Techno-economic Feasibility of Flywheel Energy Storage System in Standalone and Hybrid Applications

by

Muhammad Saad Arshad

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Engineering Management

Department of Mechanical Engineering

University of Alberta

Abstract

Electrical energy storage systems are used to store electrical energy in different forms so that it can be extracted when required. For example, they are suitable for power peak shaving applications and effective integration of renewable energy into islanded microgrids. Flywheel energy storage system (FESS) is a storage technology in which electrical energy is converted and stored in the form of kinetic energy. FESS are gaining popularity due to their high-power charging capabilities and quasi-infinite charge/discharge cycles without depth of discharge limitations.

The first part of this study involves exploring the possibility of integrating FESS as a standalone system for electric bus fleet charging, in order to achieve greatest performance and economy. A charging system with energy storage was simulated considering either FESS or electrochemical batteries. It was observed that a solution based on FESS can meet requirements and achieve peak shaving with a faster response as compared to batteries. The techno-economic performance was assessed considering net present value and internal rate of return. The results show that FESS outperformed batteries both in terms of suitability and cost effectiveness.

The application of FESS along with electro-chemical batteries as a hybrid system was also studied to explore the benefits that both technologies may offer when combined. A standalone micro-grid was simulated with two different load profiles under different scenarios. It was observed that greenhouse gas emissions were considerably decreased for some of the modeled scenarios. It was also noted that for both the load profiles, the hybrid system was not only found to fulfil the load demand but was also the cheapest solution upon performing a lifecycle cost assessment. The

levelized cost of energy and net present value of the hybrid system showed that it is the most attractive solution.

Acknowledgements

I take this opportunity to thank my supervisor Dr. Pierre Mertiny who has been supportive at every stage of the project. He provided me with invaluable guidance and resources that helped me in successful completion of my research work. It has been a great learning opportunity, and the research work further honed my problem-solving skills. Also, I would like to acknowledge the support received by the Future Energy Systems program at the University of Alberta that made this project possible.

I would like to express sincere gratitude to my City of Edmonton mentors Mr. Paul Netzband and Mr. Garry Hurkens for providing a platform to work on the electric bus project. I would like to thank them for giving me access to all the information that was necessary to achieve the objectives of the project. I would also like to thank Mr. Tyler Harrison who helped me with the simulations.

Last but not the least, I would like to thank my family members who supported me through thick and thin, and my friends who made my stay at University of Alberta an amazing experience.

Table of Contents

List of Tables

List of Figures

1 Introduction

1.1 Need for Energy Storage Systems

Global electricity generation has seen an exponential rise in the last few decades especially in non-OECD countries (OECD: Organization for Economic Co-operation and Development). Figure 1 shows the increase in electricity production from 1974 to 2018 for both the OECD and non-OECD members.

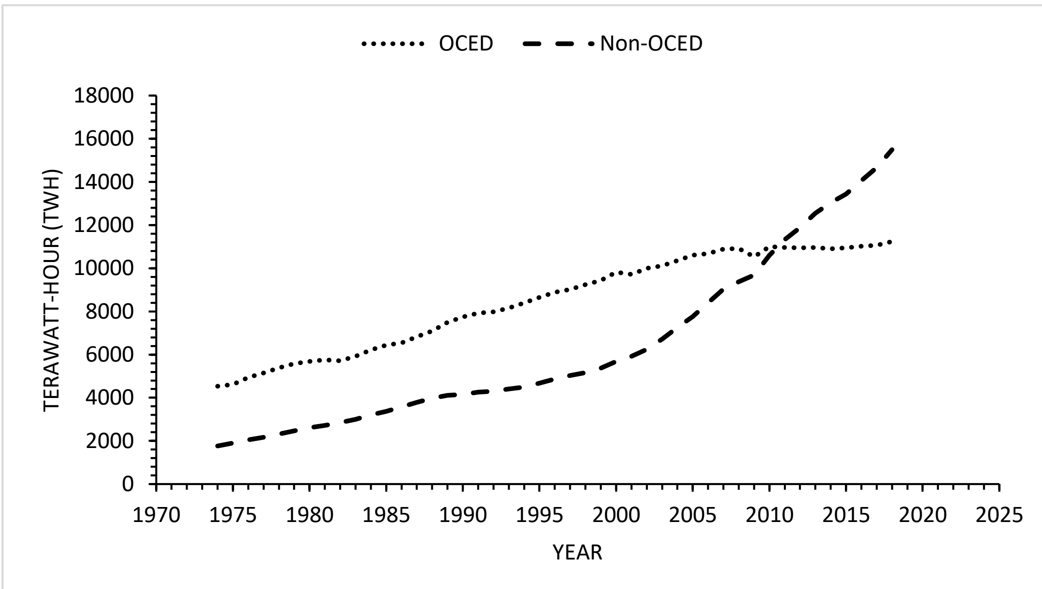


Figure 1. Total gross electricity production (1974-2018) [1].

As of 2018, the total global electricity generation was 27,730 TWh. Electricity was generated from several different sources, including but not limited to, coal, natural gas, oil, nuclear, hydro, solar, wind and geothermal. Figure 2 presents a breakdown of percentage of electricity generated by OECD countries for some of the sources mentioned above, during the period between 2008 and 2018. Electricity production from coal decreased over time, and currently natural gas is the main source of electricity generation for these countries. Electricity generation from nuclear and hydro has been somewhat steady during this time while electricity generation from renewable energy sources has seen a promising trend every year with about 1% increase in share of production every year from 2% in 2008 to 10% in 2018.

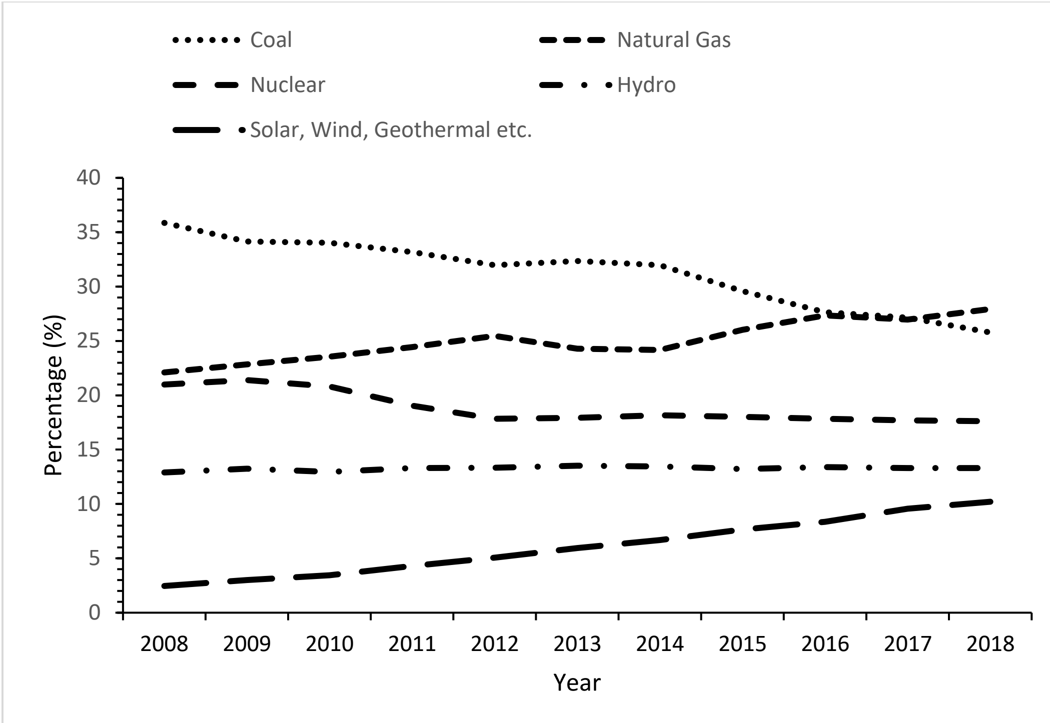


Figure 2. Gross electricity production in OECD countries by source (2008-2018) [1].

Around the globe different countries are transitioning from fossil fuels to green energy to reduce the environmental impact of greenhouse gas (GHG) emissions. But the accumulation of GHG emissions in the atmosphere from different countries makes it a global issue, and in order to have a global impact a solution asks for cooperation from all the countries [2]. This calls for a need to have an international agreement like United Nation Framework Convention on Climate Change (UNFCC) which is an international treaty signed by 197 countries to address the issues of climate change [3]. The Kyoto Protocol (1997) and Paris Agreement (2015) are two international treaties under the umbrella of UNFCC signed by the majority of countries with the mutual goal to decrease emissions globally [4]. Canada is a signing member of the Paris Agreement. Under this agreement, Canada has committed to reducing its GHG emissions by 30% from year 2005 levels by the end of year 2030 [5]. Figure 3 shows the percentage of the GHG emissions from different sectors in Canada. The oil and gas industry and transportation were the leading sources of emissions comprising more than 50% of the total GHG emissions combined, in 2018, while electricity generation contributed to 9% of the total emissions.

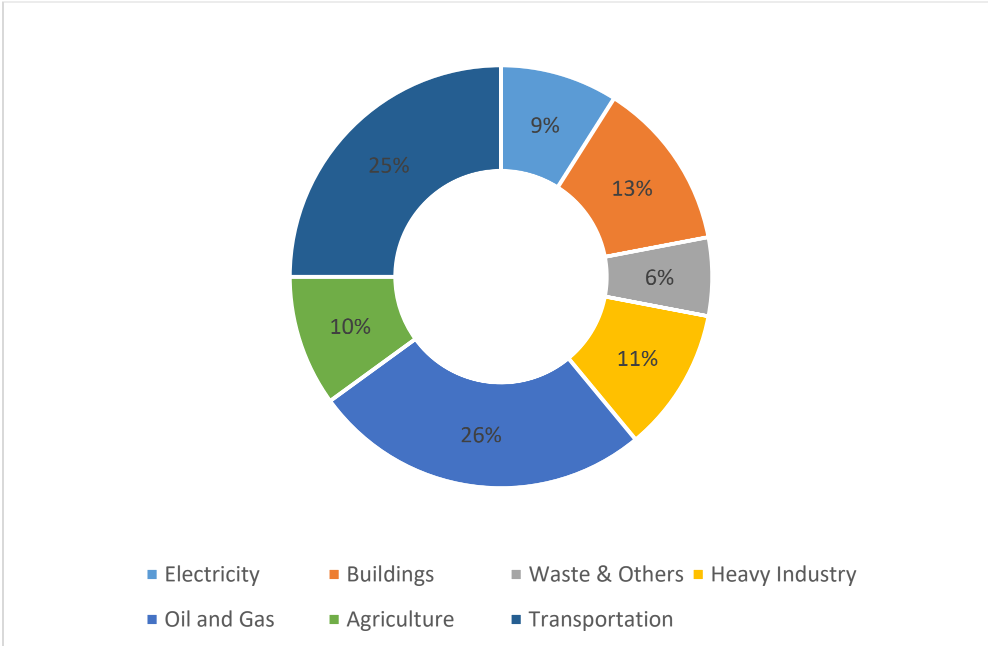


Figure 3. Percentage of GHG emissions by sector in Canada in 2018 (Canada) [6].

To decrease emissions in transportation, Canada is moving towards methods of cleaner transportation including but not limited to investments in alternatives in public transit like electric buses, incentives on purchase of low emission vehicles, and producing new fuels for vehicles [7]. Canada also intends to shift its dependence on fossils fuels and move towards renewable energy sources in its mission to decrease the GHG emissions from electricity generation [7].

The usage of renewable energy sources (RES) presents a unique challenge in terms of its intermittency. The intermittent nature of RES arises from diurnal changes and dependence on weather causing fluctuations in produced power. For that reason, supply and demand of power are typically not congruent. Hence, the ability for energy storage to guarantee power stability and energy availability is desirable [8][9]. An energy storage system (ESS) can be used to bridge the gap between electrical energy supply and demand [10].

In general, the purpose of using an ESS is to store and convert energy coming from a direct source, such as electrical power from a photovoltaic installation, into an energy form that can be stored over a period of time and then use the stored energy to meet supply gaps after converting the stored energy back to electrical power [11]. For example, different types of ESS store energy in the form of chemical, mechanical, magnetic, or thermal energy. An ESS can be classified based on its functionality or the form in which energy is stored [11]. Based on functionality, ESS solutions can be classified as long term systems (high energy density) like rechargeable batteries (also known as secondary cells) [12] or short term systems (high power density) like super capacitors [13], super conducting magnetic energy storage [14], and flywheel energy storage systems [15]. Some of the available ESS technologies categorized on the basis of stored energy form [16] [8] are listed in Table 1.

Table 1. Energy storage systems based on energy storage type.

Mechanical	Flywheel energy storage system (FESS)
	Pumped hydro energy storage (PHES)
	Compressed air energy storage (CAES)
Electrochemical	Secondary cells (Battery energy storage system, BESS) • Li-ion, lead acid, etc.
	Flow battery energy storage (FBES) • Redox flow, hybrid flow, etc.
Electrical	Super-capacitor energy storage (SCES)
	Superconducting magnetic energy storage (SMES)
Thermochemical	Solar fuels
Chemical	Hydrogen energy storage system
Thermal	Latent heat storage

1.1.1 Applications of Energy Storage Systems

ESS technologies are used for a wide range of applications some of which are mentioned below [17][18][19].

Peak shaving: ESS technologies are used when the load on the electricity grid exceeds a certain level. Energy is stored in an ESS during off-peak hours. When demand is high, power from the ESS is used. Such an approach does not only help to lessen the load on the grid infrastructure such as transmission lines but can also save considerable costs in terms of demand charges. Such an ESS application is explored in Chapter 3 of this thesis.

Integration of renewable energy sources: ESS technology can be used to store energy from RES and make power available during times of RES unavailability. ESS technology can also be used to smoothen the power output caused by the intermittent nature of RES. This application of ESS is the subject matter of Chapter 4.

Power reliability: ESS devices can be used in uninterruptable power supply (UPS) systems where they act as a back-up when power from the grid is disrupted. Such solutions are very popular in developing countries where there may be frequent power disruptions throughout the day. A suitable ESS for this application must be able of providing energy instantaneously.

Applications in vehicles: ESS technologies are used to supply power to hybrid electric vehicles and pure electric vehicles. A suitable ESS for transportation applications must be able to store a large amount of energy while being lightweight and capable of providing a fast response.

Black start: ESS technology can be used for a black start which occurs when a grid system needs to be started after an outage and sufficient energy from the grid cannot be extracted.

1.1.2 Economic Benefits of Energy Storage System

There are a variety of financial benefits of using an ESS. Some of these benefits are highlighted below based on [20].

- ESS can be used to store electricity during off-peak hours at lower prices and can be used afterwards during on-peak hours when the price is high. This approach can help in realizing significant cost savings.

- ESS can be used to provide ancillary services and help in reducing the demand charges (per amount of power of peak load). Customers can avoid these charges by using ESS during peak hours.

- ESS can help in reducing financial losses during power outages. Industrial and commercial customer can benefit from this approach, when a loss of power has high-cost implications.

- ESS decreases the losses associated with power quality issues and damage of electricity related equipment can be avoided resulting in cost savings [21].

- ESS can help in time shifting the energy generated using renewable sources. Energy is stored when the price is low, and it is utilized during the periods of high cost.

Above mentioned financial benefits makes the deployment of an ESS an attractive proposition. With the advancement in ESS technologies, associated cost is continually decreasing. According to a US Department of Energy report published in 2019, the cost of many ESS technologies will decrease substantially by the year 2025 compared to 2018 [22]. Technical and economic characteristics of the different ESS technologies are summarized in Table 2.

Table 2. Techno-economic characteristics of different ESS technologies.

ESS	Capital Cost (USD/kW)	Capital Cost (USD/kWh)	Discharge Time @ Rated Power	Lifetime (yrs)	No. of Cycles	Specific Energy (Wh/kg)	Specific Power (W/kg)
Pumped Hydro	600 to 2,000 [17]	5 to 100 [17]	6 to10 hrs [23]	40 to 60 [11]	10,000 to 30,000 [24]	0.5 to 1.5 [11]	-
Flywheel	100 to 300 [25]	1,000 to 5,000 [25]	15 sec to 15 min [26]	20 [27]	21,000+ [28]	5 to 100 [29]	400 to 1,500 [11]
Lead Acid Battery	175 to 600 [25]	150 to 200 [30]	sec to hrs [11]	5 to 15 [11]	200 to 1,800 [31]	30 to 50 [11]	250 [32]
Lithium Ion Battery	1,200 to 4,000 [17]	600 to 800 [30]	min to hrs [11]	5 to 15 [11]	1,000 to 10,000 [11]	75 to 200 [11]	300 [32]
Sodium Sulfur Battery	1,000 to 3,000 [17]	300 to 500 [17]	sec to hrs [11]	15 [28]	2,500 [11]	150 to 240 [11]	150 to 230 [11]
Nickel Cadmium Battery	500 to 1500 [25]	600 to 2,400 [25]	sec to hrs [11]	3 to 20 [31]	2,000 to 2,500 [11]	50 to 75 [11]	160 [31]
Supercapacitor	100 to 300 [17]	300 to 2,000 [17]	1 min [33]	10 to 30 [11]	50,000+ [28]	2.5 to 15 [11]	500 to 5,000 [11]
Superconducting magnetic energy storage	200 to 300 [17]	1,000 to 10,000 [17]	Upto 30 min [33]	30 [27]	20,000+ [24]	0.5 to 5 [11]	500 to 2,000 [11]
Fuel Cell	10,000+ [34]	15 [35]	sec to 24 hrs [11]	5 to 15 [11]	1,000+ [11]	800 to 10,000 [11]	500+ [11]

1.2 Thesis Objectives

As will be shown in Chapter 2, energy storage employing a flywheel energy storage system (FESS) or an electro-chemical battery energy storage system (BESS) or a combination of FESS and BESS is an attractive proposition for standalone and microgrid applications. In this context, the thesis work intends to fulfil the following two objectives:

- Study the techno-economic feasibility of a FESS for charging of the City of Edmonton's electric bus fleet and contrast such a system to a BESS. The study considers a first of its kind in-depot overhead charging system in North America. This study provides a basis for in-depot BEB charging, using FESS as a backup ESS and assesses how a FESS solution would perform in the absence of any other storage technology.
- Analyze the performance of FESS in the presence of BESS, i.e., a hybrid system, to assess if and how such solutions utilize the benefit of both technologies. The application considered herein was that of a standalone microgrid.

1.3 Thesis Structure

This thesis consists of five chapters. Following the introductory sections in Chapter 1, which provides information on the need of ESS and sheds light on the different categories of available ESS technology, Chapter 2 presents the background on the primarily considered energy storage systems, i.e., the chapter focusses in detail on BESS and FESS and the differences between them. Chapter 3 provides some background on electric vehicles operation in the context of a fleet of electric buses and presents simulation parameters and results related to role of FESS in standalone operations and a comparison to BESS. It also presents a cost benefit analysis for both the technologies under theoretical and simulation-based scenarios. Chapter 4 discusses the background and literature review on FESS integration with renewable energy sources and present two case studies for two different load profiles. Chapter 4 further includes results and a discussion for hybrid systems. Finally, Chapter 5 summarizes key findings of the thesis research.

2 Energy Storage Systems

2.1 Battery Energy Storage System

A BESS, also referred to as electro-chemical battery, stores energy in the form of chemical energy. The first practical secondary cells, a lead-acid battery, was invented by Gaston in 1860 [36]. Secondary cells can be charged and discharged repeatedly until the end of their life; hence they are also called rechargeable batteries. As seen in Table 1, electro-chemical batteries can further be classified into secondary cells and flow batteries. In secondary cells, two electrodes, the anode and cathode, are submerged in an electrolyte. During discharging, electrons are released at the negative electrode and absorbed at the positive electrode, which forms the current flow that can be extracted from the battery [36]. The energy efficiency of batteries is comparatively high, ranging anywhere between 60% to 95%, with standby losses being usually low [11]. The following types of batteries are currently available and suitable for utility-scale applications: lead acid, lithium ion, nickel cadmium, sodium sulfur and sodium nickel chloride [37]. Given their popularity, lead acid and lithium-ion batteries are explained below.

