The Impact of Different Battery Technologies for Remote Microgrids

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THE IMPACT OF DIFFERENT BATTERY TECHNOLOGIES
FOR REMOTE MICROGRIDS

BY

ALI BARJS ALLRUWAILI

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

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South Dakota State University

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THE IMPACT OF DIFFERENT BATTERY TECHNOLOGIES
FOR REMOTE MICROGRIDS

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science degree in Electrical Engineering and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Energy storage systems are considered an effective solution for remote microgrids. They allow to increase the overall system reliability, performance, and reduce operational cost by increasing the energy utilization of renewable energy resources (PV and wind energy). A battery can reduce the system's operational cost by matching a diesel generator with the load demand. There are many types of batteries which can be used in remote microgrids, such as Lead-acid, Lithium-ion, Zinc-bromine and Aqueous Hybrid Ion. By selecting a battery which provides low operational cost and longer battery life is complex, relying on many key technical features which affect the battery behavior, including efficiency, cost, and state of charge. This thesis presents the feasibility of different battery types in a remote microgrid, such as lithium ion, lead acid and unique batteries, which uses an energy management system (EMS).

The EMS uses two layer power management system: 24 schedule day ahead and real time dispatch. The schedule layer uses a goal programing approach to combining two objectives fuel and the battery wear cost. The combined objective function was minimized. It has been validated this method through a simulation study of a microgrid using IBM CPLEX v12.6.1 optimization software. A desktop with 4 GB RAM and 3.00
GHz processor was used to solve the optimization problem (goal programming approach). The time for each yearly simulation result was about 3 hours. Weight plays a significant role in achieving the goal. The weights determine the use of the generators and batteries in the objective function. Therefore, selecting a weight set point can play a significant role to provide an efficient solution for an EMS. Battery wear cost is a key factor in designing the remote microgrid.

The results showed the Tesla battery with EMS could provide 2.91% more cost effective than AHI, 4.99% than ZBB, 3.92% than lead acid, and 6% than lithium ion. Though the Tesla battery is of the lithium ion family, it is uniquely better than standard lithium ion due to its high capacity, round trip efficiency, small size, and 100% depth of discharge, which made it better than any lithium ion battery. Therefore, the Tesla battery is considered a unique battery. Also, using a Tesla battery with EMS can be 6% more cost effective than using normal lithium ion batteries. The Tesla battery, which has the lowest wear cost comparing to others, represents the most efficient solution for this study according to total operational cost of approximately $111,010 and nine year lifetime.
CHAPTER 1: INTRODUCTION

1.1 Background

Energy is very important in our lives, since most of our modern life sectors depend on electricity, including universities, factories, companies, hospitals and more. Without energy, life would be more difficult, slower and less efficient. The increase in the human population of the world has led to an increase in the electrical load demand. So, meeting this growing demand has led to an increase in fuel consumption, because the fossil fuels (oil, natural gas and coal) are the primary source of fuels in the world. The world has a high demand for oil; it was reported that oil use is approximately 1000 barrels per second, which equates to around 2 liters a day for every individual living on the earth [1]. According to the International Energy Agency (IEA), 17% of the world's population (1.2 billion people) needs access to electricity, so many people from remote areas are connected to a microgrid that operates at high cost. The IEA reports that to achieve its objective of universal access to electricity, 70% of the rural areas require a connection to a remote microgrid [2]. Finding effective solutions to meet the load demand and decrease fuel consumption is very important for remote microgrids.

A remote microgrid is defined as a small power supply system that can provide energy to a specific area. It can consist of an accumulation of renewable energy sources and load. It can operate as off-grid (island modes) [3]. The microgrids must have individual energy sources, energy storage, load demand and a controller in order to operate both with the larger grid and off the grid [4]. Remote microgrids might have one or more energy sources such as solar photovoltaics (PV), wind turbine, battery or diesel
generator. The integration of the microgrid's energy sources must have the ability to serve the load demand [5]. Typically, the main source of energy in microgrids is the diesel generator because of its low initial investment, good system stability, and easy transportability. However, the cost of energy varies during time Figure 1.1 present the fuel fluctuation since 2003 until 2012. The cost of the energy can reach $2.5/kWh [6]. The integrated of renewable energy such as (PV and wind) with the remote microgrids fossil-fueled system (diesel generator) can reduce fuel consumption [7].

![Power generation and fuel cost savings over time](image)

Figure 1.1 Power generation and fuel cost savings over time [8]

In this thesis, the focus is on system that depends on diesel generator, as the primary energy source, with the renewable energy sources working in tandem with the diesel generator to meet load demand. The primary purpose of this combination is to reduce fuel consumption. In addition, a battery bank can be used in this system to meet the peak load demand for a short time, and this battery bank can be charged with either renewable energy sources or the diesel generator. One of the solutions to reduce fuel consumption is using Energy Management System (EMS). Typically, EMS use two layers schedule and real time dispatch. The objectives of these layers are to manage the
microgrid power between the load and sources, balance the power, obtain minimum fuel consumption, and prolong the battery lifetime.

The majority of the remote areas around the world depend on fossil fuels in order to meet their load demand. So, high fuel cost could cause a massive increase in the cost of energy generation in remote areas. Other disadvantages include the operational costs and maintenance, as well as the pollution from generator use. A diesel generator's size must meet peak load demand during the day. The load is expected to be low (light load) most of the day and night, which means the diesel generator must operate in a low load mode, which causes problems such as very low efficiency, a high amount of fuel consumption and high levels of carbon emissions.

Typically, one of the primary renewable energy sources is solar energy generated by photovoltaics (PV). PV is a device that can convert solar energy (sunlight) to electrical energy by using different types of semiconductor materials such as silicon, polycrystalline and thin Films. PV has many applications, such as commercial, industrial, community, utility and remote off-grid. Using PV in a remote microgrid is valuable, based on its low energy cost and reduced fuel consumption. According to Solar Energy Industries Association (SEIA), the decreasing price of solar photovoltaics has made solar more available than ever; the price of PV systems has dropped by 33% since 2011 (Figure 1.2) [9]. However, the PV energy resource cannot generally meet the load demand. While adding PV to a remote microgrid can decrease the load on the generator, it can also cause low fuel cost. Two methods may be used to keep a diesel generator operating in a minimum loading mode, either PV power curtailment or a dump load [10]. Therefore, using a storage system may be the best solution to resolve this problem.
An energy storage system is a very important component in any remote microgrid since it has a high impact on the system. For example, it can make the diesel generator synchronize with the maximum load demand, decrease the operational cost of the system and improve the efficiency, performance and reliability of the system by matching the power demand with the generation sources. Furthermore, the battery can increase dispatch of the renewable energy sources in the remote microgrid. Also, using the battery throughput heavily can reduce fuel consumption. This storage system may also have an impact on a remote microgrid system through the utilization of $PV$ for extra energy storage [11]. A storage system is able to provide more stability for the system by injecting power to create a balanced supply and load demand to avoid any fluctuation in the load side or the supply side. Three types of storage technologies are available for electricity: electrical energy storage (capacitors and supercapacitors), mechanical energy storage (flywheels) and chemical energy storage (the type considered in this thesis).
Chemical energy storage, also called electrochemical energy storage, includes many types, such as zinc bromine, lead-acid and lithium ion [12].

The need for efficient energy storage has led to the development of new and unique storage technologies which promise reliability and increase the use of renewable by matching the load demand with the generation sources in order to reduce operational cost. One of the advantages of a battery is its ability to balance between supply fluctuations and the growing demand of electricity. Also, for short duration applications, the battery can provide frequency control and stability, while for a longer duration, the battery can provide energy management. Energy storage systems can be used to supplement a shortage of primary energy sources to meet load demand, as well as produce energy at peak load demand. As shown in Fig 1.3 the energy produced can be stored and used later.

![Figure 1.3 System response over the day with storage](image)

Figure 1.3 System response over the day with storage [13]

Figure 1.3 shows the benefit of using energy storage in an electrical network. Incorporating storage in an electrical network allows the system to handle the demand
efficiently. It is clear to see that the storage system is charged by the generating plant during the early hours of the day, from 0 to 6 am (at low demand). After that, the demand increases until midday. During peak demand starting around 6 pm, the storage is taken into account, so it runs only 4 hours of the day, which leads to a decrease in the operating cost of the system. During the rest of the day, the generating plant takes care of the load, and the storage system is charged by the generating plant.

