circuit. However, as soon as the solar generation is lost, and the load is supplied by the utility system the voltage drop suddenly increases and the regulators need to change taps to increase the voltage. The inconsistent power generated by the solar installation mean the voltage regulator must change taps every time a cloud come by which can occur dozens of times in a day. Voltage regulators only have a finite number of tap changes that can occur before the unit need to be replaced [7]. The additional tap changes that occur significantly decrease the lifespan of voltage regulators that are connected to the same circuit as the solar generation.

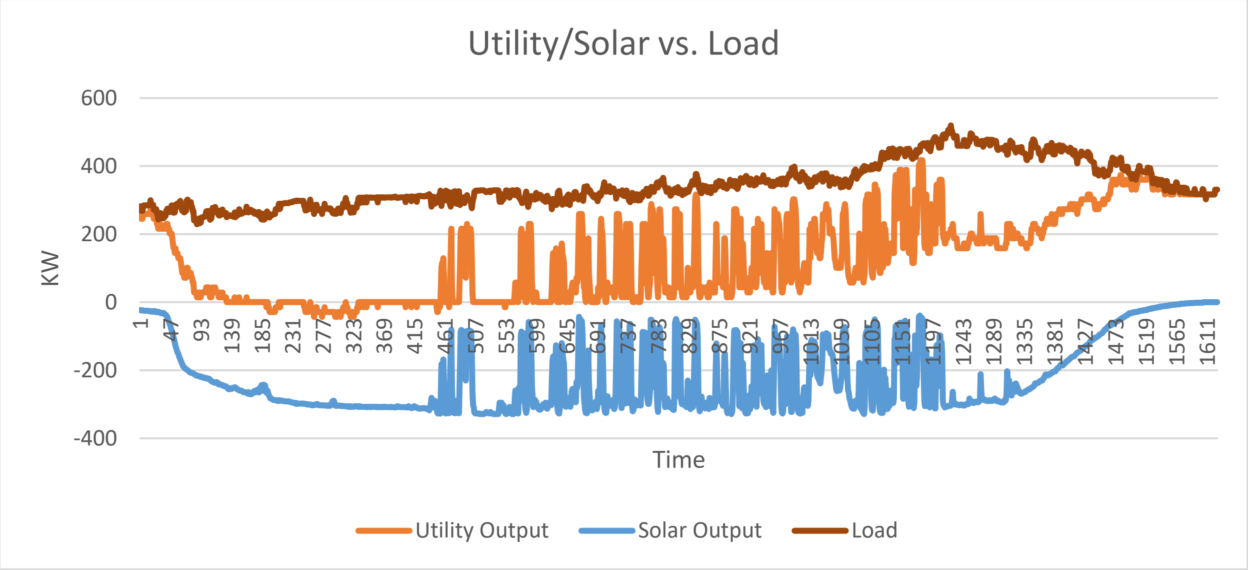

Figure 5: Utility and Solar Output vs. Load

One of the key benefits of a BESS is the ability for the system to handle significant changes in load without any decrease in system performance. The voltage output of a BESS remains consistent independent of the load it is serving. By utilizing a BESS in conjunction with a solar installation, the BESS can store a portion of the load that is output from the solar generation and then supply the load at times when there is cloud coverage and the solar generation is lost. By using the BESS to compensate for the brief loss in solar generation, the utility system sees a more consistent load which is illustrated in Figure 6. The wind and PV power shown is very sporadic, but when combined with a BESS becomes much more consistent. This more consistent load significantly reduces the number of tap changes that occur on a voltage regulator. The typical lifespan of a voltage regulator can thus be maintained, and the cost of needing to replace the unit more often is eliminated.