2.1.1 Lead Acid Batteries

A lead acid battery consists of a metallic lead anode and lead oxide cathode which are submerged in a sulfuric acid electrolyte. These components are relatively cheaper compared to other secondary cells, but they have low depth of discharge and, limited battery life (between 3 to 4 years). Energy density (50 Wh/kg) is normally lower than for lithium-ion batteries [38]. According to a US Department of Energy report published in 2019, the capital cost for lead acid batteries varied in 2018 between $129/kWh and $291/kWh and are predicted to decrease ($102/kWh to $247/kWh) by 2025 [22].

2.2.2 Lithium-Ion Batteries

In lithium-ion batteries, the anode is made of carbon and the cathode is a metal oxide. Both electrodes are immersed in an organic solvent of lithium salt [39]. This type of batteries provides higher power and energy density as compared to other secondary cells [38]. Commercially available lithium-ion batteries were first made by Sony (Tokyo, Japan) in 1990. Since then these batteries have seen substantial improvements over the years (e.g. energy density increases from 75 Wh/kg to 200 Wh/kg) [11]. Lithium ion batteries are now available featuring maintenance-free designs and with increased number of charge/discharges cycles (i.e., greater than 5000 at 80%

depth of discharge) [40]. The capital cost for lithium-ion batteries are predicted to decrease to between \$156/kWh and \$203/kWh by 2025 with currently costs ranging from \$222/kWh to \$323/kWh [22]. Advantages of lithium-ion batteries are a longer service life, high efficiency, and energy per weight ratio, which is why they are popular energy storage devices, for example for microgrids [41][11].

2.2 Flywheel Energy Storage Systems

One may think of flywheel energy storage devices as a recent invention, but the technology is known since ancient times. Oldest inventions in which the mass moment of inertia of a rotating mass was utilized dates to 6,000 BC when spindles were used to produce threads [42]. Potter's wheels are another application of flywheels known to man for centuries.

In 1784, the word flywheel was coined during the industrial revolution when flywheels were used as energy accumulators [43]. Major developments in flywheel technology commenced early in the 20th century when different rotor shapes were studied and stress analyses were performed [10]. For road vehicles, flywheels weighing around 1500 kg were first used in 1950 for the so-called gyro buses in Switzerland [43]. A plug-in flywheel concept was proposed during the 1960s and 1970s [44]. Fiber composite rotors emerged such as those tested by U.S. Flywheel Systems (Pasadena, California) and other organizations. During the 1980s the concept of magnetic bearings emerged for reducing mechanical losses [45]. Developments in the following decade proved that flywheels, also known as electro-mechanical batteries have many superior aspects to conventional electro-chemical batteries for many applications [45].

There are several advantages of flywheels as an ESS [46], [47], [48], [49]:

- FESS are capable of charging/ discharging at high rates (high-power density).
- FESS are environmentally friendly, especially compared to electro-chemical batteries, because no chemical reactions are involved and therefore no hazardous chemical disposal is required at the end of a flywheel's service life.
- FESS are also highly efficient for short-term storage (nearly 100%), yet losses increase if energy is stored for a longer amounts of time (beyond the order of minutes).
- FESS do not experience degradation in capacity. The lifetime of flywheels is not affected by depth of discharge (DOD). The total number of lifetime charge cycles can exceed 1 million.

- FESS maintenance requirements are not periodic in nature.
- The state of charge in FESS can be easily measured based on rotational motion of the rotor.

Nevertheless FESS technology is also associated with some drawbacks as follows [46][50]:

- FESS can have high standby losses, which is dependent on both intrinsic and parasitic components.
- Rotor failure may cause instantaneous harm to people and property. Hence, fast rotating flywheel rotors must be designed to meet strict safety standards. In addition, a safety enclosure is required to contain the flywheel.
- A flywheel rotor may be subject to fatigue that may arise from cyclic stresses arising from charge and discharge cycles.

2.2.1 Components of Flywheel Energy Storage Systems

As depicted in Figure 4, a FESS typically consists of the following main components.

- Rotor (rotating mass)
- Electric machine (motor/generator)
- Vacuum housing (safety enclosure)
- Bearing system

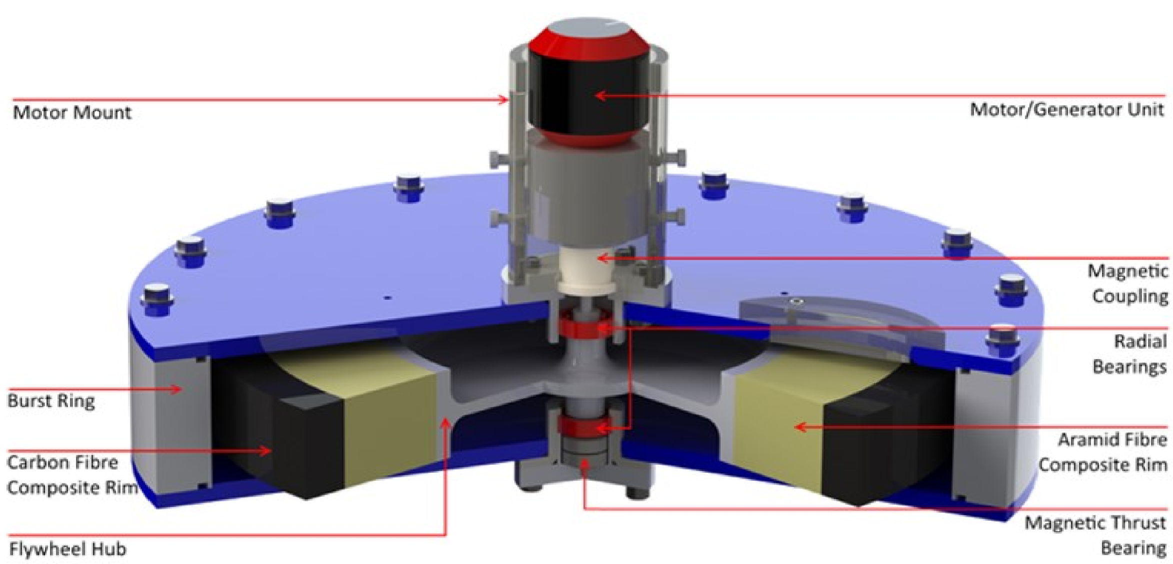


Figure 4. Example of Flywheel Energy Storage System.

2.2.2 FESS Working Principle

When a FESS is being charged, electric energy from a source such as the grid or renewable generation is converted via the electrical machine working as a motor into mechanical energy i.e., rotational motion of the rotor. The rotor thus stores energy in the form of rotational kinetic energy. The rotor may be contained in vacuum space to reduce air friction losses for a fast-spinning rotor. When electric energy is required from the FESS, mechanical energy is converted back to electrical energy by the electric machine working as a generator during discharging. The energy storage capacity of a rotor is determined by its mass and geometry. The energy stored in kinetic form, E_{kin}, is directly proportional to the moment of inertia, I, and square of the rotor angular velocity, ω, i.e.,

$$E_{kin}=\frac{1}{2}I\omega^2 \tag{1}$$

A FESS can be designed for high power or high energy applications depending on the requirements. Examples of high-power FESS includes a 20 MW plant at Hazle, Pennsylvania and Stephentown, New York, both USA [51][52]. On the other hand, FESS with high rotor specific energy are quite common, e.g., the FESS with 195 Wh/kg described in [53] which is comparable to a lithium-ion battery.

2.2.3 Comparison between Low-Speed and High-Speed Flywheels

FESS can be broadly categorized into two categories: low-speed and high-speed flywheels. Early flywheel rotors were made of steel, which results in lower rotational velocity and high system mass. With the advancement in composite materials, flywheel design shifted toward rotor made from circumferentially wound fiber-reinforced polymer composites, which resulted in higher angular speeds and considerably reduced weight compared to steel-based flywheels. Principal differences between low and high-speed FESS are summarized in Table 3.

Table 3. Low-speed FESS vs High-speed FESS [47]

Characteristics	Low-speed FESS	High speed FESS
Rotor Material	Steel	Fiber composite
Electric Machine	Asynchronous, permanent magnet synchronous, reluctance machines	Permanent magnet synchronous, reluctance machines
Vacuum Housing	Partial vacuum	High Vacuum
Housing Weight	Ranging in about double the rotor weight	Ranging in about half the rotor weight
Bearings	Usually mechanical or mechanical/magnetic	Usually magnetic
Relative Cost	1	5

2.2.4 Example Applications of Flywheel Energy Storage Systems

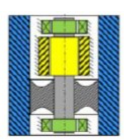
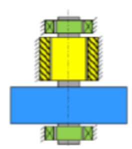
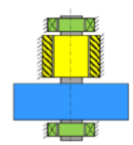
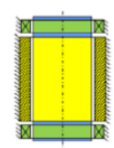
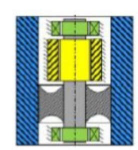
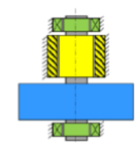
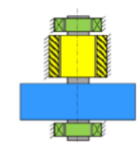
FESS technology is used in a wide range of applications involving electric vehicle, railway, marine, space, wind power, power quality and hybrid power generation systems [54]. Flywheels are commonly used in UPS applications. In a standalone grid on a Portuguese island, a flywheel with 350 kW power and 5 kWh capacity is successfully being used since 2005 [55]. The Coral Bay Project, completed in northeast Australia in 2007, uses a 500 kW and 5 kWh FESS, that absorbs power surges from wind turbines and provides energy for short amounts of time during power interruptions [56]. Aforementioned FESS plants in Hazle, Pennsylvania, and Stephentown, New York each with 20 MW and completed in 2014 and 2011, respectively, are being used for frequency regulation. The first flywheel-based grid connected energy storage facility in Canada (Minto, Ontario) with 2 MW power and 500 kWh capacity was commissioned by NRstor Inc. (Toronto, Ontario) in 2014. This facility serves to increase grid reliability [57]. Temporal Power (Mississauga, Ontario) built a 5 MW facility in Clear Creek in Ontario in 2016 which was acquired by NRstor Inc. in 2019 [58]. Simulations based on actual system measurements revealed that the use of the FESS increased renewable penetration and decreased generator fuel consumption, while also increasing system stability [55].

To date, flywheels also have some limited applications in transportation. Although most of hybrid vehicles use electrochemical batteries, i.e., nickel metal hydride batteries for mid-range applications and lithium-ion batteries for high end applications [59], sports cars like Porsche 911 GT3R and Audi R18 e-tron Quattro use FESS to absorb energy during braking and release it while accelerating [60][61].

Different FESS commercially available in Canada, the USA, Germany, and the UK are summarized in Table 4, where rated power, energy capacity, rotor angular speed (in revolutions per minute, RPM), rotor material, electrical machine type, system design, field of application are detailed along with the manufacturer.

.

Table 4. Comparison between commercially available FESS adopted from [10], [62] and websites of manufacturers

Manufacturer	**Beacon Power**	**Temporal Power**	**Stornetic**	**Rosetta T2**	**Active Power**	**PowerThru**	**Gyrotricity**	**Piller Power Bridge**
Rated Power (kW)	160	100-500	22/80	500	250	190	100	1600
Rated Energy Capacity (kWh)	30	50	3.6	4	0.9	0.63	5	4
RPM	16,000	11,500	45,000	Not available	7,700	52,000	20,000	3,300
Rotor Material	Fibre reinforced composite	Steel	Fiber reinforced composite	Fiber reinforced composite	Steel	Fiber reinforced composite	Laminated steel	Steel
Electrical Machine	Permanent magnet	Permanent magnet	Permanent magnet	Not available	Not available	Synchronous reluctance	Permanent magnet	Not available
Country of Manufacture	USA	Canada	Germany	Germany	USA	USA	UK	Germany
Application	UPS, frequency stability	Voltage stability	Railway, grid services	Recuperation	UPS	UPS	Railway, frequency stability	UPS
Topology								

2.2.5 Comparison between FESS and BESS

While both FESS and BESS are viable energy storage technologies, there are distinct aspects favoring one technology over the other. Central differences between both technologies are listed in Table 5. Given that each system has certain attributes that are superior, FESS and BESS are well suited, or unsuited, for specific standalone application requirements, while a FESS/BESS hybrid may allow for an overall improved performance if each system can contribute its strengths.

Table 5. Comparison between FESS and BESS.

Flywheel Energy Storage System	**Battery Energy Storage System**
High-power charging capabilities	High-energy storage capabilities
Quasi-infinite charge and discharge cycles	Limited charge and discharge cycles
No depth-of-discharge limitations	Depth-of-discharge limitations
Little to no maintenance required	Maintenance required

3 Study of FESS for Standalone Operations in Bus Fleet Charging

The number of electric vehicles (EVs) on the roads continue to rise every year. In 2018, there were more than 5.1 million EVs on the road, which are 2 million more than in 2017 [63] . The People's Republic of China remained the world's largest EV market followed by Europe and the United States [63]. Norway was the global leader with EV market share of 46% [63]. This can be considered a substantial step towards sustainable transportation.

Diesel vehicles, using diesel as a source of energy, have been in use for quite a long time now, especially for commercial vehicles and public transportation. Diesel vehicles can usually be in operation for extended periods throughout the day due to the high energy density of diesel fuel. As such, infrastructure requirements are limited, as opposed to e.g. trolley buses which use overhead catenary system [64]. Conversely, EVs can be in operation depending on the state of charge (SOC) of the onboard battery and may need to be recharged a number of times during the day.

Alberta greenhouse gas (GHG) emissions are the second highest per capita in Canada. As shown in Figure 3, 26% GHG emissions came from transportation which includes commercial service vehicles as well as transit fleets in 2018.

The City of Edmonton has taken an initiative to convert all its diesel buses to battery electric buses (BEBs) to reduce the environment impact of public transit [65]. There are over 1,000 diesel buses running on different routes in the city. The plan is to replace all these buses to BEBs over a period of 11 years. BEBs use electric energy to run the buses, and hence, the batteries of buses need to be charged when the buses come back to the depot. The city ordered an initial batch of 40 buses from Proterra, a US based manufacturer (Burlingame, California). Each BEB, type Catalyst E2 max, has a battery capacity of 660 kWh [66]. With an increasing number of buses, the load on the power grid increases, which becomes problematic for the grid to support charging of buses when multiple buses are in the depot charging stations. The distribution and transmission system to the depot needs to be upgraded in order to meet the power charging requirements of BEBs. Such upgrade does not only costs millions of dollars but also requires 3 to 5 years to obtain approval from the Alberta Electric System Operator (AESO). Hence, a need arises for a backup energy storage system that can facilitate quicker project implementation, performs peak load shaving, and reduces electricity costs. The backup energy storage system is charged from the grid when a majority of buses is on the road and fewer buses are in the depot for charging. The energy storage system provides power to the charging infrastructure when the load drawn from the power grid exceeds a certain threshold, which was specified by the City of Edmonton to be 1,000 kW taking in account the current distribution and transmission system. Electro-chemical and electro-mechanical energy storage options were considered in this research because these systems are seen to be the only cost-effective and mature technologies that are able to fulfill the specific demands for EV fleet charging [67].

As a risk mitigation measure, the research project involved exploring the possibility of integrating a FESS as an alternative to a BESS. One of the primary constraints of the project was to ensure that the load on the power grid does not exceed the given threshold, with a considered total number of buses of 40. To pursue a realistic approach, only commercially available FESS were considered. Refer to Table 4 for the names of FESS manufacturers and corresponding commercially available FESS power and energy ratings. The following three manufacturers in North America and Germany were contacted via email and telephone to seek techno-commercial proposals, detailed technical aspects, and life-cycle cost of different flywheel options.

Temporal Power: This Canadian based company (Mississauga, Ontario) offered FESS with steel-based rotors. FESS have a high power-to-energy ratio of 2:1. Unfortunately, upon contacting them, it came to light that the company seized operation.

Stornetic: This German based manufacturer (Jülich) was contacted a couple of times, but no response was received.

Beacon Power: This US company (Wilmington, Massachusetts) provided the required techno-commercial information, and hence, corresponding FESS specification were employed in subsequent analyses and simulations.

Beacon Power FESS, which are in commercial operation for more than 10 years now at the time of this research, have the following characteristics [68].

- The dimensions of a single FESS unit are about 2.2 m tall with a diameter of 0.92 m. Considering ancillary components, each unit requires 23.2 m^2 for installation.
- The rotor, with a mass exceeding 1,000 kg, is designed to rotate at 16,000 rpm.
- A 160 kW FESS has a power-to-energy ratio of 5:1.

- The life-time energy throughput is given at around 5,000 MWh.
- Charging and discharging is possible at full rated power without any restrictions.
- The projected number of charge and discharge cycles is between 100,000 and 175,000, even with high depth of discharge swings.

Figure 5 depicts the example of an installation for multiple Beacon Power FESS modules forming a FESS cluster. Each FESS module features a cooling system, dust control system, power control module (PCM), and FESS foundation. All FESS modules are operated through a switchgear and a cluster controller.

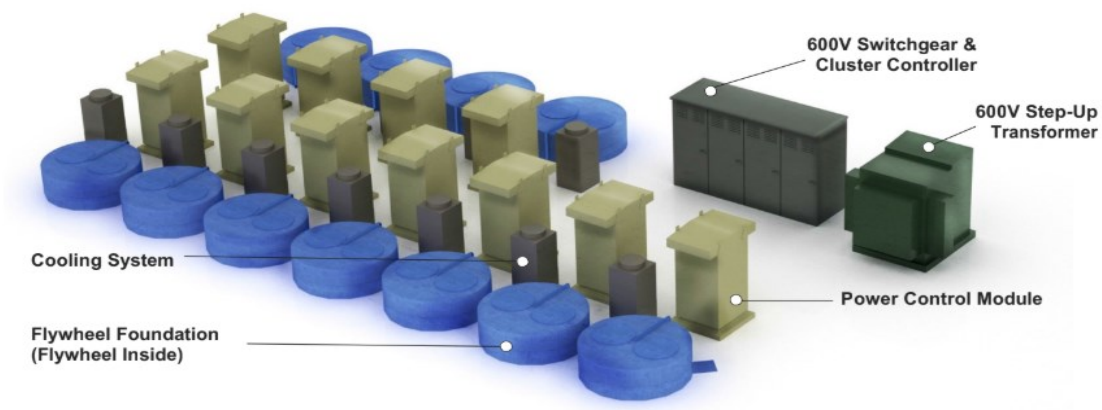


Figure 5. Flywheel Energy Storage System modules [68].

3.1 Alternating Current versus Direct Current Microgrid

The City of Edmonton is using direct current (DC) fast chargers (161.5 kW) for BEB charging. The BEB procurement project consists of two phases. In phase 1 of the project an alternating current (AC) microgrid is used because AC microgrid infrastructure is mature technology that is available from electric equipment providers such as ABB and Siemens for electric vehicle charging purposes. Figure 6 depicts a schematic of the AC microgrid. This microgrid infrastructure entails the FESS to undergo two stages of conversion from AC to DC (using the active front-end and FESS controller) and then back to AC, resulting in considerable energy losses. Also, the deployment of an AC microgrid means that an additional AC to DC converter is required at each bus charging station.

In the second phase of the project a DC microgrid will be used as shown in Figure 7. A DC microgrid is attractive because the extra conversion step at the FESS is avoided, thus minimizing energy losses. Moreover, the DC infrastructure eliminates the AC to DC conversion at each bus charging station. Consequently, one major AC to DC converter is required for the whole microgrid.