The EMS has a significant impact on improving the microgrid system efficiency. However, integrating a diesel generator with a renewable energy source and battery bank can improve many aspects of the remote microgrids, such as the overall system efficiency, by reducing the fuel consumption and the operational cost. An EMS must manage the energy between load and energy sources in the system. The novel EMS considered in this thesis focuses on two aspects: battery lifetime and fuel consumption.

The main goal of the EMS is to gather the corresponding weights, $W_1$ and $W_2$ [10]. The goal programming approach is a multi-objective optimization technique that uses weights ($W_1$ and $W_2$) to achieve the EMS goal, minimize the operational cost of the system and prolong the battery life of the system by using an EMS algorithm. This research is based on the EMS algorithm which was developed by Santosh et al [10].

1.2 Literature review

This section presents remote microgrid, which uses renewable energy, a diesel generator and battery storage. The EMS, and techniques used to solve the optimization problem and the economic operations of a remote microgrid system, are discussed further, the energy storage techniques used in remote microgrids and, how affects the
system, and which energy storage system is suitable for a remote microgrid, are discovered followed by the factors that can influence energy storage in remote microgrids.

Currently, many techniques have been developed to solve the optimization problem in EMS. One of the techniques, developed by Santosh Chalise [14], uses a multi-objective function to optimize the remote microgrid system. This system expected to reduce the total operational cost of a remote microgrid system, by reducing the fuel consumption and prolonging the battery lifetime. The results show that the lifetime of the battery was improved from 1.42 years to 5.28 years and the total operational cost was reduced by around 9%. This paper only considered a lead-acid batteries, however, so it could be more effective if different types of batteries were considered.

Wencong Su [15] developed two stochastic techniques for microgrid power scheduling: day-ahead and real-time. The main purpose of this study was to minimize the operational cost of the system and the power loss by providing the integration of renewable sources. This paper offers a unique study of power loss by studying the IEEE 37 bus feeder. Results indicate that there was no supplementary reward for storing more energy in a battery, so no solution was offered for optimal battery use.

A study on economic operations and improved reliability was presented by B. Zhao [16] Different factors were considered in remote microgrids, such as utilization of renewable energy and battery life. The battery factors studied included operational cost, life loss cost, maintenance cost, fuel cost and environmental impact. The goals of this study were to reduce the generation cost and increase the lifetime of the lead acid battery.
The International Energy Agency (IEA) researched [44] on improving the stabilization of a mini-grid by using different types of energy storage. The report discussed the ways that storage affected the stability of the mini-grid by matching load power with power generation. Nine energy storage technologies were considered: lead-acid, lithium ion, nickel-cadmium, sodium-nickel-chloride, redox flow battery and flywheels. According to the results, some batteries are not suitable for mini-grid stability. Energy storage has to have specific characteristics to be suitable for mini-grid stability, including high power density, minimum two minutes for discharge duration, high efficiency and low cost. The best energy storage technologies, according to this study, are lead-acid, Lithium-ion, double-layer capacitors \( DLC \), and flywheels, with lead-acid being the most effective. Flywheels and \( DLC \) have a high \textit{DOD} life cycle and fast response time, which make them useful for applications with high power density [44]. However, the influence of EMS was not considered.

Power-Thru [17] presented a battery technology that is used for backup and UPS systems. This report presents different factors affecting battery life, including expansion, corrosion, plate loss, temperature, design life cycle service, and overcharging, undercharging, DC ripple current and manufacturing variations. Lead acid was noted as a reliable battery due to its low need for maintenance. The battery lifetime was designed to be 3 to 10 years. This report considers only lead acid batteries.

Researched about different energy storage technology which used for remote microgrid [45]. The researched study the feasibility of Aqueous Hybrid Ion (AHI), Lead acid battery, ultra-capacitors \( UC \) and Lead acid battery. It considered only one battery of each type. Also, the research present a cost analysis of the battery with EMS in the
remote microgrid. The result shows Tesla battery and AHI battery are the most efficient battery. On the other hand, UC has a very high operational cost. Lead acid and lithium-ion have a high wear cost which leads to high cost. The research considers only one battery of lead acid and lithium-ion. So, according to the number of Lead acid and lithium-ion battery types and manufacturers, one battery cannot present Lead acid or lithium-ion family. The research is lacking to be comprehensive. Also, it is not considered other battery type such as redox flow battery.

The literature focuses and considers some different types of batteries which mean it lacks an economic analysis. Also, the literature is not considered the fuel consumption of the generator and the battery life time.

1.3 Motivation

There is a strong need to identify cost-effective energy storage technology to be used in remote microgrids with EMS to operate with a long lifetime for a remote microgrid.

1.4 Objectives

The objective of this research is to perform a feasibility study on the most effective batteries for remote microgrids in order to minimize the operational cost of the system and prolong the battery lifetime. Analyzing different types of batteries for remote microgrid systems.
1.5 Organization of Thesis

*Chapter 1* presents a background about the remote microgrids, EMS, and batteries. Also, it discusses the some Literature Review which helped to improve thesis. It presents the motivation and the objectives of the thesis work.

*Chapter 2* presents the microgrid system components and different energy storage technologies which are used in remote microgrids, and will discuss the specific characteristics of batteries in a remote microgrid.

*Chapter 3* presents the procedures for modeling and simulation of the goal programming approach algorithm. Also, describe implementation details and case studies of the simulation.

*Chapter 4* Presents the simulation results, Comparison of Batteries and analysis.

*Chapter 5* Presents the conclusions and future work.
CHAPTER 2: THEORY

This chapter presents the components which are currently used in remote microgrids, such as PV, diesel generator and battery (wind turbines are not considered in this thesis). Also, it discusses the various types of batteries that can be used in remote microgrids and the principle of operation of these batteries, including specifications and chemicals. The last part discusses the EMS in remote microgrids.

2.1 Remote Microgrid Components

A diesel generator, battery, and renewable energy sources are major components in most microgrids. Figure 2.1 shows remote microgrid components with an EMS.

![Figure 2.1 Diagram showing remote microgrid components](image-url)
2.1.1 Diesel Generator

Generally, diesel generators are considered one of the primary energy sources in remote microgrids. They play a significant role in meeting the load demand for electricity and can improve a microgrid system in areas such as reliability and performance. A diesel generator is strongly correlated with load and efficiency. Figure 2.2 shows the 30 kW diesel generator characteristics curve. According to Figure 2.2, the diesel generator obtained maximum efficiency when it operated in a full load mode. Also, the power output and the amount of fuel consumption per hour, which presented by 2.1 is a quadratic curve (positive correlation).

![Figure 2.2 Typical fuel consumption of diesel generator and efficiency](image)

\[
Fuel \ _\ Consumption(vol/\ hr) = (a \times P^2 + b \times P + c)
\]  

(2.1)

Equation 2.1 [19] explains the relationship between the fuel curve and the generator power output. The fuel curve coefficients are represented by a, b and c, while P is the generator's power output. In addition, operating a generator at the minimum
required power output \( (P_{\text{min}}) \) can decrease the amount of carbon emissions, as well as improve the lifetime of the generator, as shown in Equation 2.2 [10].

\[
P_{\text{min}} \leq P_t \leq P_{\text{max}}
\]  

\( P_{\text{min}} \) is the minimum required power output of the generator, \( P_{\text{max}} \) is the maximum power output of the generator and \( P_t \) is the power output of the generator at time \( t \). Thus, the power output of the generator should be between the minimum and maximum outputs. Most generators operate at 30\% of rated power capacity, which can extend the lifetime of the generator. On the other hand, operating a generator at less than 30\% of rated power capacity can cause engine failure or decrease the generator's life, due to liner glazing [20] and wet stacking [21, 22]. So, dumping loads may provide minimum loading [10], while operating the generator at 30\% capacity.

![Figure 2.3 Generator efficiency vs loading [10]](image)

Using two different sized generators can help generator match loads closer, improving ensure the efficiency. Figure 2.3 shows the relationship between the load and
efficiency when two generators of different sizes are used. It can be noted that the
efficiency of the smaller generator is higher in low load condition.

2.1.2 Photovoltaic (PV) System

A Photovoltaic (PV) is a system which uses solar panels to generate electricity by
converting solar radiation to electrical power. Solar panels are generating a direct current
(DC) which is converted later to (AC) by using an inverter. This can then serve the load
demand in a remote microgrid or, in its DC form, it can charge a battery bank.
Photovoltaic (PV) panels have unique characteristics which can be represented by the $I-V$
(current-voltage) curve (Figure 2.4).