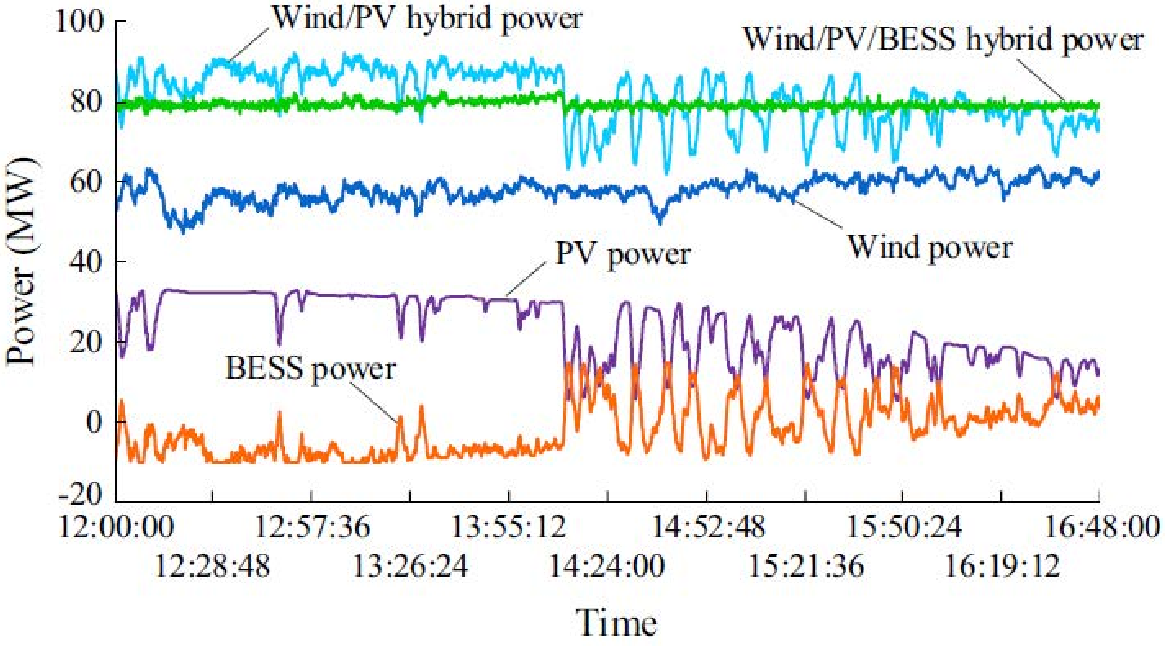

Figure 6: Individual and Hybrid Combinations of Renewables and BESS

While it is easy to see the benefits of adding a BESS in this scenario, we need to look at the cost associated with these benefits. The example shown in Figure 5 would require a 500 kW/300 KWh BESS to provide a consistent output from the solar generation. The cost of this installation at $340/kWh would be $102,000. The cost of replacing a set of regulators typically runs in the range of $50,000. The regulators can change taps anywhere from 100,000 up to 1,000,000 times before parts starts wearing out. In our scenario the regulator may change taps 150 times a day with the solar generation compared to around 10 times a day without the solar generation. At a worst-case scenario of needing to replace the unit after 100,000 tap changes, the regulators would need replaced approximately every two years. In this scenario the BESS would pay for itself after just 4 years. If the regulators were to last longer than 100,000 taps it would take longer to recoup the costs of the BESS. In this case the cost of battery replacement would be around $60,000. With a battery pack replacement approximately every five years [12], it would still make the BESS more economically viable if the regulators were able to maintain operation for up to 200,000 taps. Considering the decreasing cost that is expected for battery packs, the available operations of the regulator taps could be even higher while still maintaining the BESS as the best option.

4.3 Back-up Power Supply Scenario

Figure 7 is another real-world example of the utility feed on a circuit without any other forms of generation or redundancy to back feed the load in the event of an outage. As can be seen, there were three events over a year period that the utility feed was lost. This is typical for a utility as several different things can cause an outage ranging from storms, to wildlife, or even public damage such as cars running into poles. In this scenario, the customers on this circuit would remain without power until the damage can be isolated and repairs can be made. This could take up to an hour, or sometimes longer depending on the severity of the cause of the outage. This leads us into the next application of a BESS which is back-up power.