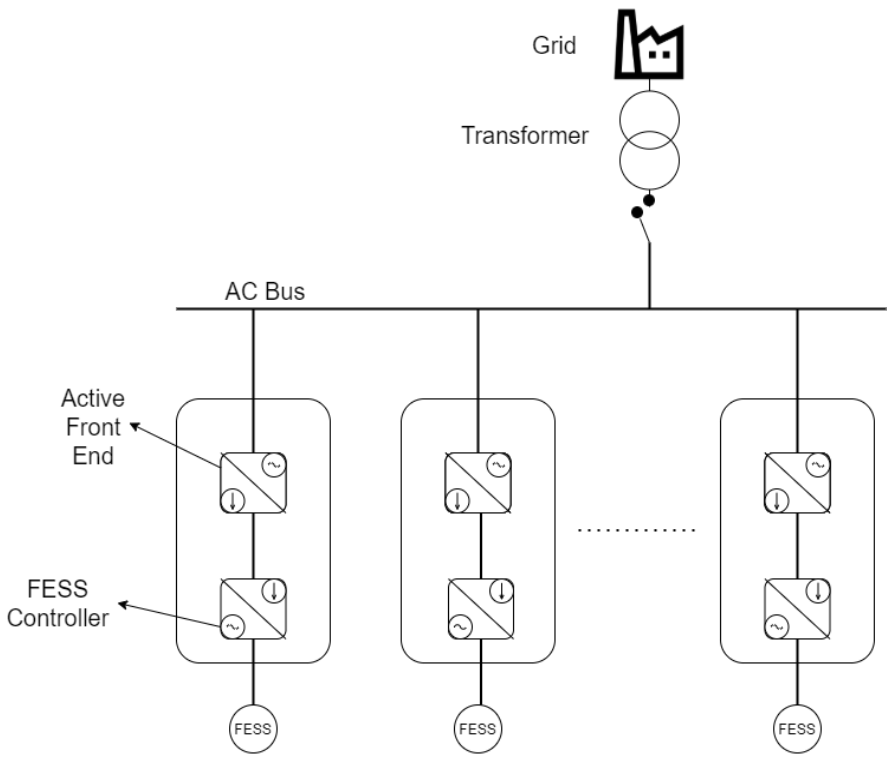


Figure 6. AC microgrid with FESS based on [68].

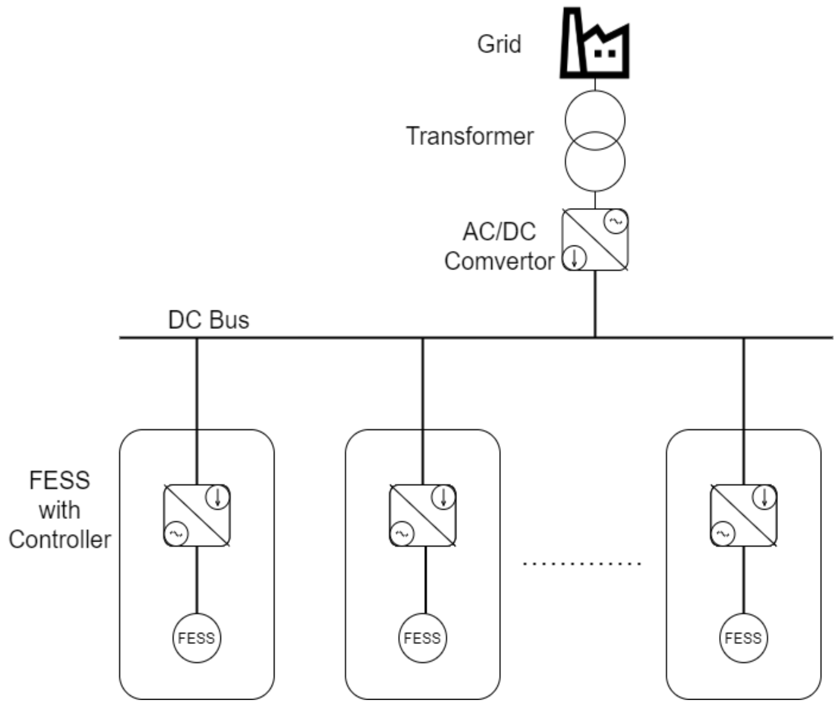


Figure 7. DC microgrid with FESS based on [68].

3.2 Simulation Parameters

Since no functional operational model was available that harmonizes with the charging of BEBs, the City of Edmonton created a new model for BEB in-depot charging. The new operational model was designed to follow planned book-out times of buses without having to change the existing bus transit schedule. SimCad Pro (CreateASoft, Aurora, Illionis, USA) was used to generate the model for the smooth integration of BEBs into the current transit system. SimCad is a discrete process simulator that uses SQLite and conditional coding as programming mediums. It is used to plan, analyze, and optimize the real-life systems including but not limited to logistics, manufacturing, automation, and healthcare. It also provides an interactive two- and three-dimensional modeling environment that allows for constraint changes during the simulation run. In a SimCad model, objects pass through different processes along connectors. Processes are the steps needed to complete a task and result in the modification of object. A connector on the other hand is defined as the path that the object takes while flowing through these processes. For example, in the current study, a BEB bus is the object that passes through different processes and connectors which decide when, where and how each BEB moves in the simulation.

3.2.1 Inputs and Outputs

The main simulation inputs were the layout of City of Edmonton's Kathleen Andrews Transit garage (total number of tracks, BEBs designated tracks and the number of charging stations), BEB characteristics (total battery capacity and useable capacity), characteristics of electrical service (available power supply), characteristics of charging stations (charging rate of each station and efficiency) and information on bus scheduling (i.e., book-in time when a bus comes into the garage, book-out time when a bus leaves the garage, and the total distance travelled by a bus on that specific run).

The main simulation outputs include the facility power consumption, total battery energy (40 buses), ESS power consumption and energy consumed and delivered by the ESS. Figure 8 shows the number of BEBs in the garage based on bus scheduling data from March 2019.

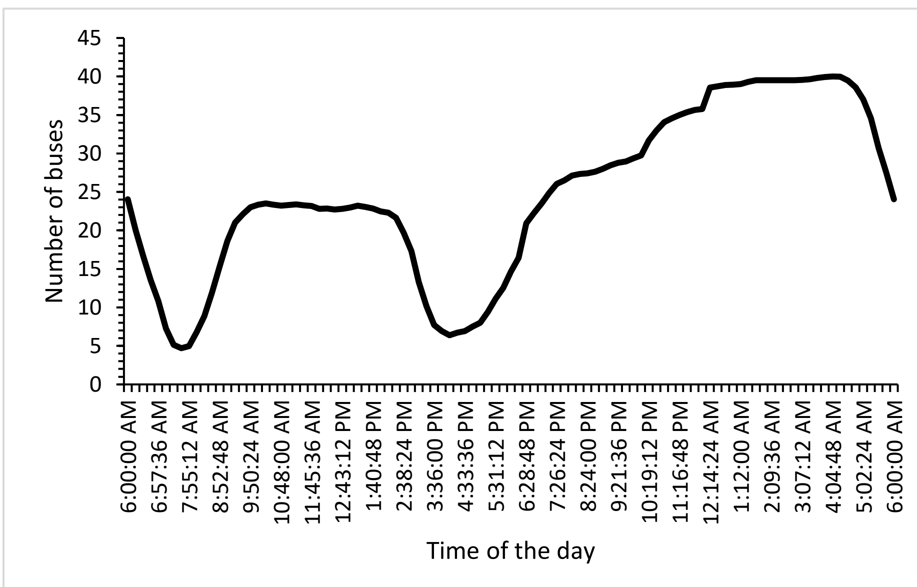


Figure 8. Anticipated number of e-buses in garage during 24 hours.

The city of Edmonton database provides the data for each bus coming in and going out of the garage. Buses are identified using a run ID, representing a specific route. For the initial 40 buses, the City of Edmonton intends to cover routes that are less than 300 km to ensure each BEB is operated without any sort of interruption. This distance limit was selected on the basis of the range covered by each bus with a single charge, which is 320 km at the beginning of the battery life and 250 km at the end of life. These values are based on a low bus energy consumption per mileage. Hence, each run ID with less than 300 km was filtered, and using the bus book-out and book-in times, the total number of buses in the garage for specific time of the day was analyzed. By doing so, an estimate of the number of buses in the garage was obtained as shown in Figure 8. It can be seen from the chart that the number of buses anticipated in the garage are in the range of 5 to 10 between 7 am and 4 pm, when a plateau can be observed in the curve. The highest number of buses in the garage are between 12 am to 4 am. It should be noted that the presence of buses in the garage does not necessarily mean they are being charged during that time. The decision for the time of bus charging depends on a number of factors that are inputs for the simulation, such as the BEB battery current energy content, planned book-out time, and charger availability.

The objective of the simulation was to generate output data that can be analyzed to evaluate whether or not candidate energy storage devices with their capacities are suited for required system and are available when needed. eCAMION Inc, a Canadian energy storage system provider (Toronto, Ontario), is supplying a 1.5 MWh BESS to the City of Edmonton. Alternatively, a single Beacon Power FESS has a capacity to provide 160 kW power and a maximum usable energy of 30 kWh. In order to match the BESS 1.5 MWh energy storage capacity, 50 FESS units would be needed. With a single FESS costing approximately $330,000, total capital expenditures amount to twice that of the same capacity of CAMION BESS. However, for the purpose of the simulation, a lesser number of FESS units was considered, justified by the FESS fast-charging capability. Using the various input data, the techno-economic feasibility of both the storage technologies was investigated and a life-cycle cost assessment was performed.

3.3 Flywheel Energy Storage System Simulation Results

Following the details of the FESS used for simulation.

- Number of Beacon Power FESS used: 25 nos.
- Useable energy: 750 kWh (i.e., half the BESS capacity)
- Useable power: 4 MW
- Power delivered during discharging: 970 kW (compared to 646 kW in the case of BESS)

Figure 9 depicts the simulation results in terms of the power consumption by the depot facility, the ESS and the chargers, for a 2-minute time interval over a whole week. As mentioned above, the actual book-in and book-out data of diesel buses for the month of March 2019 was used for the simulation. The orange, blue and grey curves in Figure 9 describe the power requirements from the chargers, the grid and the ESS throughout the week, respectively. It can be observed that, for example, at 6:38 pm on day 1 the total power for BEB charging exceeds the 1,000 kW threshold because seven buses are being charged simultaneously using seven chargers, each with a power rating of 161.5 kW. The FESS energy content is 750 kWh during this time; hence the algorithm decides to use the ESS during this time to provide the required extra energy and power. The observations made from the simulation results related to the FESS can be summarized as follows.

- The load on the grid always remains below the 1,000 kW threshold.
- There is an average of 1.5 charge and discharge cycles per day.
- It should also be noted that with the current infrastructure, no more than 14 buses can be charged concurrently (since there are currently 14 charger installation planned).
- The time gap between charging and discharging is more than 10 hours. This operation pattern needs to be improved in the future work to decrease FESS standby losses. The simulation indicated that margin exists to charge the FESS 2 hours before discharging, hence lowering energy losses over time, which are quantified by the manufacturer as 3 kW/hr.
- Analysis of simulation results shows that the maximum power delivered by the chargers over the whole week is 1,938 kW, which indicates that a total of 12 chargers are being used and hence the maximum number of buses are charged simultaneously is 12. By increasing the power available from FESS above 1 MW in future simulations, it is projected that simultaneous charging of 14 buses simultaneously would be feasible. This also indicates that the time for BEB charging will decrease.

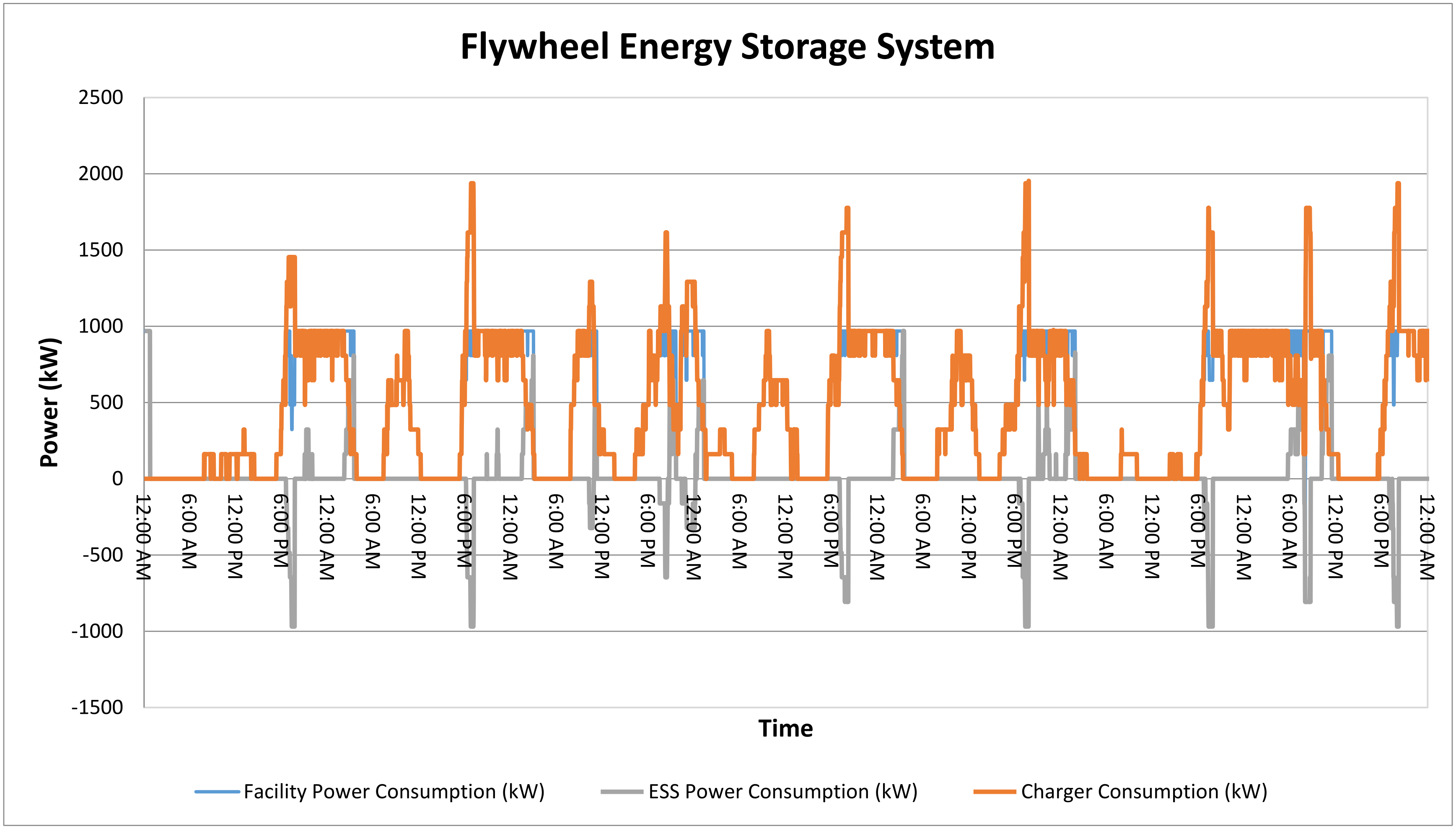


Figure 9. FESS power performance (simulation results).

3.4 Battery Energy Storage System Simulation Results

As mentioned earlier, the City of Edmonton is procuring the BESS from eCAMION. eCAMION is a Canadian Manufacturer based in Toronto and provides turn-key solutions in the energy storage industry with special focus on the integration of battery solutions. Following are the details of the BESS used in the simulation:

- Number of eCAMION battery banks used: unknown
- Useable energy: 1,500 kWh (double as compared to Beacon Power FESS)
- Useable power: 1.5 MW
- Power delivered by ESS during discharging: 646 kW (970 kW in case of Beacon Power FESS)

The following observations were made related to the BESS based on the simulation results and the data presented in Figure 10.

- Like for the FESS, the load on the grid never exceeds 1,000 kW at any point of time.
- It can be observed in Figure 10 that peaks in the (orange) curve depicting the charger consumption are wider than for the FESS case in Figure 9, indicating that more time is required for BEB charging. Similarly, broader peaks in the (grey) ESS power consumption curve indicates longer BESS recharging times.
- The simulation shows that the maximum power consumption by the chargers throughout the week is 1,615 kW, which indicates that a maximum of 10 chargers are used simultaneously, corresponding to equal number of concurrent BEB charging events.
- Note that the BESS can deliver power in excess of 646 kW, i.e., up to 1.5 MW, which can result in faster charging of BEBs. Based on the peak power values, the FESS is still expected to outperform BESS as it can deliver peak power up to 4 MW, which is 167% more than the latter. Although the power delivery capability of both ESS is under-utilized but the simulation results show that the candidate ESS, with stated discharge power values, can fulfil the charging requirements of the bus fleet.
- As with the FESS, there is an average of 1.5 charge and discharge cycles per day.

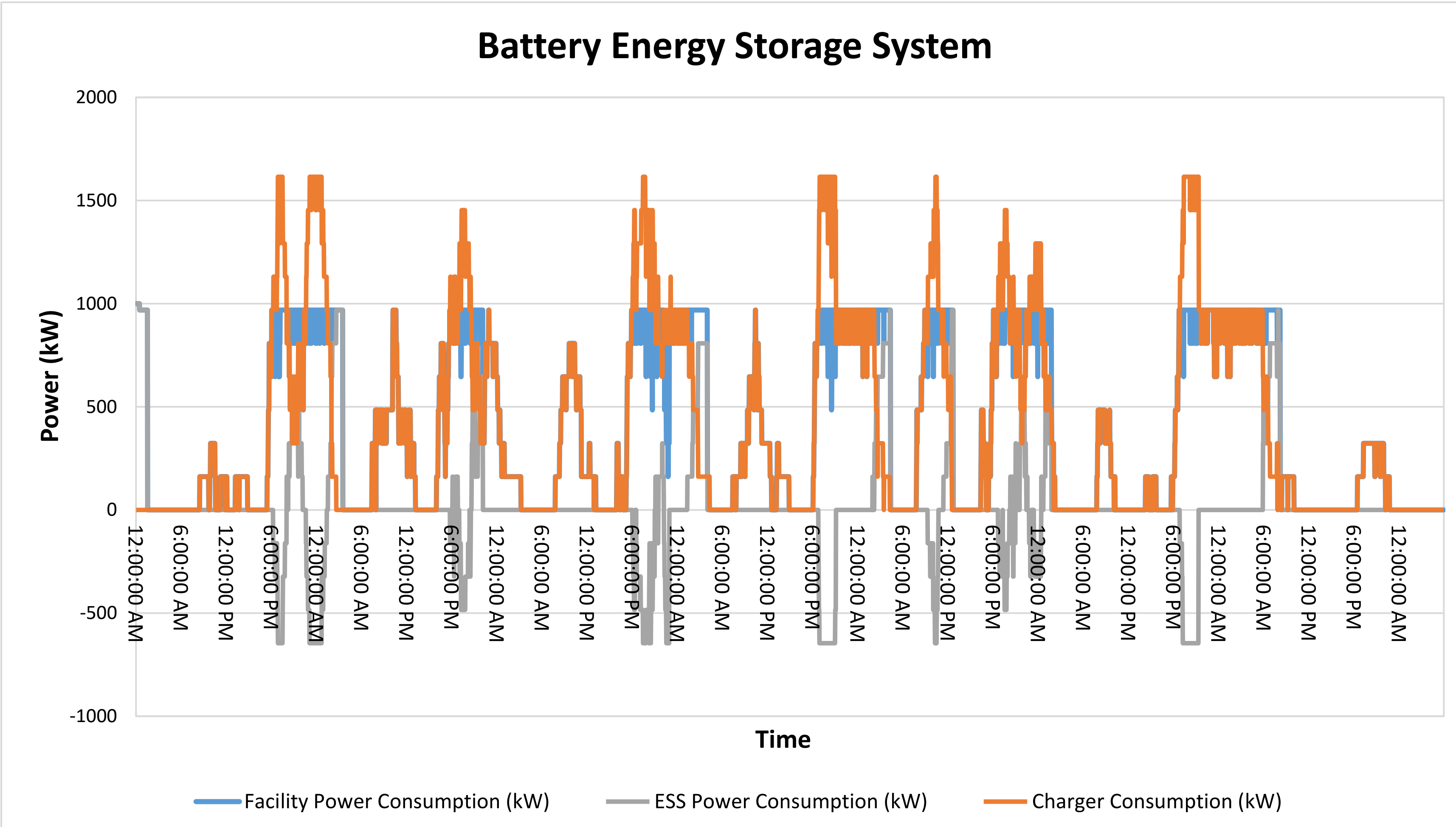


Figure 10. BESS power performance (simulation results)

3.5 Cost Benefit Analysis of BESS and FESS

In the following cost benefit analyses, comparisons between diesel buses and BEBs with BESS and FESS charging infrastructure were undertaken, considering the three scenarios presented below. The analyses were performed to assess the cost-effectiveness of the technologies.