![Figure 2.4 Typical current versus voltage curve for PV modules [23]](image-url)
Photovoltaic (PV) panels have unique characteristics which can be represented by the I-V (current-voltage) curve (Figure 2.4). The PV power depends on two factors—current short circuit (I_{sc}) and voltage open circuit (V_{oc}) which can then determine the maximum power output (P_{mpp}) of the PV panel. V_{oc} happens when the load is not connected to the PV panel or to any current flow (no load). I_{sc} is the amount of current in the solar panel when the PV panel is in the short circuit mode (0 voltage). The maximum power voltage (V_{mp}) is the amount of voltage at the maximum power point, while I_{mp} is the amount of current at the same point. So, by multiplying these factors ($V_{mp} \times I_{mp} = P_{mp}$), the highest possible power can be achieved from the PV panel [23].

Figure 2.5 PV module's current versus voltage curve varies the irradiance of sunlight [23]
All panel factors of PV modules, \( V_{oc}, I_{sc}, V_{mp}, I_{mp} \) and \( P_{mp} \), are estimated at the standard situation or standard test conditions (STC) of the temperature and irradiance. The values reported as standard test conditions are the temperature of 25°C (77°F) and irradiance of 1,000 W/m² [23]. The temperature and irradiance values change during a day, so the voltage and current of a PV panel are also variable over this period. Figure 2.5 shows the relationship of the PV curve to the sun irradiation during a day. According to this chart, the current changes dramatically based on the sun's irradiance, but the voltage is almost constant.

2.1.3 Batteries

Batteries are a crucial part of any microgrid system, since they can improve system reliability, performance and generator efficiency. The battery throughput can significantly minimize fuel consumption. This section introduces the most common battery types for the remote microgrid (lead-acid, lithium-ion, zinc-bromine, aqueous hybrid ion, Tesla, sodium nickel cadmium) and shows the impact of these batteries in a remote microgrid’s EMS. Until recently, lead-acid battery technology was considered the most economical battery compared to other types. Also, lead-acid battery technology is still developing and improving. Currently, batteries operating with zinc-bromide and lithium-ions are being developed and appear to challenge lead-acid as the most effective choice in a remote microgrid system and other modern applications.

2.1.3.1 Lead-Acid Battery

The cost is one of the greatest advantages of lead-acid batteries, which makes it a good choice for most industrial applications. However, they also require maintenance,
large space, and have a short lifetime if they experience less than 30% of discharge. These issues cause an impact on the cost, which can increase the capital costs because of the increase in energy density [13]. Lead-acid batteries are the most common batteries for the remote microgrid system due to their stabilization and energy management. This type of battery has the ability to discharge over minutes to days, and in some cases, even weeks. The power range of this battery is from 10 kW to 100 MW and could be higher in some cases. The response time for lead-acid batteries is approximately a few milliseconds [12]. Lead acid batteries cost from $300/kWh to $600/kWh, and their efficiency range is approximately 70% to 90%. On the other hand, lead acid batteries are limited by their lifetime cycle of approximately 500 to 2000 cycles. Also, they have an energy density around 30 Wh/kg to 50 Wh/kg, based on the lead density [24].

2.1.3.2 Lithium-ion Batteries

The cost of lithium-ion (Li-ion) batteries is high, which offers a major hurdle for their use in remote microgrids. These batteries require special packaging and overcharge protection circuits, which brings the cost for a Li-ion battery to more than $600/kWh [24]. Lithium-ion batteries have many advantages, such as high efficiency (around 95%) and short discharge time (from seconds to weeks), which makes their use very flexible. The power range is around 100MW or higher and the response time may be a few milliseconds [26]. In addition, they have a high energy density of 300 - 400 kWh/m3130 kWh/ton and a long life cycle of approximately 3000 at 80% DOD [24]. Li-ion batteries are very sensitive to the charge and discharge fluctuation because of the internal resistance, which makes the battery temperature high during charge or discharge modes.
at a high current. Due to that factor, the Li-ion batteries have a limited charge and discharge time.

2.1.3.3 Zinc Bromine Flow Battery (ZBB)

Zinc-bromine (ZBB) is one type of redox flow battery (refer to Figure 2.6). This type of battery contains two chemical materials, stored as two electrolytes in separate tanks. The size of the tanks determines the energy capacity of the battery, meaning the larger the tanks, the stronger the energy capacity. The power of the battery is determined by the charge/discharge reaction. One of the most important advantages of flow batteries is their ability to produce energy at a high rate of discharge (around 10 h). In addition, zinc bromine has the ability to reach 0 DOD, which means fully discharged without damage. These batteries also have a long lifetime of at least 1500 life cycles.

Figure 2.6 Schematic of flow battery [12]
The efficiency of a ZnBr battery is approximately 75%, with a discharge time ranging from minutes to weeks. The ZnBr battery response is timed in seconds, with a power range from 10 kW to more than 100 MW. The estimated cost of a zinc-bromine battery is $800/kWh [12].

2.1.3.4 Tesla Powerwall Battery

The Powerwall is a unique battery which is classified as a lithium-ion battery. It is made by Tesla Motors for home applications such as load shifting and backup power. This battery has the ability to store energy from either a utility grid or from solar panels, which make it a good choice for a remote microgrid. The energy capacity of this battery is 6.4 kWh, which makes it sufficient to serve the high load demand during an evening. This battery uses a rechargeable lithium ion technology with liquid thermal control technology. This type of battery exhibits many good specifications, such as a high round trip efficiency of 92.5%, the power of approximately 3.3 kW. This battery has the ability to reach 100% depth of discharge, while the range of its temperature operation is -4°F to 122°F (-20°C to 50°C) [25].

2.1.3.5 Aquino Energy Battery

This battery type uses a technology energy storage which depends on a saltwater electrolyte (Figure 2.7). It is made with non toxic materials, with manganese oxide, carbon titanium phosphate and a separator made of synthetic cotton. This type of battery does not require any maintenance and is designed to provide a daily deep cycle. It also has no corrosive chemical reactions in either the anode or cathode. Due to its life cycle, this type of battery is suitable for off grid and micro-grid use. It exhibits a high depth of
discharge—for example, 3000 cycles at 100% depth of discharge or 4000 cycles at 80% depth of discharge. Thus, it has a highly reliable performance on demand time because of its ability to stand at a state of charge with low self-discharge.

Figure 2.7 Configuration of an Aqueous Energy Battery (AHI) [26]

It can reach to 11.7kW peak power. Its efficiency around 90%. Its capacity is about 48.3 Ah. This battery is very good for the environment because it is non-toxic, non-flammable, non-explosive and non-corrosive [26].

The amount of energy which is left in a battery compared with the same battery with full charge gives information about how much of the battery need to be recharged. The
$SOC$ provides information about the amount of energy that is stored in the battery as a percentage and equation 2.3 present the $SOC$ [27].

$$SOC(t + 1) = SOC(t) + \frac{\eta_{erg} \times P_{b,t} \times \Delta t}{BattCap_{kWh}}$$ \hspace{1cm} (2.3)

Equation 2.3 presents the $SOC$ during charging mode, the next hour $SOC$ ($SOC$ with $t+1$), according to the current $SOC$ ($t$), current charging ($P_{b,t}$), the time interval ($\Delta t$), the capacity of the battery ($BattCap_{kWh}$) and the charging efficiency ($\eta_{erg}$).

The $SOC$ during discharge mode is presented by Equation 2.4 which depends on current discharge ($P_{b,t}$) next hour $SOC$ ($SOC$ with $t+1$), the current $SOC$ ($t$), current charging ($P_{b,t}$), the time interval ($\Delta t$), the capacity of the battery ($BattCap_{kWh}$) and the efficiency of discharge ($\eta_{dcrg}$) [27].

$$SOC(t + 1) = SOC(t) + \frac{P_{b,t} \times \Delta t}{\eta_{dcrg} \times BattCap_{kWh}}$$ \hspace{1cm} (2.4)

Some types of battery cannot reach a very deep discharge. So, to prevent that issue, the state of discharge between the maximum and the minimum values is considered, as in Equation 2.5 [10].

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad \forall t \in T$$ \hspace{1cm} (2.5)

Also, the maximum charge and discharge of the battery, as seen in Equation 2.6 [10].

$$P_{b,mcrg} > P_{b,t} > P_{b,mderg} \quad \forall t \in T$$ \hspace{1cm} (2.6)
CHAPTER 3: PROCEDURE

Chapter 3 describes the detailed procedures of the remote microgrid benchmark and its EMS [10]. The benchmarks information contains the characteristics, parameters, and component specifications and profiles. For instance, these include the efficiency characteristics of the generators, annual load profile, $PV$ profile, battery and generator mathematical cost model, battery throughput and lifetime cost calculation. The $PV$ profile and annual load profile were obtained from a remote microgrid located in North America, a microgrid very similar to the one used in this thesis. This section also describes the optimization problem, followed by the cases studied to analyze and compare the impacts of different types of batteries used in this remote microgrid.