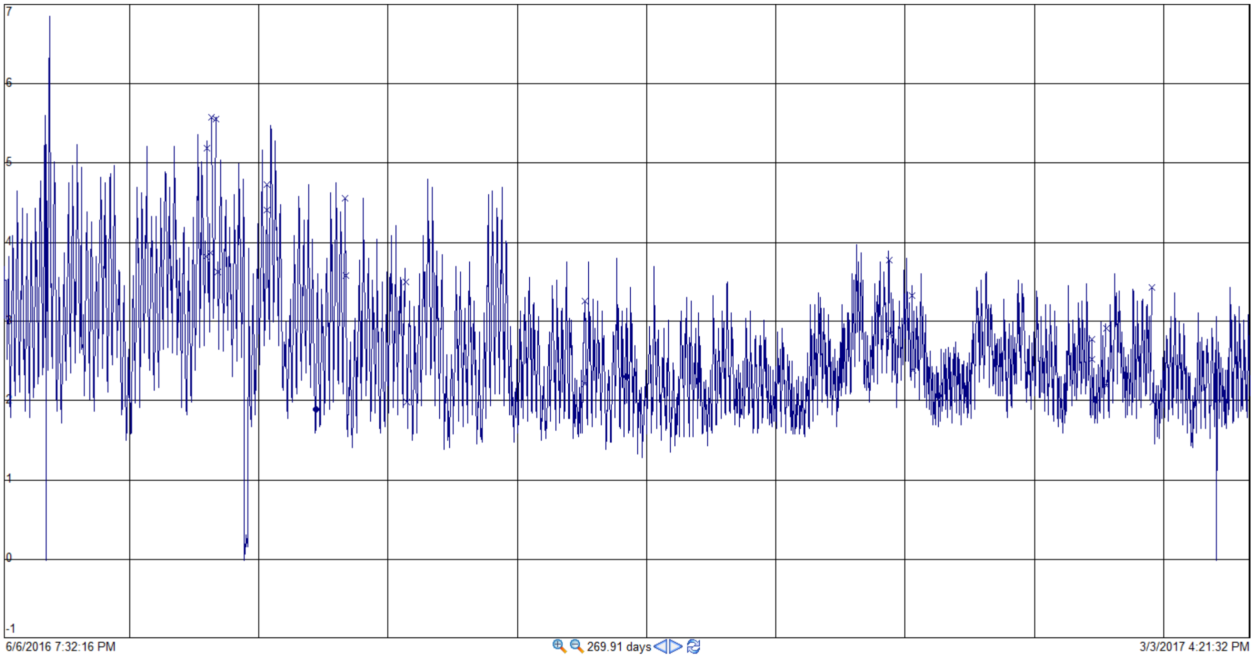

Figure 7: Power Supplied by Utility

In this application the BESS would be the main source of power for the circuit until the utility feed is restored. The system would remain in parallel with the utility feed to maintain a full charge, then be isolated from the power system if the utility feed is lost to continue serving the load without an outage being seen by the customer. To serve the load in the given scenario it would require a 6 MW/6 MWh BESS. At $340/kWh a system this size would cost approximately $2.04M. The only other alternative solution to serving the load when the utility source is lost is to install a different type of backup generation system such as a diesel generator. These systems typically run approximately $500/kW [9], which in this scenario would cost roughly $3M. While the initial cost of the system makes the BESS look more appealing, we still need to remember the battery replacement costs because batteries do not last forever. In this application the batteries are not going to cycle very often, so the life of the batteries could be extended. However, even if the batteries did not need to be replaced until after 10 years it would only take one replacement at the cost of $1.2M to push the decision back in favor of the diesel generation, even with the fuel costs taken into consideration. This is assuming the battery price at the time of replacement is the same as current prices. With the continued declining trend of battery prices, after 10 years the price of battery may be below $100/kWh. At this price the cost of replacement would be $600,000. This would make the BESS more cost effective for the next 20 years in this scenario.