- Scenario 1: Cost benefit analysis based on maximum theoretical available energy.
- Scenario 2: Cost benefit analysis based on energy consumed by ESS.
- Scenario 3: Cost benefit analysis based on average power consumption by chargers.

The cost information for the following analyses were based on the project proposal received from eCAMION and the techno-commercial proposal from Beacon Power. Before presenting the analyses, some terms shall be defined for clarity.

CAPEX: This term refers to capital expenditures, which is the capital cost of procuring the required product. In this case, CAPEX relates to the procurement of the BESS and FESS.

Maintenance cost: This cost item entails the activities required to maintain an asset and keep it in good working condition so that it is available to perform its desired functions.

Demand charge: Demand charges cover the cost allocated to the facilities supplying power to a customer [69]. Demand charges can be considered a premium that an organization pays to receive a continuous supply of power at maximum demand. They can be a part of energy charges, for instance in residential bills, but for industry, they can be charged separately [69].

Demand ratchet: Demand ratchet refers to the highest power demand that the customer used over a specific period. A customer may be charged with same demand for the rest of the year, or the demand in each corresponding month whichever is greater [69]. For example, if a customer uses 2,000 kW at any point of time in a specific month where the demand ratchet is at 1,000 kW, the customer will be charged with an additional demand charge for 1,000 kW for the remaining 11 months of the year even if the demand decreases to less than 1,000 kW in these months. Demand ratchet and demand charges are critical aspects to consider, as peak power consumption can increase energy costs considerably.

Discounted cash flow (DCF): Several methods are available to assess which alternative concept is cost attractive in terms of investment. The DCF method discounts the current and future cash inflows and outflows to the present day to check which alternative is the best [70]. This method accounts for the fact that money invested in the coming years is worth less than the money being invested during the current year [70]. Net Present Cost/Net Present Value and Internal Rate of Return are two methods of performing a DCF analysis.

Both methods are used to decide which alternative should be pursued.

Net Present Value (NPV): NPV is calculated by finding the present worth of the net cash flow (inflows minus outflows) of each year and then adding the present values for all years [71]. It is calculated by using Equation (2) [72].

$$NPV = C_0 + \sum_{y=0}^{n} \frac{C_{\text{in-out}}}{(1+i)^y} \tag{2}$$

where

C_0 is the initial investment at the start of project,

$C_{\text{in-out}}$ is the net cash flow of every year,

n is the total number of years decided for analysis, and

i is the discount rate defined as a percentage.

NPV can also be given by Equation (3).

$$NPV = \sum_{y=0}^{n} [(PV\ of\ cash\ inflow) - (PV\ of\ cash\ outflow)] \tag{3}$$

In order to know whether an alternative is economically feasible, the following conditions must be satisfied [73]:

- NPV shall not be negative.
- Even if negative, NPV of one alternative shall at least be higher than the NPV of the other alternatives it is being compared to.

NPV is found by following the below mentioned procedure:

- First, define the life cycle years of the project.

- Specify the discount rate of the project.
- Define the initial investment for each alternative, as well as replacement and maintenance cost over the years. Also clearly calculate in terms of cash inflow, the benefits that may be received directly or indirectly as a result of all the investments made. If a component needs to be replaced during the lifecycle, also determine its salvage value at the end of its life.
- Calculate the NPV using Equation (2) or (3) and make a decision using the decision criteria mentioned above.

Internal Rate of Return (IRR): IRR is defined as the value of the discount rate at which the present value of costs becomes equal to the present value of benefits [69]. It is the value of discount rate where the NPV equals zero. IRR is frequently also used to decide which alternative is best. It is sometimes preferred over NPV by organization as IRR can be compared easily to an organization's defined Minimum Attractive Rate of Return (MARR) [69].

Using the above-mentioned concepts, NPV and IRR of the BESS and FESS were calculated and compared under the three different scenarios employing theoretical and simulation-based results. Critical input values for the analyses are:
Life cycle of project: 20 years
CAPEX was obtained from the proposals provided by the ESS manufacturers.

- , i.e., CAPEX BESS = \$8,250,000 and CAPEX FESS = \$8,881,224

Other input values were selected as follows.

- Demand Charge = $\frac{\$0.0742}{\mathrm{kW}/\mathrm{day}}$
- Demand charge saving = $\frac{\$0.0742}{\mathrm{kW}/\mathrm{day}} \times 1{,}000\ \mathrm{kW} \times 365 \frac{\mathrm{day}}{\mathrm{year}} = \frac{\$27{,}093}{\mathrm{year}}$
- Price of diesel = $\frac{\$1.29}{\mathrm{L}}$
- Price of electricity = $\frac{\$0.068}{\mathrm{kWh}}$
- Diesel bus mileage = $0.2 \frac{\mathrm{L}}{\mathrm{km}}$

- Electric bus mileage = $0.77\frac{\text{km}}{\text{kWh}}$
- Station electrical efficiency = 95%
- MARR = 10%

3.5.1 Cost Effectiveness Based on Maximum Theoretical Energy

This initial theoretical scenario considers that the load on the grid is 1,000 kW at any point in time during a year, which allows establishing baseline costs of running buses on diesel versus electric power. The data presented in Table 6 was used to compute NPV and IRR.

Table 6. Input parameters for scenario 1.

Description	BESS	FESS	Unit
CAPEX	$8,881,224	$8,250,000	CAD
Salvage value	$50,000	$50,000	CAD
Useful life	6	20	year
MARR	10%	10%	10%
Electric service size	1,000	1,000	kW

Annual cost for energy are:

- Cost of electricity = $1{,}000\ \text{kW}\times\frac{\$0.068}{\text{kWh}}\times 0.95\times 24\frac{\text{hr}}{\text{day}}\times 365\frac{\text{day}}{\text{year}} = \frac{\$565{,}896}{\text{year}}$
- Cost of diesel = $1{,}000\ \text{kW}\times 0.77\frac{\text{km}}{\text{kWh}}\times 0.95\times 0.2\frac{\text{L}}{\text{km}}\times\frac{\$1.29}{\text{L}}\times 24\frac{\text{hr}}{\text{day}}\times 365\frac{\text{day}}{\text{year}} = \frac{\$1{,}653{,}249}{\text{year}}$

Hence, annual energy cost savings compared to diesel are $1,087,353.

Results for NPV and IRR are presented in Table 7. Microsoft Excel was used to calculate these results and detailed information can be found in Appendix A. Both parameters rule in favor of FESS as the preferable cost-effective technology. NPV is positive for FESS and negative for BESS. Also, the IRR > MARR > 10% for FESS while it is less than 10% for BESS, which clearly indicates that FESS is an attractive alternative.

Table 7. Cost benefit analysis results based on max. theoretical energy available.

Description	FESS	BESS
NPV	$1,160,204	$(1,070,441)
IRR	12%	8%

3.5.2 Cost Effectiveness Based on Energy Consumed by ESS

The second scenario considers the simulation results and considers the energy provided by the facility to charge the corresponding ESS. The simulation results were produced for a whole week including weekends based on actual book-in and book-out data for diesel buses. This scenario is based on energy consumed by the respective ESS for the duration of a week when the simulation is being emulated and is used as a basis for the cost benefit analysis. The data presented in Table 8 was used to find NPV and IRR.

Table 8. Input parameters for scenario 2.

Description	**BESS**	**FESS**	**Unit**
CAPEX	\$8,881,224	\$8,250,000	CAD
Salvage value	\$50,000	\$50,000	CAD
Useful life	6	20	year
MARR	10%	10%	10%
Energy transferred/week	10,002	5,825	kW

Energy cost savings were calculated by finding the difference between the cost of diesel and the cost of electricity based on the energy transferred by the FESS per week. i.e.,

- $\frac{\text{Energy transferred}}{\text{week}} = 5{,}824 \text{ kWh}$
- Cost of electricity $= 5{,}824 \frac{\text{kWh}}{\text{week}} \times \frac{\$0.068}{\text{kWh}} \times 52 \frac{\text{week}}{\text{year}} = \frac{\$20{,}594}{\text{year}}$
- Cost of diesel $= 5{,}824 \frac{\text{kWh}}{\text{week}} \times 0.77 \frac{\text{km}}{\text{kWh}} \times 0.2 \frac{\text{L}}{\text{km}} \times \frac{\$1.29}{\text{L}} \times 52 \frac{\text{week}}{\text{year}} = \frac{\$60{,}164}{\text{year}}$

The energy savings of BEBs with FESS supported charging compared to diesel buses are therefore \$39,520 per year. Similarly, for BESS charging infrastructure, i.e.,

- $\frac{\text{Energy transferred}}{\text{week}} = 10{,}022 \text{ kWh}$
- Cost of electricity $= 10{,}022 \frac{\text{kWh}}{\text{week}} \times \frac{\$0.068}{\text{kWh}} \times 52 \frac{\text{week}}{\text{year}} = \frac{\$35{,}438}{\text{year}}$
- Cost of diesel $= 10{,}022 \frac{\text{kWh}}{\text{week}} \times 0.77 \frac{\text{km}}{\text{kWh}} \times 0.2 \frac{\text{L}}{\text{km}} \times \frac{\$1.29}{\text{L}} \times 52 \frac{\text{week}}{\text{year}} = \frac{\$103{,}530}{\text{year}}$

Annual energy cost savings for the BESS case compared to diesel powered buses are \$68,000.

The results of DCF methods are shown in Table 9. Please note that in this scenario the analysis yielded negative NPV for both technologies, which may indicate that both are not worth the investment. Still, taking into account the second condition for NPV explained above, one would select the higher NPV value, indicating that the FESS solution is more attractive in comparison to BESS. Also note that a solution in term of IRR is not defined in this case because IRR does not converge to any specific value when NPV is set to zero.

Table 9. Cost benefit analysis results based on energy available from ESS.

Description	FESS	BESS
NPV	$(7,760,589)	$(9,748,768)
IRR	No solution	No solution

3.5.3 Cost Effectiveness based on Average Power Consumption by Chargers

This final scenario is based on the average power consumed for BEB charging during a week. Power from charging may come from all sources, including the grid power and the ESS. Table 10 summarizes the parameters used for the cost benefit analysis for this scenario.

Table 10. Input parameters for scenario 3

Description	BESS	FESS	Unit
CAPEX	$8,881,224	$8,250,000	CAD
Salvage value	$50,000	$50,000	CAD
Useful life	6	20	year
MARR	10%	10%	10%
Average power consumption/week	408.5	465	kW

Following similar steps as for analysis in Scenario 2, the energy cost savings for FESS based BEB charging are evaluated first. The energy required in this case is:

- $\frac{\text{Average power consumption}}{\text{Week}} = 465\text{ kW}$
- $\frac{\text{Energy transferred}}{\text{day}} = 465\text{ kW} \times 24\text{ hr} = 11{,}160\text{ kWh}$

Energy costs corresponding to BEB and diesel bus operation are as follows:

- Cost of electricity $= 11{,}160\,\frac{\text{kWh}}{\text{day}} \times \frac{\$0.068}{\text{kWh}} \times 365\,\frac{\text{day}}{\text{year}} = \frac{\$276{,}991}{\text{year}}$

- Cost of diesel $= 11{,}160\,\frac{\text{kWh}}{\text{day}} \times 0.77\,\frac{\text{km}}{\text{kWh}} \times 0.2\,\frac{\text{L}}{\text{km}} \times \frac{\$1.29}{\text{L}} \times 365\,\frac{\text{day}}{\text{year}} = \frac{\$809{,}222}{\text{year}}$

The energy cost savings of BEB with FESS charging infrastructure over diesel bus operation are therefore $532,231. For BESS charging infrastructure, energy requirements are:

- $\frac{\text{Average power consumption}}{\text{week}} = 408.5\ \text{kW}$
- $\frac{\text{Energy transferred}}{\text{day}} = 408.5\ \text{kW} \times 24\ \text{hr} = 9{,}804\ \text{kWh}$

The annual costs of energy are therefore:

- Cost of electricity $= 9{,}804\,\frac{\text{kWh}}{\text{day}} \times \frac{\$0.068}{\text{kWh}} \times 365\,\frac{\text{day}}{\text{year}} = \frac{\$243{,}335}{\text{year}}$
- Cost of diesel $= 9{,}804\,\frac{\text{kWh}}{\text{day}} \times 0.77\,\frac{\text{km}}{\text{kWh}} \times 0.2\,\frac{\text{L}}{\text{km}} \times \frac{\$1.29}{\text{L}} \times 365\,\frac{\text{day}}{\text{year}} = \frac{\$710{,}897}{\text{year}}$

Energy savings of BEBs with BESS charging infrastructure thus amount to $467,562 per year.

Results in terms of NPV and IRR for Scenario 3 are summarized in Table 11. Similar to Scenario 2, NPV of both the technologies is negative. The higher NPV value of the FESS indicates that it is a better alternative as compared to BESS. Also, the IRR value of both the technologies is less than the MARR value, which implies that both the solutions are unworthy of investment. But, a positive IRR value of FESS still makes it an preferable solution over the BESS.

Table 11. Cost benefit analysis results based on average power consumption.

Description	FESS	BESS
NPV	$(3,565,863)	$(6,347,071)
IRR	3%	-4%

3.5.4 Summary of Cost Benefit Analysis for Different Scenarios

Table 12 presents all major input parameters related to the lifecycle costs for both ESS technologies. These values were used to perform DCF analysis as explained above. Electric service size was used for the theoretical comparison between FESS and BESS in Scenario 1. Maximum theoretical energy available from the grid was used to provide a comparison in Scenario 1. The values of energy consumed by the corresponding ESS, were used to develop a cost comparison in

Scenario 2. Average power consumption values were used to perform the cost benefit analysis in the final scenario.

Table 13 provides the NPV and IRR values for the investigated three scenarios. NPV of FESS was positive in Scenario 1 and IRR (12%) was greater than MARR (10%), which shows that a FESS is a better option compared to a BESS. In Scenario 2 and 3, both technologies had a negative NPV but since NPV of the FESS was higher in comparison to the BESS, the FESS is the preferable alternative. In summary, all three scenarios identified the FESS as the better option when compared to the BESS. This study indicates that the FESS is a feasible technology to provide backup power for charging of BEBs. The FESS are not only able to meet the load demand in this particular application but are also cost effective as compared to a BESS.

Table 12. Input parameters for cost benefit analysis.

Description	BESS	FESS	Unit
CAPEX	$8,881,224	$8,250,000	CAD
Salvage value	$50,000	$50,000	CAD
Useful life	6	20	year
MARR	10%	10%	-
Electric service size	1,000	1,000	kW
Energy transferred/week	10,002	5,825	kW
Average power consumption/week	408.5	465	kW

Table 13. Summary of DCF analysis.

ESS	Scenario 1 (NPV/IRR)	Scenario 2 (NPV/IRR)	Scenario 3 (NPV/IRR)
FESS	$1,160,204/12%	$(7,760,589)/No solution	$(3,565,863)/3%
BESS	$(1,070,441)/8%	$(9,748,768)/No solution	$(6,347,071)/-4%

4 Hybrid Energy Storage System for Islanded Microgrids

Many countries around the globe are moving from centralized grids to decentralized grids in an effort to rely more on renewable energy sources (RES) [74]. This move is the need of the hour as it helps in reducing greenhouse gas emissions and provides electricity to areas which are not connected to the grid [75]. Islanded microgrids are decentralized systems that use distributed energy resources and can function independently without any connection to a centralized grid [76]. The US department of Energy (DOE) defines the microgrid as:

"a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode [77]*."*

There are a number of motivations that favor the deployment of microgrids, which can broadly be categorized into three groups: (i) integration of green energy, (ii) cost benefits, and (iii) energy reliability [75]. Historically, microgrids were frequently used in conjunction with diesel based generators to provide power to remote rural areas because of lower capital cost [78]. More recently, it has been realized that by integrating RES with certain energy storage systems can help in reducing the cost and adverse environmental impact of fossil fuel usage [79]. It has been highlighted that small islands around the globe will save around $10 billion a year if they utilize RES for electricity generation [80]. The decentralized or standalone microgrid operating on RES needs an ESS to store energy, which can be made available when the RES are not able to support the load demand. The challenge in using an ESS is that a single type of ESS may not be ideal for the microgrid because, due to load and RES generation variation, an ESS is needed that is both power dense and energy dense. There are certain limitations to each type of ESS, and no ESS is capable of providing both functionalities [81]. It is therefore required to have a combination of ESS (i.e., a hybrid ESS) that complement each other to support a microgrid. Bocklisch [82] presented several advantages of using a hybrid ESS which are as follows:

- Using hybrid ESS technologies is more cost effective as compared to a single ESS. It results in lower investment costs since by decoupling power and energy capacity, a high capacity ESS only needs to cover the average power demand and not peak power events.

- A hybrid ESS may increase the total efficiency of the system because the high capacity ESS operation occurs at optimized operating points.

- Hybrid ESS technologies help in increasing the lifetime of each ESS because of reductions in high capacity ESS stress levels caused by peak power events.

In September 2018, the World Bank committed to one billion dollars for BESS implementation for developing countries to help them increase the utilization of RES with a prime focus on solar and wind energy [83]. The future of the microgrids looks promising. According to an international renewable energy agency report, the installed cost of BESS may decrease by 50% to 66%, and 35% for FESS system, by the year 2030 [84].

4.1 Previous Research on Hybrid Energy Storage Systems

A number of studies have been completed to study the effect of employing two or more ESS to maximize the benefits of each storage technology. Several studies related to the hybrid combination of BESS and ultracapacitor can be found in the technical literature. As seen in Table 2 (in Chapter 1), ultracapacitors possess high specific power density typically ranging from 500 W/kg to 5,000 W/kg while BESS like lithium-ion batteries offer high specific energy ranging from 75 Wh/kg to 200 Wh/kg. The application of hybrid ESS with a BESS and ultracapacitors can be found in electric vehicles as well as RES [85]. Cao and Emadi [86] used a combination of a BESS and ultracapacitor for electric vehicles and showed that a smooth load profile is created by ultracapacitor for the BESS. The power burden on the BESS is therefore decreased. Glavin and Hurley [87] presented a BESS and ultracapacitor configuration for standalone photovoltaic systems and observed that both the technologies complement each other. Also, the cost of a hybrid system was less in comparison to BESS alone. Wang et al. [88] proved that the power output for a 1 MW solar PV plant was smoothened by using a BESS and ultracapacitor configuration. Li et al. [89] used a real time simulator to study the effect of power smoothing in wind applications using a BESS and ultracapacitor configuration. There are some studies that present evidence that coupling of BESS with other ESS technologies can actually help in increasing the life of the former [90]. It was shown in [12] that a BESS and super conducting magnetic energy storage based hybrid system helps in increasing the lifetime of the BESS by reducing the number of charge and discharge cycles. One of the biggest disadvantages of a BESS is their depth of discharge limitations when used under the cyclic loading conditions. Typically, studies on extending the life of a BESS in energy storage applications is linked to limiting the BESS charge and discharge cycles [90]. Gee et al. [91] presented a study based on a wind energy conversion system and showed that using a BESS/ultracapacitor configuration, the life of the BESS can be increased. It was observed that the hybrid system performed better in smoothing the fluctuations as compared to an individual ESS.

4.1.1 FESS based Hybrid ESS

As previously mentioned, FESS have high specific power which can range from 400 W/kg to 1500 W/kg. Discharge times at rated power can range from 15 seconds to 15 minutes. With the introduction of high performance magnetic levitating bearings, discharge time can reach even tens of minutes [92]. Windhorn et al. [93] were one of the first to present a hybrid FESS and BESS configuration in 1992. They proposed a hybrid configuration for a UPS system to overcome the drawbacks in static and rotary UPS systems. The system employed a FESS consisting of a motor-generator unit driven by a BESS-operated inverter, to deal with fluctuations in power sources. The proposed system had the added advantage of better reliability, reduced impedance, and better isolation.

