2018-01-01

Economic and Environmentally Efficient Energy Management System for Optimal Microgrid Operation

Olayinka Samuel Obafemi
University of Texas at El Paso, yinkobaf@gmail.com

ECONOMIC AND ENVIRONMENTALLY EFFICIENT ENERGY
MANAGEMENT SYSTEM FOR OPTIMAL
MICROGRID OPERATIONS

OLAYINKA SAMUEL OBAFEMI
Master's Program in Industrial Engineering

APPROVED:

____
Tzu-Liang (Bill) Tseng, Ph.D., Chair

____
Paras Mandal, Ph.D., Co-Chair

____
Eric Smith, Ph.D.

____
Charles Ambler, Ph.D.
Dean of the Graduate School

ECONOMIC AND ENVIRONMENTALLY EFFICIENT ENERGY MANAGEMENT SYSTEM FOR OPTIMAL MICROGRID OPERATIONS

by

OLAYINKA SAMUEL OBAFEMI, BSc.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Industrial and Systems Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2018

Acknowledgements

I would like to express my sincere appreciation to my thesis Chair, Dr. Bill Tseng, for guiding and giving me this research opportunity and his mentorship and contribution throughout my master's program. I would like to thank my thesis Co-Chair, Dr. Paras Mandal, for his assistance and continuous encouragement towards my research work. I would like to thank my former classmate and close friend, Tandin Dendup, for his continuous encouragement towards my individual and professional development. I also want to extend my appreciation to the U.S. Department of Education – DHSIP Program for its support.

I am very grateful to my Aunty, Mrs. Dupe Hughes, for her prayers, moral support and believing in my dreams and reminding me that the sky is the limit. She has been a big inspiration in my life. Finally, I am thankful to my family for encouraging me not to put limitations on my goals.

Abstract

The aim of this thesis is to study and understand the economic analysis of integrating renewable energy resources for the purpose of improving the system grid, identifying and monetizing benefits and cost. This thesis discusses the approach taken and solution created to tackle the current problems facing the production and consumption of electricity and how the microgrid has become a platform for improvement in power system operation. A microgrid in islanded and connected mode are simulated using Homer Pro for optimization and its results help gain an insight into analyzing and monetizing cost and benefits with one common goal in mind, i.e., meeting consumers demand at all times. Another scenario that is considered is the environmental impact of providing electricity to consumers. The impact of carbon emission on the environment has been a major issue for most communities, government. Policy makers continuously find ways to create laws and incentives that encourage the reduction of carbon emission. Five cases are examined in this study, with each case uniquely performing cost and benefits analysis, and the end result identifies the optimum solution. This project primarily reviews a conventional energy and brings to light, the effect of changes in fuel price and how it affects the cost of producing electricity. In this thesis, a diesel generator, a wind turbine, two solar panels, and a battery storage form the microgrid system and the easy integration of renewable energy sources show how the microgrid has a better chance of carbon emission reduction, and cost minimization. The first case simulates only a conventional energy without a storage system and the results are displayed. The second, third, fourth, and fifth cases simulate the conventional energy with the inclusion of different options of renewable energy sources and the case with the best result is selected. The two different options considered are islanded mode and connected mode and each option takes into account five cases and the optimum solution is provided. The main contribution of this thesis is to provide an energy management system (EMS) that will minimize cost through simulations, use renewable energy resources to reduce carbon emission, and find ways to monetize

benefits such as purchasing electricity from or selling electricity to the main grid while in connected mode.

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Chapter 1: Introduction

1.1 Background and Research Motivation

In today's world, about 1.2 billion people lack access to electricity [1]. Over 95% of this populace live in developing countries and 84% in rustic territories. A considerate measure of rustic groups are without power and they live in scattered territories with very low population density and mostly where the national grid extension cost is very high [2].

In 2016, the average annual electricity consumption for a U.S. residential utility customer was 10,766 kilowatt-hours (kWh), an average of 897 kWh per month. Louisiana had the highest annual electricity consumption at 14,881 kWh per residential customer and Hawaii had the lowest at 6,061 kWh per residential customer [3]. There is a very strong potential for Microgrids for emergency response and reliable power during unforeseen and extreme events. Microgrid can deliver the optimum solution to the current problems facing electricity supply and consumption. Even in places with more reliable grids, outages can have very high cost, particularly for places with critical loads, such as research labs, hospitals, and data centers. Events like the 2012 super storm sandy that affected the northeastern United States. Supply of electricity to millions of consumers was disrupted by this event and it caused loss in billions of dollars. In the most recent decades, the enthusiasm on distributed generation (DG) has been expanding, basically because of the technical developments on generation systems that meet environmental and energy policy concerns. A comprehensive review on distributed energy resource (DERs) and current practices in microgrids as well as interaction problems arising from the integration of various DERs in a microgrid can be found in [4].A microgrid can work in two distinct modes: Interconnected or connected. In an interconnected mode, the microgrid is connected to the distribution network, bringing in or sending out power. When in crisis mode, the microgrid works secluded from the distribution network and utilizes local resources or nearby assets. The monetary investigation distinguishes the significant cost brought about while setting up a microgrid and the benefits that results from potential reliability improvements, and to manufacture a choice model for the circumstance [5]. An insight into the concept of a microgrid is shown in Figure 1.1.

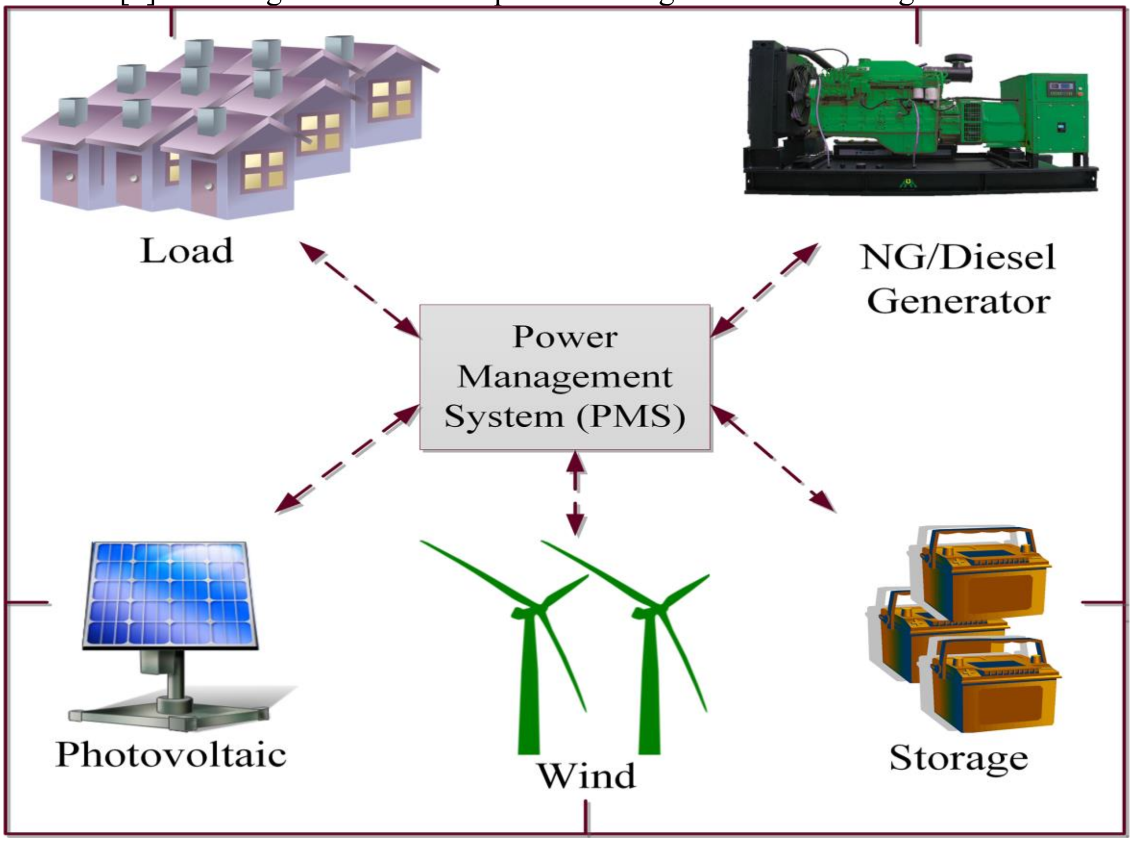

Figure 1.1: A Microgrid System [6].

1.2 Problem Statement and Rationale for the Study

The examination and outline of microgrid don't just take under consideration the system requirements but in addition some uncertain factors, for example, the load variation, the cost of fuel or adequacy of fuel. The vulnerability gets bigger as many renewable energy sources such as wind generators and solar panels have variant output due to seasonal or incidental insolation and change in wind power [7]. Addressing the difficulties of long-term sustainability depend vigorously on choices that are been made now. The most critical choices that are being made are focused on our electricity infrastructure. Electricity assumes a vital role in all parts of the worldwide political economy, including both the wellspring of energy behind our homes and hospitals, however likewise as a primary contributor to greenhouse gas emissions [8]. The policy of climate change was conceived directly out of the environmental policy agenda area of feasible improvement. Tending to environmental change is subsequently, a globally perceived segment of keeping up the stability among environment, economy, and wide civilian society. Climate change assumes a critical part in expanding the earth's normal surface temperature, cultivating the phenomenon known as global warming.

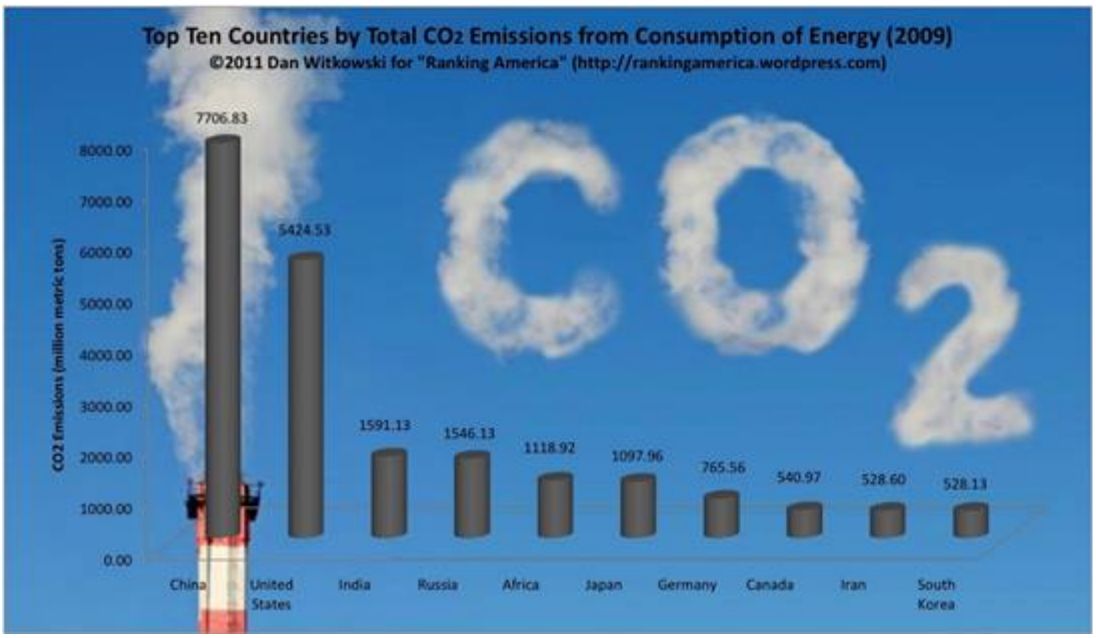

Figure 1.2: Data from U.S. Energy Information Administration [3].

Figure 1.2 shows the impact of CO_2 emissions from consumption of energy. In 2015, emissions of carbon dioxide by the U.S. electric power sector were 1925 million metric tons, or about 37% of the total U.S. energy-related carbon emission of 5271 million metric tons [3]. The need to reduce pollution caused by carbon emission and the liberalization of the electricity markets have led to a large-scale development of renewable energy generators in electrical grids [9].One of the biggest and emphasized importance of microgrids is the ability to easily integrate renewable energy resources and the significant reduction they have on carbon emission. However, the increase in penetration of renewable energy resources, results to the increase in the sensitivity of the microgrid system.

1.3 Objectives of Thesis

The aim of this thesis is to study and understand the economic analysis of integrating renewable energy resources for the purpose of improving the system grid, identifying and monetizing benefits and cost. Specifically, the objectives of this thesis are:

- **Objective 1:** To minimize the cost of producing electricity and incentivize excess electricity in order to gain maximum profit.

  Objective-1 focuses on the stand alone conventional system (diesel generator) and compares its analysis to the advantages of having renewable energy resources and their effect on cost minimization, reliability, and dependability.

- **Objective 2:** Performs the analysis of carbon emission through the integration of renewable energy resources.

  Objective-2 emphasizes the effect of renewable energy resources on the reduction in carbon emission and the contribution to promoting a clean environment. The idea is to understand that the increase in renewable energy resources and reduction in conventional energy generation results in less emission of carbon into the environment.

1.4 Scope and Limitations

A community microgrid is analyzed in order to promote the use of renewable energy resources and identify its effect on the economy of a microgrid. As defined by the U.S. department of energy, "a microgrid is a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously." In order to get a scope of the entire microgrid system, the need to understand how a microgrid works is important. The grid associates homes, organizations and different structures to focal power sources, which enables consumers to utilize machines, warming/cooling systems. However, this interconnectedness implies that when part of the grid needs to be repaired, everyone is affected. A microgrid for the most part works while associated with the grid, yet significantly, it can detach and work independently, using local generation sources in times of crisis like storms or blackouts, or for different reasons. Economics often dictates that a microgrid must readily accommodate connection and disconnection of DER units and loads while maintaining its operation [10].

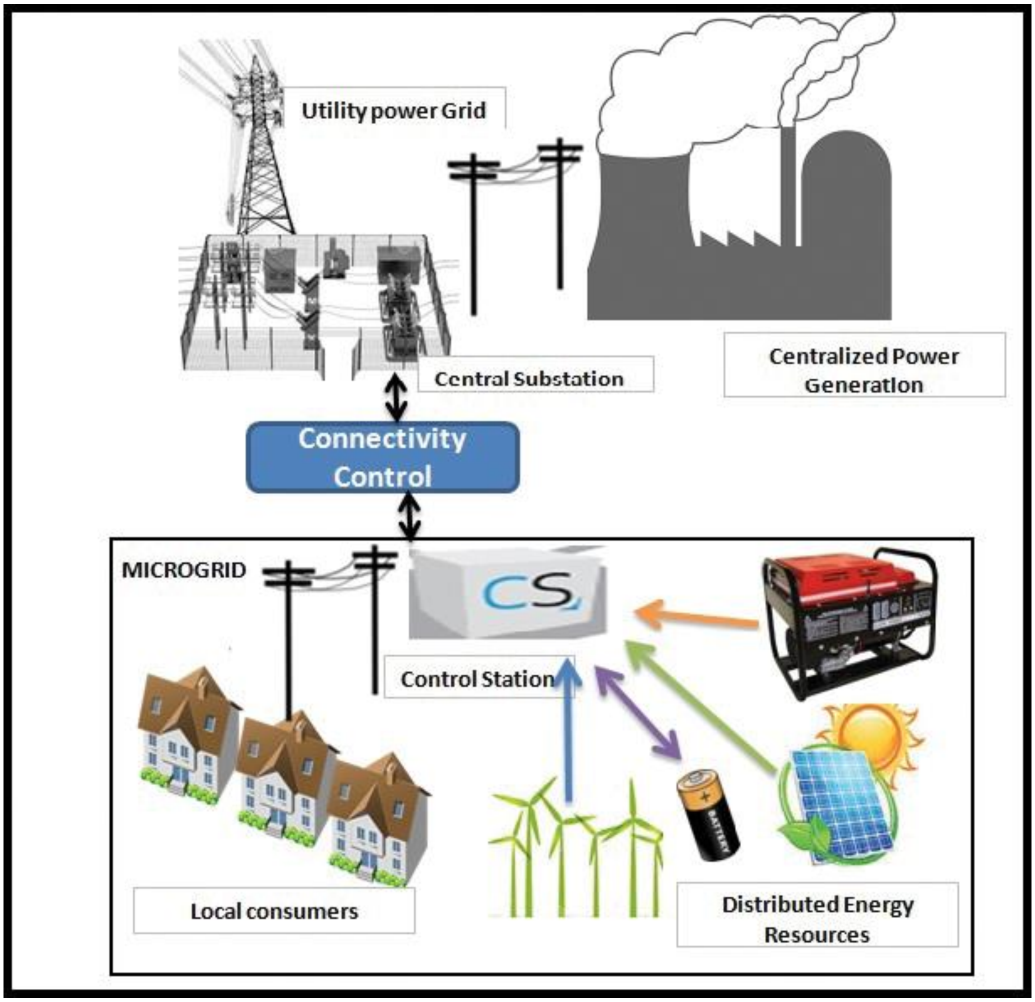

Figure 1.3: A Microgrid management and connectivity control [11].

Figure 1.3 displays the connection of a microgrid to the utility main power grid. A microgrid can be powered by generators with power from natural resources such as distributed generators, batteries, and additionally sustainable energy such as wind energy and solar power. Renewable DGs offer several benefits including sustainability, being emission free, and benefiting from a common primary source of energy [12]. Contingent upon how it's energized and how its necessities are dealt with, a microgrid may run inconclusively. A microgrid interfaces with the main grid at a point of common coupling as shown in Figure 1.3, that keeps up voltage at an indistinguishable level from the main grid unless there is some type of problem on the main grid or other motivation to disconnect. A microgrid can function autonomously because of the switch that can isolate the microgrid from the main grid.

Even though microgrids are of great advantage to the power system and so many power companies view microgrid as the best go to option to tackle problems facing electricity production and consumption, there are still some limitations on the microgrid itself.
These are the limitations listed below.

- Homer Pro software capability and algorithms. The software is able to effectively perform cost benefit analysis (with built-in algorithms) on a small scale microgrid with a capacity of 500 kW or less. However, there is a recommendation to use a different and more robust software such as MATLAB when the renewable energy integration gets close to 25% in a microgrid with 1 MW or more, due to increase in sensitivity of the system. An example is the fluctuations in wind power which can cause the microgrid to have frequency instability [13], [14].
- Lack of access to main grid information limits the ability to fully gain an insight into the technicality behind the operations and availability of the main grid and also understanding the economy behind the buying of electricity from the main grid and the selling of electricity to the main grid. However, the Homer Pro software uses the information given, to perform cost benefit analysis and looks for the optimum solution. The problem in this kind of situation is that, there might be a better solution than the optimum solution, if more information is given about the economic break down of the main grid.
- Protection of a microgrid is the most influential challenge facing the fulfillment of microgrids. Once a microgrid is shaped, it is vital to guarantee the loads, lines, and the distributed generations on the island are protected [15]. The two-alternating current constraining algorithms to keep the stream of large line currents and protection of microgrid amid utility-voltage sags [16].

- Limited availability to data resource such as wind speed, solar radiation, and load profile. These resources are of vital importance to the microgrid management planning. For instance, the average wind speed is needed in order to understand the amount of electricity a wind turbine can contribute to a microgrid. Also, limited access to historic load data can hinder the predicting or anticipation of electricity demand.

1.5 Thesis Organization

This thesis is organized in form of six chapters and the presentation is tailored in the following ways. Figure 1.4 illustrates the whole structure of the thesis.