3.1 Remote Microgrid Benchmark

Figure 3.1 describes the benchmark which was used for this study. The remote microgrid benchmark contains two diesel generators, a KOHLER 30 kW (model 30REOZJC) and a 75 kW (model KT75), along with a 27 kW $PV$ battery bank and load. The diesel generators exhibit the characteristics presented in Chapter 2, including a minimum value of 30% of the rated capacity, which means the $P_{\text{max}}$ for these generators are 30 kW and 75 kW, while the $P_{\text{min}}$ for these generators are 9 kW and 22.5 kW. These generators operate in isochronous mode. The diesel fuel cost of the generators is assumed $9 per gallon [27]. The capacities of the battery banks are different from each other, which allows them to meet the average load for four hours to improve reliability and fuel efficiency through increased renewable energy utilization. This type of microgrid is a hybrid system which uses a hybrid EMS to control it.
Figure 3.1 Remote microgrid benchmark [10]

The central controller gives instructions to the generators, batteries, and load. In this study, assumed that the voltage levels are the same in the microgrid. Power losses and reactive power are both neglected in the study.

Figure 3.2 shows the fuel consumption curve for the 30 kW diesel generator (model 30REOZJC) and the 70 kW diesel generator (model KT75) according to the manufacturer data sheet.
In Figure 3.3 the efficiency of the 30 kW diesel generator is higher than 70 kW generator in a low load situation.
3.1.1 Load Profile

In this thesis, two types of loads are included. First, a critical load was considered, which is important for residential and commercial purposes such as a health clinic. Second, non-critical loads were included, for purposes such as water pumps. The annual load profile is presented in Figure (3.4) which was collected from Nemiah Valley microgrid [6]. The loads were given in hourly basis throughout a year. The minimum, maximum, and average loads of the system are 3 kW, 64 kW, and 25 kW respectively. Figure (3.4) shows that the value of the average load is comparatively high in the winter season and low in the summer. The hourly peak load was in January and minimum was in July.

Figure 3.4 Load demands profile [10]
3.1.2 PV Profile

The hour basis yearly PV profile is presented in Figure (3.5) which was collected from [6]. The average and maximum value of PV power is about 5 kW and 30 kW respectively. The generation of PV power is high in the summer season and low in the winter. The peak value PV is obtained at solar noon which depends on the geographical location. All PV panels are connected together in order to produce 30 kW with the same irradiation.

![Scaled data Monthly Averages](image.png)

Figure 3.5 Yearly PV irradiance [10]

3.1.3 Diesel Generator Cost Model

The generator cost modeling, content fuel consumption, generator replacement cost, emission cost and maintenance cost are omitted in this study. The fuel consumption calculated with a quadratic equation. The operational fuel cost of the generator was calculated by multiplying the fuel volume with fuel cost/unit volume. Equation 3.1 presents the daily operational cost of the generator. Both generators have a limited
operation mode of 30% of the rated capacity. So, equation 3.2 then presents the limitations of both generators [10].

\[ C_n(P_n) = C_{\text{diesel}} \times \sum_{t=1}^{24} \left( a_n \times P_{n,t}^2 + b_n \times P_{n,t} + c_n \times U_{n,t} \right) \]  \hspace{1cm} (3.1)

\[ U_{n,t} \times P_{n,\text{min}} \leq P_{n,t} \leq U_{n,t} \times P_{n,\text{max}} \quad \forall t \in T, \forall n \in N \]  \hspace{1cm} (3.2)

\( C_{\text{diesel}} \): Diesel fuel cost ($/gallon)

\( P_{n,t} \): Power output of \( n^{th} \) generator at \( t \) (kW)

\( a_n, b_n, c_n \): Generator fuel curve coefficients

\( U_{n,t} \): Generator ON/OFF control at \( t \) (1=ON, 0=OFF)

Another factor should also be considered—the generator’s hourly replacement cost. The hourly replacement cost of the generator is calculated from the generator’s lifetime hours, which depend on parameters such as frequency of use and maintenance of the generator [28]. According to some current microgrids in operation and manufacturers' data sheets, the lifetime of a diesel generator is estimated at 40,000 hours [27, 28, 29]. The generator's hourly replacement cost ($/hr) is then calculated by dividing the initial cost of the generator ($) by the expected lifetime in hours. The generator's maintenance cost is then estimated to be $8,000 per year. Based on the small size of the generator in the remote microgrid, the startup and shutdown of the generator were neglected based on [30]. The total generator's operational cost was calculated by the sum of the fuel cost and the hourly replacement cost (obj1).
\[ C_{g, h} = G^{th} \text{ Generator Hourly Replacement Cost, } \frac{\$}{hr} \]  

\[ = \frac{\text{Generator Initial Cost, } \$}{\text{Total Lifetime Working Hours}} \]  

3.1.4 Battery Wear Cost Model

Determining the battery wear cost (\$/kWh) is very important in order to obtain the battery lifetime throughput. So, the battery lifetime throughput can be obtained from the battery datasheet, which is based on standard test conditions. Two types of battery operation conditions were considered. The first is the standard test condition which depends on the battery specification sheet disclosing the discharge rate, rated DOD, life cycle, and so on. The second condition is the actual working condition, which then includes the high penetration of the stochastic PV system and battery throughput. Schiffer in [31] presented a weighted Ah method to calculate actual battery lifetime and Ah throughput. Both conditions are explained further, as follows.

3.1.4.1 Battery Datasheet Specifications

In order to calculate the battery lifetime throughput and the battery wear cost, the most important parameters for each battery should be presented, as noted in the battery datasheet. Table 3.1 present the speciation of the batteries Battery Capacity, Rated DOD, voltage and efficiency. This information used to calculate the battery wear cost and lifetime throughput.
In order to take into account variations in cost for lead acid batteries, five types of lead acid battery are considering: Battery-I PbA [32], Battery-II PbA [33], Battery-III PbA [34], Battery-IV PbA [35] and Battery-V PbA [36]. Similarly, five lithium ion batteries are considered: Battery-I LIB [37], Battery-II LIB [38], Battery-III LIB [39], Battery-IV LIB [40] and Battery-V LIB [41].

Table 3.1 Battery datasheet specifications [26], [25], [43] and [32]-[41]

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>amp hour ratings, Ah at C/20</th>
<th>Rated DOD</th>
<th>Life Cycle at Rated DOD</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHI</td>
<td>47.3</td>
<td>0.9</td>
<td>3500</td>
<td>0.85</td>
</tr>
<tr>
<td>ZBB</td>
<td>10000</td>
<td>1</td>
<td>4000</td>
<td>0.85</td>
</tr>
<tr>
<td>Tesla</td>
<td>6400</td>
<td>1</td>
<td>5000</td>
<td>0.925</td>
</tr>
<tr>
<td>Lead acid (PbA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery-I PbA</td>
<td>1110</td>
<td>0.5</td>
<td>1400</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-II PbA</td>
<td>245</td>
<td>0.5</td>
<td>3000</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-III PbA</td>
<td>258</td>
<td>0.5</td>
<td>1000</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-IV PbA</td>
<td>696</td>
<td>0.5</td>
<td>1750</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-V PbA</td>
<td>1104</td>
<td>0.5</td>
<td>1400</td>
<td>0.9</td>
</tr>
<tr>
<td>Lithium ion (LIB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery-I LIB</td>
<td>180</td>
<td>0.8</td>
<td>2000</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-II LIB</td>
<td>19.6</td>
<td>0.9</td>
<td>3000</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-III LIB</td>
<td>138</td>
<td>0.8</td>
<td>2800</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-IV LIB</td>
<td>75</td>
<td>1</td>
<td>2000</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery-V LIB</td>
<td>100</td>
<td>0.8</td>
<td>2000</td>
<td>0.9</td>
</tr>
</tbody>
</table>

3.1.4.2 Calculate Lifetime Throughput

Ah lifetime throughput:

Lifetime throughput is the total amount of discharging energy from a battery during its float lifetime. It was calculated to estimate the lifetime of the batteries and to determine the fuel consumption of the diesel generators. It was considered that the
batteries are expired when the estimated battery throughput reaches the amount of lifetime throughput within the float life. It was also required to calculate the battery wear cost. The average lifetime Ah throughput was calculated in terms of rated depth of discharge (DOD), number of life cycles (Lc,DOD), and battery ampere hour rated capacity (BattCapAh) by using Equation (3.4) [42]

\[ Ah_{\text{lifetime}} = L_{c,DOD} \times DOD_R \times BattCap_{Ah} \]  \hspace{1cm} (3.4)

Average total Ah lifetime:

The average total kWh lifetime throughput is calculated by using equation 3.5.

\[ kWh_{\text{lifetime,avg}} = \frac{Ah_{\text{lifetime,avg}} \times BatteryVolt}{1000} \]  \hspace{1cm} (3.5)

The information of rated DOD, and Lc,DOD, BattCapAh were obtained from the manufacturer data sheets.