Beaman and Rao [94] described the advantage of using a FESS and BESS configuration in an aerospace application. They noted that using a hybrid system improves spacecraft performance, decreases its weight by reducing the size of the solar array, and extends the mission life. Briat et al. [95] simulated the integration of FESS into the drive train of a heavy-duty electric vehicle. This solution employs the FESS during acceleration and deceleration so that battery power is maintained within rated levels, which helps increasing vehicle performance. They validated the simulation results with an experimental setup. Lee et al. [96] proposed a hybrid configuration to stabilize the output of a wind farm in Cheju Island in Korea. The simulation results showed that using a FESS with a BESS was more effective than using just the BESS. It was also observed that increasing the FESS capacity above a certain threshold did not improve performance, therefore they suggested that further investigation needs to be done to determine the optimal capacity and combinations of energy storage technologies. Prodromidis and Coutelieris [97] simulated nine scenarios using RES, for a specific load profile in Naxos Island, Greece. Three scenarios used just the BESS, while the remaining six were a combination of a FESS and BESS. It was observed that using the FESS-based hybrid scenarios incurred higher capital cost, but NPV was equivalent to other scenarios. This indicated that the future commercialization of FESS is a feasible proposition. Ramli et al. [98] studied economic aspects of a solar PV, generator, FESS, and BESS based hybrid system. They considered the load profile of the city of Makkah in Saudi Arabia. They showed that a scenario using the hybrid system is more economical than a scenario that did not use a FESS. Barelli et al. [79] proposed a hybrid (FESS and BESS based) system for the Kitobo microgrid in Uganda. The FESS would help in diminishing power spikes and increased life of the BESS when coupled in hybridized environment. It was also concluded that the cost of energy for the hybrid system was low as compared to non-hybrid systems. Zhao et al. [15] designed a hybrid system using a FESS and a compressed air storage system to control the intermittent nature of wind power. Hou et al. [99] investigated the role of hybrid systems in isolating the load fluctuations of an electric ship propulsion system from a shipboard network. A FESS and BESS hybrid configuration was suggested and compared with a BESS and ultracapacitor configuration. The former configuration performed better than the latter one in terms of efficiency and compensating for power fluctuations. The FESS-based solution was also favorable by reducing battery peak current. Notable, a real world, €4 million hybrid ESS project under the European Union's Horizon Program 2020 involving FESS and BESS is underway in Europe, with the goal of grid stabilization [100]. The project named as "AdD Hystor" is being completed in two phases. The first phase, being implemented in Ireland, is completed by Schwungrad Energie in coordination with EirGrid. The second phase will consist of installing a system in the UK at a 2 MW BESS facility at the University of Sheffield [101]. Figure 11 depicts a schematic of the proposed hybrid ESS at the University of Sheffield.

The study performed herein focuses on a hybrid ESS, motivated by aforementioned advantages, utilizing BESS and FESS along with RES and a diesel generator to provide electricity to a large business or small community. It considers an islanded microgrid that is independent of a grid connection and operates as a standalone system relying mainly on renewable energy with diesel generator support as a risk mitigation back-up. Solar energy is the focus of this study since according to International Energy Agency (IEA), solar is now least expensive source of electricity worldwide [102]. As shown in Figure 12, electricity generation from solar energy from 2000 to 2019 was less than wind energy, yet the outlook until 2040 under the IEA Sustainable Development Scenario (SDS) and Stated Policies Scenario (STEPS) shows solar energy to become the leading source of electricity generation among the two sources.

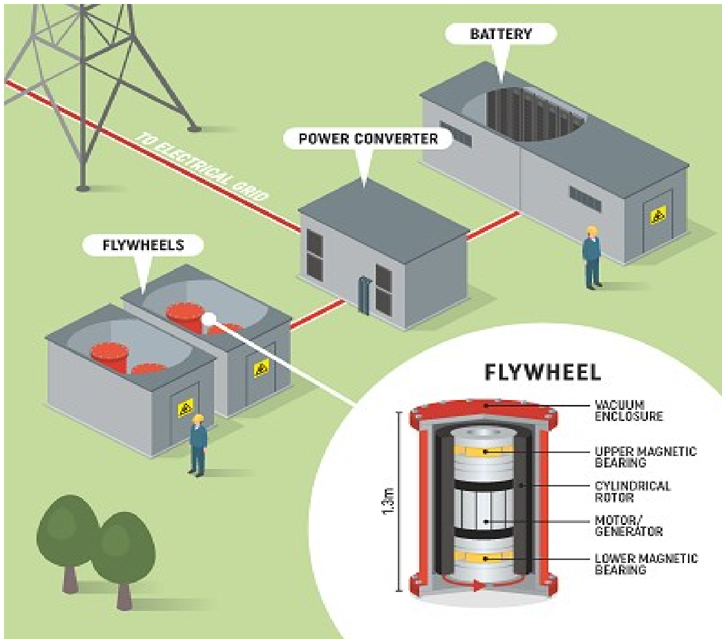


Figure 11. Hybrid energy storage system at University of Sheffield [103]**.**

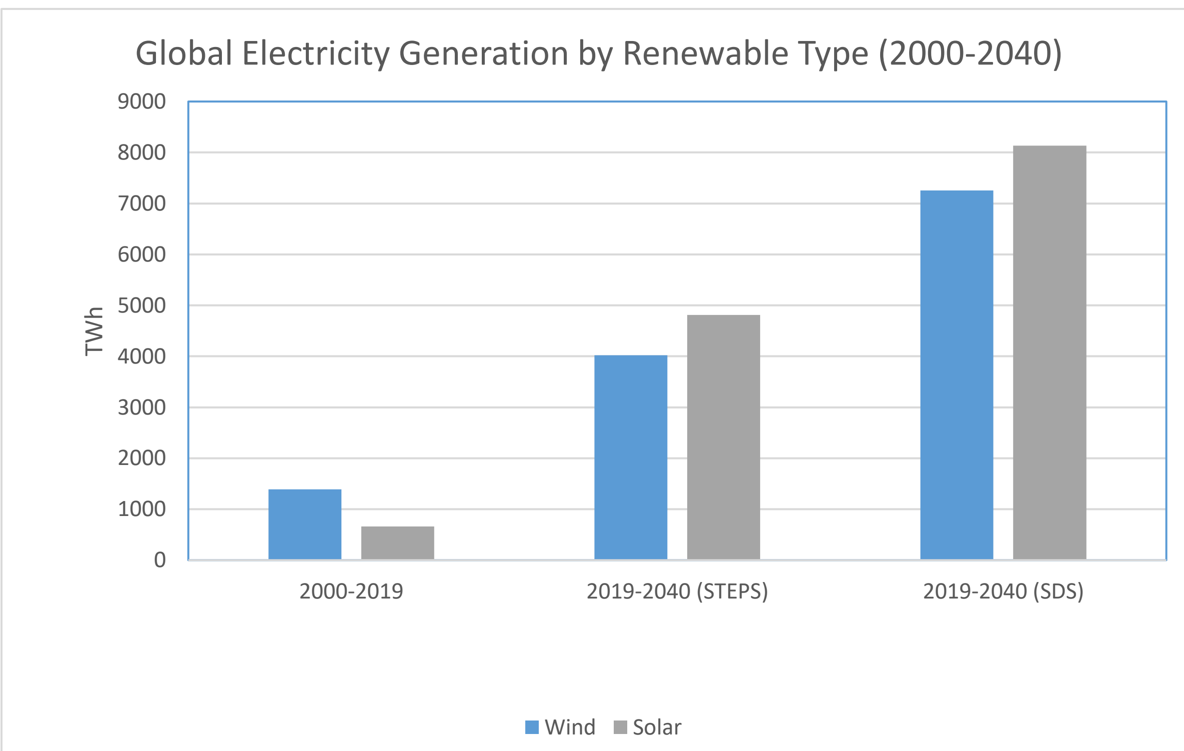


Figure 12. Solar and wind outlook in electricity generation 2000 to 2040 [104]**.**

Two case studies are presented herein utilizing two load profiles at two different locations in North America. For these case studies, simulations were performed using the software 'Hybrid Optimization of Multiple Energy Resources' – HOMER (National Renewable Energy Laboratory, Golden, Colorado, USA). HOMER has two main configurations, namely HOMER Grid and HOMER Pro. The former mainly focuses on grid connected systems and the latter addresses islanded grids [105]. The software performs simulations, optimization, and sensitivity analysis, and simulates several system configurations to find a solution that techno-economically viable, i.e., it provides the best solution that is cost effective and fulfills the load demand [106]. The cost-effective solution is based on total net present cost (TNPC) and levelized cost of energy (LCOE). The optimization problem for the two case studies is defined as follows:

Objective function: HOMER Pro is mono-objective optimization tool which focuses on the minimization of NPC.

Optimization variables: An optimization variable is subjected to change during the simulation, and an optimal value sought during the optimization process. Optimization variables for the presented case studies are as follows: (i) size of the PV array, (ii) number of battery units for the BESS, (iii) number of flywheel units, and sizing of (iv) a power converter, and (v) a generator.

Constraints: The objective function is subjected to the following constraints:

- The maximum annual capacity shortage is set as 0%, which indicates that the system should always meet the load demand. By setting the maximum annual capacity to zero, the system will be able to serve the intermittent increase in load demand.
- The operating reserve (surplus operating capacity) as a percentage of load in the current time step is set as 10%, which means that the system should be capable of serving the surplus load demand even if there is a sudden increase (10%) in load.
- The operating reserve as a percentage of solar power output is set as 80%, which means that at any point of time, the system should be capable of serving the load even if there is a sudden decrease (80%) of PV array output.
- The minimum state of charge (SOC) of the BESS is set as 20%. The BESS should not be discharged to less than 20% of its total storage capacity.

4.2 Hybrid Large Business Microgrid Standalone Operation

4.2.1 Inputs

The first step in the simulation is to define parameters necessary for the calculation of NPV, also known as Net Present Cost (NPC). The discount and inflation rate were set as 8% and 2%, respectively. A project lifecycle of 25 years was used for the cost benefit analysis. A diesel-powered generator was considered as the prime source of electricity in one scenario and as a backup in others. The generator and FESS are providing power output in the form of alternating current (AC) while solar PV array and lithium-ion batteries are delivering output as direct current (DC). Hence, the different power sources are respectively connected to an AC and DC bus, and a converter is used for conversion to meet load requirements.

4.2.2 Load Profile:

HOMER Pro offers an open access database that provides access to load data of numerous locations in the USA. Locations in Canada or any other country can be matched to locations with similar climate in the USA, using the Koeppen-Geiger classification system. In this manner, load profiles for a multitude of locations can be created. The load profile selected for the present study is for a business (large office space) with a 498,558 ft^2 floor space having a total of 12 floors, at the location of 9211-116 Street NW, Edmonton, Alberta. Load data is provided in one-hour time intervals, and the day-to-day variability of the load profile was set to 30%. The average daily consumption of the given load profile is 14,573 kWh with average power requirements of 608 kW. The monthly load profile is depicted in Figure 13. Months with peak electric load are June, July and August, with low consumption occurring in November and December.

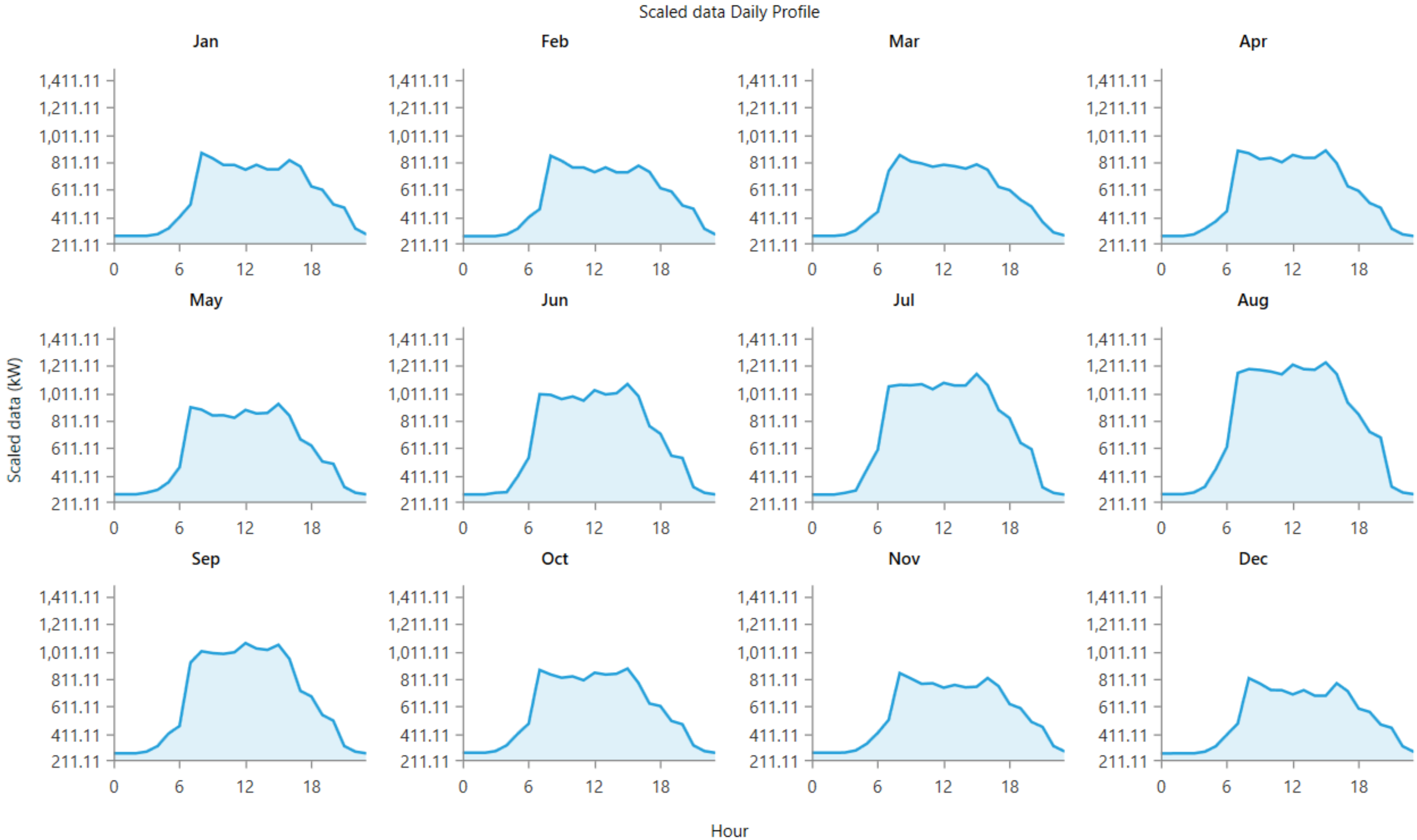


Figure 13. Hourly load profile for business (large office) for each month of a year.

4.2.3 Components and Storage Systems

The components of the microgrid generation system are solar PV modules, a diesel generator, and an AC-DC-AC converter. The storage devices are a BESS and a FESS. Simulation input parameters for these components are presented in the following.

4.2.3.1 Solar PV modules

Before selecting specifications for the PV modules, the solar irradiance at the location of interest for the simulation needs to be determined. Notably, the selected location is a desirable location for solar PV installations as Edmonton has the fifth highest solar potential in Canada [105]. For the solar irradiance data, monthly average values from the period of July 1983 until June 2005 were used, provided by the NASA SSE database. The solar irradiance for latitude and longitude of respectively 53°31.7'N and 113°31.8W' was employed in the analysis.

A combination of 1 kW flat plate type PV modules was used with a capital cost and replacement cost of $3,300/kW and yearly operations and maintenance (O&M) costs of $13.2/kW. A derating factor of 80% was set, which accounts for the decrease in PV array power output in a real-life scenario. Tracking of the PV modules was not considered in this study to avoid the cost implications. Equation (4) is used by the HOMER software [107] to calculate the PV array output.

$$P_{\mathrm{out}}=P_{\mathrm{rat}}f\left(\frac{G_t}{G_{t,\mathrm{stc}}}\right)\left(1+\alpha_{\mathrm{p}}\left[T_{\mathrm{c}}\text{-}T_{\mathrm{c,stc}}\right]\right) \tag{2}$$

where P_{out} and P_{rat} are power output of the PV array (kW) and the power output in standard test conditions (kW); f is the derating factor of for the PV modules (%), G_t and $G_{t,\mathrm{stc}}$ are the solar irradiance in the current time step $\left(\frac{\mathrm{kW}}{\mathrm{m}^2}\right)$ and the solar irradiance in standard test conditions $\left(1\,\frac{\mathrm{kW}}{\mathrm{m}^2}\right)$; α_{p} is the power temperature coefficient $\left(\frac{\%}{°C}\right)$; and T_{c} and $T_{\mathrm{c,stc}}$ are the PV cell temperature in the current time step (°C) and the PV cell temperature in standard test condition (25°C), respectively.

4.2.3.2 Diesel Generator

A diesel generator was considered for the analysis. The amount of fuel used by the unit to generate electricity is defined by its fuel curve. The fuel curve is a function of the fuel curve intercept coefficient, C_{c} (units/hr/kW), the slope of fuel curve, C_{s} (units/hr/kW), the generator's rated capacity, P_{rat} and its output in kW, P_{out} [108]. The fuel consumption is hence given by Equation (5). The fuel curve of the selected generator is shown in Figure 14.

$$C = C_{\mathrm{c}}P_{\mathrm{rat}} + C_{\mathrm{s}}P_{\mathrm{out}} \tag{5}$$

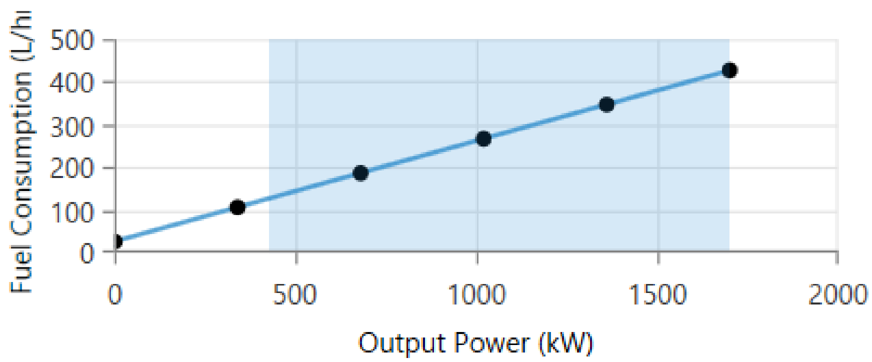


Figure 14. Fuel consumption curve of generator.

Both the capital and replacement cost of the selected generator is $650/kW, with O&M costs of $0.039/kW/operational hour. The various parameters and properties relating to generator operation are summarized in Table 16.

Table 14. Summary of parameters and properties relating to generator operation.

Emissions	Fuel properties	Other parameters
16.5 g/L CO	43.2 MJ/kg LHV	$1.29/L
0.72 g/L unburned HC	820 kg/m^3 density	25.9 L/hr fuel curve intercept
0.1 g/L particulates	88% carbon content	0.236 L/hr/kW fuel curve slope
15.5 g/L NOX	0.4% sulfur content	$650/kW capital cost, $650/kW replacement cost, $0.039//kW/hour O&M costs

4.2.3.3 Converter

Converter consists of two components: an inverter and a rectifier. The inverter is responsible for DC to AC conversion from the batteries and the PV array. The rectifier is responsible for AC to DC conversion from the generator unit and the FESS. The inverter input is defined in terms of its lifetime and its efficiency at which DC power is converted to AC power. On the other hand, the determining aspects for the rectifier are its capacity relative to the inverter and its efficiency for AC to DC conversion [109]. The capital and replacement cost of the converter were set as $396/kW, with an efficiency for both the inverter and rectifier of 95%. The relative capacity of the rectifier as compared to inverter was set as 100%.

4.2.3.4 *Flywheel energy storage system*

A flywheel unit with 160 kW power and 30 kWh energy storage capacity was considered to support short-term energy storage, providing high power for short amounts of time if needed. The FESS can also bridge a possible power gap associated with diesel generator startup [98]. The considered capital and replacement cost are \$330,000 with O&M costs of \$1,320/year. Since a FESS is capable of quasi-infinite charge/discharge cycles, the lifetime of a single unit was set as 25 years. All the above-mentioned parameters are presented in Table 14.