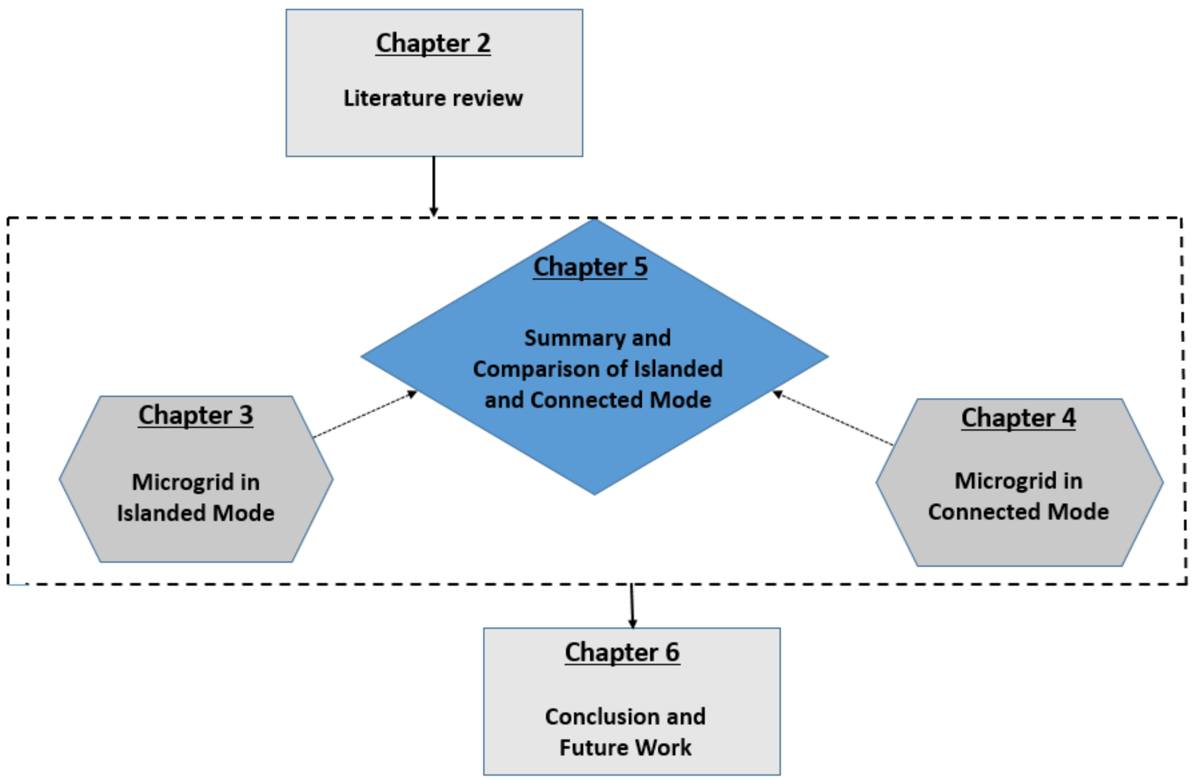

Figure 1.4: Organization of thesis.

- *Chapter 2* presents the literature review, giving the affirmation of techniques and their performance that have already been used in the analysis of microgrids. This chapter elaborates on factors that contribute to the economy, impact and future of the microgrid.

Reviewing the current influence of energy in today's market and finance, and finally the emission of carbon and the effect it has on the environment and alternative solutions.

- *Chapter 3* presents the economic analysis of microgrid in islanded mode using the Homer Pro software simulation tool and evaluates the cost and benefits of alternative energy sources to find the optimum solution for the purpose of profit maximization. A conventional energy generator is used as the base case, and then various alternative renewable energy sources are simulated with the base case. The simulation also reveals analysis on carbon emission and how the integration of renewable energy sources (wind energy, battery storage, and solar energy) creates a significant reduction in carbon emission.
- *Chapter 4* presents the economic analysis of microgrid in connected mode, and the importance and advantage of this mode is the ability to export and import electricity to and from the utility grid. The benefits in the area is the ability to sell excess electricity to the main grid which can be seen as waste minimization and cost recovery. Also, the ability to be able to purchase electricity from the utility company if more electricity is needed by the microgrid for any unforeseen or emergency reasons.
- *Chapter 5* compares and evaluates the economic analysis of microgrid in islanded and connected mode so as to identify ways of making the two systems better and assimilate when connected. And the benefits seen from the connected mode can be examined in order to generate more revenue. However, the islanded mode provides the opportunity for continuous power supply during any kind emergency.
- *Chapter 6* draws the conclusion of this thesis and introduces new ideas on future development and challenges due to population increase and evolving technologies.

Chapter 2: Literature Review

The objective of this chapter is to understand the ideas that contribute to the findings and development of a microgrid and the continuous researches that help to sustain the ability of the microgrid.

2.1 Introduction

Today's electricity markets must balance growing consumer demand with regulatory or market-based policy requirements to reduce greenhouse gas emissions. Continuous researches can help policy makers understand how domestic and international market for electricity responds to government actions, consumer patterns, and market uncertainties. In the course of the most recent 25 years, electricity markets have advanced to address complex economic and engineering challenges. In spite of a few bumps along the way, the markets have largely succeeded in the objective of providing reliable electricity at least cost to consumers. An example is using renewable energy generators such as wind power or photovoltaic generators to reduce fuel consumption and greenhouse gas emissions [17]. It's no simple task. Every second, supply and demand must balance. A huge amount of resource and network constraint must be fulfilled. Furthermore, the market must send the right price signals to motivate efficient generation and investment in resources over time [18].

2.2 Microgrid Energy Management System (MEMS)

A microgrid usually requires an energy management strategy, assigning active and reactive power references, and ensuring coordination between the controllable units to achieve stable and economic operation [19], [20]. The International Electrotechnical Commission in the standard IEC 61970, defines an EMS as "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [21], [22]. An energy management system (EMS) has been in charge of the administration and control tasks in the traditional power systems, and now there is the utmost importance to advance the EMS in order to adapt with emerging challenges [23]. The one of a kind attributes and elements of a microgrid's components gives a one of a kind challenge with respect to grid control and operation. Contingent upon the characteristics and penetration of renewable energy resources within a specific microgrid, the desired energy management scheme can be altogether different from a traditional power system. A typical microgrid runs in two operational modes [24], [25], which are the islanded mode and connected mode. In islanded mode, the microgrid operates autonomously, meaning, separated from the main grid. In connected mode, the microgrid is linked to the main grid. The end goal of the microgrid energy management system (MEMS) is to minimize the microgrid's operating costs such as fuel cost, operation and maintenance cost, and cost of purchase of electricity from the main grid.

2.2.1 Microgrid Energy Management System in Islanded Mode

When disconnected from the main grid, the highest priority of the microgrid is to keep a reliable power supply to customers instead of economic benefits [26]. In islanded mode, the topmost priority is to guarantee continuous supply of electricity, instead of economic benefits. So, the operation objective of microgrids is to maximize satisfaction rate of loads with minimum operation cost. Ideally, the wind and solar generation power should be completely consumed to make up for where there is lack in electricity and part of load could be cut off to balance power when necessary [27].

2.2.2 Microgrid Energy Management System in Connected Mode

Because of the connection to the main grid, load demand can be met at all times. In this mode, the operating objective of microgrids is to maximize profits according to DG bids and market price. For benefits to the environment and saving energy, it is of great advantage for the wind and solar power to be totally used [27]. The requirements of voltage and power flow are taken into consideration, especially at the point of common coupling (PCC).

2.3 General Components in Microgrid Energy Management System

A MEMS is a control programming that can optimally apportion power output among distributed generators (DG) units, economically serve the load, and consequently enable the system resynchronization reaction to the working change amongst islanded and connected modes based on real-time operating conditions of microgrid components and the system status. Figure 2.1 shows a control hierarchy of a microgrid.

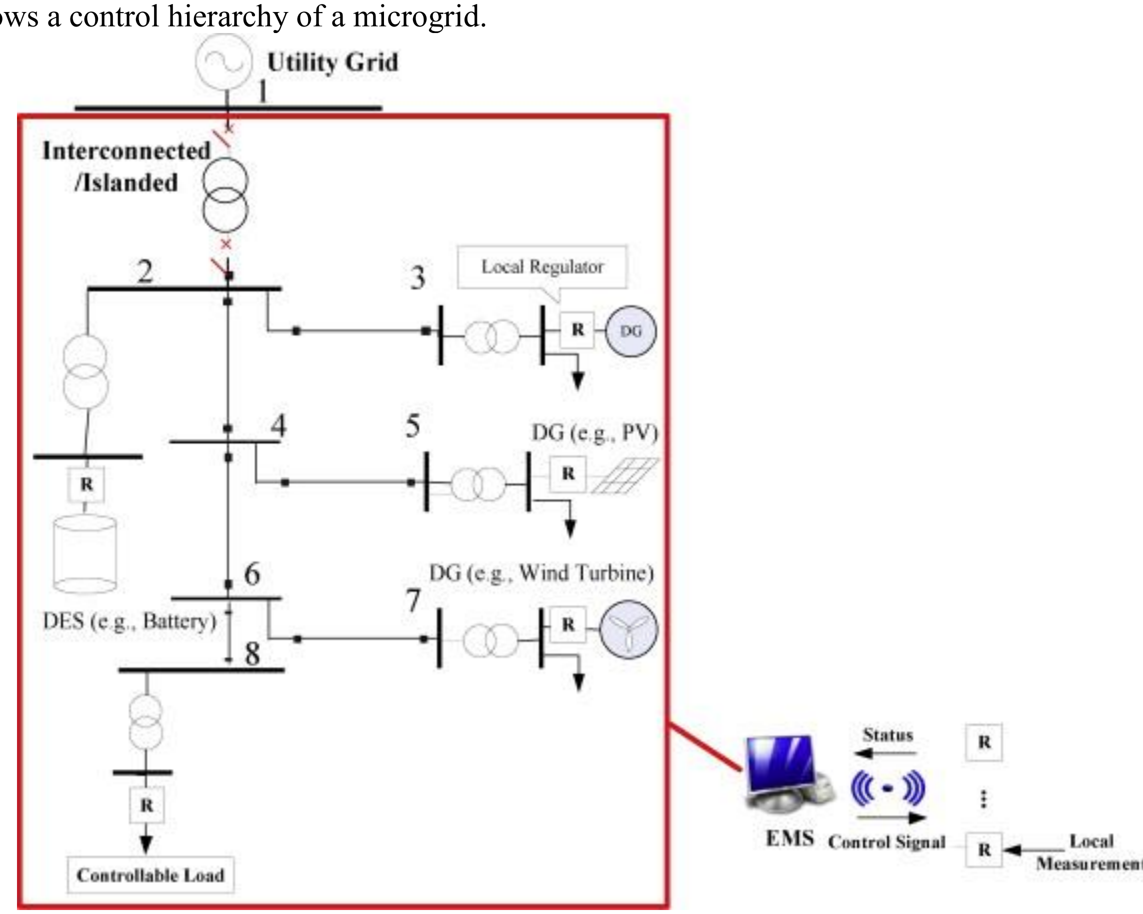

Figure 2.1: Control hierarchy in microgrid [28].

Despite the fact that there isn't an all-inclusive meaning of what constitutes a microgrid, it can be for the most part that a microgrid is composed of several major components which normally do not exist in traditional power systems. High penetration of these components increases the complexity of the MEMS. These components consist of, but are not limited to: DGs (reciprocating internal combustion engines with generators, fuel cells, wind turbines, and photovoltaic arrays), DES (battery banks, flywheels, super-capacitors, compressed air energy storage), Controllable load (commercial and residential building, plug-in electric vehicle (PEV), plug-in hybrid electric vehicle (PHEV), heating, ventilation, and air-conditioning (HVAC)), Critical loads (hospitals, schools, data centers), PCC (static switch). The functionalities of these components are briefly described below [28].

- *Distributed Generator:* This is normally characterized as a small scale (e.g., kilowatts) electric power generator which is directly connected to the distribution system at or close to the load feeder. Conversely, traditional power plants supply electricity through high voltage transmission lines with a capacity of hundred megawatts.
- *Distributed Energy Storage:* This system enables the microgrid to be more cost effective by storing energy when the energy purchased from the main is cheap or when there is excessive generation from the local DGs. Distributed energy storage (DES) can likewise be worked as an extra generator amid peak demand periods. The detailed operations are performed by the embedded local regulators within DES while the microgrid-level EMS will control when to dispatch the stored energy and how much.
- *Controllable Loads:* These are the loads that can adjust their own electric energy utilization based on real-time set points. In a traditional distribution system, consumers have little flexibility to fully take part in electricity markets. Controllable loads are usually tied with the ideas of demand-side management (DSM). An example of controllable load is the residential or commercial lighting control which has been verified to be successful [29].
- *Critical Load:* In the connected mode, the DGs and DES can be used to help as many critical loads as possible. While a microgrid is operating in islanded mode, not all of its loads can be supplied. Some controllable load may have to be shed accordingly, in order to improve the availability and reliability of power supply for critical loads.
- *Point of Common Coupling (PCC):* PCC is the point at which the power production, distribution network, and customer interface meet. DGs, DESs, and loads are tied together

in their own feeders in the most common configuration, which are then connected to the main grid at a single PCC.

2.3.1 Functionalities of Microgrid Energy Management System

MEMS is relied upon to screen the operational conditions, and optimally dispatch power from DES and DER nodes to supply the controllable and critical loads. As seen in Figure 2.2 [28], the role of MEMS is related with electricity market, utility, customers, policy, load/DER forecast, DGs, and DES. The microgrid receives all these information in order to decide the best accessible controls on power flow, load dispatch, power purchase from utility, and scheduling of DG/DES.

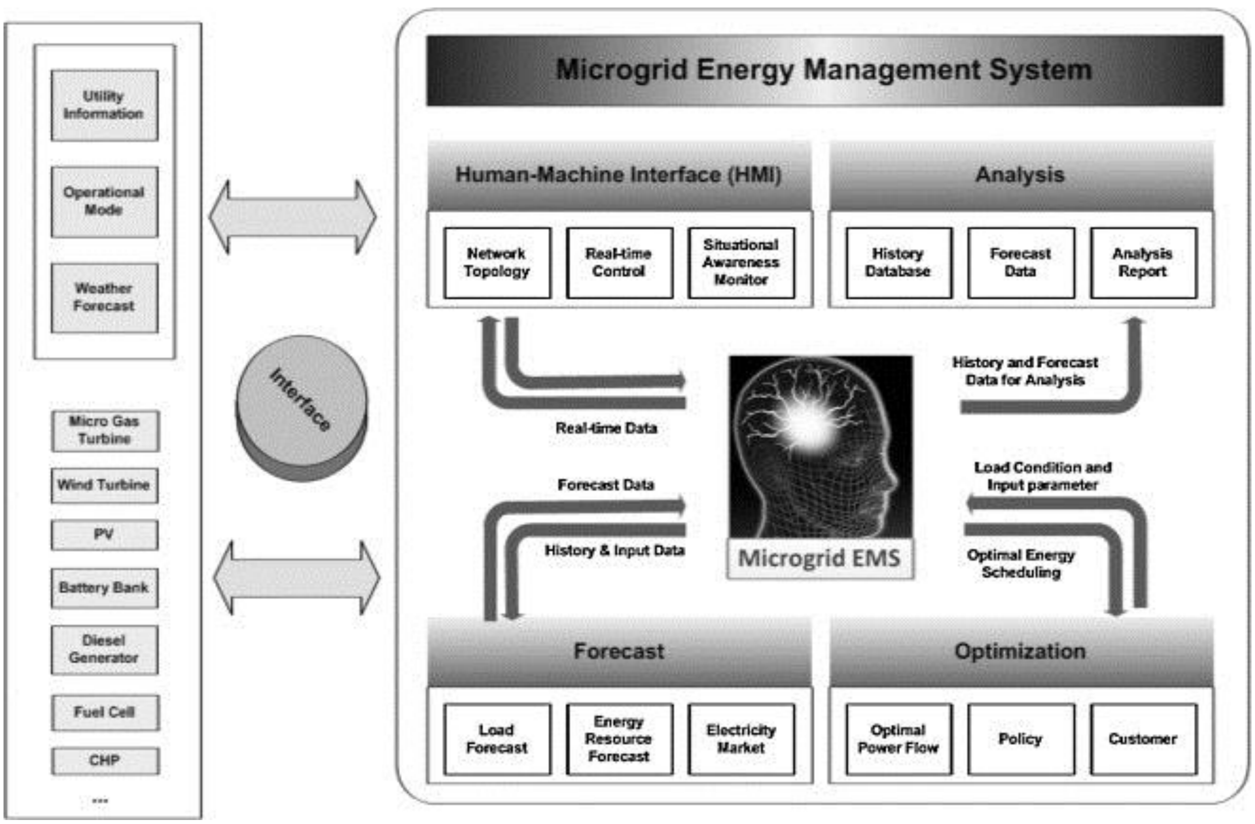

Figure 2.2: A microgrid energy management system (MEMS) [28].

2.4 Challenges in Microgrid Energy Management System

One of the challenges in MEMS is the dynamics in energy supply. There continues to be a significant rise in the installations of microgrids and integration of low-voltage distribution systems. Therefore, distributed generation systems in microgrid will become significant in numbers with different individual characteristics as compared to the main grid in which there must be strategic implementations in designing suitable controls to anticipate the difference. The microgrid aims to optimize production and consumption of electricity for the purpose of efficiency improvement. There is the possibility of conflicting requirements and limited communications, due to the controlling of large numbers of REs with different characteristics. There may be large mismatches between generation and loads when transitioning from connected to islanded mode. The plug and play capability can create a serious problem, since the process of disconnection and connection simultaneously involves large number of micro sources. The inherent intermittency and variability of a renewable energy resource (for example, wind speed and solar radiation) has complicated implications for microgrid due to dramatical fluctuations based on the time of the day or year [30]. The use of storage systems has been encouraged in recent years, in the design of active generators, which are able to provide an energy reserve with a less fluctuating output power [31]–[33] This sort of variability and uncertainty need to be carefully examined under forecasting in MEMS design.

2.5 Conclusion

For long term goals, microgrids are becoming reliable and dependable technologies for economic gains and contribution to the consistency in quality electricity supply to end users. In the grid-connected mode, the microgrid adjusts power balance of supply and demand by purchasing power from the main grid or selling power to the main grid to maximize operational benefits. In the stand-alone mode, the microgrid is separated for the main grid with a goal of meeting consumer electricity demands at all times using DG bids [34]. A battery storage system can help in the alleviation of power fluctuations including power regulation of each dispatchable DG unit, charging and discharging of energy storage system (ESS), and load shedding [35]. Economic advantages of microgrids are extensively discussed in the literature [36]–[44].

Chapter 3: Economic Analysis and Optimal Energy Management Models for Microgrid System in Islanded Mode

3.1 Introduction

This section of the thesis presents the analysis of five different cases when the microgrid is isolated from the main grid.

A microgrid for 120-community homes is designed with the consideration of possible population growth in the community. The microgrid has a capacity of about 900 kW, including a diesel generator, wind turbine, two solar panels, a storage system and a system converter for storage battery and PV.

3.1.1 Load and Data Resources

Table 3.1: Microgrid system components.

Microgrid System Capacity (0.9MW)	**Generator Type**				**Storage Type**	**Component Type**
	Diesel Generator	Wind Turbine	PV Solar Panel	PV Solar Panel	Battery	Converter
Nominal Characteristics	680kW	100kW	60kW	60kW	3500Ah	60kW
Brand Name	CAT	WES 18	SMA Sunny Tripower	SMA Sunny Tripower	Iron Edison	ABB-MGS

The analysis of the system is done by entering the information as seen in Table 3.1 in the Homer Pro software for optimization, sensitivity analysis and carbon emission analysis. The simulation mimics time varying loads, wind resources, solar radiation resources, and the optimization finds the least cost solution (based on Net Present Cost).

- *Load Data:* A load data received from a credible online source is used in this simulation. As can be seen in Figure 3.1, the seasonal profile depicts what is generally expected in electricity usage, in approximation during an entire year.

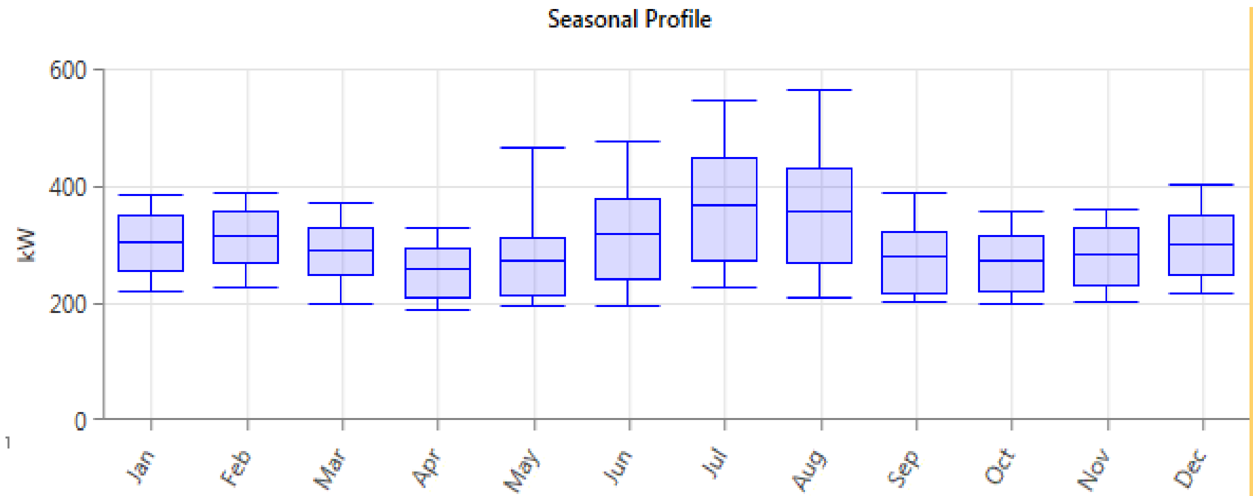

Figure 3.1: Graphical display of average monthly electricity usage analyzed from the load profile.