4.4 Frequency Regulation Scenario

Frequency regulation is another common application for a BESS and is becoming more common each year. The key feature of a BESS being able to quickly respond to rapid changes in demand make it very suitable for a frequency regulation application. Also, with a BESS being able to act as a load in certain situations to lower the system frequency gives it a distinct advantage over traditional means of regulating frequency. Aside from storage, regulation can also be maintained using steam turbines, combustion turbines, hydro, and demand response. Cost savings can be made in some scenarios just based on initial installations costs. The cost for a combustion turbine plant can be around $1000/kW. The cost of a coal-fired steam turbine plant can be upwards of $2000/kW. This compared to around a $340/kWh cost for a BESS, initial savings can be made compared to other alternatives. A BESS has advantages over traditional turbine and hydro facilities due to their long ramp times. A BESS also has additional flexibility over demand response due to the ability to act as a load or power source, and full control is always maintained by the operator.

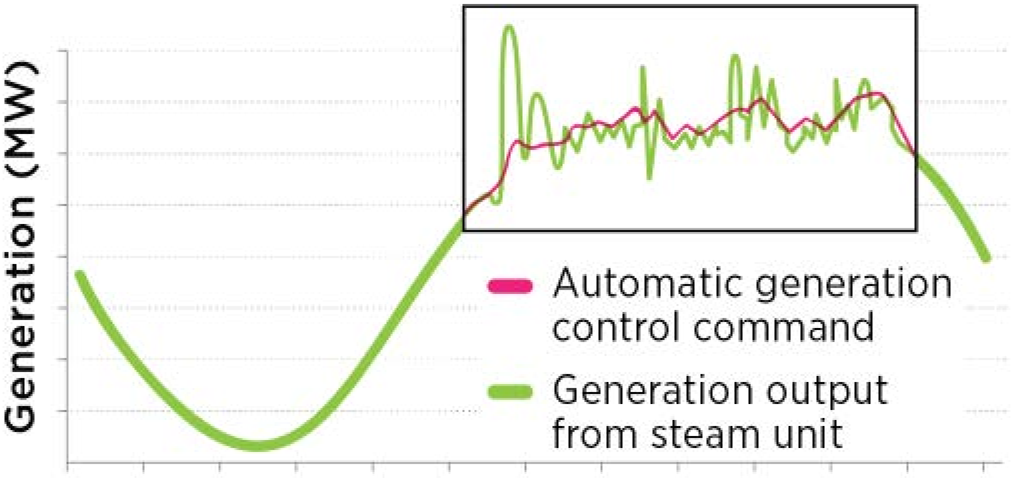

Figure 8: Generation Output vs. Frequency Regulation Signal

Another source of revenue can be stemmed from regulation markets. In regulation markets compensation is given to resources based on how they respond to signals from the RTO. In Figure 8 it shows how a signal could be generated based on the existing generation output. The response from this signal is how regulation helps to stabilize the system. PJM is an RTO that breaks up their signals into two types: Regulation A and Regulation D. Regulation A is for longer and slower fluctuations. Whereas, regulation D is for faster changes that require a near instantaneous response [13]. This is an example of how markets functions are evolving which are best suited for a BESS application. This additional revenue is more than enough to cover any maintenance/replacement costs for the BESS and has the potential to still make a profit for life of the system to potentially pay for itself all together. A case study by Xu et al. [14] uses the PJM market to calculate the potential profits from a 10MW BESS. Using the worst-case scenario, the operating profits are $381,100. At $340/kWh this system would cost $3.4M. Using this yearly profit, it would take less than 9 years for the system to pay for itself and continue generating revenue.