Table 15. Summary of parameters and properties relating to FESS operation.

Power output	160 kW
Capital cost	\$330,000
Replacement cost	\$330,000
O&M costs	\$1,320/yr
Lifetime	25 years

4.2.3.5 *Battery energy storage system*

HOMER Pro provides the option of selecting different types of batteries. For this study, 100 kWh capacity lithium-ion batteries were selected with a depth of discharge set to 80% and service life corresponding to a total net storage of 300,000 kWh or 15 years life whichever comes first. It should be noted that a lead acid BESS was disregarded because of the long life, high energy density and round-trip efficiency that lithium-ion batteries provide. According to International Renewable Energy Agency (IRENA), capital expenditures for lithium-ion batteries are high, yet, they offer the lowest cost per cycle (0.39 euro/kWh) in renewable energy applications, which is favorably compared to lead acid batteries (0.44 euro/kWh/cycle) [38]. The capital and replacement cost of the BESS was set as \$92,400 with O&Ms cost per year of \$1,320. The HOMER software uses Equation (6) to compute the maximum power the BESS can discharge.

$$P_{\text{dis}} = \frac{-kcE_{\max} + kE_1 e^{-k\Delta t} + Ekc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{6}$$

where E_1 and E are the available energy and total energy at the start of a time step (kWh), respectively; $E_{\max}$ is the total storage capacity of the battery (kWh); Δt, k and c are correspondingly the length of time step (h), the storage rate constant (h-1) and the storage capacity ratio (unitless). All parameters associated with the BESS operation are summarized in Table 15.

Table 16. Summary of parameters and properties relating to BESS operation.

Energy capacity	100 kWh
Capital cost	$92,400
Replacement cost	$92,400
O&M costs	$1,320/yr
Useful life	15 yrs/ 300,000 kWh

4.2.4 Cost Calculations

The algorithm implemented in the HOMER software makes decisions based on 'best cost' attractive technical solution, i.e., final results are provided in terms of NPC and LCOE. To recapitulate, LCOE is defined as the average cost to produce a unit of energy (kWh) and is the ratio of total cost incurred (in dollars) to total load served in kWh. Capital, replacement, and O&M costs, and the salvage value are all considered in the LCOE.

4.2.5 Results and Discussion

Three scenarios were considered in this case study:

- Scenario 1 - no usage of RES and ESS
- Scenario 2 – usage of solar PV, generator, and BESS
- Scenario 3 – usage of solar PV, generator, and hybrid ESS with FESS and BESS

The discount and inflation rate and the lifetime of the systems were kept constant for the different scenarios so a clear understanding about the merit of each scenario can be gained from the comparison of results. While it is conceivable that Scenario 1 produces the highest GHG emissions from among the different scenarios, it is shown that Scenario 1 is also an expensive solution. Of course, utilizing RES reduces GHG emissions in Scenarios 2 and 3, yet it is not necessarily apparent that LCOE are lower compared to Scenario 1. In fact, Scenario 3 is the most attractive solution as it allows for the highest solar PV penetration. Detailed results from the analyses of the different systems are given in the following.

4.2.5.1 Scenario 1 – Business Microgrid with Diesel Generator

In this scenario, only the diesel generator (also known as a genset) was employed to fulfil the load demand of the business. Figure 15 depicts a schematic of the microgrid, which depends merely on fossil fuel for energy generation. The rated power output of the generator is 1,700 kW. The analysis yielded NPC and cost of energy of $44,350,000 and $0.645/kWh, respectively. The generator produced 5,885,344 kWh of electricity using 1,615,438 L of diesel fuel. Figure 16 depicts the discounted cash flow over 25 years using the capital, replacement, fuel, and O&M costs, and salvage value of the generator. The majority of costs comes from fuel consumption, with an average consumption of 3.07 L per hour. Note that replacement costs are also considerable given that the service life for this type of generator is 15,000 hours. Figure 17 depicts the power output for a particular year. It can be observed that peak power output occurs in June, July, and August corresponding to the respective load profiles. GHG emissions for this scenario are listed in Table 17. The produced emissions are considerable with over 4 million kilograms of carbon dioxide annually.

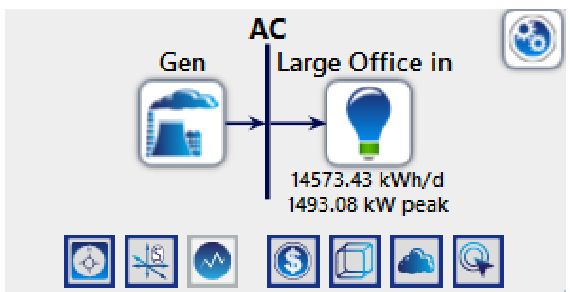


Figure 15. Schematic of standalone microgrid with diesel generator (Scenario 1 – Business microgrid)

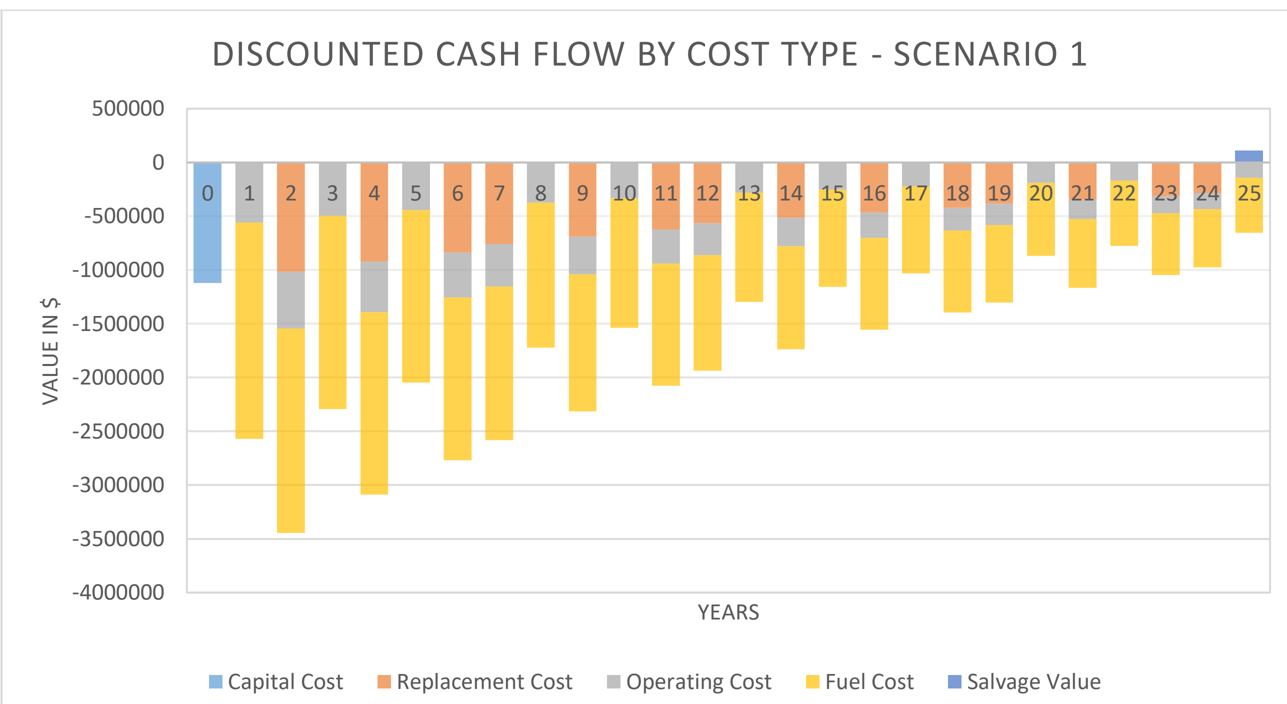


Figure 16. Discounted cash flow by type of cost incurred for microgrid with diesel generator (Scenario 1 - Business microgrid).

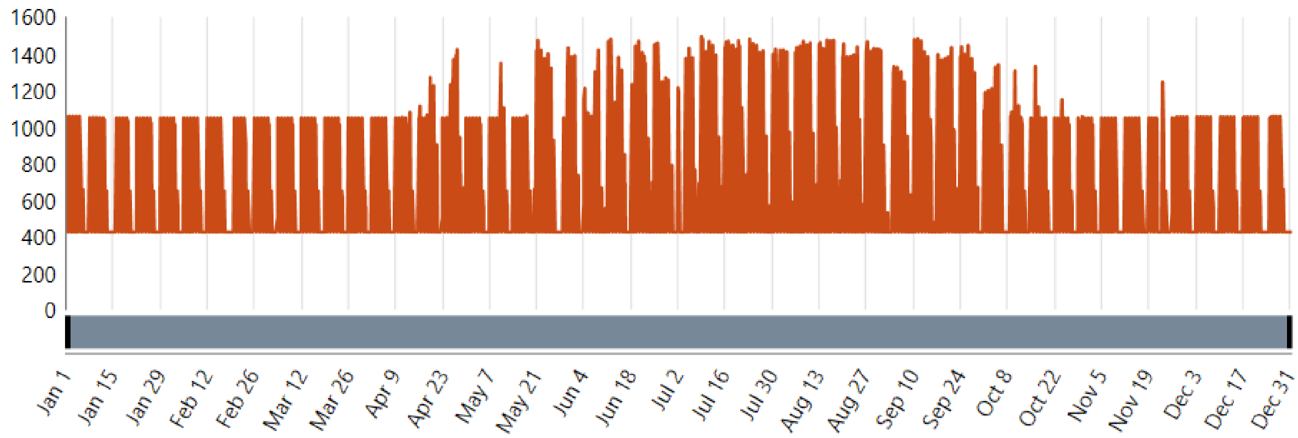


Figure 17. Generator power output (kW) for microgrid with diesel generator (Scenario 1 – Business microgrid).

Table 17. GHG emissions for microgrid with diesel generator (Scenario 1 – Business microgrid).

Emission	**Value**	**Unit**
Carbon dioxide	4,228,595	kg/yr
Carbon monoxide	26,655	kg/yr
Unburned hydrocarbons	1,163	kg/yr
Particulate matter	162	kg/yr
Sulfur dioxide	10,355	kg/yr
Nitrogen oxides	25,039	kg/yr

4.2.5.2 Scenario 2 – Business Microgrid with Diesel Generator, Solar PV, and BESS

The microgrid in this scenario uses two sources of electricity generation to serve the load, i.e., a diesel generator and a PV array. The microgrid includes only one ESS, that is, a 100 kWh lithium-ion BESS. A converter is required for the AC-DC conversion. The HOMER software simulated 1,080 solutions, of which 368 were feasible. 712 solutions were infeasible because they could not meet the capacity shortage constraint that was set as 0%. Out of the 330 feasible solutions, 75 were omitted because they were missing a converter, 35 had an unnecessary converter, and 208 had no source of power generation. The optimal solution consisted of 85 batteries (100 kWh each), 2,653 kW of PV modules, and a 725 kW generator that runs roughly 4,493 hours (approximately half compared to Scenario 1). The renewable penetration divided by load and generation, respectively, was 60.5% and 51.2%. Figure 18 shows a schematic of the system.

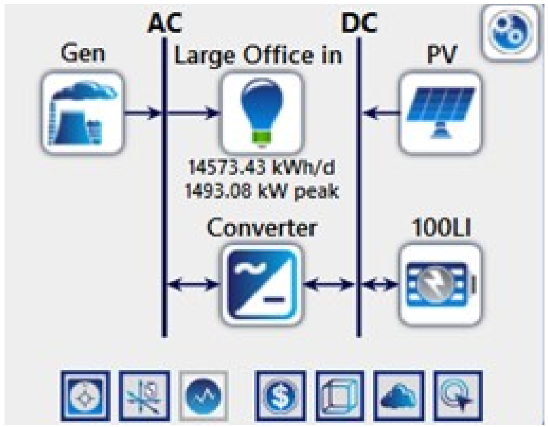


Figure 18. Schematic of standalone microgrid with diesel generator, solar PV, and BESS (Scenario 2 - Business microgrid).

The mean output of PV array during a single day was 8,814 kWh and the yearly total produced electricity was 3,217,219 kWh. The COE of the PV array was calculated to be \$0.222/kWh and the yearly hours of operation were 4,378. An example of daily power output over one week is depicted in the graph in Figure 19. Note that the power output is subject to variability throughout the year.

The generator used 853,396 L of fuel per year with a specific fuel consumption value of 0.279 L/kWh. The fixed generation cost was \$69/hr and the marginal generation cost was \$0.313/kWh. The average operational life was 3.34 year with mean electrical efficiency of 36.4%. A one-week section of generator power output is depicted in Figure 20.

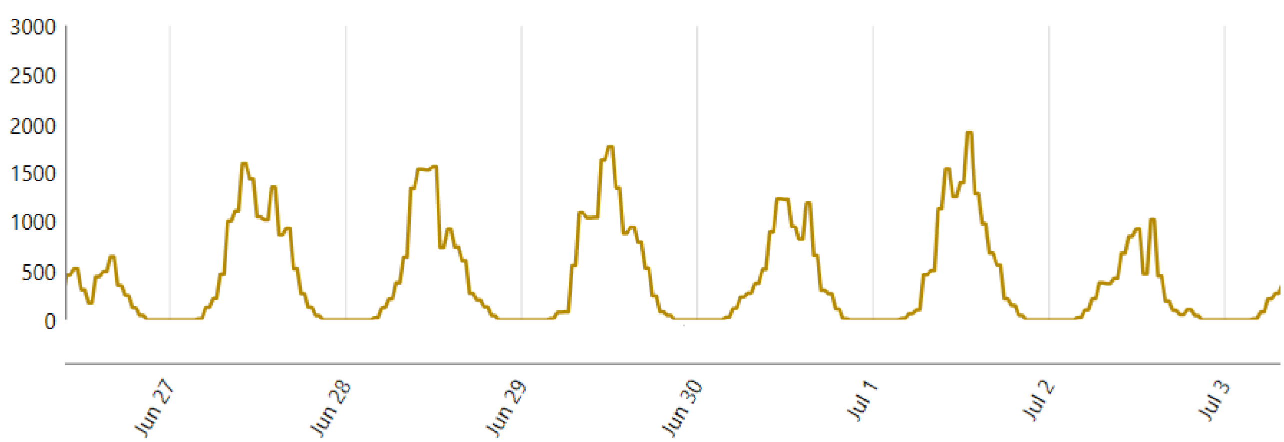


Figure 19. Sample PV array power output (kW) for microgrid with diesel generator, solar PV, and BESS (Scenario 2 – Business microgrid).

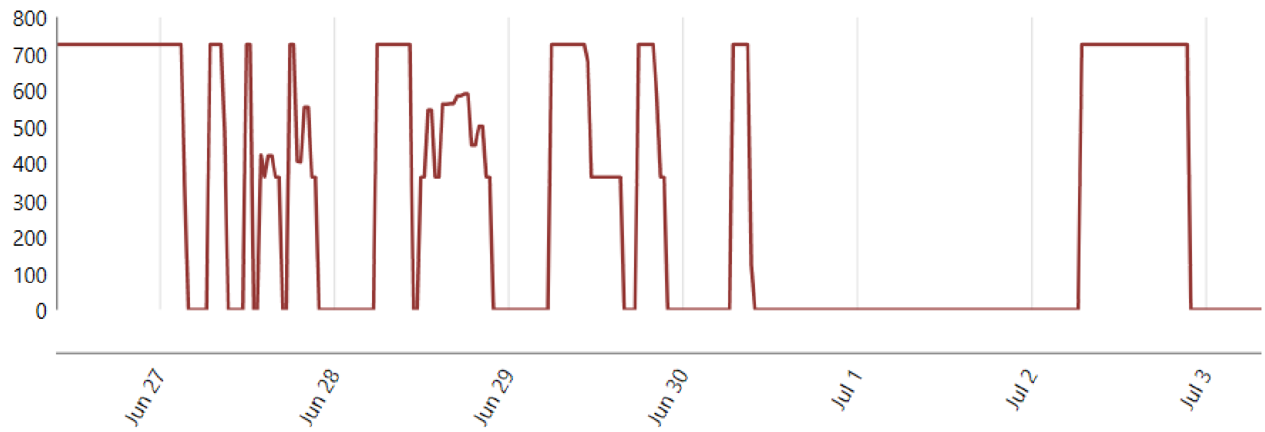


Figure 20. Sample Generator power output (kW) for microgrid with diesel generator, solar PV, and BESS (Scenario 2 – Business microgrid).

For the BESS, 85 units of 100 kWh lithium-ion batteries (8,500 kWh nominal capacity) were determined to be the most optimal solution, out of which 6,800 kWh was the usable capacity. The average COE was $0.197/kWh with the total energy stored by the BESS of 1,178,781 kWh per year. The total energy losses in a year were 118,047 kWh. The constraint on state of charge (SOC) was set as 20%, which was implemented to ensure the battery banks are not depleted, because decreasing the depth of discharge increases the life of a BESS.

The optimal capacities of the inverter and rectifier were found as 1,143 kW. The inverter operated for 6,820 hours while the rectifier operated 1,716 hours in a single year. The mean output power and energy output of the inverter was 313 kW and 2,740,535 kWh/year, respectively. The rectifier, on the other hand, had 52.2 kW mean power output, and the energy output was 457,643 kWh/year.

<u>Summary of Scenario 2 – Business Microgrid:</u> This section provides the summary of results of the complete system. With the architecture using generator, BESS, and PV, the capital cost is $17.42 million, the NPC is $38.4 million and overall LCOE is $0.56/kWh. The generator generated 3,060,609 kWh of electricity during a given year and electricity produced by PV was 3,217,219 kWh per year. Figure 21 provides the incurred cost during the 25 years by component type. It can be seen that the highest cost is allocated to lithium-ion BESS and PV modules at the start of the project which is the capital cost. The cost of the generator is considerable low at the start, but it is highest compared to other components of the system, each respective year, mainly due to the cost of fuel required to run the generator. The emissions information can be found in

Table 18. Carbon dioxide is the largest contributor to emissions with more than 2 million kilograms are produced in a year, followed by carbon monoxide and nitrogen oxides.

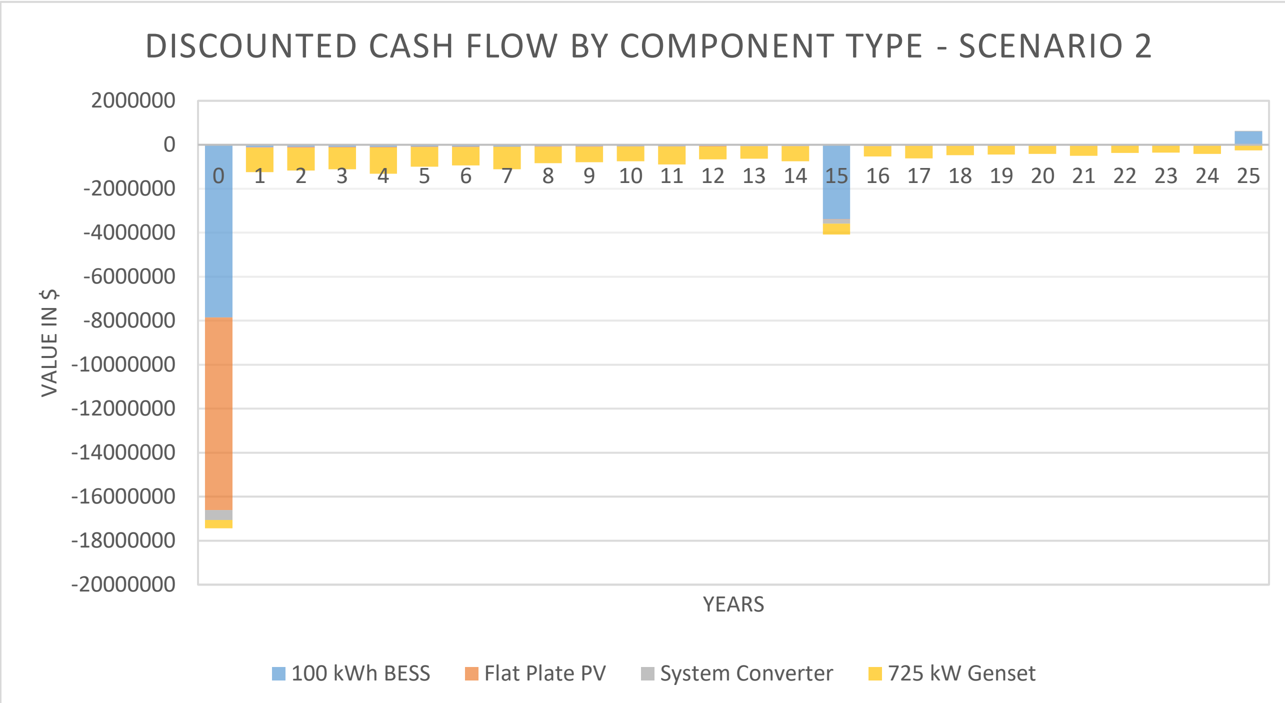


Figure 21. Discounted cash flow by component type for microgrid with diesel generator, solar PV and BESS (Scenario 2 - Business microgrid).