Since summer tends to be the hottest of all in the season, it can be seen in Figure 3.1 that June to August are the months with the highest electricity usage, since the demand for electricity goes up during this time. The annual average electrical load is 7, 263.7 kWh/d, average load is 302.66 kW, and the peak daily load is 565.94 kW as shown in Table 3.2.

Table 3.2: Averages for annual electrical load, average load, and peak daily load.

Metric	Baseline	Scaled
Average (kWh/d)	7,263.7	7,263.7
Average (kW)	302.66	302.66
Peak (kW)	565.94	565.94
Load Factor	0.53	0.53

- *Wind Resource:* The wind speed is used by the wind turbine to convert mechanical energy to electrical energy. The data is shown below in Figure 3.2.

Figure 3.2: Average monthly wind speed from NASA.

As seen in Table 3.3 and Fig 3.2, the wind speed data is downloaded from NASA surface meteorology and solar database. Wind speed at 50m above the surface of the earth for terrain similar to airports, monthly averaged values over 10-year period (July 1983 – June 1993). The wind speed is converted into electricity through a wind turbine. Annual average wind speed is 4.20m/s.

- *Solar GHI Resource:* The data is the Solar global horizontal irradiance that is transformed into electricity through a solar panel.

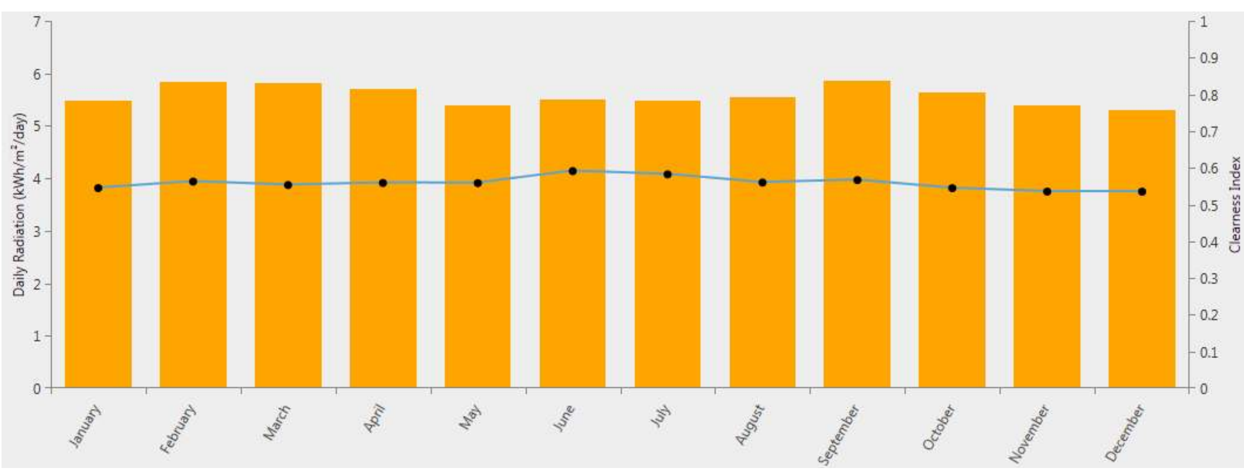

Figure 3.3: Average monthly global irradiance horizontal data.

As displayed in Table 3.4 and Figure 3.3, the data downloaded from NASA shows the global horizontal radiation, and monthly averaged values for over a 22-year period (July 1983 – June 2005). The panels are made of semi-conductor that sunlight to be converted directly into electricity.

3.1.2 Microgrid Components

- *Diesel Generator:* With a capacity of 680 kW, the Caterpillar generator is primarily the base system. The initial capital cost for the diesel generator is at $200,000, while the cost to replace it is at $180,000. The cost of operations and management is set at $1/hr. Since this generator will be running on diesel fuel, the cost of fuel is also taken into account. The system is of course sensitive to fuel price.

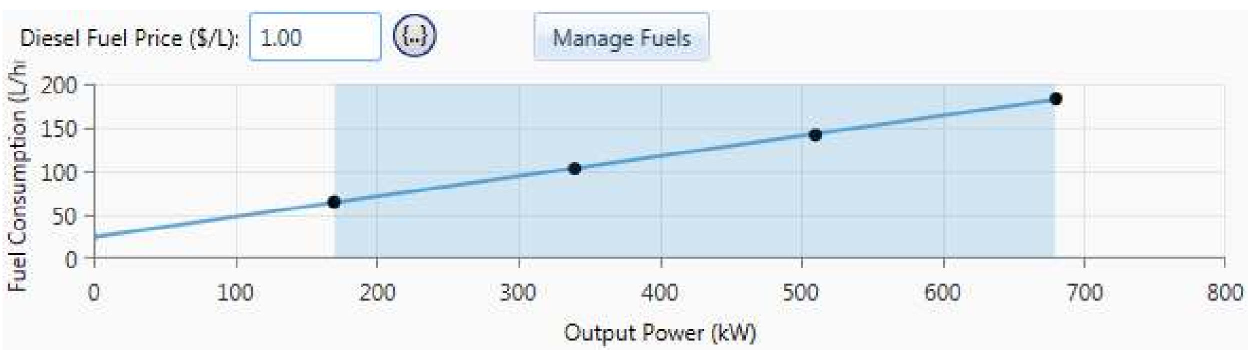

Figure 3.4: Rate of consumption of fuel vs power output by diesel generator.

As shown in Figure 3.4, fuel consumption (liter/hour) affects the output power the generator produces. For example, at 50 L/h, the generator produces about 180 kW of electricity, and at 150 L/h, the generator produces about 510 kW of electricity.

- *Wind Turbine:* The WES-18 wind turbine, with the capacity of 100 kW is one of the renewable energy resources used in this thesis. Maintainance is suggested for twic a year. Tower height possibilities can be at 18m, 24m, and 30m. The power curve for this generator can be seen in Figure 3.5.

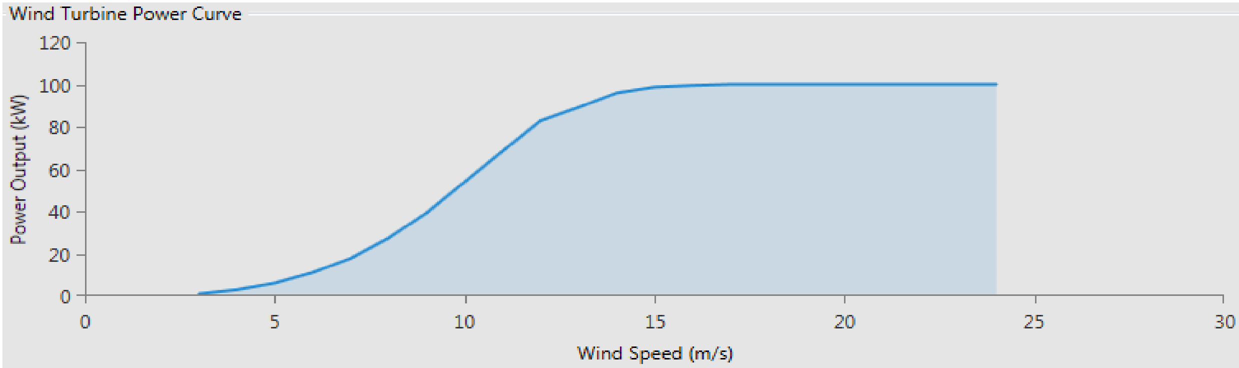

Figure 3.5: Wind speed vs power output.

The power curve shows the conversion of wind speed into electricity through the concept of mechanical energy conversion into electrical energy. The cut-in speed is at 3m/s and the cut-out speed is at 25m/s. Shown in Table 3.3 is the detailed wind speed conversion for the wind turbine.

Table 3.3: Wind Turbine Power curve table.

Wind Speed (m/s)	**Power Curve (kW)**
3	1
4	2.9
5	6
6	11
7	17.7
8	27.3
9	39.2
10	53.8
11	68.4
12	82.8
13	89.1
14	95.9

15	98.7
16	99.5
17	100
18	100
19	100
20	100
21	100
22	100
23	100
24	100

- *PV:* The SMA SUNNY Tripower is a 60 kW flat plate. Its operating temperature is 45 degrees Celsius. The initial capital cost for the PV is $3000, replacement cost is $3000, and the operation and management cost per year is $10.
- *Battery Storage:* The Iron Edison LFP system is a storage system with a nominal capacity of 168kWh. The initial capacity cost is $136,500, and the replacement cost is $136,500.

There are 5 number of cases in this chapter and each case is outlined below.

3.2 Case 1: Considering Only Diesel Generator as a Distributed Energy Resource in Islanded Mode

In case 1, a stand-alone diesel generator is observed and the simulation results are presented.

- CAT-680 represents a diesel generator.

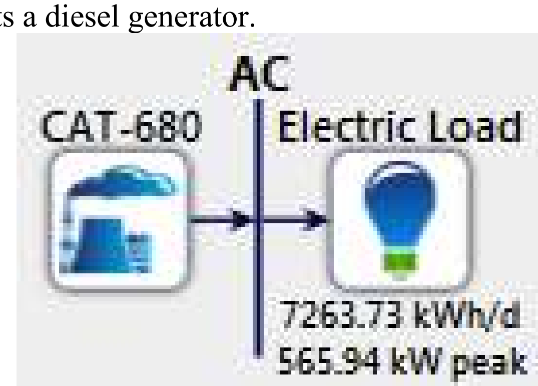

Figure 3.6: Schematic for stand-alone diesel generator in islanded mode.

As displayed in Figure 3.6, is the use of a conventional system (diesel generator) for electricity generation. This generator caters to a load of 2,651,261 kWh/yr, which is equal to the amount of the electricity production of 2,651,261 kWh/yr. There is no surplus electricity in this case.

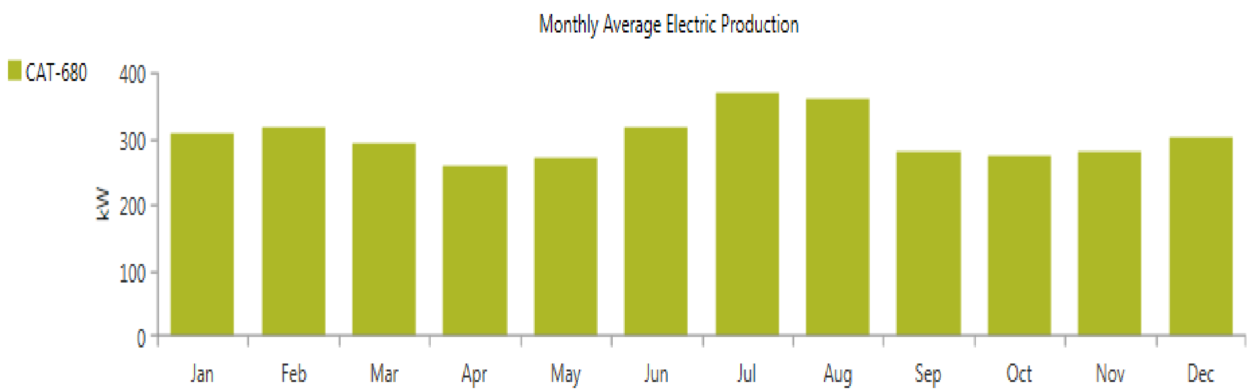

Figure 3.7: Monthly average electricity production by stand-alone diesel generator in islanded mode.

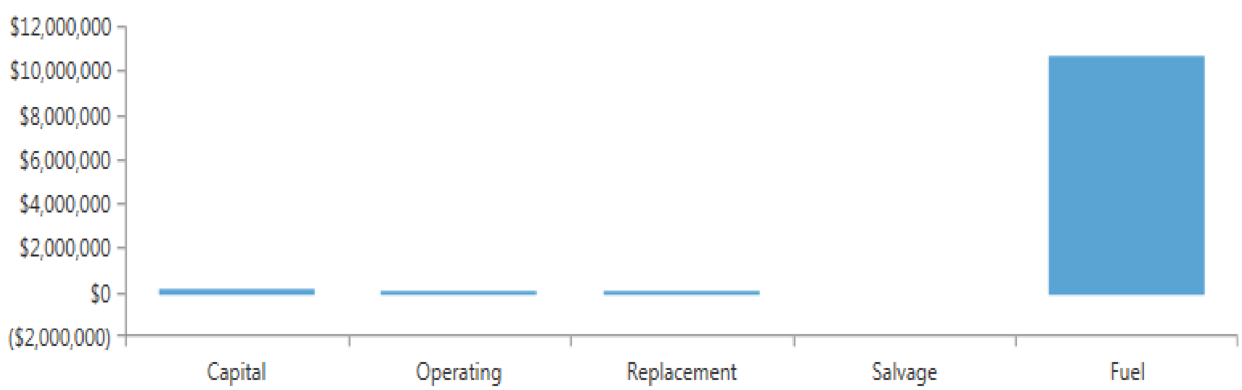

Figure 3.8: Summary of cost by type of investment on stand-alone diesel generator in islanded mode.

As seen in Figure 3.8, the fuel cost is where most of the money used in the production is going. About 96% of the production money is spent on fuel. Information is displayed in Table 3.4 below. Figure 3.9 is the graphic display of the cash flow for the system. As noticed in Figure 3.9, the orange color depicts the amount spent on fuel which is the largest.

Table 3.4: Summary of cost by type of investments in tabular form for stand-alone diesel generator in islanded mode.

Component	CAT-680kW	System
Capital ($)	$200,000.00	$200,000.00
Replacement ($)	$155,670.17	$155,670.17
O&M ($)	$113,245.04	$113,245.04
Fuel ($)	$10,734,473.97	$10,734,473.97
Salvage ($)	($24,434.90)	($24,434.90)
Total ($)	$11,178,954.29	$11,178,954.29

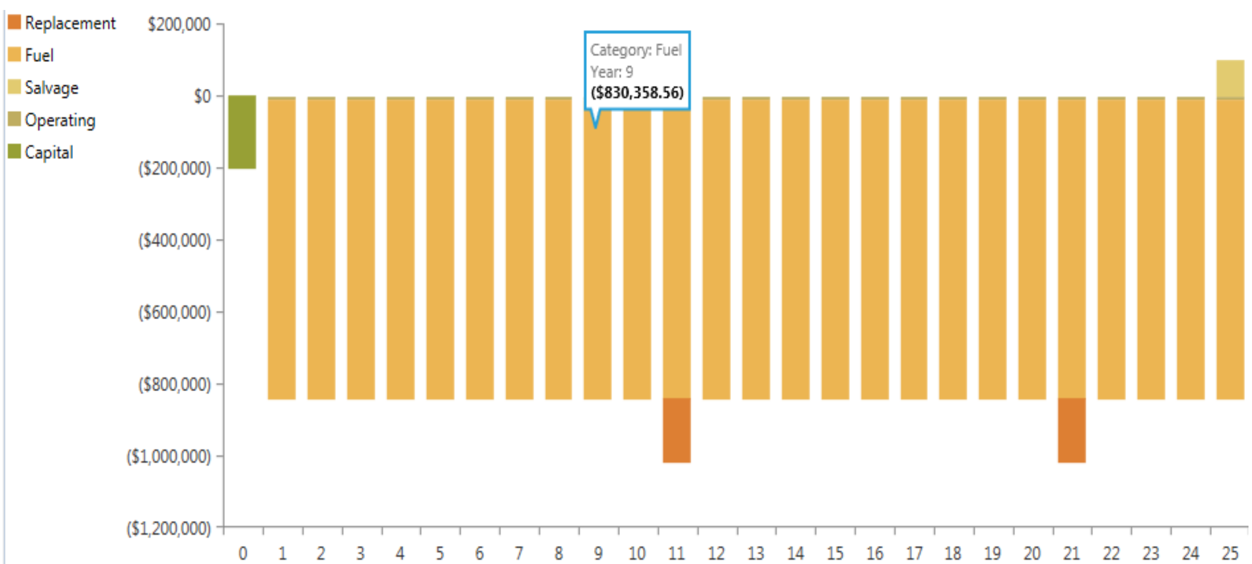

Figure 3.9: Cash flow for stand-alone diesel generator in islanded mode.

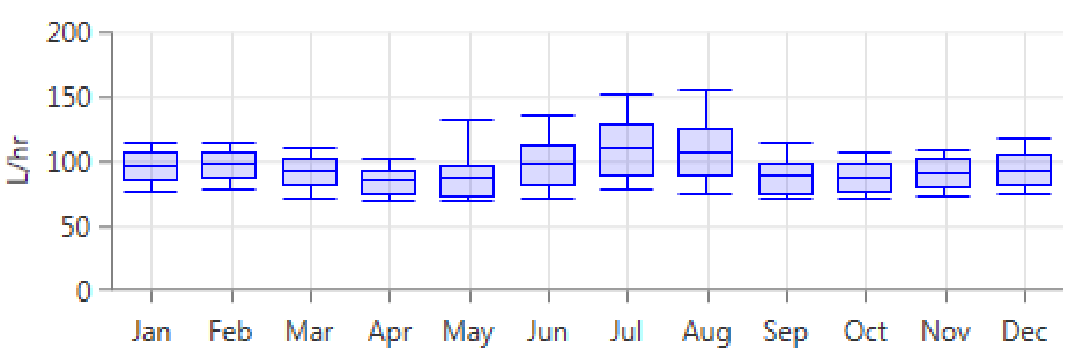

Figure 3.10: Graph display for fuel usage of stand-alone diesel generator in islanded mode.

As seen in Figure 3.10, the graph displays the average consumption of fuel for every month in L/hr. As it evidently shows, the highest months of fuel consumption are June, July, August which is completely understandable, since that is when the demand for electricity goes up. Total fuel consumed for the whole year is shown in Table 3.5 below.

Table 3.5: Tabular display of fuel consumption rate for a stand-alone diesel generator in islanded mode.

Quantity	Value	Units
Total Fuel Consumed	830,359	L
Average Fuel Per Day	2,275	L/day
Average Fuel Per Hour	94.8	L/hour

Table 3.6: Total cost of project for stand-alone diesel generator in islanded mode.

Total NPC	$11,178,950.00
Levelized COE	$0.3262
Operating Cost	$849,270.20

In summary for Case 1, Table 3.6 shows the Total Net Present Cost (NPC) of the system.

3.2.1 Summary of Case 1

The net present cost (or life-cycle cost) of a component is the present value of all the costs of installing and operating the component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. The levelized cost of energy is the net present value of the unit-cost of electricity over the lifetime of a generating asset. It is often taken as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime. Operating cost are the expenses that are associated with the operation of the project. These costs are the resources used to maintain the existing of the project.

3.3 Case 2: Considering Diesel Generator and Battery Storage as Distributed Energy Resources in Islanded Mode

- CAT-680 represents a diesel generator.
- ABB-MGS represents a battery storage.

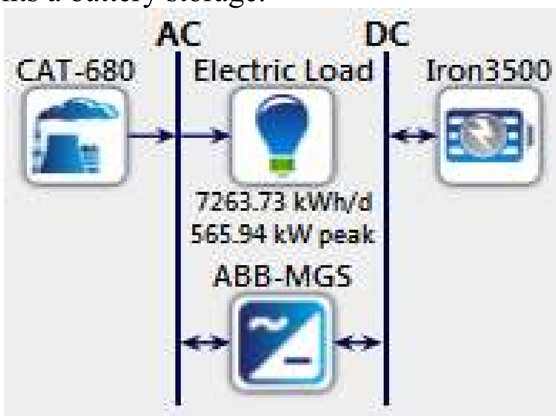

Figure 3.11: Schematic for diesel generator with battery storage in islanded mode.

As displayed in Figure 3.11, is the use of a conventional system (diesel generator) and a battery storage system for electricity generation. This generator caters to a load of 2,651,261 kWh/yr, which is equal to the amount of the electricity production of 2,651,261 kWh/yr. There is no surplus electricity in this case. As seen in Figure 3.13, the fuel cost is where most of the money used in the production is going. About 96% of the production money is spent on fuel, even with the addition of a battery storage system. Information is displayed in Table 3.7 below.