Calculation battery bank size

The battery bank was sized to meet the peak energy demand of the system (64 kW). The size of the battery bank is different for considering types in the system which depend on the peak load, discharge efficiency, and the rated DOD. It was calculated by using Equation (3.6). There are two factors affect the size of the battery bank discharge efficiency and the rated DOD. For example, increasing the
battery Depth of Discharge or the battery efficiency can guarantee a decrease in battery bank capacity which causes a decreasing in the initial cost.

\[
\text{Batt Size req} = \frac{\text{system size}}{\eta \times \text{DoD}}
\]  \hspace{1cm} (3.6)

Battery wear cost calculation

Wear cost ($/kWh) is the key factor to analyze the impact of a battery to the EMS of remote microgrids. It was calculated by dividing the initial cost ($) by the lifetime throughput (kWh) as the Equation (3.7)

\[
C_{batt, \text{per kWh}} = \frac{C_{\text{initial, batt}}}{\text{kWh}_{\text{lifetime, avg}} \times \eta_{\text{dcr}}}
\]  \hspace{1cm} (3.7)

Number of battery requirement:

Since one single battery is not enough to meet the system load. Therefore, designing a battery bank is required. That means the battery bank has to contain a number of batteries in order to meet the system load. The number of batteries in the battery bank obtained from equation (3.8). The number of required batteries for the system is required to obtain the battery initial cost.

\[
\# \text{ Battery req (kWh)} = \frac{\text{Batt Size req (Wh)} \times 1000}{\text{Batt Cap (Ah)} \times \text{nominal voltage (V)}}
\]  \hspace{1cm} (3.8)
Battery initial cost:

The initial cost of the battery is very important to obtain the battery wear cost which means decrease the initial cost can reduce the battery wear cost. Therefore, can obtain the battery initial cost by multiply the number of battery required by the battery cost. Equation (3.9) present the initial cost of the battery. Increase the number of a battery will increase the battery initial cost.

\[
\text{Battery initial cost} = \# \text{Battery req} \times \text{Batt Cap} \tag{3.9}
\]

3.2 Energy Management System

The objective of an EMS is to manage the power between the energy sources and loads in a remote microgrid. The EMS contains two layers (day ahead 24-hour scheduling and real-time dispatch) which are able to control and manage the behavior of the generators and the operation of the battery (Figure 3.6) [10].

3.2.1 Day Ahead 24-Hour Scheduling

A day ahead 24-hour scheduling layer estimates the power of the dispatchable resources one day in advance in order to meet the minimum operational cost. This layer depends on three factors: available resources, load demand and the forecasting of the PV power.
The EMS algorithm which was developed by [10] contained two objectives: (1) to minimize fuel consumption, and (2) to minimize the throughput of the battery in order to prolong the battery lifetime. Meeting these two objectives are required in order to minimize the total operational cost. In order to achieve these goals at the same time, the EMS algorithm which depends on a goal programming approach is used. The goal programming approach can be presented by equation 3.10 where obj₁ represents the fuel consumption, obj₂ prolongs the battery lifetime. \( W_1 \) and \( W_2 \) are the weights [10].

\[
obj = (W_1 \times \text{obj}_1 + W_2 \times \text{obj}_2)
\]  

(3.10)

These weights decide the priority of \( \text{obj}_1 \) and \( \text{obj}_2 \). The sum of the weights should equal (1) at all times. If both weights are equal [\( W_1 \) (0.5) and \( W_2 \) (0.5)], that means that both objectives are equal. In the case that one of the weights is higher than the other weight, the objective with the higher weight is more crucial to achieving the overall goal.

3.2.2 Real Time Dispatch

The real time dispatch layer calculated the resource from day ahead scheduling and dispatch. This layer ensures the power balance by compensated any variation from the forecast (this thesis focus on 24-hour scheduling).
3.3 Determining Weights $W_1$ and $W_2$

The yearly analysis using a deterministic approach was considered in this study in order to determine the proper use of the generator and the battery through weights $W_1$ and $W_2$.

The weights ($W_1$ and $W_2$) present the amount of use for batteries and generators in the objective function. So, any set of weights provides the minimum operational cost was considered to achieve the optimization problem. The generator cost (obj1) includes the generator’s hourly replacement cost and fuel cost. The battery cost (obj2) includes the battery wear cost and the float life cost.
According to the batteries data sheet, all the batteries lifetime throughput which considers it in this study were designated for a 10-year float life except lithium ion batteries which designated for 5-year. So, the yearly throughput has to be equal or more than the battery designated in order to be utilized. Otherwise, the battery will not be utilized and the battery float life cost will be different between designated and utilized throughout multiplied by wear cost of the battery.

The lowest set of the operational cost which obtained from weights was compared to the other different sets of weights in order to have the best-set of weight.

3.4 Optimization Problem

The objective function with weights $W_1$ and $W_2$ was presented in Equation 3.11 [10] which was obtained by using Equation 3.1 and equation 3.7. The $PV$ operational cost, converters cost and the maintenance cost assume to be neglected since those are constant. The generators or the batteries can be the master unit in the system. In equation 3.11, $W_1$ is the weight, which related to generator cost. On the other hand, $W_2$ represents the weight of the battery wear cost. The main objective of the optimization problem is to minimize the combined operational cost which depends on the use of a generator and battery. For instance, when $W_1$ increased fuel consumption reduces because more consideration was given to the generator. When $W_2$ increase, more consideration was given to the battery cost. That is causing an increase in fuel consumption and prolonging the battery lifetime by reducing throughput. Furthermore, the summation of $W_1$ and $W_2$ equal 1. So, $W_1$ and $W_2$ present the use of the battery and the generator. For example, when $W_1$ is higher than $W_2$ less fuel is consumed, which means the operational cost of the
generator is low because it takes more weight, in that case, the battery throughput is high which lead to a decrease in the battery lifetime.

Combined objective function:

\[
obj = \min \left\{ W_1 \times \left( \sum_{n=1}^{N} C_n \left( P_n \right) \right) + \sum_{i=1}^{24} \sum_{n=1}^{N} U_{n,i} \times C_{n,hrc} \right\} + W_2 \times C_{batt,24hr}
\]

(3.11)

Where: \((t)\) time, \((n)\) number of generators, \((U_{n,i})\) on, off generator mode, \((P_n)\) the generator power output of \(n\) @ time \(t\), \((C_n)\) generator cost, \((C_{n,hrc})\) generator hourly replacement cost $/hr,

3.5 Case of Studies

Batteries are categorized in three family Lead acid, lithium ion and unique batteries.

Simulation Process:

Calculate the key factors for each battery such as Battery wear cost, Battery Initial cost, kWh lifetime average, battery size requirement and the number of battery requirement.

Validate the optimization model for different types of batteries considering fuel consumption, battery throughput, operation cost and battery Lifetime. This study used IBM ILOG CPLEX 12.1 software to solve the optimization model.
3.6 Weight Selection Process

Step 1: Yearly scheduling (365 days)

- Calculate cumulative battery throughput
- Calculate cumulative fuel consumption
- Calculate float life
- Calculate operational cost

Step 2: Change weights and repeat Step 1

Step 3: Select weight that provides minimum operational cost for each battery

Step 4: Compare the weight in step 3 to decide the best battery for this case study

Step 5: Find the best battery that can provide a better cost effective solution than other batteries.
CHAPTER 4: RESULT AND ANALYSIS

This chapter presents the results obtained from this case study and the analysis of data. Section 4.1 shows the calculation summary of wear cost and battery specifications which were used to obtain an annual simulation result. Other analysis includes total operational cost, battery lifetime, battery throughput, and fuel consumption gallons. Section 4.2 describes the simulation results for a variety of battery types, including lead-acid, lithium ion, AHI, ZBB and Tesla, considering the total operational cost, battery lifetime (estimated float life), battery throughput, and fuel consumption in gallons. Section 4.3 presents the comparison of different batteries.