Table 18. GHG emissions for microgrid with diesel generator, solar PV and BESS (Scenario 2 – Business microgrid).

Emission	Value	Unit
Carbon dioxide	2,239,751	kg/yr
Carbon monoxide	9,387	kg/yr
Unburned hydrocarbons	1,075	kg/yr
Particulate matter	269	kg/yr
Sulfur dioxide	5,590	kg/yr
Nitrogen oxides	9,387	kg/yr

4.2.5.3 Scenario 3 – Business Microgrid with Diesel Generator, Solar PV, BESS, and FESS

The proposed hybrid microgrid in Scenario 3, uses the same two sources of electricity generation as Scenario 2, i.e., a diesel generator and PV array. But the microgrid employs two energy storage technologies, i.e., a 160 kW Beacon Power FESS and a 100 kWh lithium-ion BESS. Figure 22 shows the schematic of proposed system. 2,272 solutions were simulated by

HOMER Pro, out of which 712 were feasible. 150 were omitted for lacking a converter, 108 for having extra converter and 344 for no source of power generation. The optimal solution in this scenario was the one with 77 batteries, 1 FESS, 2,857 kW of solar PV array, and the generator that runs roughly 4,108 hours (less than half as compared to Scenario 1). The renewable penetration divided by load and generation was 64.2% and 54.3%, respectively.

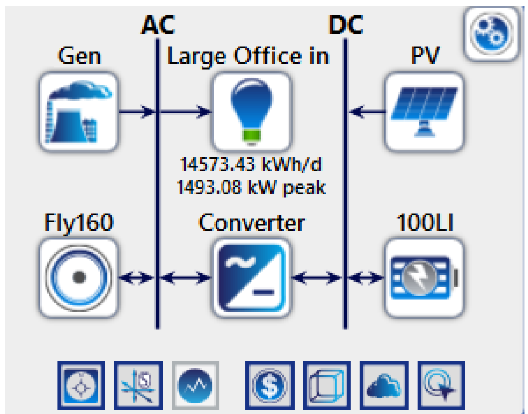


Figure 22. Schematic of standalone microgrid with diesel generator, solar PV, BESS and FESS (Scenario 3 - Business microgrid).

The COE of PV array was calculated to be 0.168 $/kWh and the annual hours of operation were 4,378. The mean output by PV array during a single day was 9,392 kW and the yearly total produced electricity was 3,427,969 kWh. An example of daily power output over one week is depicted in the graph in Figure 23.

The generator used 800,874 L of diesel fuel during a year with a specific fuel consumption value of 0.278 L/kWh. The fixed generation cost and the marginal generation cost was, $0.237/kWh and $52.3/hr., respectively. The average operational life was 3.65 year with mean electrical efficiency of 36.6%. A one-week section of generator power output is depicted in Figure 24.

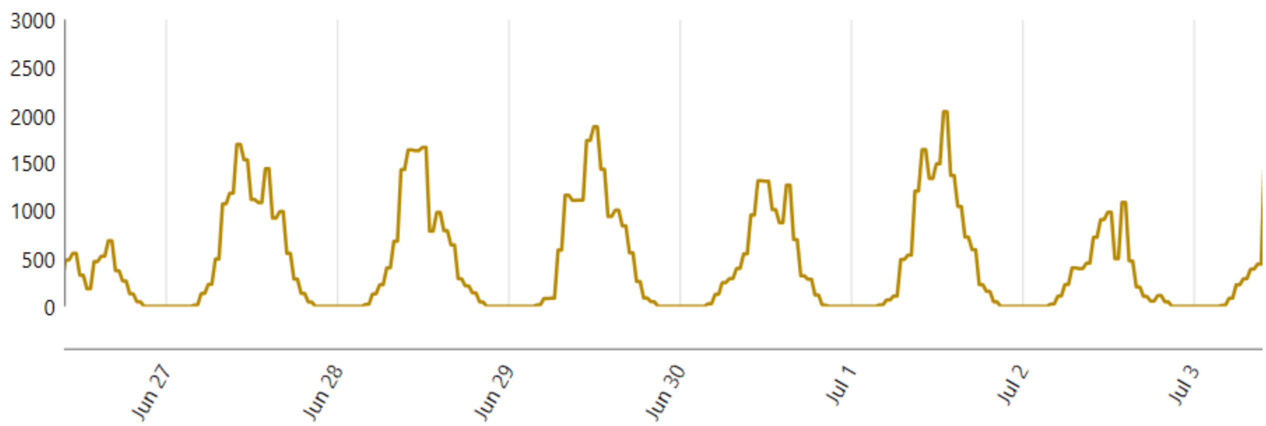


Figure 23. Sample PV array power output (kW) for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 – Business microgrid).

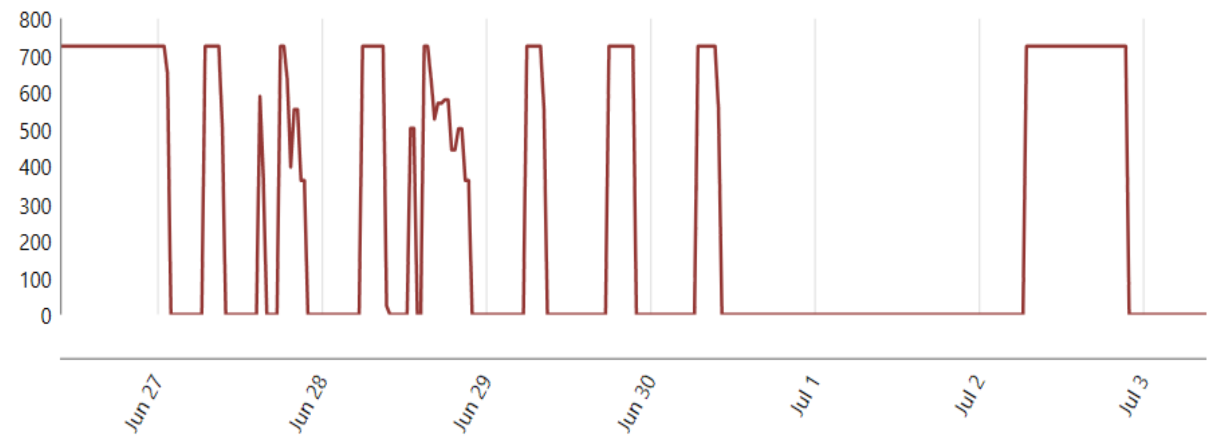


Figure 24. Sample Generator power output (kW) for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 – Business microgrid).

77 parallel strings of 100 kWh lithium-ion BESS were determined to be the most optimal solution. The average COE was \$0.147/kWh with the total energy stored by the BESS of 1,190,182 kWh per year. The total energy losses in a year were 119,179 kWh. The optimal capacities of the inverter and rectifier were found as 1,955 kW. The inverter operated 6,779 hours while the rectifier operated 1,757 hours in a single year. The mean output power and energy output of the inverter was 337 kW and 2,949,579 kWh/year, respectively. The rectifier, on the other hand, had 53.3 kW mean power output and the energy output was 466,978 kWh/year.

<u>Summary of Scenario 3 – Business Microgrid:</u> This selected microgrid infrastructure employs a generator, a BESS, a FESS, a generator, and a solar PV array. The capital cost was determined as \$17.95 million, the NPC as \$37.6 million, and the LCOE per kWh as \$0.546. The generator

generates 2,885,144 kWh of electricity during a given year. Electricity produced by the PV array is 3,427,969 kWh/yr. Figure 25 shows the discounted cash flow over the 25 years lifecycle by component type. It is observed that the capital costs of the project are comparatively high while operating costs in most years is minimal compared to the capital expenditures. GHG emissions information are summarized in Table 19. The emissions are considerably lower compared to the scenarios presented previously.

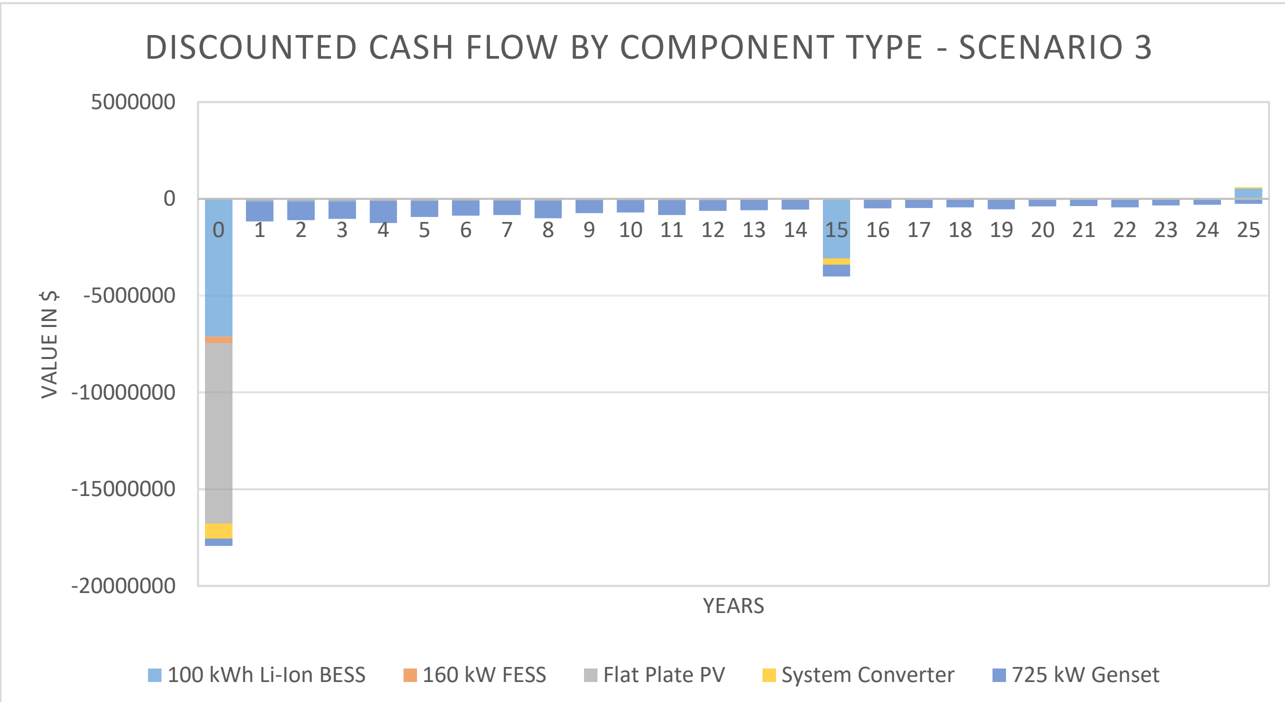


Figure 25. Discounted cash flow by component type for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 - Business microgrid).

Table 19. GHG emissions for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 – Business microgrid).

Emission	Value	Unit
Carbon dioxide	2,101,907	kg/yr
Carbon monoxide	8,810	kg/yr
Unburned hydrocarbons	1,009	kg/yr
Particulate matter	252	kg/yr
Sulfur dioxide	5,246	kg/yr
Nitrogen oxides	8,810	kg/yr

4.2.6 *Summary of Case Study 1 – Business Microgrid*

Of the three simulated scenarios, using 8% discount rate, 2% inflation rate and 25 years of project lifetime, Scenario 3 (generator, PV, BESS, and FESS) produced the lowest GHG emissions followed by Scenario 2 (generator, PV, and BESS) and Scenario 1 (generator only). The CO_2 emissions without an ESS were 4,228,595 kg/yr. The emissions without and with a FESS in Scenarios 2 and 3 were 2,239,751 kg/yr and 2,101,907 kg/yr, respectively. Along with lesser GHG emissions and more solar penetration, the hybrid microgrid in Scenario 3 was found to be the most cost-effective solution. Hence, compared to the other scenarios, Scenario 3 is advantageous in both aspects, cost and being environmentally friendly. The minimum cost to produce electricity (COE) was $0.546/kWh when both FESS and BESS were used as ESS. The summary of the results for Case Study 1 is presented in the Table 20.

In terms of FESS implementation, the FESS was used to provide power for short intervals of time. The use of FESS decreased the annual fuel consumption by 53,000 L, saving approximately $70,000 every year. RES penetration was also the highest when the FESS was used. While capital costs were the lowest ($1.12 million) when only the generator was used, the NPC was the highest ($44.35 million). In Scenario 2 (system consisting of generator, PV, and BESS), capital cost and NPC were the second highest ($17.42 million and $38.41 million, respectively). The best-case Scenario 3 with generator, PV, FESS and BESS had the highest capital cost ($17.95 million) but the NPC was the lowest ($17.42 million). Based on these results, when considering a standalone microgrid to power a 500,000 ft^2 office space at the specified location, it is recommended to use a hybrid solution with solar PV, diesel generator, BESS and FESS.

Table 20. Summary of results of Case Study 1 – Business microgrid

Description	**Scenario 1**	**Scenario 2**	**Scenario 3**
NPC	$44.35 million	$38.41 million	$37.62 million
COE	$0.645	$0.56	$0.546
Fuel consumed	1,615,438 L	853,396 L	800,874 L
CO_2 emissions	4,228,595 kg/yr	2,239,751 kg/yr	2,101,907 kg/yr

4.3 Hybrid Small Community Microgrid

As it is of interest to explore how hybrid systems perform under different load profiles and under different solar irradiation conditions (i.e., Global Horizontal Irradiance - GHI: total solar radiation incident on a horizontal surface). In Case Study 2, a standalone operation microgrid with the load profile of a small community (200 homes) was simulated, again using the HOMER Pro software tool. The chosen load profile provides a basis for a decentralized microgrid for remote communities where grid expansion is not possible or not a cost-effective solution. This section provides a summary of the results, with the detailed analysis presented in Appendix B, C and D for brevity. Similar to scenarios discussed in the previous section, the present case study also provides a comparison between the following three different microgrid architectures: (i) generator based, (ii) generator, BESS and PV based, and (iii) generator, FESS, BESS and PV based. A schematic of the hybrid grid structure for the third scenario is depicted in Figure 26.

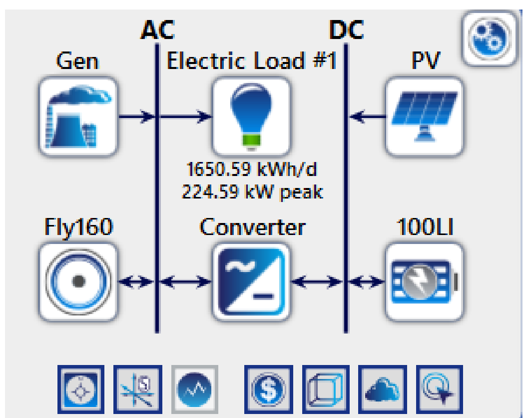


Figure 26. Schematic of standalone microgrid with diesel generator, solar PV, BESS and FESS (Scenario 3 - Community microgrid).

4.3.1 Scenario 1 - Community Microgrid with Diesel Generator

A 250 kW generator was deemed suitable for the selected load profile. Using only a generator for power generation, the net present cost was calculated as \$6.2 million, and the cost of energy was \$0.797/kWh. The capital cost was \$165,000 with O&M costs of \$86,742 per year. The capital cost required for this scenario is the lowest from among the three scenarios, but the NPC is the highest, which indicates that it may not be the best solution. Scenario 1 also produces a comparatively large amount carbon dioxide emission (573,658 kg/year), which is greater than for the other scenarios. This microgrid solution is not only expensive but also has the worst environmental impact relative to the other two scenarios.

4.3.2 Scenario 2 - Community Microgrid with Diesel Generator, Solar PV, and BESS

The optimal solution for this architecture includes a BESS with 19 lithium-ion batteries, a 315 kW PV array, and a 75 kW generator, which is designated as a backup power supply. The NPC and COE of $5.27 million and $0.677/kWh is less than for Scenario 1. The initial capital required for this scenario, $2.89 million, was the highest from among considered scenarios. The ratio of RES penetration with respect to generation and load is 69.2% and 82.7%, respectively, which decreases the carbon dioxide emissions from 573,658 kg/year (Scenario 1) to 178,225 kg/year. Correspondingly, generator operation decreases from 8,760 hours to 3,006 hours.

4.3.3 Scenario 3 - Community Microgrid with Diesel Generator, Solar PV, BESS, and FESS

The microgrid in Scenario 3, which also includes a FESS, presents itself as a promising solution. The minimum cost to produce 1 kWh of electricity (COE) was $0.599. The NPC of this configuration was the lowest ($4.66 million) as compared to the other scenarios in the case study. The optimal system uses a BESS with only seven lithium-ion batteries (100 kWh each) along with one FESS (160 kW) for energy storage. The sources of power supply are a 275 kW PV system and a 75 kW generator. The initial capital required was about half a million dollars less than Scenario 2, yet, carbon dioxide emissions were about 58% greater.

4.3.4 Summary of Case Study 2 – Community Microgrid

The above-mentioned simulation results are summarized in Table 21. Case Study 2 also demonstrates that the use of an ESS, including a FESS, may provide tangible benefits to microgrid architectures in terms of cost while a tradeoff in terms of GHG emissions may have to be accepted. Relevant figures related to PV power output, generator output, cash flows are provided in Appendix B, C and D.

Table 21. Summary of results of Case Study 2 – Community microgrid

Description	Scenario 1	Scenario 2	Scenario 3
NPC	\$6.2 million	\$5.27 million	\$4.66 million
COE	\$0.797	\$0.677	\$0.599
Fuel consumed	219,153 L	68,080 L	107,630 L
CO_2 emissions	573,658 kg/yr	178,225 kg/yr	281,765 kg/yr

5 Conclusions

Energy storage systems are used for several different applications, including, but not limited to, grid stabilization, providing uninterruptible power supply, load leveling, and increasing renewable energy sources penetration. From among the commercially available energy storage systems, this thesis focused on electrochemical battery (BESS) and electromechanical flywheel storage systems (FESS). The former is used primarily for applications where high energy density is required while the latter is most suitable for applications require fast response times and high-power density. FESS store energy in a fast-spinning rotor made of steel or fiber reinforced polymer composites in the form of rotational kinetic energy. The rotor, which rotates in a vacuum enclosure to reduce friction losses, is connected to an electric machine that can operate as a motor or generator depending on whether energy needs to be stored or retrieved from the FESS.

In Chapter 3 of this study the application of FESS as a standalone back up energy storage system for the grid connected charging of battery electric buses (BEB) was explored. The City of Edmonton is transitioning from diesel buses to BEB, which requires BEB to run on the same routes and schedules as diesel buses, so real book-in and book-out data of the diesel bus fleet was used in the analysis. The BEB can run a distance of 300 km after a single charge based on their energy consumption per kilometer. A simulation was performed to validate that planned infrastructure was suitable to avoid any disruption in bus service. The simulation was based on information involving book-in and book-out times, BEB state of charge, number of chargers, state of charge of FESS and BESS, a 1000 kW cap on grid power. In terms of FESS, 25 commercially available FESS, each with 160 kW power and 30 kWh capacity (Beacon Power, Wilmington, Massachusetts, USA) were considered for the simulation. Simulation results showed that using a FESS aided in peak shaving when the power required from the grid exceeds the 1000 W threshold. A BESS with a 1.5 MWh capacity (eCAMION, Toronto, Ontario) were also used to perform the simulation. The BESS was found to also fulfil the system requirements, but its response was slow as compared to the FESS. For better decision making, a cost benefit analysis was performed, which involved a life cycle assessment of 20 years. Net present value (NPV) and internal rate of return (IRR) criteria of discounted cash flows were followed to determine the most attractive alternative for this specific application. Three scenarios were presented based on theoretical and simulation results. All the three scenarios showed that using the FESS will be a cost attractive solution. Some results showed that the NPV was negative for both the alternatives (BESS and FESS), nevertheless, the general notion would be to adopt the option with the least negative value. Considering the findings from the techno-economic feasibility study, it is recommended to use a FESS as an energy storage system for BEB charging infrastructure.