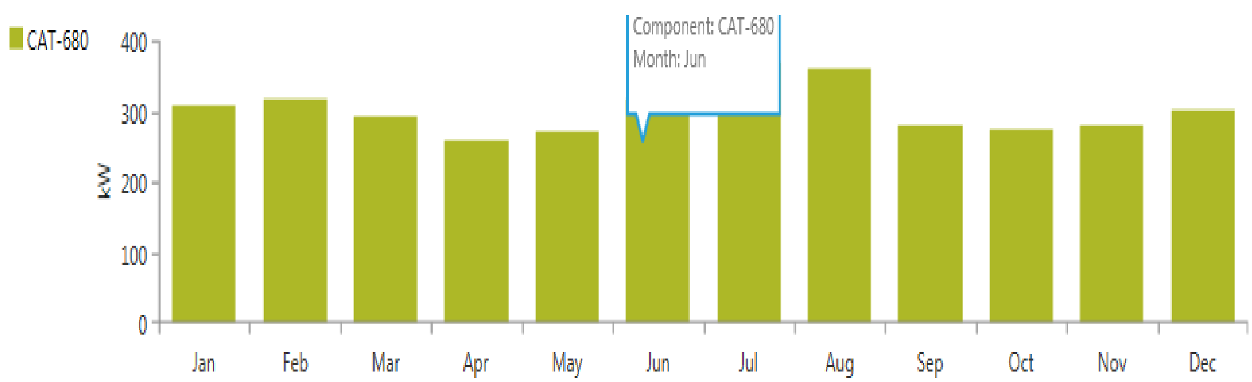

Figure 3.12: Monthly average electricity production by diesel generator with battery storage in islanded mode.

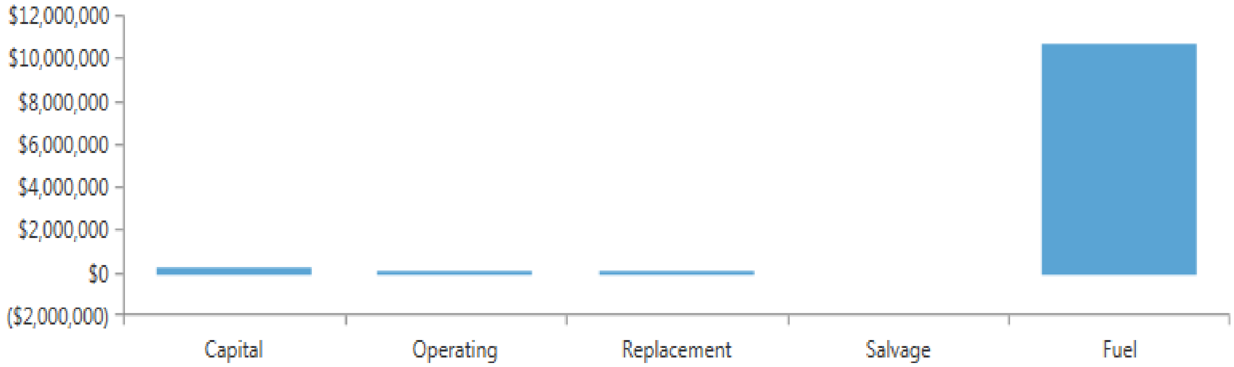

Figure 3.13: Summary of cost by type of investment on diesel generator with battery storage in islanded mode.

Table 3.7: Summary of cost by type of investments in tabular form for diesel generator with battery storage in islanded mode.

Component	**CAT-680kW**	**Iron Edison LFP**	**System**
Capital ($)	$200,000.00	$136,500.00	$336,500.00
Replacement ($)	$155,670.17	$0.00	$155,670.17
O&M ($)	$113,245.04	$33.04	$113,278.08
Fuel ($)	$10,734,473.97	$0.00	$10,734,473.97
Salvage ($)	($24,434.90)	($31,882,09)	($104,650.95)
Total ($)	$11,178,954.29	($56,316,99)	$11,283,605.24

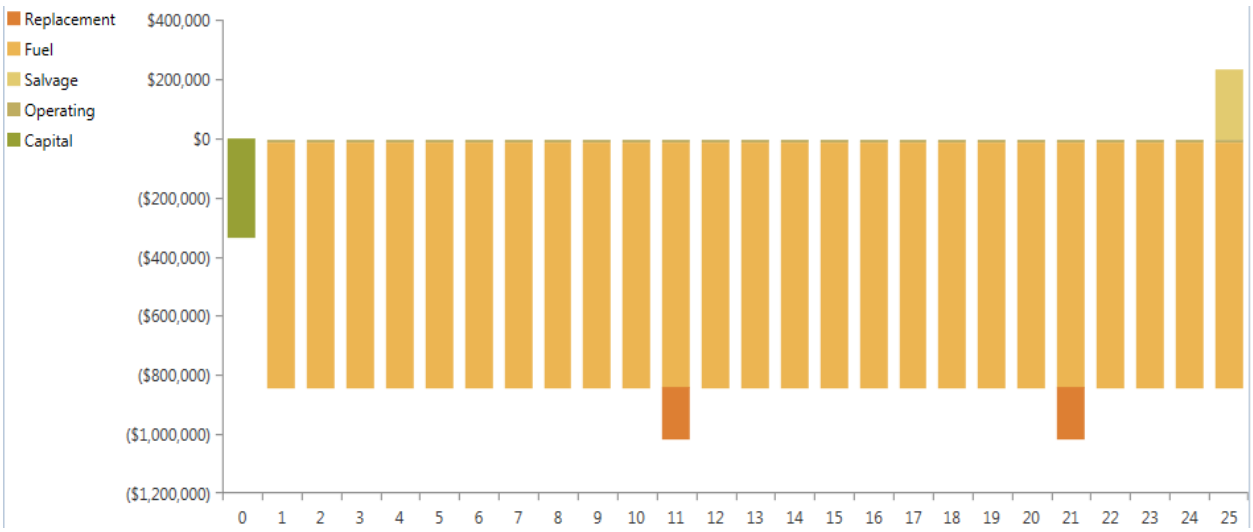

Figure 3.14: Cash flow for diesel generator with battery storage in islanded mode.

As seen in Table 3.7, the storage system has increased the total cost of the system, however it is not a better solution at this point, since it is just adding more cost (Capital, O&M, Salvage) to the system. Figure 3.14 is the graphic display of the cash flow for the system. As noticed in the above diagram, the orange color depicts the amount spent on fuel which where most of the money is going throughout the 25-year span of the project.

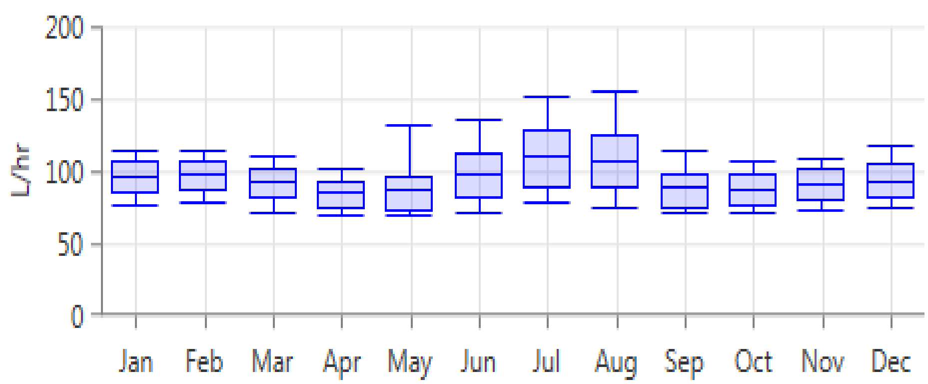

Figure 3.15: Graph display for fuel usage of diesel generator with battery storage in islanded mode.

As seen in Figure 3.15, the graph displays the average consumption of fuel for every month in L/hr. As it evidently shows, the highest months of fuel consumption are June, July, August which is completely understandable, since that is when the demand for electricity goes up. Total fuel consumed for the whole year is shown in Table 3.8 below. The Total Net Present Cost (NPC) of the system for Case 1 is shown in Table 3.9.

Table 3.8: Tabular display of fuel consumption rate for a diesel generator with battery storage in islanded mode.

Quantity	Value	Units
Total Fuel Consumed	830,359	L
Average Fuel Per Day	2,275	L/day
Average Fuel Per Hour	94.8	L/hour

Table 3.9: Total cost of project for diesel generator with battery storage in islanded mode.

Total NPC	$11,283,600.00
Levelized COE	$0.3292
Operating Cost	$846,806.50

3.3.1 Summary of Case 2

As seen in Table 3.9, there is a slight increase in the NPC and this is due to the investment and installation of a battery storage system. The battery storage system is highly important in microgrids in situations like load shedding, surplus electricity, and providing stability during intermittency and variance in renewable resources (e.g., wind speed and solar) in islanded mode.

3.4 Case 3: Considering Diesel Generator, Wind Turbine, and Battery Storage as Distributed Energy Resources in Islanded Mode

- CAT-680 represents a diesel generator.
- WES100 represents a wind turbine.
- ABB-MGS represents the battery storage.

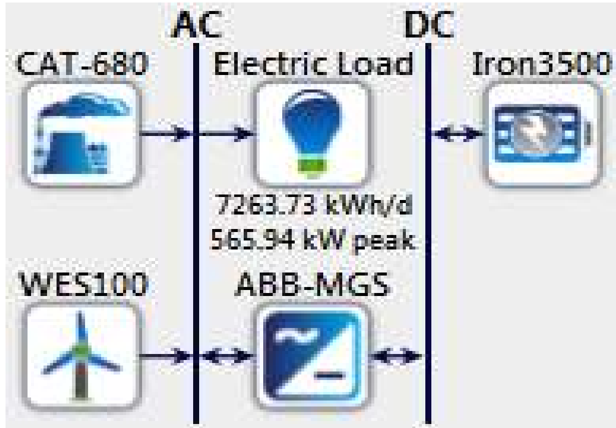

Figure 3.16: Schematic for diesel generator, wind turbine, with battery storage in islanded mode.

As displayed in Figure 3.16, the combination of a diesel generator, wind turbine and battery storage system are simulated, and the results are displayed. Since this simulation includes a renewable energy system, there should be decrease in fuel usage, which will reduce the cost spent on fuel, but the capital cost and maintenance cost of the renewable also need to be considered when finding the optimum solution. There is surplus electricity of 23.3 kWh/yr in this case.

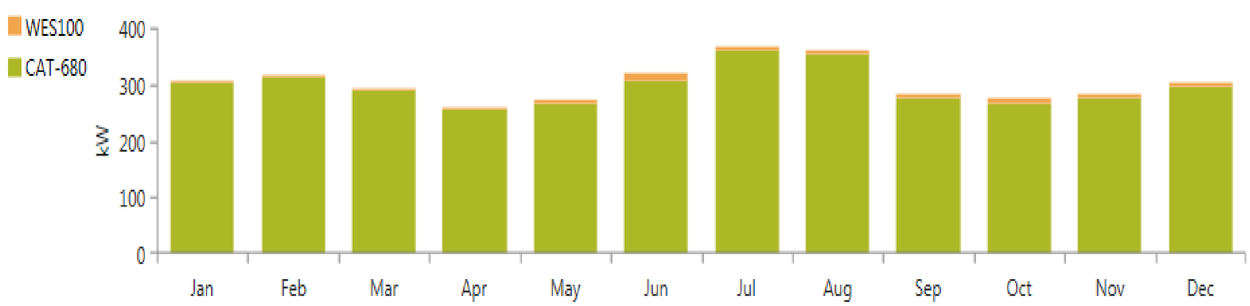

Figure 3.17: Monthly average electricity production by diesel generator, wind turbine, with battery storage in islanded mode.

Figure 3.17 shows a 2% renewable energy integration, as highlighted in orange. The wind turbine is contributing 50,504 kWh/yr of electricity production to the system. This integration reduces the production amount of the diesel generator from 2,651,285 kWh/yr to 2,600,781 kWh/yr and in turn reduces fuel usage by the diesel generator, and the amount is displayed in Figure 3.18 and Table 3.12. Figure 3.19 displays the summary of the cash flow in form of a bar chart. The integration of the wind turbine has reduced the cash spent on fuel which can be seen in the chart. As seen in Figure 3.20, the graph displays the average consumption of fuel for every month in L/hr. Shown below is Table 3.11 for the amount of fuel consumption in Liters. In summary for Case 3, Table 3.12 shows the Total Net Present Cost (NPC) of the system.

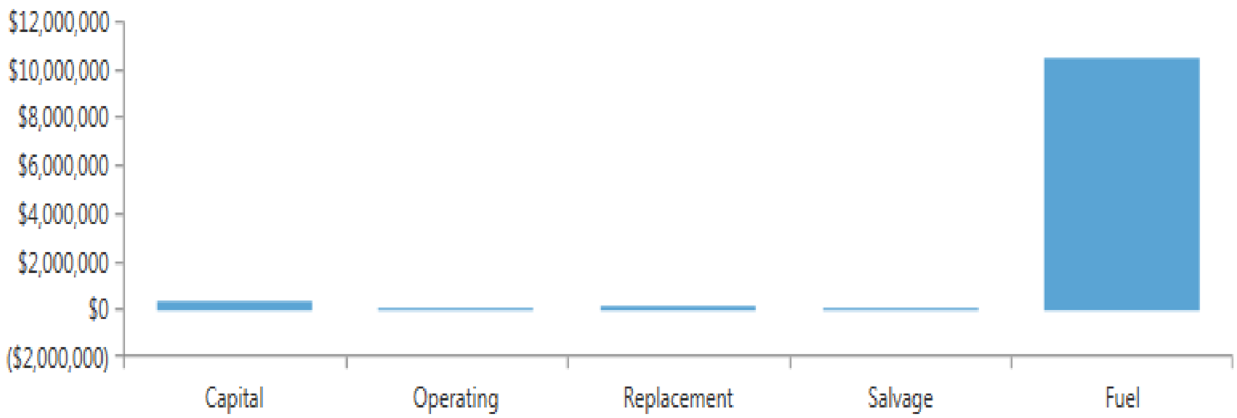

Figure 3.18: Summary of cost by type of investment on diesel generator, wind turbine, with battery storage in islanded mode.

Table 3.10: Summary of cost by type of investments in tabular form for diesel generator, wind turbine, with battery storage in islanded mode.

Component	CAT-680kW	Iron Edison LFP	WES 18	System
Capital ($)	$200,000.00	$136,500.00	$80,000.00	$416,500.00
Replacement ($)	$155,670.17	$0.00	$25,504.59	$181,174.76
O&M ($)	$113,245.04	$33.04	$10,342.01	$123,620.10
Fuel ($)	$10,583,403.22	$0.00	$0.00	$10,583,403.22

Salvage ($)	($24,434.90)	($31,882,09)	($14,373.47)	($101,473.13)
Total ($)	$11,027,883.54	$104,650,95	$101,473.13	$11,234,007.62

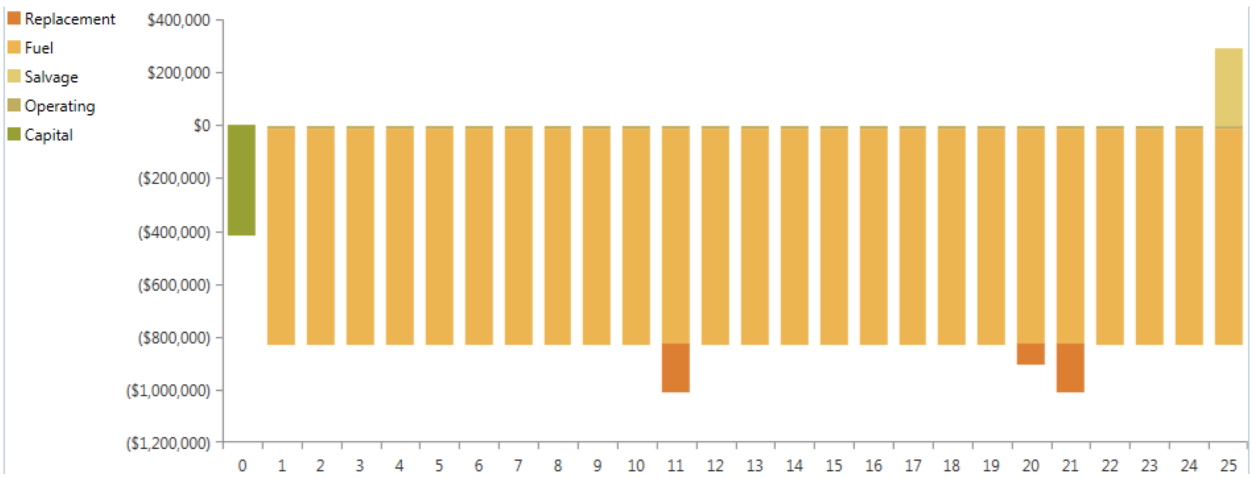

Figure 3.19: Cash flow for diesel generator with battery storage in islanded mode.

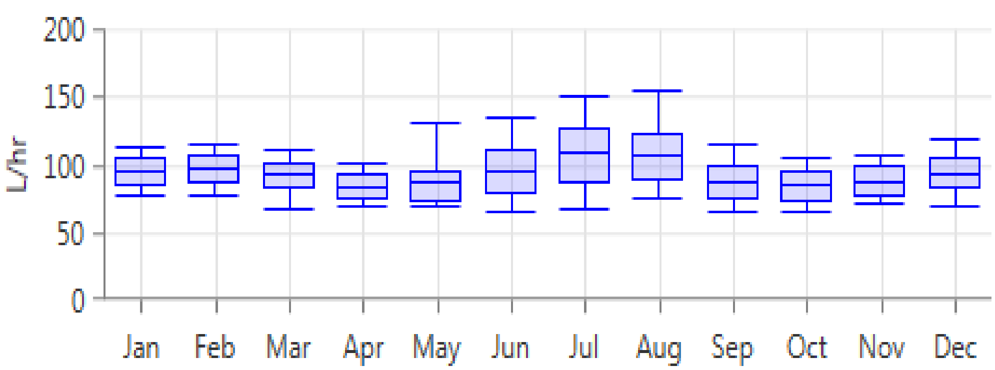

Figure 3.20: Graph display for fuel usage of diesel generator, wind turbine, with battery storage in islanded mode.

Table 3.11: Tabular display of fuel consumption rate for a diesel generator, wind turbine, with battery storage in islanded mode.

Quantity	Value	Units
Total Fuel Consumed	818,673	L

Average Fuel Per Day	2,243	L/day
Average Fuel Per Hour	93.5	L/hour

Table 3.12: Total cost of project for diesel generator, wind turbine, with battery storage in islanded mode.

Total NPC	$11,234,010.00
Levelized COE	$0.3278
Operating Cost	$836,781.60

3.4.1 Summary of Case 3

Table 3.14 summarizes the total cost of case 3, and as previously mentioned, even though there is reduction in fuel usage, other costs such as capital cost, O&M cost need to be taken into account when considering the optimum solution. This case includes the wind turbine which is helps in fuel reduction but adding to the investment cost. However, it is of advantage in cost savings in a long-term goal and carbon emission reduction.

3.5 Case 4: Considering Diesel Generator, Two Solar PV Panels, and Battery Storage as Distributed Energy Resources in Islanded Mode

- CAT-680 represents a diesel generator.
- 2 SMA60 represents solar PV panel.
- ABB-MGS represents the battery storage.

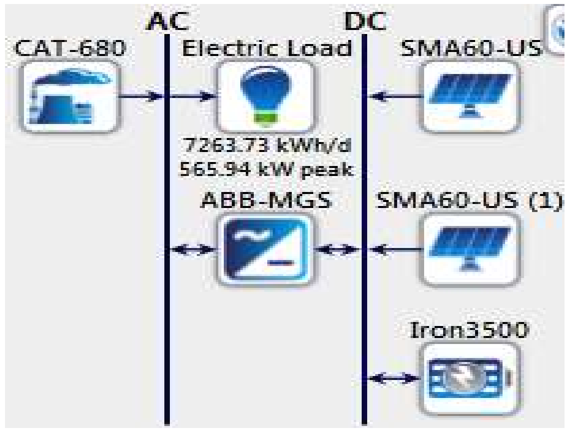

Figure 3.21: Schematic for diesel generator, two solar PV panels, with battery storage in islanded mode.

In this case, the system considers a diesel generator, a battery storage system, and two solar panels. Since this simulation includes a renewable energy system, there is decrease in fuel usage, which reduces the cost spent on fuel, but the amount of reduction in this Case 4 is greater than that of Case 3. The reason is stated below. There is also surplus electricity of 32,668 kWh/yr in this case.