CHAPTER 5

RESULTS

5.1 Methods

For this thesis a benefit cost analysis was done to compare the viability of a lithium-ion BESS versus traditional means based on different applications as described in Chapter 4. The costs utilized are the costs of physical assets that would be procured by the utility. This includes the initial costs of the material and installation of the equipment, as well as any equipment replacement costs needed to keep the system in service. Any O&M costs were neglected based on the assumption that any options compared would require about the same amount of maintenance or monitoring. The benefits for this analysis were based on any revenue that might be generated by the deployment of a system. Revenue generated by the customer usage of the energy was neglected based on the assumption that the sale of energy would be the same for both options presented in each scenario. Social costs or benefits such as customer perception, and environmental implications such as reduced carbon emissions were not included in the scope of this thesis. The costs and benefits were compared over a 20-year period to analyze the viability of the use of this technology for utilities. Future battery replacement costs were determined using prices that are fixed at the current rate and prices based on declining costs as predicted by market price trends. The declining costs were based on an 8% reduction in costs until prices remain flat for lithium-ion batteries at just under $100/kWh. The battery costs make up 60% of the total system costs. The remaining system costs were assumed to decrease at the same rate as the battery costs [11].

5.2 Results

5.2.1 Load Shifting Results

In Figure 9 it shows that the decreasing battery costs will be make the BESS a more appealing solution than the alternative compared to battery costs staying fixed at current prices. The cost benefits of installing a BESS for load shifting plays an important role in saving existing assets. A BESS can be used to reduce loads that are close to exceeding the capacity on critical equipment. The more it costs to replace that equipment to increase capacity, the more viable a BESS becomes.

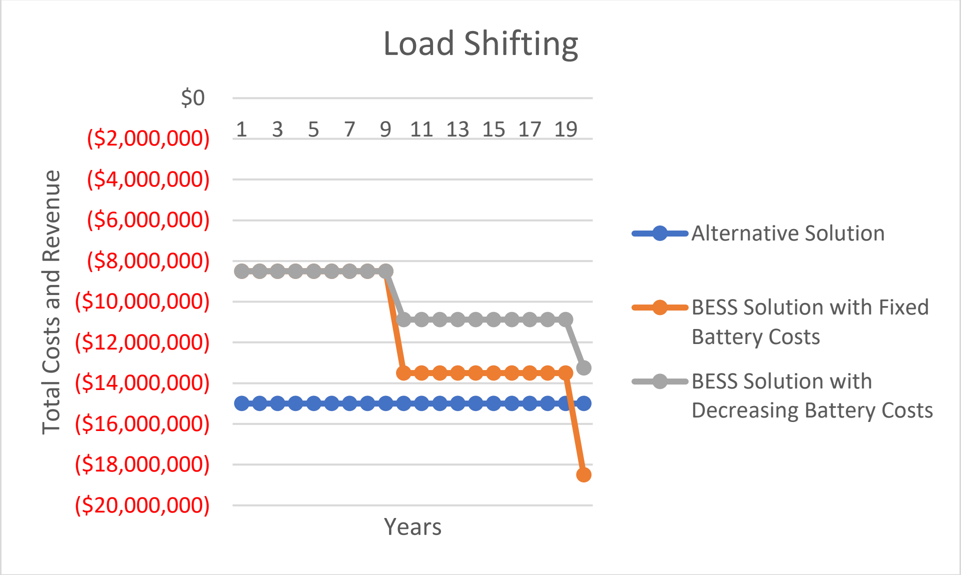

Figure 9: Load Shifting Results

5.2.2 Voltage Support Results

The use of a BESS for voltage support to maintain output from renewable generation becomes more cost effective when the size of the BESS can be smaller and still maintain adequate voltage. In this scenario, if we needed double the storage capacity to maintain voltage the battery costs would double. However, the alternative solution costs would remain the same making this option more economically viable.