4.1 Batteries Wear Cost

The wear cost is the key factor in determining a battery's operational cost. The wear cost depends on four parameters: initial cost, lifetime throughput, $DOD$ and discharge efficiency.

Table 4.1 presents the calculations result to obtain the battery wear cost for the unique batteries. The AHI, ZBB, and Tesla battery wear cost are 0.189 kWh, 0.235 kWh, and $0.101/kWh respectively. The lowest wear cost presented by Tesla about 0.101. Also, Tesla provides a high battery throughput about 352,000 kWh, which is the highest.
Table 4.1 Simulation parameters for unique batteries

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>System Peak load kW</th>
<th>Battery Size Req, kWh</th>
<th>Lifetime Throughput, kWh</th>
<th>Battery Initial Cost, $</th>
<th>Battery wear. Cost, $/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHI</td>
<td>64</td>
<td>83.66</td>
<td>264,615</td>
<td>42,735</td>
<td>0.189</td>
</tr>
<tr>
<td>ZBB</td>
<td>64</td>
<td>75.29</td>
<td>320,000</td>
<td>64,000</td>
<td>0.235</td>
</tr>
<tr>
<td>Tesla</td>
<td>64</td>
<td>69.18</td>
<td>352,000</td>
<td>33,000</td>
<td>0.101</td>
</tr>
</tbody>
</table>

Table 4.2 presents the simulation parameters for lead acid batteries. Lead acid batteries have wear cost range between $0.260/kWh and $0.506/kWh. The battery size required (battery capacity) for each battery is 142.22 kWh. That because of the DOD and efficiency is same for each battery (see table 3.1).

Table 4.2 Simulation parameters for lead acid batteries

<table>
<thead>
<tr>
<th>Lead acid</th>
<th>Max Power Capacity kW</th>
<th>Battery Size Req, kWh</th>
<th>Lifetime Throughput, kWh</th>
<th>Battery Initial Cost</th>
<th>Battery wear. Cost, $/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery-I PbA</td>
<td>64</td>
<td>142.22</td>
<td>101,010</td>
<td>23,689</td>
<td>0.260</td>
</tr>
<tr>
<td>Battery-II PbA</td>
<td>64</td>
<td>142.22</td>
<td>229,320</td>
<td>65,477</td>
<td>0.317</td>
</tr>
<tr>
<td>Battery-III PbA</td>
<td>64</td>
<td>142.22</td>
<td>71,208</td>
<td>32,430</td>
<td>0.506</td>
</tr>
<tr>
<td>Battery- IV PbA</td>
<td>64</td>
<td>142.22</td>
<td>124,236</td>
<td>38,811</td>
<td>0.347</td>
</tr>
<tr>
<td>Battery- V PbA</td>
<td>64</td>
<td>142.222</td>
<td>98,918</td>
<td>37,740</td>
<td>0.423</td>
</tr>
</tbody>
</table>

Table 4.3 presents the simulation parameters for lithium Ion batteries. Lithium Ion batteries have wear cost range between $0.287/kWh and $0.673/kWh. The battery size
required (battery bank capacity) are different for each lithium Ion batteries. Lithium Ion batteries have a battery bank capacity between 71 kWh and 88 kWh.

Table 4.3 Simulation parameters for lithium Ion batteries

<table>
<thead>
<tr>
<th>Lithium Ion</th>
<th>Max Power Capacity kW</th>
<th>Battery Size Req kWh</th>
<th>Lifetime Throughput kWh</th>
<th>Battery Initial Cost</th>
<th>Battery wear. Cost, $/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery-I LIB</td>
<td>64</td>
<td>88</td>
<td>142,848</td>
<td>27,900</td>
<td>0.2</td>
</tr>
<tr>
<td>Battery-II LIB</td>
<td>64</td>
<td>79.01</td>
<td>213,405</td>
<td>91,650</td>
<td>0.477</td>
</tr>
<tr>
<td>Battery-III LIB</td>
<td>64</td>
<td>71</td>
<td>197,836</td>
<td>137,980</td>
<td>0.77</td>
</tr>
<tr>
<td>Battery-IV LIB</td>
<td>64</td>
<td>71</td>
<td>144,000</td>
<td>75,000</td>
<td>0.578</td>
</tr>
<tr>
<td>Battery-V LIB</td>
<td>64</td>
<td>88.80</td>
<td>142,336</td>
<td>36,851</td>
<td>0.287</td>
</tr>
</tbody>
</table>

4.2 Simulation Results

Table 4.4 offers an example of the yearly simulation result for a ZBB battery. The rest of the batteries have similar tables which displaying results as figures (Figures 4.1 - 4.12). This table presents the simulation result which obtained from simulations of the optimization problem using IBM ILOG CPLEX 12.1.6. There are five factors can be obtained by simulating the optimization problem such as fuel consumption, battery throughput, total cost of operation, float life cost and battery life. The table presents these factors for only ZBB battery. When $W_i$ increases fuel consumption decrease and battery throughput increase.
Table 4.4 Yearly simulation result of ZBB

<table>
<thead>
<tr>
<th>Weight</th>
<th>Fuel Consumption</th>
<th>Battery Throughput (kWh)</th>
<th>Float Life Cost ($)</th>
<th>Total Cost of Operation ($)</th>
<th>Maximum Battery Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_1$</td>
<td>$W_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
<td>12,381</td>
<td>4,623</td>
<td>6,434</td>
<td>122,270</td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
<td>12,208</td>
<td>9,087</td>
<td>5,384</td>
<td>120,620</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>11,973</td>
<td>16,633</td>
<td>3,611</td>
<td>118,390</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
<td>11,889</td>
<td>21,015</td>
<td>2,581</td>
<td>117,500</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3</td>
<td>11,811</td>
<td>28,376</td>
<td>852</td>
<td>116,560</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
<td>11,756</td>
<td>36,898</td>
<td>0</td>
<td>116,980</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>11,728</td>
<td>43,280</td>
<td>0</td>
<td>118,080</td>
</tr>
<tr>
<td>1.0</td>
<td>0</td>
<td>11,711</td>
<td>58,279</td>
<td>0</td>
<td>121,170</td>
</tr>
</tbody>
</table>

4.2.1 Lead Acid Family (PbA)

This family contains five types of battery in order to make a range of lead acid batteries. This section presents the simulation results for these batteries. Also, the economics of lead acid batteries were analyzed, using characteristics from the lead acid specification data sheet such as DOD, efficiency, etc. The analysis was based on four factors, including operational cost, battery throughput, lifetime and fuel consumption.
Operational cost depends on the generators operational cost, battery float life cost and wear cost. Figure 4.1 presents the yearly operational cost versus weight for a range of lead acid batteries, including five samples.

![Figure 4.1 Operational cost vs weight using PbA](image)

According to Figure 4.1 when \( W_i \) increases, the total operational cost decreases up to \( W_i=0.6 \), and then increases for \( W_i>0.6 \). The lowest operational cost was obtained at Weight \( W_i=0.6 \). The range of weights \( (0.5 < W_i < 6) \) was determined to be the most effective considering the minimum total operational cost At \( W_i=0.6 \), the lowest operation cost was achieved, considering a balance between fuel cost and battery cost.

When a battery has reached a limited amount of throughput, it is considered dead. For example, the maximum amount of throughput for Battery-I PbA is 101,010 kWh, and
after utilizing that amount, battery-I PbA will be expired. That means the battery-I PbA has used its lifetime throughput. The low wear cost guaranteed the EMS to utilize more throughput. Battery throughput affects the lifetime in many ways, since a surplus amount of throughput will cause a reduction of battery lifetime. According to Figure 4.2, the battery throughput increases as the weight increases.

Figure 4.2 PbA Battery throughput vs weight
Increasing the battery lifetime is one of the optimization goals in remote microgrids. Additionally, an EMS tries to minimize the utilization of battery throughput while maintaining a long lifetime. Lower battery throughput leads to higher float life cost. Float cost is the amount of energy that will not be used after the battery lifetime has expired. For example, the float life for Battery-II PbA is 10 years, and the estimated yearly throughput of Battery-II PbA is 22,932 kWh yearly. But at $W_f=0.5$, the battery throughput is 16,640 kWh. So, at 6285 kWh of unused energy, the cost is $1948 \text{ (wear cost} \ 0.31 /\text{kWh})$. Figure 4.3 demonstrates the lifetime information for lead acid batteries. This study used battery warranty as battery float life. So, the maximum float life used for the lead acid battery is 10 years, as determined by the manufacturer. Figure 4.3 demonstrates the lifetime information for lead acid batteries. In this study, we use battery warranty as battery float life. So, the maximum float life used for the lead acid battery is 10 years, as determined by the manufacturer.