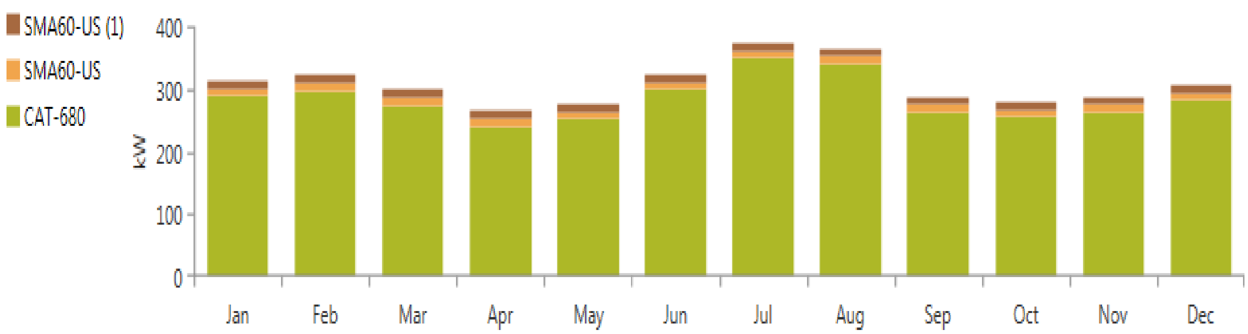

Figure 3.22: Monthly average electricity production by diesel generator, two solar PV panels, with battery storage in islanded mode.

Figure 3.22 shows an 8% renewable energy integration, as highlighted in orange and wine color. The two solar panels are each contributing 106,354 kWh/yr of electricity production to the system. Total electricity production is 212,708 kWh/yr for the two solar panels. This integration reduces the production amount of the diesel generator from 2,651,261 kWh/yr to 2,480,223 kWh/yr and in turn reduces fuel usage by the diesel generator, and the amount is displayed in

Figure 3.23 and Table 3.13. The total electricity production in this case is $2,692,931 kWh/yr. Figure 3.24 displays the summary of the cash flow in form of a bar chart. The integration of the two solar panels has reduced the cash spent on fuel which can be seen in the chart. As seen in Figure 3.25, the graph displays the average consumption of fuel for every month in L/hr. As can be seen, is the reduction in fuel usage. Shown below is the table for the amount of fuel consumption in Liters. In summary for Case 4, Table 3.15 shows the Total Net Present Cost (NPC) of the system.

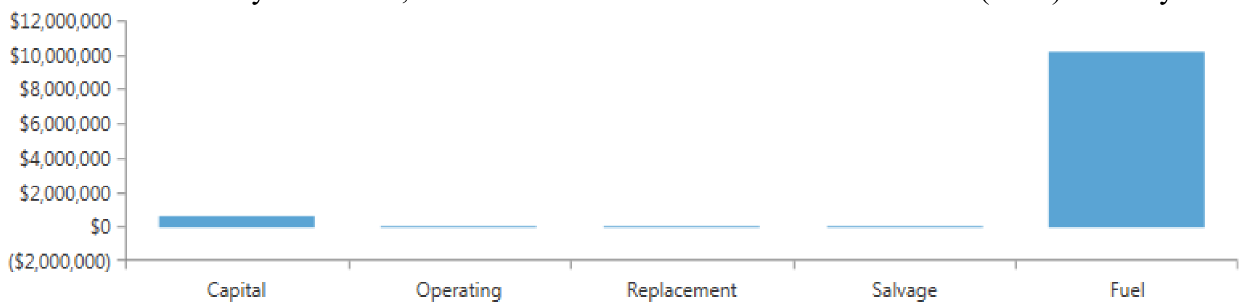

Figure 3.23: Summary of cost by type of investment on diesel generator, two solar PV panels, with battery storage in islanded mode.

Table 3.13: Summary of cost by type of investments in tabular form for diesel generator, two solar PV panels, with battery storage in islanded mode.

Component	**CAT-680kW**	**Iron Edison LFP**	**SMA Sunny Tripower 60**	**SMA Sunny Tripower 60**	**System**
Capital ($)	$200,000.00	$136,500.00	$179,850.00	$179,850.00	$696,200.00
Replacement ($)	$155,670.17	$0.00	$0.00	$0.00	$155,670.17
O&M ($)	$113,245.04	$33.04	$7,750.05	$7,750.05	$128,778.18
Fuel ($)	$10,222,615.25	$0.00	$0.00	$0.00	$10,222,615.25
Salvage ($)	($24,434.90)	($31,882,09)	$0.00	$0.00	($53,316.99)
Total ($)	$10,667,095.57	$104,650,95	$187,600.05	$187,600.05	$11,146,946.61

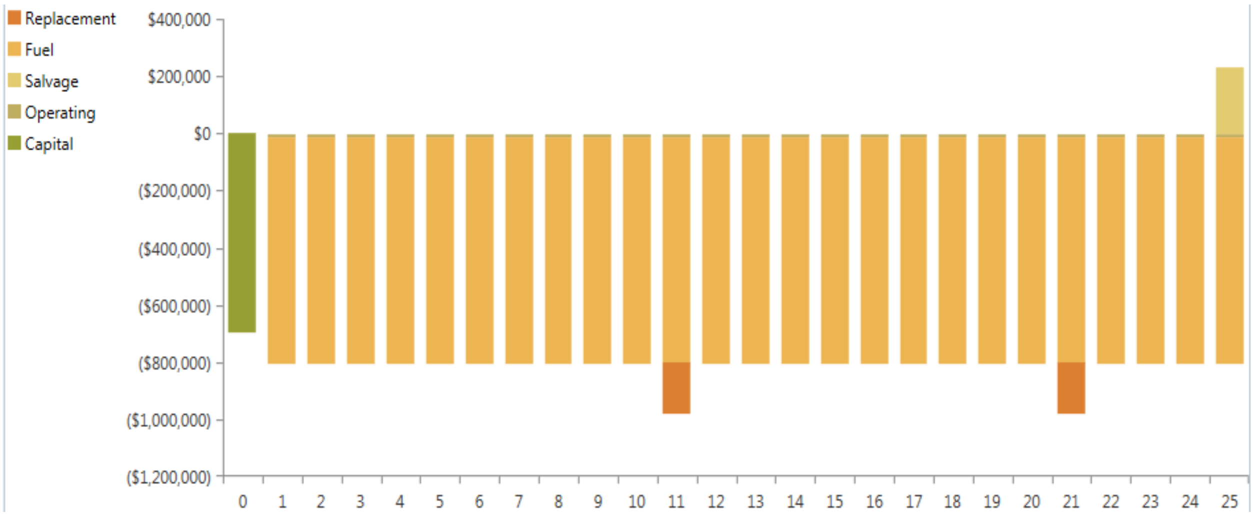

Figure 3.24: Cash flow for diesel generator, two solar PV panels, with battery storage in islanded mode.

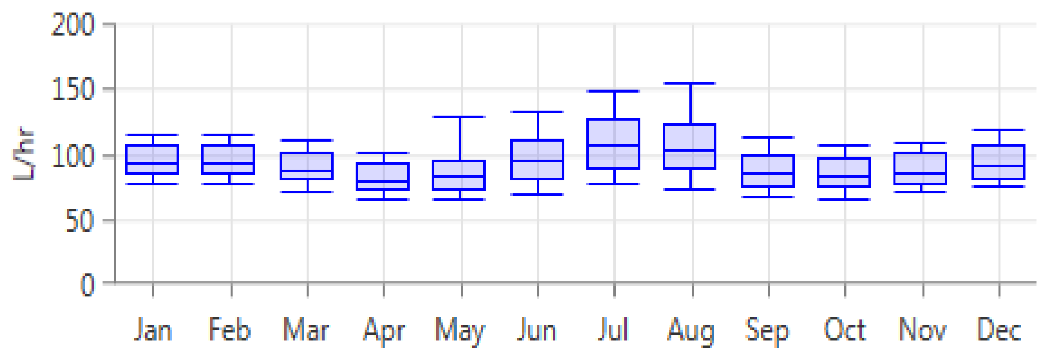

Figure 3.25: Graph display for fuel usage of diesel generator, two solar PV panels, with battery storage in islanded mode.

Table 3.14: Tabular display of fuel consumption rate for a diesel generator, two solar PV panels, with battery storage in islanded mode.

Quantity	Value	Units
Total Fuel Consumed	790,764	L
Average Fuel Per Day	2,167	L/day
Average Fuel Per Hour	90.3	L/hour

Table 3.15: Total cost of project for diesel generator, two solar PV panels, with battery storage in islanded mode.

Total NPC	$11,146,950.00
Levelized COE	$0.3252
Operating Cost	$808,411.00

3.5.1 Summary of Case 4

Table 3.17 shows the summary the total cost of Case 4, and as seen in the table, there is much improvement in cost reduction, and this is due to the 8% penetration of the renewable energy (two solar panels). However, the investment costs on the solar PV panels are taken into account when considering the minimum cost.

3.6 Case 5: Considering Diesel Generator, Wind Turbine, Two Solar PV Panels, and Battery Storage as Distributed Energy Resources in Islanded Mode

- CAT-680 represents a diesel generator.
- Two SMA60 represents solar PV panel.
- WES100 represents the battery storage.
- ABB-MGS represents the battery storage.

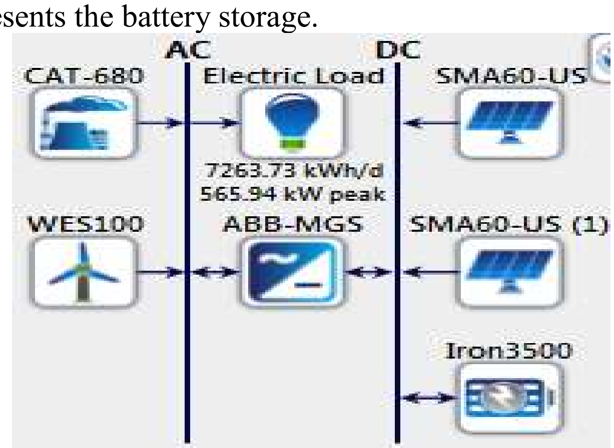

Figure 3.26: Schematic for diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

In this case, the system considers a diesel generator, a battery storage system, wind turbine, and two solar panels. Since this simulation includes renewable energy systems, there is more decrease in fuel usage, which reduces the cost spent on fuel, and the amount of reduction in this Case 5 is the best in all cases. The reason is stated below. There is surplus electricity of 32,768 kWh/yr in this case.

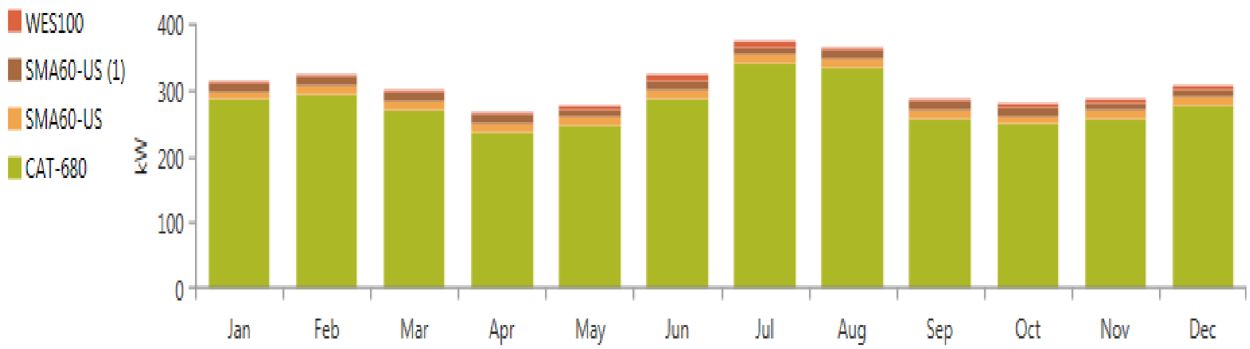

Figure 3.27: Monthly average electricity production by diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Figure 3.27 shows a 10% renewable energy integration, as highlighted in orange, wine, and red colors. The two solar panels are each contributing 106,354 kWh/yr of electricity production to the system. Total electricity production is 212,708 kWh/yr for the two solar panels. The wind turbine is producing 50,504 kWh/yr. This integration reduces the production amount of the diesel generator from 2,651,261 kWh/yr to 2,429,816 kWh/yr and in turn reduces fuel usage by the diesel generator, and the amount is displayed in Figure 3.28 and Table 2.18. The total electricity production in this case is $2,693,028 kWh/yr. Figure 3.29 displays the summary of the cash flow in form of a bar chart. The integration of the two solar panels has reduced the cash spent on fuel which can be seen in the chart. As seen in Fig 3.30, the graph displays the average consumption of fuel for every month in L/hr. There is good amount of reduction in fuel usage. Shown below in Table 3.17 is the amount of fuel consumption in Liters. In summary for Case 5, Table 3.18 shows the Total Net Present Cost (NPC) of the system.

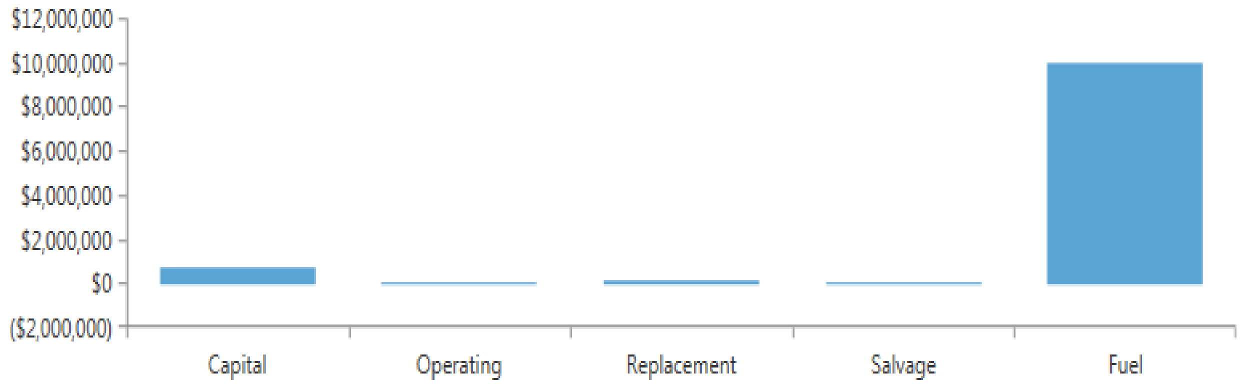

Figure 3.28: Summary of cost by type of investment on diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Table 3.16: Summary of cost by type of investments in tabular form for diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Component	**CAT-680kW**	**Iron Edison LFP**	**SMA Sunny Tripower 60**	**SMA Sunny Tripower 60**	**WES-18**	**System**
Capital ($)	$200,000	$136,500	$179,850	$179,850	$80,000	$776,200
Replacement ($)	$155,670.17	$0.00	$0.00	$0.00	$25,504	$181,174.76
O&M ($)	$113,245.04	$33.04	$7,750.05	$7,750.05	$10,342.01	$139,120.19
Fuel ($)	$10,071,763.88	$0.00	$0.00	$0.00	$0.00	$10,071,763.88
Salvage ($)	($24,434.90)	($31,882.09)	$0.00	$0.00	($14,373.47)	($70,690.46)
Total ($)	$10,667,095.57	$104,650,95	$187,600.05	$187,600.05	$101,473.13	$11,097,568.37

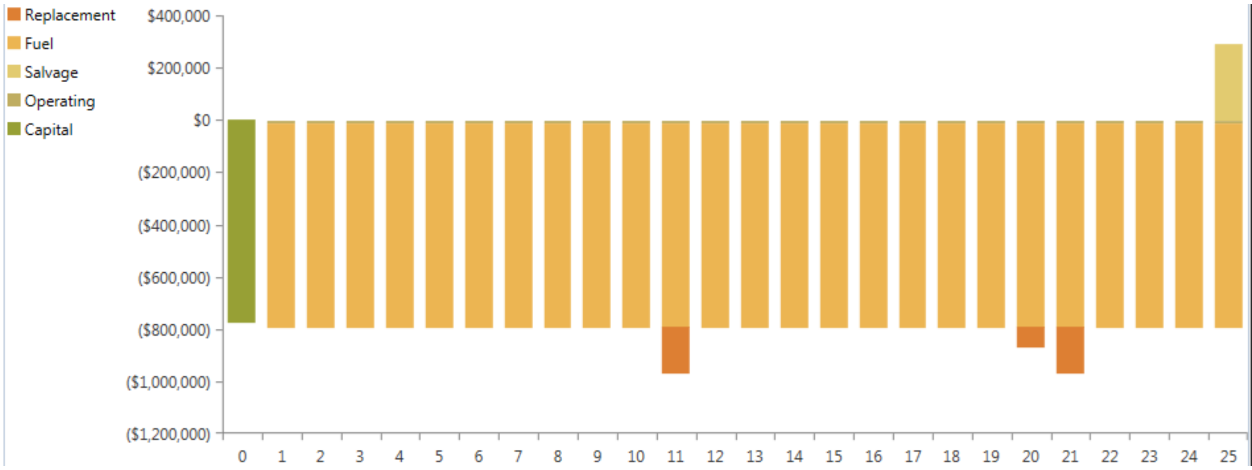

Figure 3.29: Cash flow for diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

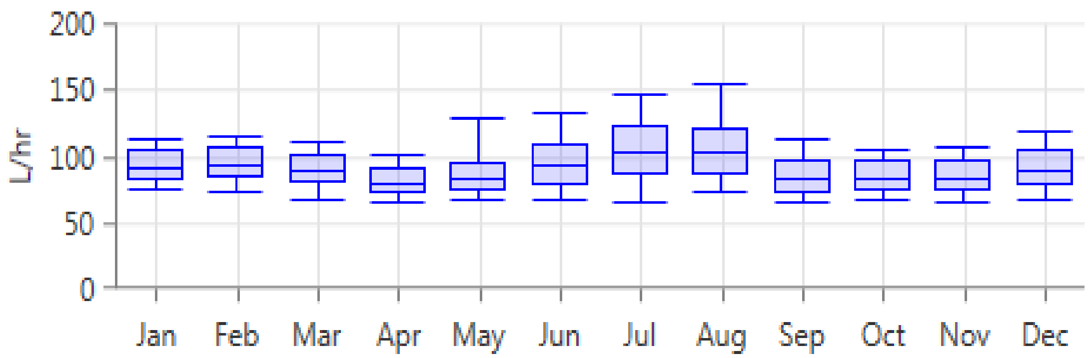

Figure 3.30: Graph display for fuel usage of diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Table 3.17: Tabular display of fuel consumption rate for a diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Quantity	Value	Units
Total Fuel Consumed	779,095	L
Average Fuel Per Day	2,135	L/day
Average Fuel Per Hour	88.9	L/hour

Table 3.18: Total cost of project for diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Total NPC	$11,097,570.00
Levelized COE	$0.3238
Operating Cost	$798,403.00

3.6.1 Summary of Case 5

Table 3.18 shows the summary the total cost of Case 5, and this is obviously the optimum solution, due to the 10% penetration of the renewable energy (two solar panels and a wind turbine) which in turn has the maximum reduction in the cost spent on fuel for the diesel generator in all 5 Cases. This case has the highest penetration of renewable energy (10%).

3.7 Conclusion

In conclusion, the analysis of this microgrid in disconnected mode showing all 5 Cases has helped to understand the importance of saving money, monetizing benefits, the impact of renewable energy on the environment and the chances of having different option availability in terms of exploring natural resources such as wind speed and sun radiation. It can be concluded that the microgrid system is the best option to explore when it comes to saving cost and contributing to a clean environment. Table 3.19 and 3.20 below show the NPC arranged in order of the least minimum cost and carbon emission analysis on all 5 Cases.

Table 3.19: Total cost of project for diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Case Type	Total NPC	Levelized COE	Operating Cost
Case 5	$11,097,570.00	$0.3238	$798,403.00
Case 4	$11,146,950.00	$0.3252	$808,411.00
Case 1	$11,178,950.00	$0.3262	$849,270.20
Case 3	$11,234,010.00	$0.3278	$836,781.60
Case 2	$11,283,600.00	$0.3292	$846,806.50

Table 3.20: carbon emission analysis for all 5 Cases in islanded mode.

QUANTITY	Case 1	Case 2	Case 3	Case 4	Case 5
Carbon Dioxide	2,196,022 kg/yr	2,196,022 kg/yr	2,165,117 kg/yr	2,091,308 kg/yr	2,060,447 kg/yr
Carbon Monoxide	531 kg/yr	531 kg/yr	524 kg/yr	506 kg/yr	499 kg/yr
Unburned Hydrocarbons	49.8 kg/yr	49.8 kg/yr	49.1 kg/yr	47.4 kg/yr	46.7 kg/yr
Particulate Matter	49.8 kg/yr	49.8 kg/yr	49.1 kg/yr	47.4 kg/yr	46.7 kg/yr
Sulfur Dioxide	5,447 kg/yr	5,447 kg/yr	5,370 kg/yr	5,187 kg/yr	5110 kg/yr
Nitrogen Oxides	14,648 kg/yr	14,648 kg/yr	14,441 kg/yr	13,949 kg/yr	13,743 kg/yr

Table 3.20 shows the emission of carbon, and it is clear that the integration of renewable energy sources is of advantage to the environment. Case 5 has the most reduction, since it has the highest percentage of renewable energy integration (10%).