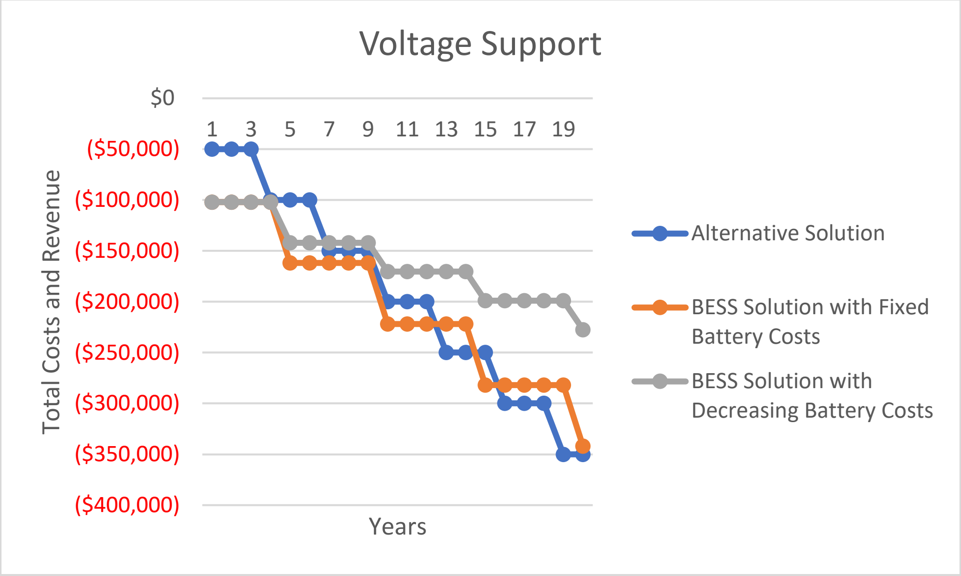

Figure 10: Voltage Support Results

5.2.3 Back-up Power Supply Results

For Back-up Power Supply, a BESS is a more economically viable option compared to the alternative solution based on the initial costs. However, the alternative solution could become more appealing depending on the life of the equipment. In this scenario after 20 years, due to equipment replacements, costs could potentially exceed the costs of the alternative solution.

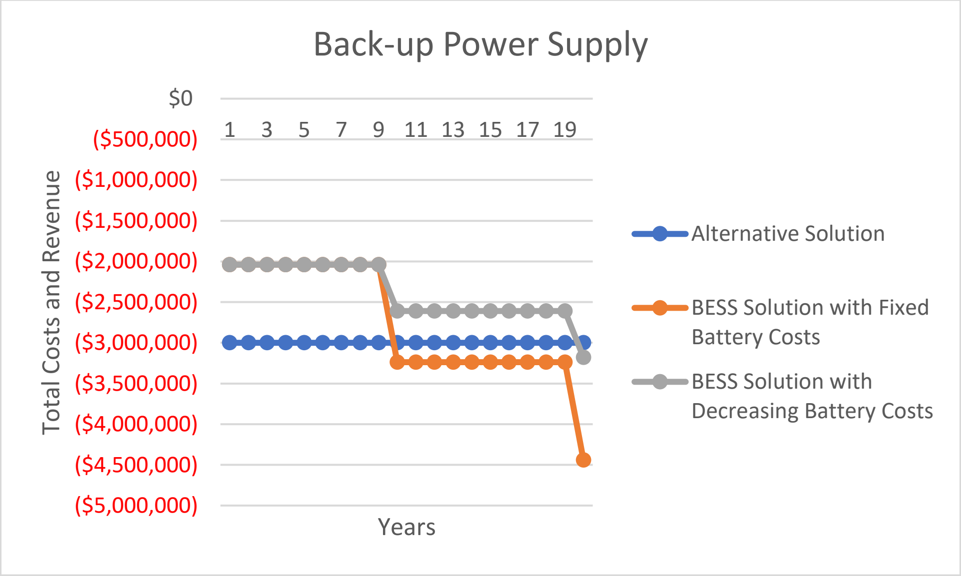

Figure 11: Back-up Power Supply

5.2.4 Frequency Regulation Results

For this scenario the benefits were based on a case study [14] from which the profits were used as the benefits. The profits in the study considered battery replacements costs which is why fixed and decreasing battery costs were not included in the comparison. The revenue generated in this study was based on a market that was designed for battery storage. Therefore, there is no comparable alternative. The alternative for this study is to not participate in this specific market, which would have no related costs or benefits. This scenario shows that the system could potentially pay for itself and continue generating revenue for the utility.