![Battery Life vs Weight (wr1)](image)

Figure 4.3 PbA battery lifetime vs weight
The fuel consumption of a generator depends on the amount of battery throughput that is utilized by the system. According to Figure 4.4, the fuel consumption decreases and $W_i$ increases for the whole range of weights.

![Figure 4.4 Fuel consumption by generators vs weight using PbA batteries](image)

Figure 4.4 Fuel consumption by generators vs weight using PbA batteries
4.2.2 Lithium ion Family (LIB)

Five types of Lithium Ion battery were included in this range of batteries. Figure 4.5 presents the system operational cost versus weight for the range of Lithium ion batteries used in this study. Figure 4.5 indicates that as $W_i$ increases, the total operational cost decreases up to $W_i=0.7$, and then increases further for $W_i>0.7$.

![Figure 4.5 Operational cost vs weight using LIB batteries](image)

The lowest operational cost is obtained at weight $W_i=0.7$, with the range of weights $(0.7<W_i<0.8)$ determined to be the most effective in order to reduce the total operational cost. At $W_i=0.7$, the system presents the lowest operational cost to achieve the balance between fuel cost and battery cost. The variation of the operational cost at $W_i = 1$, related
to the EMS used battery more than a generator. Also, each battery has a different amount of wear cost which made that variation for all weights. The high variation in the operational cost is resulted from two factors, the battery float life cost and battery wear cost. The estimated float lifetime of lithium ion battery in this study is five years. Dividing the total throughput of the battery by float lifetime (5 years) yields maximum yearly throughput of the battery. The float life of the battery is the difference of the maximum yearly throughput and the yearly throughput obtained from the simulation. The float life is the amount of that difference multiplied by the battery wear cost. Table (4.5) shows the yearly simulation results, when Battery-II LIB is used for EMS. The table presents the amount of the fuel consumption, yearly throughput of the battery and the total operational cost. For example, when $W_1 = 0.8$, the yearly throughput is 25,299 kWh.

From table (4.3) the wear cost of the Battery-II (LIB battery) is 0.477 $/kWh. The total battery throughput which can be obtained from this battery is 213,405 kWh. Dividing this amount by the float lifetime (5 years) yields the maximum yearly throughput of the battery, which is 42,681 kWh.

So, the battery throughput which obtained from the simulation result is 25,299 kWh. That means the battery did not reach to the maximum yearly throughput (42,681). So, an amount of 17,382 kWh is unused, which is equivalent to a cost of $8,291. The unused energy can identify the variation in the operational cost in figure (4.5). On the other hand, when $W_1 = 1$, the yearly throughput is higher than maximum yearly throughput, which means that the battery served less than the maximum lifetime (5 years).
Table 4.5 Simulation results of Battery-II LIB

<table>
<thead>
<tr>
<th>Weight</th>
<th>Fuel Consumption, Gallon</th>
<th>Battery Throughput (kWh)</th>
<th>Estimated Battery Life (Years)</th>
<th>Float Life Cost ($)</th>
<th>Total Cost of Operation ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>W2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
<td>12,489</td>
<td>2,872</td>
<td>5</td>
<td>18,989</td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
<td>12,435</td>
<td>3,669</td>
<td>5</td>
<td>18,609</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>12,359</td>
<td>5,158</td>
<td>5</td>
<td>17,898</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
<td>12,139</td>
<td>11,229</td>
<td>5</td>
<td>15,000</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3</td>
<td>11,946</td>
<td>18,132</td>
<td>5</td>
<td>11,710</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
<td>11,848</td>
<td>25,299</td>
<td>5</td>
<td>8,291</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>11,765</td>
<td>36,588</td>
<td>5</td>
<td>2,906</td>
</tr>
<tr>
<td>1.0</td>
<td>0</td>
<td>11,724</td>
<td>58,554</td>
<td>3.64</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.6 shows the battery throughput vs weight for a wide range of Lithium Ion batteries. As indicated, when the weight increases, the battery throughput also increases. Each battery has a different amount of throughput. So increasing the use of the battery can increase the amount of throughput. Figure 4.6 shows more used of the battery in the EMS caused more throughput. In addition, all the batteries have limited amount of throughput.
Figure 4.7 shows the lifetime vs weight for Lithium Ion batteries. According to the battery manufacturer, the maximum float life for a Lithium Ion battery is 5 years. When looking at Figure 4.7 comparatively, the batteries have a five-year lifetime for a wide range of weights, with $W_i$ between 0.3 to 0.7. After that, the battery lifetime decreases for weights $W_i$=0.8 to 1, according to the battery throughput. However, the surplus amount of throughput will cause a reduction in the battery lifetime.
According to Figure 4.8, the fuel consumption for a wide range of weights decreases when $W_1$ increases, which indicates that the EMS tries to minimize only the generator fuel consumption cost at $W_1 = 1$, but for $W_1 < 1$ the EMS considers the battery utilization as well. Typically, heavy use is the main thing that decreases battery life. It implies using the battery for more than the estimated total throughput. The estimated battery life is the total throughput divided by the yearly throughput.

For example, total throughput of Battery-II LIB for 5 years is 213,405kWh. When $W_1 = 1$, the yearly battery throughput is 58,554 kWh, found by simulation. Therefore, dividing the total throughput of Battery-II LIB by yearly battery throughput gives the estimated
battery life (3.64 years). That means the estimated battery life is dependent on two factors; the total throughput and the yearly battery throughput obtained from the simulation. The variation of the lifetime at $W_i=1$ is emerged from those factors, since each battery has a different amount of total throughput.

Each battery has a different specification such as $DOD$, life cycle, efficiency and battery ampere-hour rated capacity, affecting the total throughput of the battery. The amount of total throughput will be different for each battery. For example, Battery-V LIB has 0.8 $DOD$, 90% efficiency and 2000 life cycle resulting total throughput and the battery life to be 142,336 kWh and 2.4 years respectively. Battery-II LIB is rated differently, having 0.9 $DOD$, 90% efficiency and 3000 life cycle yielding total throughput and battery life to be 213,405 kWh 3.64 years. In addition, the yearly battery throughput was found to be almost equal at $W_i=1$. 
4.2.3 Unique Batteries

This group includes three batteries, AHI, ZBB and Tesla, which are classified as unique batteries according to their high specifications such as very deep discharge (Refer to Chapter 2 for battery specifications).

Figure 4.9 presents the operational cost versus weight for the AHI, ZBB, and Tesla batteries. This graph shows that, for the Tesla battery and the AHI, \( W_i \) increases and total operational cost decreases up to \( W_i = 0.6 \), and then increases further for \( W_i > 0.6 \). In the case of the ZBB battery, the operational cost decreased and \( W_i \) increased up to \( W_i = 0.7 \). At greater weights \( W_i > 0.7 \), the operational cost increased. The range of weights
0.6< \ W_1<0.7 \ were \ determined \ to \ be \ the \ most \ effective \ for \ the \ ZBB \ battery \ in \ order \ to 
reduce \ the \ total \ operational \ cost, \ while \ the \ range \ of \ weights \ 0.5< \ W_1<0.6 \ was \ found \ to \ be 
the \ most \ effective \ for \ the \ Tesla \ battery \ and \ AHI \ battery.

![Operational Cost vs Weight, W1](image)

Figure 4.9 Operational cost

Figure 4.10 shows the battery throughput vs weight for ZBB, Tesla, and AHI batteries. The graph shows that when weight \ W_1 \ increased, \ the \ battery \ throughput 
increased \ as \ well. \ It \ is \ clear \ to \ see \ that \ the \ Tesla \ battery \ has \ the \ highest \ battery 
throughput \ compared \ to \ AHI \ and \ ZBB \ for \ each \ value \ of \ weight \ W_1, \ almost \ 1.5 \ times 
higher \ than \ AHI \ and \ ZBB \ at \ the \ different \ values \ of \ weight \ W_1. \ AHI \ and \ ZBB \ have \ very
similar battery throughput at the various weights.