Chapter 4: Economic Analysis and Optimal Energy Management Models for Microgrid System in Connected Mode

4.1 Introduction

A microgrid operates in two ways when connected to a main grid, and that is either importing or exporting electricity. The reason for this is to identify the benefits of the connected mode and then monetize this benefit. So, this section reviews the 5 Cases in the previous chapter while the microgrid is connected to the main grid and performs a cost benefit analysis for the purpose of finding the optimum solution.

Table 4.1: Electricity Trade Price between main grid and microgrid in connected mode.

Grid Power Price ($/kWh)	$0.100
Grid Sellback Price ($/kWh)	$0.050

In connected mode, the price to purchase electricity from the main grid is $0.10/kWh, while it is $0.50/kWh to sell back to the main grid when there is surplus electricity production from the microgrid's side. In this case, a microgrid using only diesel generator as its source of generation is connected to a main grid and the results of the analysis are presented below. Figure 4.2 shows the whole electricity supply is coming from the main grid. This production caters to a demand of 2,651,261 kWh/yr primary load. Figure 4.3 shows the purchase of electricity from the grid for the whole 365 days. The diesel generator in Figure 4.4 is supplying zero electricity as displayed in the graph. Table 4.2 summarizes the monthly energy purchased from the grid, and no energy is sold to the grid in this case, since the diesel generator from the microgrid is not producing any electricity. So, all energy production is bought from the main grid, since this option is cheaper. Figure 4.5 below shows the additional cost to the system, the total cost of the system including capital, operating, replacement, salvage and fuel are displayed. Table 4.3 gives a visual explanation of the total cost.

4.2 Case 1: Considering Only Diesel Generator as a Distributed Energy Resource in Connected Mode

➢ CAT-680 represents a diesel generator.

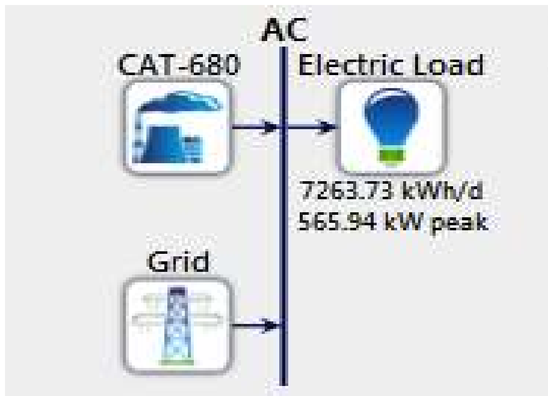

Figure 4.1: Schematic for diesel generator in connected mode with grid.

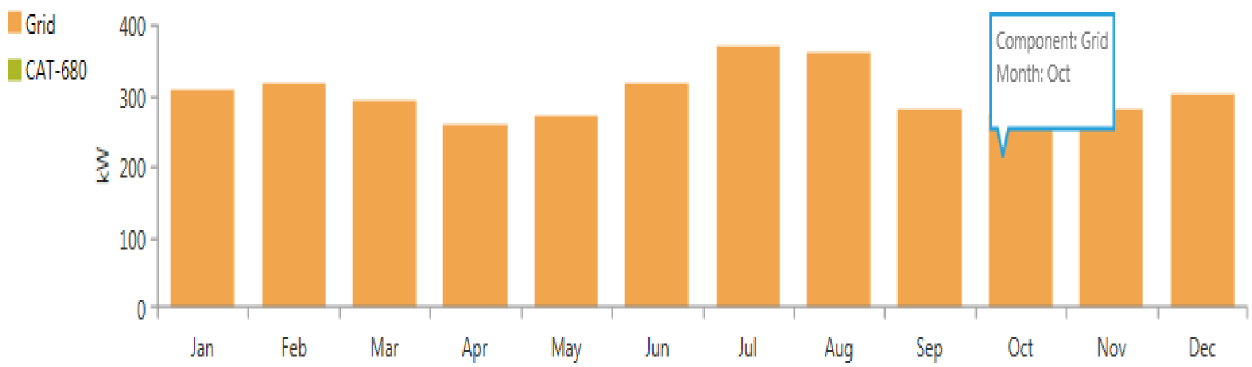

Figure 4.2: Monthly average electricity production by stand-alone diesel generator in connected mode with grid.

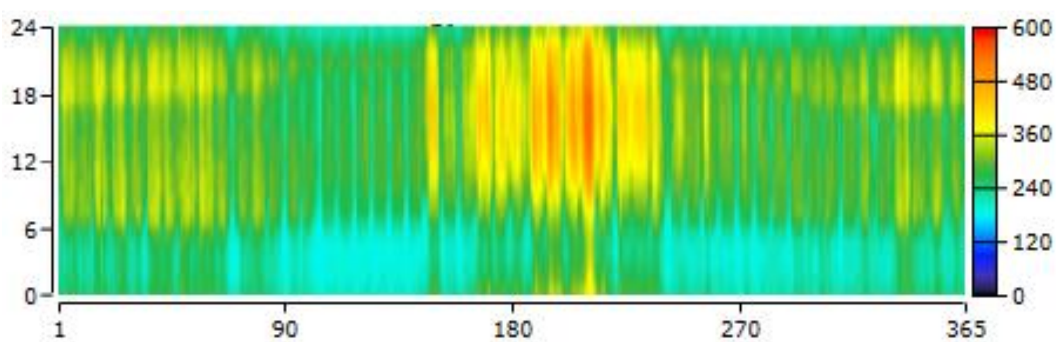

Figure 4.3: Energy purchased from grid for case 1 in connected mode.

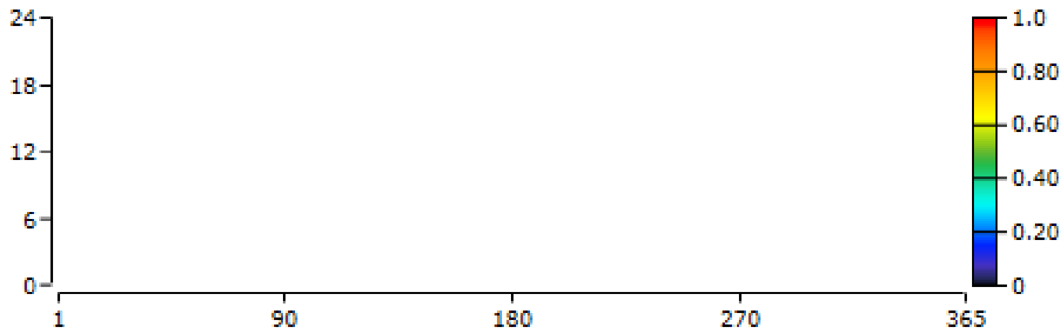

Figure 4.4: Energy sold to grid for case 1 in connected mode.

Table 4.2: Monthly rate schedule for case 1 in connected mode.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
January	228,406	0	228,406	386	$22,840.62	$0
February	212,673	0	212,673	390	$21,267.27	$0
March	218,044	0	218,044	373	$21,804.37	$0
April	187,120	0	187,120	330	$18,712.00	$0
May	201,784	0	201,784	465	$20,178.37	$0
June	228,865	0	228,865	476	$22,886.45	$0
July	273,828	0	273,828	546	$27,382.81	$0
August	267,364	0	267,364	566	$26,736.38	$0
September	202,568	0	202,568	390	$20,256.78	$0
October	204,116	0	204,116	358	$20,411.58	$0
November	202,563	0	202,563	360	$20,256.28	$0
December	223,932	0	223,932	404	$22,393.22	$0
Annual	2,651,261	0	2,651,261	566	$265,126.1	$0

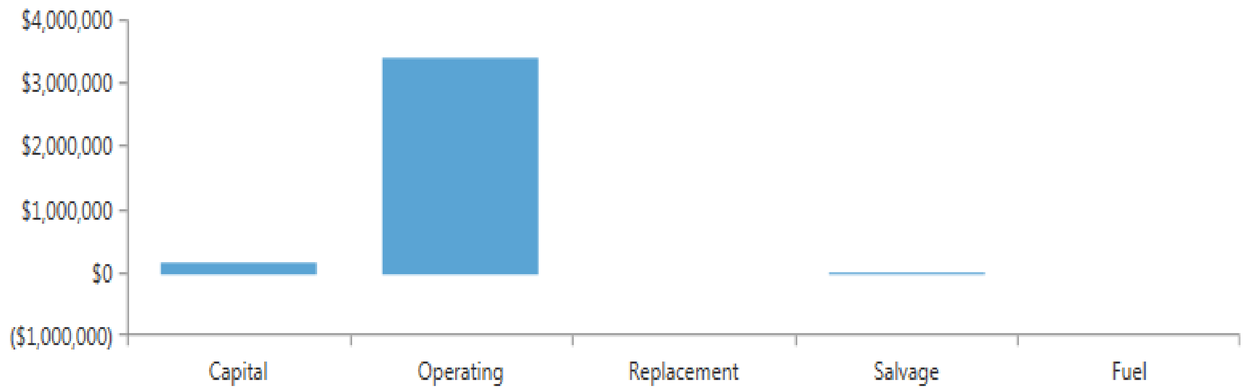

Figure 4.5: Summary of cost by type of investment on diesel generator in connected mode.

Table 4.3: Summary of cost by type of investments in tabular form for diesel generator in connected mode.

Component	CAT-680kW	Grid	System
Capital ($)	$200,000.00	$0.00	$200,000.00
Replacement ($)	$0.00	$0.00	$0.00
O&M ($)	$0.00	$3,427,422.44	$3,427,422.44
Fuel ($)	$0.00	$0.00	$0.00
Salvage ($)	($42,042.40)	($0.00)	($42,042.40)
Total ($)	$157,957.60	$3,427,422.44	$3,585,380.04

Table 4.3 details the total cost of the system and it is evident that replacement and fuel cost are all zeros, since the diesel generator is not producing anything, and then utility company is responsible for the any cost incurred by the main grid. In this situation, the utility company only charges for the sale of the electricity to the microgrid operator, which is displayed under O&M in Table 4.3. The Net Present Cost in this case is displayed in Table 4.4.

Table 4.4: Total cost of project for diesel generator in connected mode.

Total NPC	$3,585,380.00
Levelized COE	$0.1046
Operating Cost	$261,874.00

4.2.1 Summary of Case 1

This case gives an insight to the cost benefit analysis of a microgrid (with only a diesel generator component) in connected mode, and as can be seen in Table 4.4, it is evident that it is way cheaper to purchase electricity from the main grid. In this case, it would be a waste of resources to have the diesel generator produce any electricity. The best result in this case is to purchase all electricity usage from the main grid.

4.3 Case 2: Considering Diesel Generator, and Battery Storage as Distributed Energy Resources in Connected Mode

- CAT-680 represents a diesel generator.
- ABB-MGS represents a battery storage.
- Grid represents the main grid.

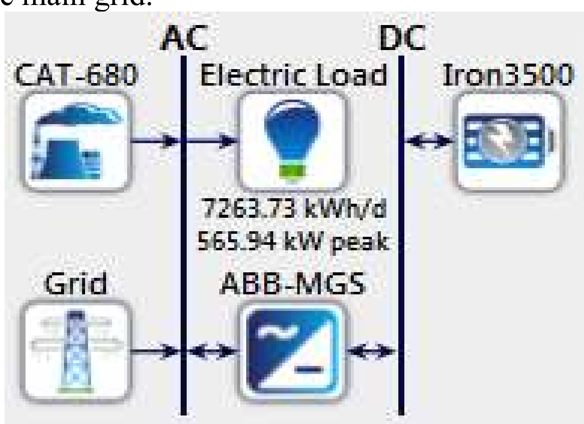

Figure 4.6: Schematic for diesel generator with battery storage in connected mode with grid.

This case reviews the benefits and addition of a battery storage system. It is most likely obvious that this addition would not be of much benefit to the system, since all the electricity production is purchased for the main grid as seen in Figure 4.7 below. Figure 4.7 has the same graph as Figure 3 in Case 1. This confirms that the only difference in this case is the capital investment spent on the battery storage system and the O&M. The information displayed in Table 4.5 shows the cost breakdown. The net present cost for Case 2 is shown in Table 4.6. The only difference with this case from Case 1 is the addition of the investment cost in battery storage system. At this point, it wouldn't be wise to have a battery storage system since it is not beneficial to the system in terms of cost minimization.

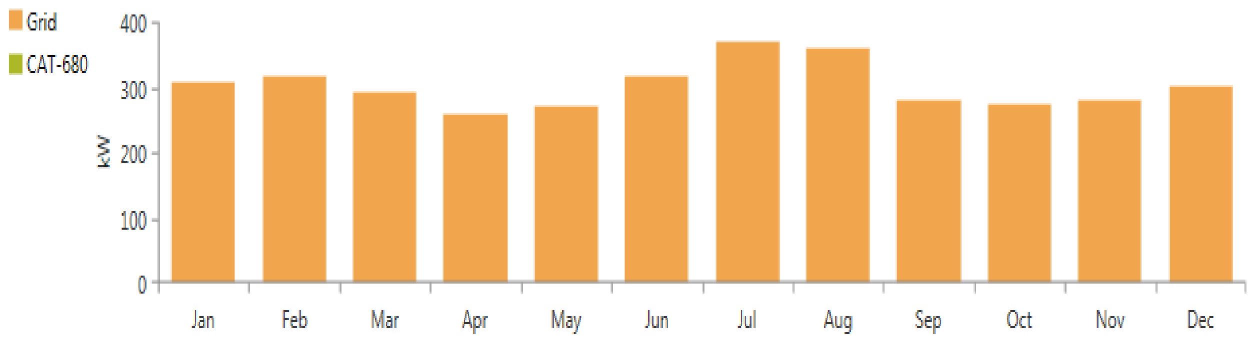

Figure 4.7: Monthly average electricity production by diesel generator with battery storage in connected mode with grid.

Table 4.5: Summary of cost by type of investments in tabular form for diesel generator with battery storage in connected mode.

Component	CAT-680kW	Grid	Iron Edison LFP	System
Capital ($)	$200,000.00	$0.00	$136,500.00	$336,500.00
Replacement ($)	$0.00	$0.00	$0.00	$0.00
O&M ($)	$0.00	$3,427,422.44	$33.04	$3,427,455.48
Fuel ($)	$0.00	$0.00	$0.00	$0.00
Salvage ($)	($42,042.40)	($0.00)	($31,882.09)	($73,924.49)
Total ($)	$157,957.60	$3,427,422.44	($104,650.95)	$3,690,030.99

Table 4.6: Total cost of project for diesel generator with battery storage in connected mode.

Total NPC	$3,690,031.00
Levelized COE	$0.1077
Operating Cost	$259,410.30

4.3.1 Summary of Case 2

This case is almost identical to Case 1, but the only difference is the inclusion of a battery storage which explains why the NPC is higher than the NPC in Case 1. As mentioned in Case 1, the whole electricity supply is purchased from the main grid, so the battery storage is not serving a purpose presently.

4.4 Case 3: Considering Diesel Generator, Wind Turbine, and Battery Storage as Distributed Energy Resources in Connected Mode

- CAT-680 represents a diesel generator.
- WES100 represents the wind turbine.
- Iron3500 represents a battery storage.
- ABB-MGS is the converter (DC-to-AC) for the battery.
- Grid represents the main grid.

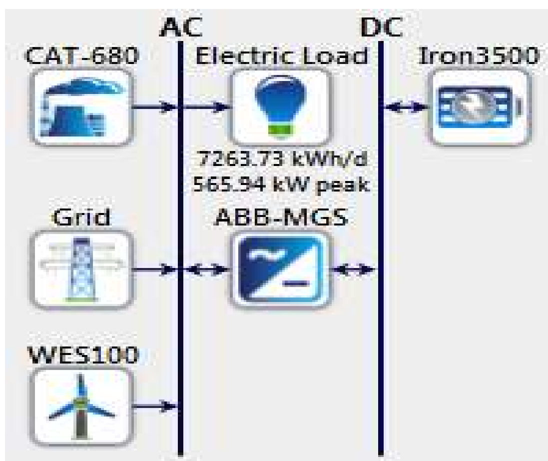

Figure 4.8: Schematic for diesel generator, wind turbine, with battery storage in connected mode with grid.

In this case, the sources of power generation for the microgrid are diesel generator, wind turbine, and a storage system, while in connected mode. The results and analysis are displayed below. Figure 4.9 shows the graph for the production from two energy sources (diesel generator and wind turbine) and purchase of electricity from the main grid. The diesel generator is giving zero output production in this particular case as shown in Table 4.7 below.

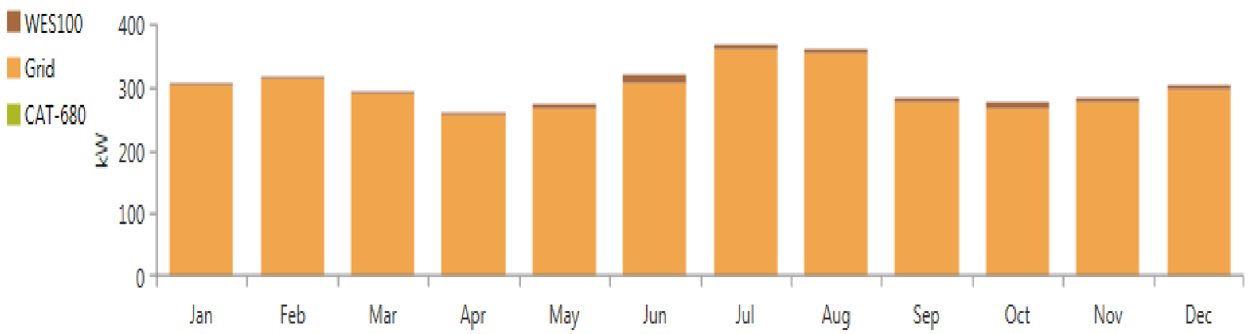

Figure 4.9: Monthly average electricity production by diesel generator, wind turbine, with battery storage in connected mode with grid.

Table 4.8 summarizes the monthly energy purchased from the grid, and no energy is sold to the grid in this case, since the diesel generator from the microgrid is not producing any electricity. So, most of the electricity production is bought from the main grid, since it's cheaper, while 50,504 kWh of electricity output is produced by the wind turbine. Figure 4.10 below shows the additional cost to the system. The total cost of the system including capital, operating, replacement, salvage and fuel are displayed in Figure 4.10 and Table 4.9 gives a visual explanation of the total cost. The net present cost for Case 3 is shown in Table 4.10.

Table 4.7: Total electricity generation by diesel generator, wind turbine, and grid purchase in connected mode.

Production	kWh/yr
Diesel Generator	0
Wind Turbine	50,504
Grid Purchases	2,600,758
Total	2,651,261

Table 4.8: Monthly rate schedule for Case 3 in connected mode.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
January	225,976	0	225,976	381	$22,597.56	$0
February	210,263	0	210,263	390	$21,026.28	$0
March	215,830	0	215,830	370	$21,582.95	$0
April	184,839	0	184,839	330	$18,483.86	$0
May	197,605	0	197,605	458	$19,760.54	$0
June	221,088	0	221,088	476	$22,108.80	$0
July	268,005	0	268,005	544	$26,800.53	$0
August	262,914	0	262,914	561	$26,291.37	$0
September	197,937	0	197,937	390	$19,793.71	$0
October	198,778	0	198,778	350	$19,877.81	$0
November	197,358	0	197,358	359	$19,735.78	$0
December	220,166	0	220,166	404	$22,016.58	$0
Annual	2,600,758	0	2,600,758	561	$26,075.7	$0

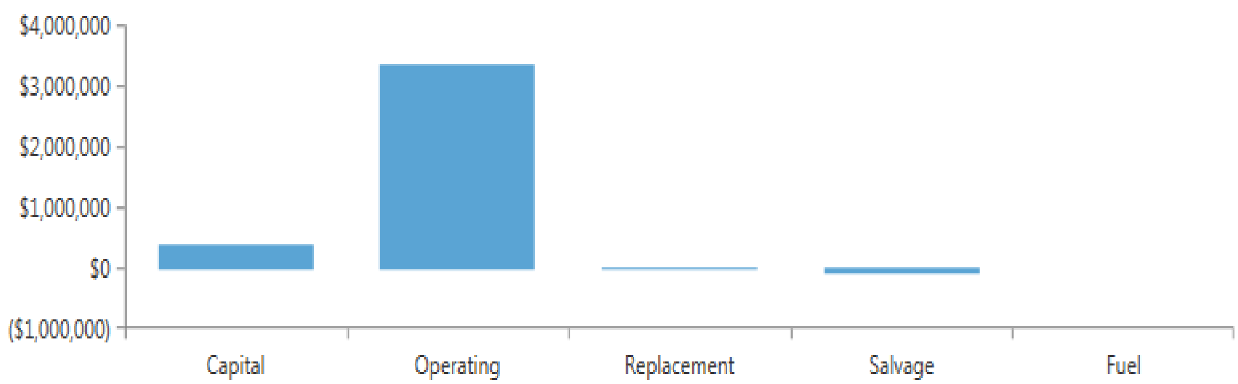

Figure 4.10: Summary of cost by type of investment on diesel generator, wind turbine, with battery storage in connected mode.