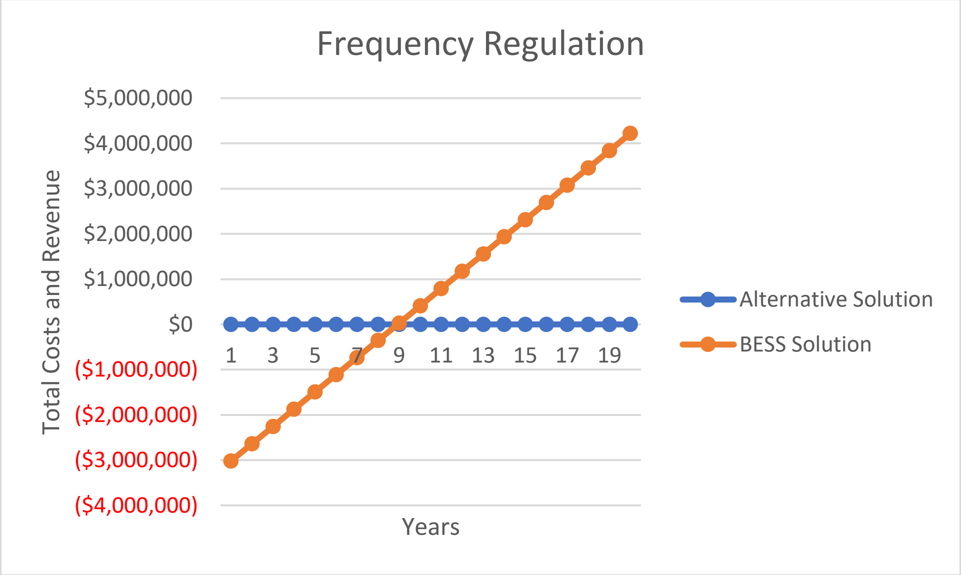

Figure 12: Frequency Regulation Results

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 Conclusion

Rapid technological developments in recent years have cause a shift in the way consumers use power. High levels of reliability have become an expectation for consumers. While at the same time, social and environmental policies have cause a shift in the way power is generated to come from a less reliable source. The intermittency in renewable energy is in stark contrast to the reliability that consumers demand. It is up to the utility to find a solution to this challenge. A potential solution to this issue comes in the form of a BESS.

This thesis shows that at current market prices a lithium-ion BESS is competitive with common alternative solutions to many of the issues that face the utility today. The scenarios presented show single use BESS solutions for specific applications. Additional benefits may be gained by applying a single BESS for multiple different applications. For instance, using the same BESS for voltage support and load shifting could maximize the benefits gained [15]. The flexibility of this system provides numerous capabilities that a utility could harness to provide their consumers with reliable power to meet present day demands. Future lithium-ion battery price trends predict prices to drop by nearly 50% in the next 5 years. While prices could stagnate at this point, it could also produce a higher demand in batteries for use in storage applications [16]. This increase in market demand could also produce even more of a demand in R&D for lithium-ion technology [17]. The push for R&D could produce enhanced performance from the technology to last longer and require fewer batteries than current technology allows. Lithium technology in power systems has been around for less than a decade which is a very short time for most power system technology. A lithium-ion BESS is proven to be a formidable tool available to utilities. Further adoption needs to be generated for the benefit of the power system and consumers alike.

6.2 Future Work

For future work, specific case studies can be analyzed to prove these findings in a real-world situation. Additional scenarios can also be reviewed to see how a lithium-ion BESS may be more economically viable in other applications. The use of lower cost batteries recycled from EV's at a lower capacity can also be analyzed in each of these applications.

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