As noted by the manufacturers, the float life of AHI, ZBB and Tesla are 10 years. Figure 4.11 shows that the ZBB battery has the highest battery lifetime compared to the AHI and Tesla battery for each value of weight $W_1 >0.6$. According to this graph, the AHI, ZBB and Tesla batteries have similar lifetimes for a wide range of weights $W_1 >0.5$, while all the battery lifetimes start to decrease at a certain weight. For example, the Tesla

**Figure 4.10 Battery throughput vs weight**

As noted by the manufacturers, the float life of AHI, ZBB and Tesla are 10 years. Figure 4.11 shows that the ZBB battery has the highest battery lifetime compared to the AHI and Tesla battery for each value of weight $W_1 >0.6$. According to this graph, the AHI, ZBB and Tesla batteries have similar lifetimes for a wide range of weights $W_1 >0.5$, while all the battery lifetimes start to decrease at a certain weight. For example, the Tesla
battery starts to decrease in lifetime at weight $W_1 = 0.5$, while the AHI battery decreases at weight $W_1 = 0.6$ and the ZBB battery at weight $W_1 = 0.7$

Figure 4.11 Battery lifetime vs weight
According to Figure 4.12, the fuel consumptions decrease as $W_i$ increases in this case study. Fuel consumption is somewhat higher at each value of $W_i$ in the case of a ZBB battery. On the other hand, the lowest fuel consumption for the system obtained in the case of used Tesla battery.

![Fuel Consumption vs Weight, W1]

Figure 4.12 fuel consumption vs weight

4.3 Comparison of Batteries

Minimizing the generator's operational cost and the battery's operational cost are the main objectives of an EMS. Weights ($W_1$, $W_2$) play a significant role in achieving the main objective (goal programming approach) of an EMS by defining the battery throughput and the generator's fuel consumption.
For instance, when $W_i$ increased, more consideration was given to the generator in order to reduce fuel consumption. When $W_i$ decreased, more consideration was given to the battery cost, causing an increase in fuel consumption and prolonging the battery lifetime by reducing throughput. For example, Figures 4.3 and 4.4 present the case which results in a decrease in fuel consumption and a reduction in battery lifetime. Table 4.2 presents the best cases of simulation results for the various battery types AHI, ZBB, Tesla, the Lead acid family and Lithium family with a goal of minimizing the cost of the system (fuel and battery operational cost).

By using Lead Acid batteries, the operation cost ranges from $115,370 to $117,980 at weight $W_i = 0.6$ (the optimum weight for minimum operation cost). This battery has a lifetime of 7.17 to 10 years. This family can provide a more cost effective solution than the lithium-ion family. On the other hand, the lithium-ion group provides an operation cost from $117,680 to $134,300 with a 5-year lifetime.

Table 4.6 Best cases of simulation results

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Weight $W_i$</th>
<th>Fuel Consumption, Gallon</th>
<th>Battery Throughput (kWh)</th>
<th>Total Cost of Operation ($)</th>
<th>Max Battery Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Ion</td>
<td>0.7</td>
<td>11,946 - 11,975</td>
<td>18,132- 24,623</td>
<td>117,680 - 139,720</td>
<td>5</td>
</tr>
<tr>
<td>Lead Acid</td>
<td>0.6</td>
<td>11,907 - 12,182</td>
<td>9,923 - 19,948</td>
<td>115,370 - 117,980</td>
<td>7.17 - 10</td>
</tr>
<tr>
<td>AHI</td>
<td>0.6</td>
<td>11,823</td>
<td>25,318</td>
<td>114,250</td>
<td>10</td>
</tr>
<tr>
<td>ZBB</td>
<td>0.7</td>
<td>11,811</td>
<td>28,376</td>
<td>116,560</td>
<td>10</td>
</tr>
<tr>
<td>Tesla</td>
<td>0.6</td>
<td>11,624</td>
<td>38,975</td>
<td>111,010</td>
<td>9</td>
</tr>
</tbody>
</table>
The AHI and ZBB batteries were observed to have the same battery lifetime of 10 years, but the AHI provided a better operation cost at $114,250 (at $W_1 = 0.6$), compared to $116,560$ in the case of ZBB (at $W_1 = 0.7$). AHI provides a more cost effective solution than lead acid, lithium ion, or ZBB.

The Tesla battery was shown to provide the most cost effective solution compared to all other battery types. If using a Tesla battery, the cost is approximate $111,010$, the lowest operating cost of all options. It also has the highest battery throughput, and the fuel consumption was low. The Tesla battery has a lifetime of 9 years, which is also high compared to the other batteries studied.

4.4 Cost Variation vs Performance

Reducing battery cost will increase the EMS performance by increase the amount of the battery throughput and decrease the fuel consumption. If the operational cost of the system is high, that means high battery cost. For example, there is a big variation in the lithium ion battery operational cost about $42,020$ which consider it high. According to that cost, the EMS efficiency is low because the operational cost is high and the fuel consumption is high as well.

For lead-acid, the operational cost variation is lower than lithium ion about $18,320$ which increase the system performance but the lifetime of the battery will decrease if use the battery heavily, that causes an increasing in the operational cost, which presented in figure 4.1 at $W_1 = 1$ the cost will increase to be around $135,000$ because of the increasing of the battery throughput to be 58,000 kWh. That mean reduces the system performance by 14%.
For the battery that has a high performance such as AHI and ZBB, operational cost the variation is not big like what found in the lithium ion and lead acid that because the ability of these batteries can provide a high amount of throughput with a small increase in the operational cost. For example, the variation cost of Tesla can be around $2000, which is low comparing to the other battery.

In summary, the wear cost is the main thing to obtain high or low cost. Low battery cost will increase the EMS performance by increase the amount of the battery throughput. So, the battery which has a high amount of throughput and low wear cost has a high ability to decrease the fuel consumption by reducing the used of the generator.
CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

Energy is very important in our life. There are many areas around the world lack access to electricity. Remote microgrid is a new solution to serve electricity in the remote area. Typically, most of the remote microgrids depend on the fossil fuel. Also, the remote microgrid has renewable energy sources such as photovoltaics, wind power, which can help to reduce the fuel consumption of the generators. Battery plays a significant role to increase the remote microgrid performance by increasing the utilization of the renewable energy sources.

Most of the research work consider two or three batteries for comparison. Also, most of the literature not considered Tesla battery, a new technology. This rehearse can be a new set for the comparison between the lead acid and lithium-ion battery. One of the strong motivations behind this research is the need to have a cost effective storage technology to use in remote microgrids. The objective is to study the feasibility of using different batteries for remote microgrids. The main objective is to minimize the operational cost of the system and prolong the battery lifetime.

There are many types of batteries which can be used in the remote microgrid. Those batteries such as ZBB, AHI, LIB and lead Acid battery can provide a good cost effective solution. This thesis used an optimization techniques to fix the goal programing approach. It uses IBM CEPLX optimization software to solve the problem.

Economic analysis was presented in order to determine the best battery technology based on this case study. According to simulation results, the Tesla battery
can provide a better cost effective solution than the AHI, ZBB, Lead acid and lithium ion batteries, based on the total operation cost of approximately $111,010. This battery also has a very high throughput of 38,975 kWh with a 9-year lifetime. While the ZBB and AHI have a higher lifetime of 10 years, their operational cost was higher than Tesla by $6,500 and $4,240 consecutively. The lithium ion battery is not an effective solution for this case of study since its lifetime is low at 5 years. The weights which provide an effective solution for an EMS are different with various battery types. For example, the best weights came from Tesla at $W_1 = 0.6$ and the lithium ion battery at $W_1 = 0.7$.

Wear cost of the battery is a very important factor in order to design a system. Low wear cost can provide a high amount of battery throughput which affects the EMS by decreasing the fuel consumption, that can reduce the total operation cost, which presented by Tesla battery.

Considering Tesla battery in any microgrid can reduce the operational cost of the system and the fuel consumption but this solution is applicable for small scales or remote microgrids. So, considering Tesla in the large application may have higher impact to the remote microgrids. Because the Tesla can provide 6% more cost effective. So, considering Tesla in the large application may increase that percentage.
5.2. Future Work

This thesis considers only battery as a storage device to work in the EMS. So, considering other energy storage technology such as a flywheel and fuel cell could provide an effective solution of EMS. The future work can be, the impact of different energy storage technology in the remote microgrid system such as flywheel and fuel cell.

Also, this case study did not include the wind turbine in its renewable energy options. Incorporating a wind turbine in a remote microgrid system and determining its impact on the energy storage system would be a useful study to undertake.
References