Table 4.9: Summary of cost by type of investments in tabular form for diesel generator, wind turbine, with battery storage in connected mode.

Component	CAT-680	Grid	Iron Edison LFP	WES 18	System
Capital ($)	$200,000.00	$0.00	$136,500.00	$80,000.00	$416,500.00
Replacement ($)	$0.00	$0.00	$.00	$25,504.59	$25,504.59
O&M ($)	$0.00	$3,427,422.44	$33.04	$10,342.01	$3,372,508.71
Fuel ($)	$0.00	$0.00	$0.00	$0.00	$0.00
Salvage ($)	($42,042.40)	($0.00)	($31,882.09)	($14,373.47)	($88,297.96)
Total ($)	$157,957.60	$3,427,422.44	$104,650.95	$101,473.13	$3,726,215.34

Table 4.10: Total cost of project for diesel generator, wind turbine, with battery storage in connected mode.

Total NPC	$3,726,215.00
Levelized COE	$0.1087
Operating Cost	$256,021.00

4.4.1 Summary of Case 3

This case confirms the advantage of integrating renewable energy (wind turbine) in a microgrid system. Even though, the penetration of the wind turbine is at approximately 2%, its contribution to the electricity supply cannot be ignored in a long-term goal. The initial investment costs on the wind turbine evidently contributes to the NPC for case 3.

4.5 Case 4: Considering Diesel Generator, Two Solar PV panels, and Battery Storage as Distributed Energy Resources in Connected Mode

- CAT-680 represents a diesel generator.
- Two SMA60 represent the solar panels.

➢ Iron3500 represents a battery storage.

➢ ABB-MGS is the converter (DC-to-AC) for the battery and solar panels

➢ Grid represents the main grid.

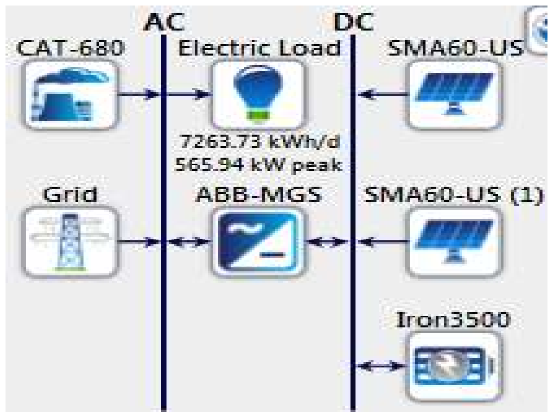

Figure 4.11: Schematic for diesel generator, two solar PV panels, with battery storage in connected mode with grid.

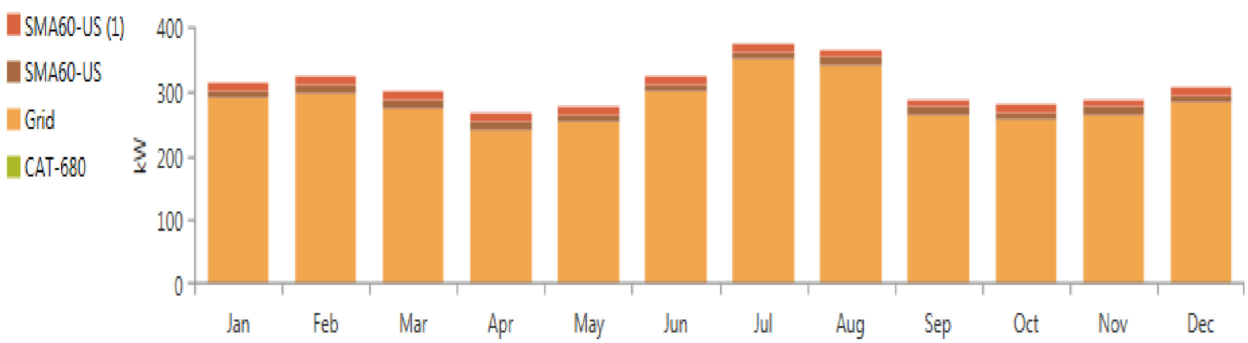

Figure 4.12: Monthly average electricity production by diesel generator, two solar PV panels, with battery storage in connected mode with grid.

Figure 4.12 displays the contribution of each generator and the main grid. The diesel generator is giving zero output production in this particular case as shown in Table 4.11 below. The surplus electricity amount in this case is 32,664 kWh/yr. Table 4.12 summarizes the monthly energy purchased from the grid, and no energy is sold to the grid in this case, even though there is surplus electricity. 2,480,220 kWh/yr of the electricity production is bought from the main grid, since it's cheaper, while 106,354 kWh of electricity output is produced by one solar panel. So, the production from two solar panels totals up to 212,708 kWh/yr. The figure below shows the overall cost of the system for this case in Figure 4.13. Figure 4.13 is the graphical display of the overall cost of the microgrid system in this case, including the electricity purchased from the main grid. Table 4.13 below shows the detailed breakdown of the costs. The net present cost in this case is $3,844,117.00 as seen in Table 4.14.

Table 4.11: Total electricity generation by diesel generator, two solar PV panels, and grid purchase in connected mode.

Production	**kWh/yr**
Diesel Generator	0
SMA Sunny Tripower	106,354
SMA Sunny Tripower	106,354
Grid Purchases	2,480,220
Total	2,692,928

Table 4.12: Monthly rate schedule of purchased and sold energy for Case 4 in connected mode.

Month	**Energy Purchased (kWh)**	**Energy Sold (kWh)**	**Net Energy Purchased (kWh)**	**Peak Demand (kW)**	**Energy Charge ($)**	**Demand Charge ($)**
January	214,588	0	214,588	386	$21,458.84	$0
February	199,374	0	199,374	390	$19,937.43	$0
March	203,383	0	203,383	373	$20,338.28	$0
April	172,607	0	172,607	330	$17,260.72	$0
May	187,251	0	187,251	453	$18,725.13	$0
June	214,506	0	214,506	465	$21,450.60	$0
July	258,891	0	258,891	532	$25,889.15	$0

August	252,817	0	252,817	559	$25,281.71	$0
September	188,375	0	188,375	382	$18,837.51	$0
October	189,204	0	189,204	358	$18,920.40	$0
November	189,197	0	189,197	360	$18,919.69	$0
December	210,025	0	210,025	404	$21,002.55	$0
Annual	2,480,220	0	2,480,220	559	$248,002.0	$0

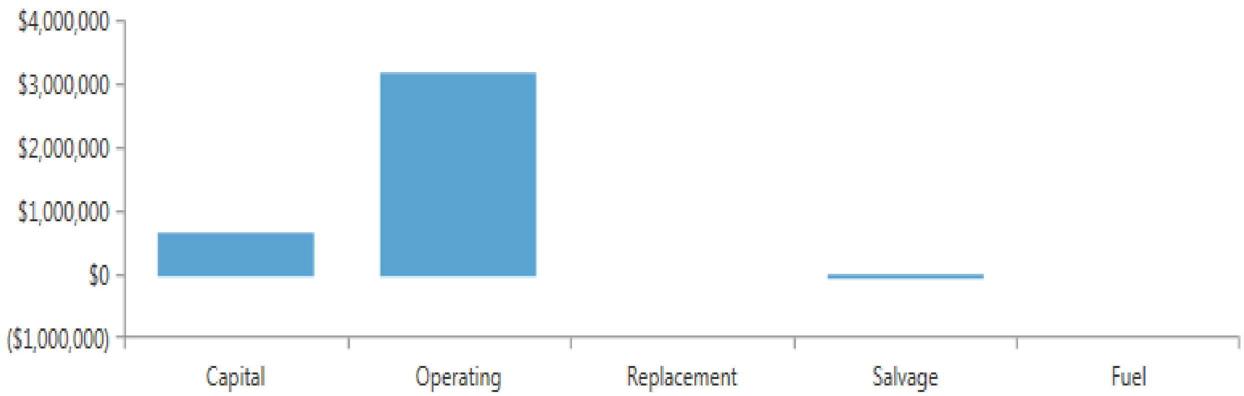

Figure 4.13: Summary of cost by type of investment on diesel generator, two solar PV panels, with battery storage in connected mode.

Table 4.13: Summary of cost by type of investments in tabular form for diesel generator, two solar PV panels, with battery storage in connected mode.

Component	**CAT-680**	**Grid**	**SMA Sunny Tripower**	**SMA Sunny Tripower**	**Iron Edison LFP**	**System**
Capital ($)	$200,000.00	$0.00	$179,850	$179,850	$136,500.00	$696,200.00
Replacement ($)	$0.00	$0.00	$.00	$0.00	$0.00	$0.00
O&M ($)	$0.00	$3,206,308.54	$7,750.05	$7,750.05	$33.04	$3,221,841.67

Fuel ($)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Salvage ($)	($42,042.40)	($0.00)	$0.00	$0.00	($31,882.09)	($73,924.49)
Total ($)	$157,957.60	$3,206,308.54	$187,600.05	$187,600.05	$104,650.95	$3,844,117.18

Table 4.14: Table 4.10: Total cost of project for diesel generator, two solar panels, with battery storage in connected mode.

Total NPC	$3,844,117.00
Levelized COE	$0.1122
Operating Cost	$243,505.20

4.5.1 Summary of Case 4

This case is similar to Case 3, the two major differences are that the percentage of penetration of renewable energy (two solar PV panels) has gone up to approximately 8% and its contribution to the supply of electricity usage is much higher than that of Case 3. This case proves that, in this particular study, based on the energy resources and components, one solar PV panel is producing more energy twice as one wind turbine.

4.6 Case 5: Considering Diesel Generator, Wind Turbine, Two Solar PV panels, and Battery Storage as Distributed Energy Resources in Connected Mode

- CAT-680 represents a diesel generator.
- WES100 represents the wind turbine.
- Two SMA60 represent the solar panels.
- Iron3500 represents a battery storage.
- ABB-MGS is the converter (DC-to-AC) for the battery and solar panels

➢ Grid represents the main grid.

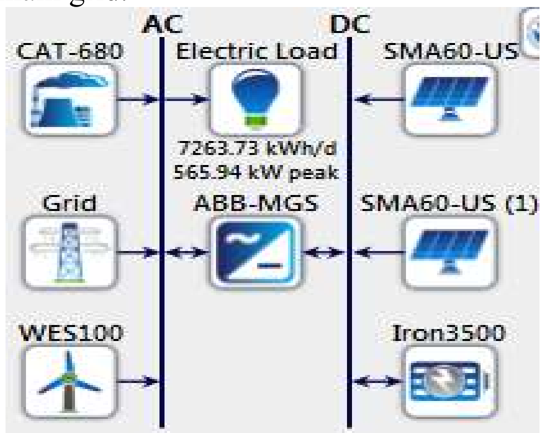

Figure 4.14: Schematic for diesel generator, wind turbine, two solar PV panels, with battery storage in connected mode with grid.

In this case, the sources of power generation for the microgrid are diesel generator, wind turbine, two solar panels, and a storage system, while in connected mode. The results and analysis are displayed below. Figure 4.15 shows the graph for the production from three energy sources (wind turbine, two solar panels) and purchase of electricity from the main grid. The diesel generator is giving zero output production in this particular case as shown in Table 4.15 below. The surplus electricity amount in this case is 32,664 kWh/yr.

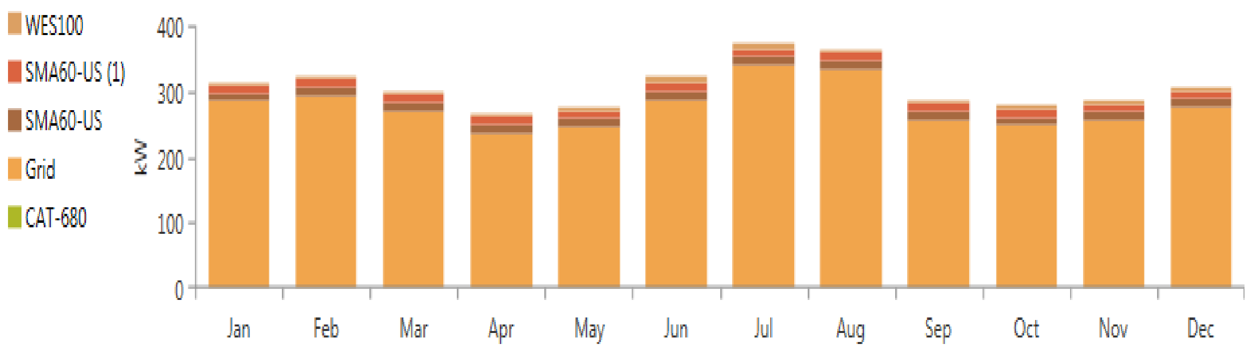

Figure 4.15: Monthly average electricity production by diesel generator, wind turbine, two solar PV panels, with battery storage in connected mode with grid.

Table 4.16 summarizes the monthly energy purchased from the grid, and no energy is sold to the grid in this case, even though there is surplus electricity. 2,429,716 kWh/yr of the electricity production is bought from the main grid, since it's cheaper, while 106,354 kWh of electricity output is produced by one solar panel and 50,504 kWh/yr of electricity is produced by the wind turbine. So, the production from two solar panels totals up to 212,708 kWh/yr. The figure below shows the overall cost of the system for this case in Figure 4.16. Figure 4.16 is the graphical display of the overall cost of the microgrid system in this case, including the electricity purchased from the main grid. Table 4.17 below shows the detailed breakdown of the costs. The net present cost in this case is $3,880,302.00 as seen in Table 4.18.

Table 4.15: Total electricity generation by diesel generator, wind turbine, two solar PV panels, and grid purchase in connected mode.

Production	kWh/yr
Diesel Generator	0
WES 18	50,504
SMA Sunny Tripower	106,354
SMA Sunny Tripower	106,354
Grid Purchases	2,429,716
Total	2,692,928

Table 4.16: Monthly rate schedule of purchased and sold energy for Case 5 in connected mode.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
January	212,158	0	212,158	381	$21,215.77	$0
February	196,964	0	196,964	390	$19,696.44	$0
March	201,169	0	201,169	370	$20,116.85	$0
April	170,326	0	170,326	330	$17,032.58	$0
May	183,073	0	183,073	446	$18,307.31	$0

June	206,729	0	206,729	464	$20,672.95	$0
July	253,069	0	253,069	527	$25,306.87	$0
August	248,367	0	248,367	556	$24,836.70	$0
September	183,744	0	183,744	382	$18,374.43	$0
October	183,866	0	183,866	345	$18,386.63	$0
November	183,992	0	183,992	359	$18,399.19	$0
December	206,259	0	206,259	404	$20,625.91	$0
Annual	2,429,716	0	2,429,716	556	$242,971.6	$0

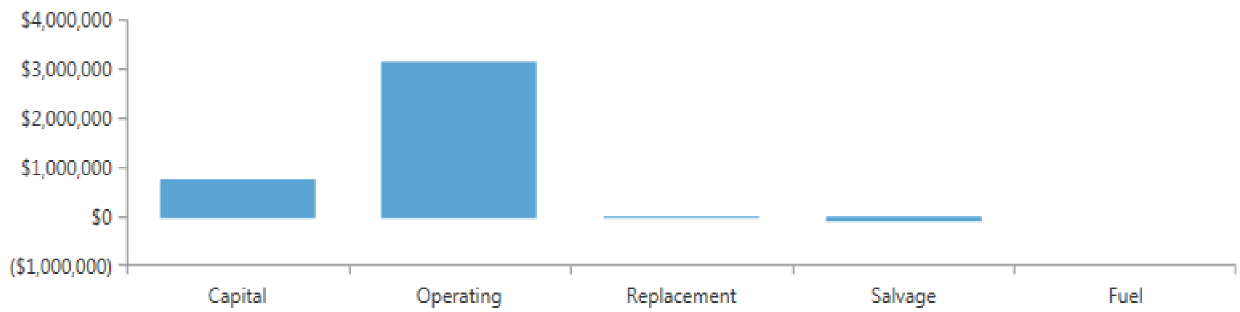

Figure 4.16: Summary of cost by type of investment on diesel generator, wind turbine, two solar PV panels, with battery storage in connected mode.

Table 4.17: Summary of cost by type of investments in tabular form for diesel generator, wind turbine, two solar PV panels, with battery storage in connected mode.

Component	**CAT-680**	**Grid**	**SMA Sunny Tripower**	**SMA Sunny Tripower**	**Iron Edison LFP**	**WES 18**	**System**
Capital ($)	$200,000.00	$0.00	$179,850	$179,850	$136,500.00	$80,000.00	$776,200.00
Replacement ($)	$0.00	$0.00	$.00	$0.00	$0.00	$25,504.59	$25,504.59

O&M ($)	$0.00	$3,141,019.76	$7,750.05	$7,750.05	$33.04	$10,342.01	$3,166,894.90
Fuel ($)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Salvage ($)	($42,042.40)	($0.00)	$0.00	$0.00	($31,882.09)	($14,373.47)	($88,297.96)
Total ($)	$157,957.60	$3,141,019.76	$187,600.05	$187,600.05	$104,650.95	$101,473.13	$3,880,301.53

Table 4.18: Total cost of project for diesel generator, wind turbine, two solar panels, with battery storage in connected mode.

Total NPC	$3,880,302.00
Levelized COE	$0.1132
Operating Cost	$240,115.80

4.6.1 Summary of Case 5

This case combines the whole generation components, and the it is confirmed that one of the main advantages in the integration of renewable energy is the reduction of carbon emission. The impact of renewable energy on cost minimization can be realized in a long-term goal. However, this case is not the best solution in this study as seen in the results. The cost of investment on the generators is obviously not an advantage for the NPC.

4.7 Conclusion

In conclusion, the analysis of this microgrid in connected mode showing all 5 Cases has played an important factor in decision making when choosing the optimum solution. In connected mode, the microgrid system prefers to get most of its electricity from the main grid because it is cheaper to purchase electricity from the utility company than generate most of its electricity usage from local resources. It can be concluded that Case 1 in all 5 Cases is the best option to explore when it comes to saving money while the microgrid is in connected mode. Tables 4.19 and 4.20 below shows the NPC and carbon emission analysis on all 5 Cases.

Table 4.19: Total cost of project for diesel generator, wind turbine, two solar PV panels, with battery storage in connected mode.

Case Type	Total NPC	Levelized COE	Operating Cost
CASE 1	$3,585,380.00	$0.1046	$261,874.00
CASE 2	$3,690,031.00	$0.1077	$259,410.30
CASE 3	$3,726,215.00	$0.1087	$256,021.00
CASE 4	$3,844,117.00	$0.1122	$243,505.20
CASE 5	$3,880,302.00	$0.1132	$240,115.80

Table 4.20: carbon emission analysis for all 5 cases in islanded mode.

Quantity	Case 1	Case 2	Case 3	Case 4	Case 5
Carbon Dioxide	1,675,597 kg/yr	1,675,597 kg/yr	1,643,679 kg/yr	1,567,499 kg/yr	1,535,581 kg/yr
Carbon Monoxide	0 kg/yr	0 kg/yr	0 kg/yr	0 kg/yr	0 kg/yr
Unburned Hydrocarbons	0 kg/yr	0 kg/yr	0 kg/yr	0 kg/yr	0 kg/yr
Particulate Matter	0 kg/yr	0 kg/yr	0 kg/yr	0 kg/yr	0 kg/yr
Sulfur Dioxide	7,264 kg/yr	7,264 kg/yr	7,126 kg/yr	6,796 kg/yr	6,657 kg/yr
Nitrogen Oxides	3,553 kg/yr	3,553 kg/yr	3,485 kg/yr	3,323 kg/yr	3,256 kg/yr

Table 4.20 shows the carbon emission, and it is clear that there is little difference in the reduction, since most of electricity is from the main grid. Case 5 has the most reduction, since it has the highest percentage of renewable energy integration (10%), but the significance in its reduction from other cases is not much.

Chapter 5: Summary and Comparison of Microgrid in Islanded and Connected Modes

5.1 Introduction

A microgrid in islanded mode can encourage independence from the main grid and promote clean environment. The advantage of a microgrid in islanded mode is that it encourages high integration of renewable energy. In chapter 3, even though the highest percentage of renewable energy integration is about 10%, there is an absolute chance of a 50% renewable energy integration depending on the resource availability and level of energy. This will definitely increase the sensitivity of the system. As evident in chapter 3, the annual average wind speed is about 4.2m/s. In the case, where the annual average wind speed goes up to about 20m/s, the penetration of renewable energy will definitely go up to approximately 24%. Below are the results an analysis for the optimum solution from all 5 Cases in chapter 3 when there is a 24% renewable energy integration.

Table 5.1: Monthly Average Wind Speed Data for a 24% renewable (wind turbine, two solar panels, battery storage) energy penetration.

Month	**Average (m/s)**
January	19.590
February	19.680
March	19.490
April	19.560
May	20.220
June	21.210
July	20.690
August	20.300
September	20.400

October	20.560
November	20.570
December	20.090

5.2 Microgrid Operation and Economic Analysis with 24% Renewable Energy Penetration Reviewing the Optimum Solution in Islanded Mode (Case 5)

- CAT-680 represents a diesel generator.
- Two SMA60 represents solar PV panel.
- WES100 represents the battery storage.
- ABB-MGS represents the battery storage.

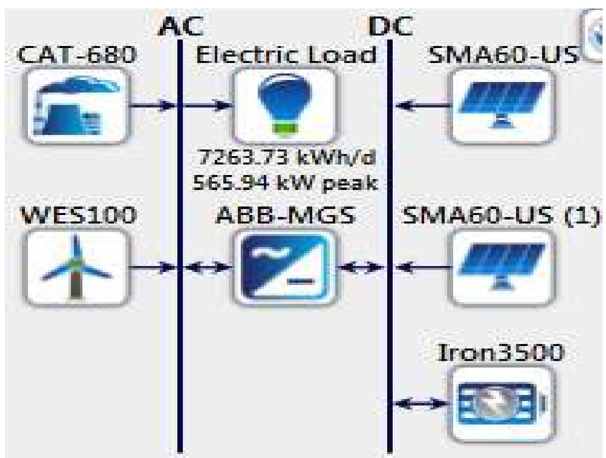

Figure 5.1: Schematic for microgrid (diesel generator, two solar PV panels, battery storage, and wind turbine) in islanded mode with 24% renewable energy.

As seen in Figure 5.1, this is Case 5 of chapter 3, and it remains the optimum solution regardless of the 24% renewable energy integration. However, there is improvement in the system based on minimum cost. As seen in Figure 5.2, the diesel generator is producing about 76% of electricity, the two solar panels are producing about 8% of the electricity, while the wind turbine is producing about 16%. Table 5.2 below displays the detailed production for each generator.

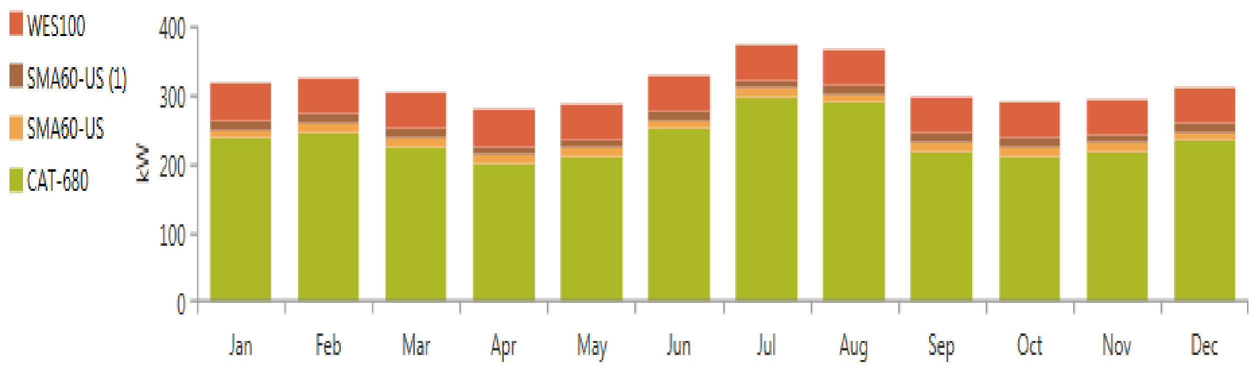

Figure 5.1: Monthly average electricity production (24% renewable energy) by diesel generator, wind turbine, two solar PV panels, with battery storage in islanded.

Table 5.2: Total electricity generation by diesel generator, wind turbine, and two solar PV panels, with battery storage in islanded mode.

Production	**kWh/yr**
Diesel Generator	2,076,066
WES 18	459,453
SMA Sunny Tripower	106,354
SMA Sunny Tripower	106,354
Total	2,692,928

Table 5.3: Summary of cost by type of investments in tabular form for diesel generator, wind turbine, two solar PV panels, with battery storage in islanded mode.

Case Type	**Component**	**CAT-680**	**Iron Edison LFP**	**SMA Sunny Tripower**	**SMA Sunny Tripower**	**WES 18**	**System**
Case 5 Islanded Mode	Fuel ($)	$10,071,763.88	$0.00	$0.00	$0.00	$0.00	$10,071,763.88

Optimum Solution Islanded Mode	Fuel ($)	$9,013,112.00	$0.00	$0.00	$0.00	$0.00	$9,013,112.00
Savings	Fuel ($)	$1,058,651.88	$0.00	$0.00	$0.00	$0.00	$1,058,651.88

As seen in Table 5.3, there is a savings of $1,058,651.88 based on the reduction in fuel usage and this proves the effect of renewable energy on carbon emission reduction, since the usage of fuel contributes to carbon pollution in the environment. Comparisons are only made for the islanded mode in chapter 3 and 5, since the diesel generator generates 0 kWh/yr electricity in connected mode. Table 5.4 details the carbon emission analysis and the reduction in carbon emission when the renewable energy integration is increased to 24%.

Table 5.4: Difference in carbon emission.

Quantity	Case 5 (Chapter 3)	24% Renewable Energy Case 5	Reduction Amount
Carbon Dioxide	2,060,447 kg/yr	1,843,872 kg/yr	216,575 kg/yr
Carbon Monoxide	499 kg/yr	446 kg/yr	53 kg/yr
Unburned Hydrocarbons	46.7 kg/yr	41.8 kg/yr	4.9 kg/yr
Particulate Matter	46.7 kg/yr	41.8 kg/yr	4.9kg/yr
Sulfur Dioxide	5,110 kg/yr	4,573 kg/yr	537 kg/yr
Nitrogen Oxides	13,743 kg/yr	12,299 kg/yr	1,444 kg/yr

5.3 Microgrid Operation and Economic Analysis with 24% Renewable Energy Penetration Reviewing the Optimum Solution in Connected Mode (Case 3)

A microgrid in connected mode can encourage the purchase and selling of surplus electricity from and to the main grid. However, one thing to keep in mind is that since the main goal of the microgrid system is to minimize cost, the optimum solution would be the option with the minimum cost. In this case, purchasing most of the electricity usage from the main grid is cheaper than generating electricity from local sources while the microgrid is in connected mode.

- CAT-680 represents a diesel generator.
- WES100 represents the wind turbine.
- Iron3500 represents a battery storage.
- ABB-MGS is the converter (DC-to-AC) for the battery.
- Grid represents the main grid.

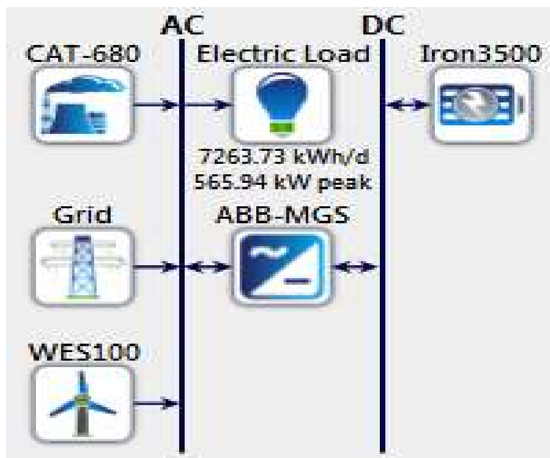

Figure 5.3: Schematic (with 24% renewable energy penetration) for diesel generator, wind turbine, with battery storage in connected mode.

As seen in Figure 5.3, this is Case 3 in chapter 4, and it is now chosen to be the optimum solution. In Figure 5.4, the graph displays the amount of renewable energy integration from the wind turbine. As seen in Figure 5.4, 83% of electricity generation is purchased from the main grid, and about 17% of electricity production is supplied by the wind turbine. There is no supply of electricity from the solar panels, since they are not included in this particular case. The diesel generator is supplying zero output power and the reasons are clear in the results presented below. Table 5.5 below displays the detailed production for each generator.

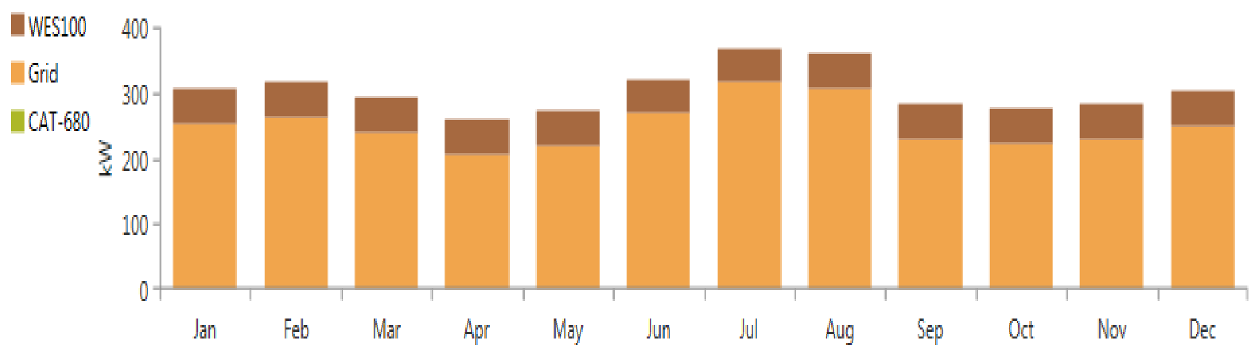

Figure 5.4: Monthly average electricity production (24% renewable energy) by diesel generator, wind turbine, with battery storage in connected mode.

Table 5.5: Total electricity generation for the selected optimum solution with 24% renewable energy penetration.

Production	kWh/yr
Diesel Generator	0
WES 18	459,453
Grid Purchases	2,191,808
Total	2,651,261

Since there is additional electricity generation coming from the wind turbine, the amount of electricity purchase from the main grid has reduced. The biggest comparison between chapter 3 and 4 is the total net present cost (NPC). As seen in the Table 5.6 below, there is a huge difference in NPC between both chapters. The reason for the big difference in the NPC when in islanded and connected mode is the fuel cost of the microgrid diesel generator. When the system is in connected mode, the diesel generator from the microgrid is not used, which helps save a lot on fuel purchase. As highlighted in orange and blue, the optimum solutions for the NPC of chapters 3 and 4 are realized. Another comparison is the carbon emission of the system when there is a 24% renewable energy integration. The carbon emission analysis between the islanded and connected mode for the two optimum solutions can be seen in Table 5.7 below. It shows the significant reduction in carbon emission due to the increase in renewable energy integration, and this confirms that renewable energy plays a vital role in clean environment.

Table 5.6: Cost analysis of entire project.

Chapter Number	Case Type	Total NPC
Chapter 3	Case 1	$11,178,950.00
	Case 2	$11,283,600.00
	Case 3	$11,234,010.00
	Case 4	$11,146,950.00
	Case 5	$11,097,570.00
Chapter 4	Case 1	$3,585,380.00
	Case 2	$3,690,031.00
	Case 3	$3,726,215.00
	Case 4	$3,844,117.00
	Case 5	$3,880,302.00
Chapter 5	Optimum Solution (24% renewable energy) Case 5	$10,038,920.00
	Optimum Solution (24% renewable Energy) Case 3	$3,197,545.00

Table 5.7: Difference in carbon emission for 24% renewable energy penetration in islanded and connected mode.

QUANTITY	ISLANDED WITH 24% RENEWABLE	CONNECTED WITH 24% RENEWABLE
Carbon Dioxide	1,843,872 kg/yr	1,385,223 kg/yr
Carbon Monoxide	446 kg/yr	0 kg/yr

Unburned Hydrocarbons	41.8 kg/yr	0 kg/yr
Particulate Matter	41.8 kg/yr	0 kg/yr
Sulfur Dioxide	4,573 kg/yr	6,006 kg/yr
Nitrogen Oxides	12,299 kg/yr	2,937 kg/yr

5.4 Conclusion

As evident in the above Table 5.6, there is a huge difference in the total cost for the islanded mode and connected mode. This cost of the islanded mode is higher due to extra amount spent on capital investments on generators for the wind turbine, two solar PV panels, battery storage, and diesel generator. It is important to note that while in connected mode, the microgrid benefits from the main grid through reduction in cost of money spent on fuel purchase for the diesel generator, however, the microgrid' s impact is seen in the reduction of CO_2 emission when there is renewable energy penetration. The amount of reduction in the CO_2 is based on the percentage of penetration from the renewable energy.

Table 5.8: Complete summary of NPC, CO_2 emission for entire project.

Case Type	**Total NPC**		**CO_2 Emission**	
	Islanded Mode	**Connected Mode**	**Islanded Mode**	**Connected Mode**
Case 1	$11,178,950.00	$3,585,380.00	2,196,022 kg/yr	1,675,597 kg/yr
Case 2	$11,283,600.00	$3,690,031.00	2,196,022 kg/yr	1,675,597 kg/yr
Case 3	$11,234,010.00	$3,726,215.00	2,165,117 kg/yr	1,643,679 kg/yr

Case4	$11,146,950.00	$3,844,117.00	2,091,308 kg/yr	1,567,499 kg/yr
Case 5	$11,097,570.00	$3,880,302.00	2,060,447 kg/yr	1,535,581 kg/yr
25% REs Integration for Optimum Solutions	$10,038,920.00	$3,197,545.00	1,843,872 kg/yr	1,385,223 kg/yr

Chapter 6: Conclusions and Recommendations for Future Work

6.1 General

This thesis analyzed the economics of a microgrid with different options of generation sources in islanded mode and the solution with the minimum cost was selected. Also, in chapter 4, the economic analysis of the microgrid was done while connected to the main grid and the solution with the minimum cost was selected. The results from the islanded and connected mode were compared and it can be concluded that most savings occurred while the microgrid is in connected mode. Chapter 6 discusses the conclusion and summary of this thesis. 6.1 draws the summary and concludes the whole of chapters 2, 3, 4, and 5, while 6.2 discusses future recommendations.

6.2 Summary and Conclusions

It is determined that the main importance of microgrid is realized when there really is a need for any kind of emergency response in times when the main grid is not able to perform to its full potential. Emergency could be like the events that happened in Puerto Rico where Hurricane Maria destroyed a lot of the island's infrastructure and electrical grid. About 870,000 customers lost access to power for about six months. A microgrid is very important in this kind of situation. This thesis contributes to the economic aspects of the power system by finding alternatives to minimize cost, contribute to a cleaner environment, and create a robust system in terms of resiliency. The summary is outlined below.

- *Chapter 1* offered the motivation for the research, background and challenges of the microgrid system. It also touches on issues that face matching demand with supply in electricity.
- *Chapter 2* detailed the literature review and the economics of the microgrid. This part focused more on researches, problem tackling, technology developments of the microgrid, and how it can continuously keep up with the evolving technology.

- *Chapter 3* considered the microgrid in islanded mode, and a cost benefit analysis was done using the Homer Pro software. The optimum solution was selected based on minimum cost and the carbon emission was analyzed to understand the impact of renewable energy integration in the microgrid system.
- *Chapter 4* considered the microgrid when connected to the main grid, and a cost benefit analysis was done. The optimum solution was selected based on minimum cost. In connected mode, the system encourages the import and export of electricity from the microgrid to the main grid. However, this chapter only analyzed the export of electricity from the main grid to the microgrid.
- *Chapter 5* compared the analysis between the islanded and connected mode in chapter 3 and 4. An analysis was also done with renewable energy integration increased to 24% in islanded and connected mode and the results of the optimum solutions were displayed and compared, including the carbon emission analysis.

6.3 Recommendations for Future Work

One important measure to understand about the microgrid system is that the increase in renewable energy integration increases the sensitivity of the system due to unpredictability of the weather. So, a sensitivity analysis is highly important for high renewable energy penetration for the purpose of system stability. Furthermore, the Homer Pro software system recommended a more robust software for simulation in chapter 5 when the renewable energy penetration increased to 25%. The future work will help in the anticipation of (i) matching demand with response, (ii) providing quality electricity at all times by completely eliminating possible fluctuations in RES (e.g., wind and solar).

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Appendix I

Data Resources for Wind Speed, Solar GHI, and Load Profile

Wind speed data downloaded from NASA surface meteorology and solar energy database. Wind speed at 50m above the surface of the earth for terrain similar to airports, monthly averaged values over 10-year period (July 1983 – June 1993).

- Cell Number: 90180
- Cell Dimensions: 1-degree x 1-degree
- Cell Midpoint Latitude: 0.5
- Cell Midpoint Longitude: 0.5
- Anemometer Height: 50

Table AI.1: Monthly Average Wind Speed Data.

Month	Average (m/s)
January	3.590
February	3.680
March	3.490
April	3.560
May	4.220
June	5.210
July	4.690
August	4.300
September	4.400
October	4.560
November	4.570
December	4.090

Solar global horizontal Irradiance downloaded from NASA surface meteorology and solar energy database. Global horizontal radiation, monthly averaged values over 22-year period (July 1983 – June 2005).

- Cell Number: 90180
- Cell Dimensions: 1-degree x 1-degree
- Cell Midpoint Latitude: 0.5
- Cell Midpoint Longitude: 0.5

Table AI.2: Monthly Average Solar Global Horizontal Irradiance.

Month	Clearness Index	Daily Radiation ($kWh/m^2/day$)
January	0.545	5.480
February	0.562	5.840
March	0.553	5.810
April	0.559	5.700
May	0.558	5.390
June	0.591	5.500
July	0.582	5.490
August	0.560	5.550
September	0.566	5.850
October	0.544	5.640
November	0.535	5.400
December	0.535	5.300

Load data profile was acquired from publicly available electricity market load data. The load data was reduced by subtracting 0.999992% of the original load from the original load, and this was done in order to fit the load size to the capacity of the microgrid in this study, since the original load is too big for a micro grid. A 60-minute time step size for January profile is presented in Table AI.3 below.

Table AI.2: Load for January profile.

Hour	Load (kW)
0	265.63
1	257.38
2	253.69
3	253.39
4	258.79
5	275.8
6	305.41
7	322.91
8	325.53
9	326..72
10	327.1
11	325.33
12	321.95
13	319.15
14	315.62
15	315.3
16	325.05
17	349.9

18	355.94
19	352.57
20	344.99
21	329.7
22	306.85
23	283.58

Appendix II

List of Abbreviations

CO_2: Carbon Dioxide

DER: Distributed Energy Resources

DES: Distributed Energy Sources

DG: Distributed Generator

EMS: Energy Management System

GHI: Global Horizontal Irradiance

HVAC: Heat, Ventilation, and Air-Conditioning

MEMS: Microgrid Energy Management System

NPC: Net Present Cost

O&M: Operations and Management

PCC: Point of Common Coupling

PEV: Plug-in Electric

PHEV: Plug-in Hybrid Electric

PV: Photovoltaic

Vita

Olayinka S. Obafemi was born in Lagos, Nigeria and moved to the U.S. at the age of 22. He received his Bachelor of Science in Electrical Engineering at the University of Texas at El Paso in 2012.

In August 2016, he started his Master of Science in Industrial Engineering (M.S.I.E). In January of 2017, he started his research under the supervision of Dr. Paras Mandal who helped guide him throughout his entire research career. Before his Master's degree, he had a minimum knowledge in microgrid and power system. During this thesis period, he gained good research skills and knowledge on renewable energy, and microgrid and this has helped him improve in his research and presentation skills.

He would like to express his gratitude for the support and platform provided to him by UTEP to further his education and complete his Master's degree. Additionally, he would like to extend his appreciation to his thesis advisors, Dr. Bill Tseng and Dr. Paras Mandal for mentoring him through the completion of this M.S.I.E. thesis titled "*Economic and Environmentally Efficient Energy Management System for Optimal Microgrid Operations* ".

Permanent address: 200 Wallington Drive

El Paso, Texas, 79902

This thesis/dissertation was typed by Olayinka Samuel Obafemi.