In Chapter 4, two case studies were investigated based on standalone microgrids supported by a renewable energy source (solar) and a diesel fuel generator. A hybrid system using two energy storage technologies was proposed to store energy, i.e., BESS and FESS. The purpose of using two energy storage technologies is to capitalize on the unique benefits that each storage system provides. The ideal energy storage system would be the one that has both high power and energy density, yet, no technology is fully capable of meeting these functions. That is why a FESS, having high power density, and a lithium-ion BESS, having high energy density, were proposed to support the microgrid. The first case study employed a load profile for a 500,000 ft^2 of a large office building. Three scenarios were presented and compared. The first scenario used only the generator to meet the load requirements. Not only was this the most expensive alternative; it also produced the highest GHG emissions. The second and third scenario used a BESS and BESS/FESS combination along with the solar PV and generator back-up. The FESS/BESS combination was found to be the most attractive solution with the lowest NPV, lowest GHG emissions and the highest solar penetration. The second case study explored a standalone microgrid with the load profile for a small community. Three scenarios similar to the first case study were again explored. The best solution for the second case study was also a hybrid solution, yet, trade-offs exist between the most cost-effective or most environmentally friendly solution. Both studies demonstrate that employing a hybrid system with different energy storage technologies can yield optimal solutions as a hybrid system utilizes the benefits of both technologies.

From the different studies on FESS implementation as an energy storage solution, ranging from a standalone application to usage in hybrid configurations, it can be established that flywheel energy storage technology is an attractive technology. While FESS are normally associated with higher initial capital cost, the fact that they are not affected by deep cycling, require little to no maintenance, and consist of environmentally friendly components, make them a desirable choice for energy storage in various applications.

References

[1] "Electricity Information 2019 – Analysis - IEA." [Online]. Available: https://www.iea.org/reports/electricity-information-overview. [Accessed: 19-Nov-2020].

[2] R. Stavins *et al.*, "International Cooperation: Agreements & Instruments," pp. 1001–1082.

[3] "About the Secretariat | UNFCCC." [Online]. Available: https://unfccc.int/about-us/about-the-secretariat. [Accessed: 25-Nov-2020].

[4] K. Zhang and Q. M. Liang, "Recent progress of cooperation on climate mitigation: A bibliometric analysis," *Journal of Cleaner Production*, vol. 277. 2020.

[5] "CANADA'S 2017 NATIONALLY DETERMINED CONTRIBUTION SUBMISSION TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE." [Online]. Available: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Canada First/Canada First NDC-Revised submission 2017-05-11.pdf. [Accessed: 05-Dec-2020].

[6] "Greenhouse gas sources and sinks: executive summary 2020 - Canada.ca." [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/sources-sinks-executive-summary-2020.html. [Accessed: 05-Dec-2020].

[7] "Canada's actions to reduce emissions - Canada.ca." [Online]. Available: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/reduce-emissions.html. [Accessed: 06-Dec-2020].

[8] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy*, vol. 137. pp. 511–536, 2015.

[9] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 6–7. pp. 1513–1522, 2009.

[10] M. Amiryar, K. Pullen, and D. Nankoo, "Development of a High-Fidelity Model for an Electrically Driven Energy Storage Flywheel Suitable for Small Scale Residential Applications," *Appl. Sci.*, vol. 8, no. 3, p. 453, 2018.

[11] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progress in Natural Science*, vol. 19, no. 3. pp. 291–312, 2009.

[12] J. Li, A. M. Gee, M. Zhang, and W. Yuan, "Analysis of battery lifetime extension in a SMES-battery hybrid energy storage system using a novel battery lifetime model," *Energy*, vol. 86, pp. 175–185, 2015.

[13] A. Kuperman *et al.*, "Supercapacitor sizing based on desired power and energy performance," *IEEE Trans. Power Electron.*, vol. 29, no. 10, pp. 5399–5405, 2013.

[14] J. Zhu *et al.*, "Experimental demonstration and application planning of high temperature

superconducting energy storage system for renewable power grids," *Appl. Energy*, vol. 137, pp. 692–698, 2015.

[15] P. Zhao, Y. Dai, and J. Wang, "Design and thermodynamic analysis of a hybrid energy storage system based on A-CAES (adiabatic compressed air energy storage) and FESS (flywheel energy storage system) for wind power application," *Energy*, vol. 70, pp. 674–684, 2014.

[16] A. W. Bizuayehu, P. Medina, J. P. S. Catalão, E. M. G. Rodrigues, and J. Contreras, "Analysis of electrical energy storage technologies' state-of-the-art and applications on islanded grid systems," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2014.

[17] M. Aneke and M. Wang, "Energy storage technologies and real life applications–A state of the art review," *Appl. Energy*, vol. 179, pp. 350–377, 2016.

[18] A. B. Gallo, J. R. Simões-Moreira, H. K. M. Costa, M. M. Santos, and E. M. dos Santos, "Energy storage in the energy transition context: A technology review," *Renew. Sustain. energy Rev.*, vol. 65, pp. 800–822, 2016.

[19] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015.

[20] J. M. Eyer, J. J. Iannucci, and G. P. Corey, "SANDIA REPORT Energy Storage Benefits and Market Analysis Handbook A Study for the DOE Energy Storage Systems Program."

[21] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton, "Challenges in integrating distributed energy storage systems into future smart grid," in *2008 IEEE international symposium on industrial electronics*, 2008, pp. 1627–1632.

[22] K. Mongird *et al.*, "Energy Storage Technology and Cost Characterization Report," 2019.

[23] D. Rastler, "EPRI Project Manager Electricity Energy Storage Technology Options," 2010.

[24] M. Beaudin, H. Zareipour, A. Schellenberglabe, and W. Rosehart, "Energy storage for mitigating the variability of renewable electricity sources: An updated review," *Energy Sustain. Dev.*, vol. 14, no. 4, pp. 302–314, 2010.

[25] F. Nadeem, S. M. S. Hussain, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, "Comparative review of energy storage systems, their roles, and impacts on future power systems," *IEEE Access*, vol. 7, pp. 4555–4585, 2018.

[26] "ELECTRICITY STORAGE ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME." [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/IRENA-ETSAP-Tech-Brief-E18-Electricity-Storage.pdf. [Accessed: 15-Dec-2020].

[27] S. M. Schoenung, "Characteristics and Technologies for Long-vs. Short-Term Energy Storage A Study by the DOE Energy Storage Systems Program," 2001.

[28] J. Kondoh *et al.*, “Electrical energy storage systems for energy networks,” *Energy Convers. Manag.*, vol. 41, no. 17, pp. 1863–1874, 2000.

[29] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, “Overview of current and future energy storage technologies for electric power applications,” *Renew. Sustain. energy Rev.*, vol. 13, no. 6–7, pp. 1513–1522, 2009.

[30] G. J. May, A. Davidson, and B. Monahov, “Lead batteries for utility energy storage: A review,” *J. energy storage*, vol. 15, pp. 145–157, 2018.

[31] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and R. Villafáfila-Robles, “A review of energy storage technologies for wind power applications,” *Renew. Sustain. energy Rev.*, vol. 16, no. 4, pp. 2154–2171, 2012.

[32] F. A. Farret and M. G. Simoes, *Integration of alternative sources of energy*. John Wiley & Sons, 2006.

[33] “Flow Batteries.” [Online]. Available: http://www.epqu.agh.edu.pl/archives/magazine/mv3i1/mv3i1_22.pdf. [Accessed: 15-Dec-2020].

[34] H. Zhao, Q. Wu, S. Hu, H. Xu, and C. N. Rasmussen, “Review of energy storage system for wind power integration support,” *Appl. Energy*, vol. 137, pp. 545–553, 2015.

[35] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, “Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality,” *Renew. Sustain. Energy Rev.*, vol. 91, pp. 1205–1230, 2018.

[36] P. Kurzweil, “Gaston Planté and his invention of the lead–acid battery—The genesis of the first practical rechargeable battery,” *J. Power Sources*, vol. 195, no. 14, pp. 4424–4434, 2010.

[37] A. P. Karpinski, B. Makovetski, S. J. Russell, J. R. Serenyi, and D. C. Williams, “Silver–zinc: status of technology and applications,” *J. Power Sources*, vol. 80, no. 1–2, pp. 53–60, 1999.

[38] G. Albright, J. Edie AllCell Technologies, P. Crossley, and A. Vassallo, “IRENA Battery Storage Report 2015,” 2015.

[39] S. O. Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, “Overview of energy storage in renewable energy systems,” *Int. J. Hydrogen Energy*, vol. 41, no. 45, pp. 20914–20927, 2016.

[40] “Battery Energy Storage for Smart Grid Applications.” [Online]. Available: https://www.eurobat.org/images/news/position-papers/eurobat_smartgrid_publication_may_2013.pdf. [Accessed: 15-Dec-2020].

[41] K. Li and K. J. Tseng, “Energy efficiency of lithium-ion battery used as energy storage devices in micro-grid,” in *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, 2015, pp. 5235–5240.

[42] “History of flywheel energy storage systems | Gerotor AG,” *Gerotor AC*, 2018. [Online].

Available: https://gerotor.tech/history-of-flywheel-energy-storage-systems/. [Accessed: 19-Nov-2020].

[43] P. R. S. Shelke and D. G. Dighole, “A review paper on dual mass flywheel system,” *Int. J. Sci. Eng. Technol. Res*, vol. 5, no. 1, pp. 326–331, 2016.

[44] A. Buchroithner and M. Bader, “History and development trends of flywheel-powered vehicles as part of a systematic concept analysis,” *Methods*, pp. 1–12, 2011.

[45] J. G. Bitterly, “Flywheel technology past, present, and 21st century projections,” in *Proceedings of the Intersociety Energy Conversion Engineering Conference*, 1997, vol. 3–4, pp. 2312–2315.

[46] G. Genta, *Kinetic energy storage: theory and practice of advanced flywheel systems*. Butterworth-Heinemann, 2014.

[47] R. Sebastián and R. Peña Alzola, “Flywheel energy storage systems: Review and simulation for an isolated wind power system,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 9. pp. 6803–6813, 2012.

[48] M. Hedlund, J. Lundin, J. De Santiago, J. Abrahamsson, and H. Bernhoff, “Flywheel energy storage for automotive applications,” *Energies*, vol. 8, no. 10, pp. 10636–10663, 2015.

[49] B. Bolund, H. Bernhoff, and M. Leijon, “Flywheel energy and power storage systems,” *Renew. Sustain. Energy Rev.*, vol. 11, no. 2, pp. 235–258, 2007.

[50] I. P. Gyuk, “EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications.” [Online]. Available: https://www.sandia.gov/ess-ssl/publications/ESHB 1001834 reduced size.pdf. [Accessed: 17-Dec-2020].

[51] “Stephentown, New York | Beacon Power.” [Online]. Available: https://beaconpower.com/stephentown-new-york/. [Accessed: 19-Nov-2020].

[52] “Hazle Township, Pennsylvania | Beacon Power.” [Online]. Available: https://beaconpower.com/hazle-township-pennsylvania/. [Accessed: 19-Nov-2020].

[53] M. Hedlund, J. Lundin, J. de Santiago, J. Abrahamsson, and H. Bernhoff, “Flywheel energy storage for automotive applications,” *Energies*, vol. 8, no. 10. pp. 10636–10663, 2015.

[54] F. Faraji, A. Majazi, and K. Al-Haddad, “A comprehensive review of flywheel energy storage system technology,” *Renew. Sustain. Energy Rev.*, vol. 67, pp. 477–490, 2017.

[55] N. Hamsic *et al.*, “Increasing renewable energy penetration in isolated grids using a flywheel energy storage system,” in *2007 International Conference on Power Engineering, Energy and Electrical Drives*, 2007, pp. 195–200.

[56] “Coral Bay wind/diesel/PowerStore Western Australia.” [Online]. Available: https://library.e.abb.com/public/33d7473dc0436cc7c1257afd004e3d8c/Case study_Coral Bay_9AKK100580A2549_Dec2012_HR.pdf. [Accessed: 17-Dec-2020].

[57] “NRStor Project Spotlight: 2MW/500kWh Minto Flywheel Project.” [Online]. Available:

http://nrstor.com/wp-content/uploads/2019/06/flywheels.pdf. [Accessed: 18-Dec-2020].

[58] "NRStor Completes Acquisition of 5MW Energy Storage Facility in Clear Creek, Ontario - NRStor." [Online]. Available: http://nrstor.com/2019/05/30/nrstor-completes-acquisition-of-5mw-energy-storage-facility-in-clear-creek-ontario/. [Accessed: 18-Dec-2020].

[59] G. Pistoia, *Electric and hybrid vehicles: Power sources, models, sustainability, infrastructure and the market*. Elsevier, 2010.

[60] "Porsche 911 GT3 R Hybrid Using Williams Flywheel KERS - Green Car Congress." [Online]. Available: https://www.greencarcongress.com/2010/02/gt3r-20100211.html. [Accessed: 18-Dec-2020].

[61] "Audi R18 e-tron quattro: diesel hybrid Le Mans racer with electric flywheel energy storage - Green Car Congress." [Online]. Available: https://www.greencarcongress.com/2012/03/r18etron-20120301.html. [Accessed: 18-Dec-2020].

[62] A. Sánchez Muñoz, M. Garcia, M. Gerlich Reviewer, and T. Rautiainen, "Overview of storage technologies."

[63] IEA, "Global EV Outlook 2019 – Analysis - IEA," *Iea*. 2019.

[64] M. Rogge, S. Wollny, and D. U. Sauer, "Fast charging battery buses for the electrification of urban public transport-A feasibility study focusing on charging infrastructure and energy storage requirements," *Energies*, vol. 8, no. 5, pp. 4587–4606, 2015.

[65] "City: Edmonton to boast Canada's largest fleet of electric buses - Edmonton | Globalnews.ca." [Online]. Available: https://globalnews.ca/news/5136476/edmonton-electric-bus-fleet/. [Accessed: 19-Nov-2020].

[66] "ZX5 Electric Bus | Proterra." [Online]. Available: https://www.proterra.com/vehicles/zx5-electric-bus/. [Accessed: 19-Nov-2020].

[67] A. Buchroithner, H. Wegleiter, and B. Schweighofer, "Flywheel energy storage systems compared to competing technologies for grid load mitigation in ev fast-charging applications," in *2018 IEEE 27th International Symposium on Industrial Electronics (ISIE)*, 2018, pp. 508–514.

[68] "Resources | Beacon Power." [Online]. Available: https://beaconpower.com/resources/. [Accessed: 19-Nov-2020].

[69] B. L. Capehart, W. C. Turner, and W. J. Kennedy, *Guide to energy management*. Crc Press, 2020.

[70] D. Harris, *A guide to energy management in buildings*. Taylor & Francis, 2016.

[71] G. S. Smith, *Managerial accounting for libraries and other not-for-profit organizations*. American Library Association, 2002.

[72] J. E. Pope, *Rules of thumb for mechanical engineers*. Elsevier, 1996.

[73] P. Belli, *Economic analysis of investment operations: analytical tools and practical applications*. World Bank Publications, 2001.

[74] M. Green, "Community power," *Nat. Energy*, vol. 1, no. 3, p. 16014, Mar. 2016.

[75] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renew. Sustain. Energy Rev.*, vol. 90, pp. 402–411, 2018.

[76] "The role and interaction of microgrids and centralized grids in developing modern power systems: A case review." [Online]. Available: https://www.iea-isgan.org/wp-content/uploads/2018/02/ISGAN_DiscussionPaper_MicrogridsCentralizedGrids_2016-1.pdf. [Accessed: 09-Dec-2020].

[77] "The U.S. Department of Energy's Microgrid Initiative." [Online]. Available: https://www.energy.gov/sites/prod/files/2016/06/f32/The US Department of Energy%27s Microgrid Initiative.pdf. [Accessed: 09-Dec-2020].

[78] "Deaigning Sustainable Off-Grid Rural Electrification Projects: Principles and Practices." [Online]. Available: http://documents1.worldbank.org/curated/pt/120391468313811877/pdf/470220WP0Box331C10OffgridGuidelines.pdf. [Accessed: 09-Dec-2020].

[79] L. Barelli, G. Bidini, P. Cherubini, A. Micangeli, D. Pelosi, and C. Tacconelli, "How hybridization of energy storage technologies can provide additional flexibility and competitiveness to microgrids in the context of developing countries," *Energies*, vol. 12, no. 16, 2019.

[80] P. Blechinger, C. Cader, P. Bertheau, H. Huyskens, R. Seguin, and C. Breyer, "Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands," *Energy Policy*, vol. 98, pp. 674–687, 2016.

[81] A. Etxeberria, I. Vechiu, H. Camblong, and J. M. Vinassa, "Hybrid energy storage systems for renewable energy sources integration in microgrids: A review," *2010 9th Int. Power Energy Conf. IPEC 2010*, pp. 532–537, 2010.

[82] T. Bocklisch, "Hybrid energy storage systems for renewable energy applications," *Energy Procedia*, vol. 73, no. 2015, pp. 103–111, 2015.

[83] "World Bank Group Commits $1 Billion for Battery Storage to Ramp Up Renewable Energy Globally." [Online]. Available: https://www.worldbank.org/en/news/press-release/2018/09/26/world-bank-group-commits-1-billion-for-battery-storage-to-ramp-up-renewable-energy-globally. [Accessed: 09-Dec-2020].

[84] "Electricity storage and renewables: Costs and markets to 2030." [Online]. Available: https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets. [Accessed: 09-Dec-2020].

[85] V. Bolborici, F. P. Dawson, and K. K. Lian, "Hybrid energy storage systems: Connecting batteries in parallel with ultracapacitors for higher power density," *IEEE Ind. Appl. Mag.*, vol. 20, no. 4, pp. 31–40, 2014.

[86] J. Cao and A. Emadi, "A new battery/ultracapacitor hybrid energy storage system for

electric, hybrid, and plug-in hybrid electric vehicles," *IEEE Trans. power Electron.*, vol. 27, no. 1, pp. 122–132, 2011.

[87] M. E. Glavin and W. G. Hurley, "Optimisation of a photovoltaic battery ultracapacitor hybrid energy storage system," *Sol. energy*, vol. 86, no. 10, pp. 3009–3020, 2012.

[88] G. Wang, M. Ciobotaru, and V. G. Agelidis, "Power smoothing of large solar PV plant using hybrid energy storage," *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 834–842, 2014.

[89] W. Li, G. Joós, and J. Bélanger, "Real-time simulation of a wind turbine generator coupled with a battery supercapacitor energy storage system," *IEEE Trans. Ind. Electron.*, vol. 57, no. 4, pp. 1137–1145, 2009.

[90] L. Barelli *et al.*, "Flywheel hybridization to improve battery life in energy storage systems coupled to RES plants," *Energy*, vol. 173, pp. 937–950, 2019.

[91] A. M. Gee, F. V. P. Robinson, and R. W. Dunn, "Analysis of battery lifetime extension in a small-scale wind-energy system using supercapacitors," *IEEE Trans. energy Convers.*, vol. 28, no. 1, pp. 24–33, 2013.

[92] R. T. Doucette and M. D. McCulloch, "A comparison of high-speed flywheels, batteries, and ultracapacitors on the bases of cost and fuel economy as the energy storage system in a fuel cell based hybrid electric vehicle," *J. Power Sources*, vol. 196, no. 3, pp. 1163–1170, 2011.

[93] A. Windhorn, "A hybrid static/rotary UPS system," *IEEE Trans. Ind. Appl.*, vol. 28, no. 3, pp. 541–545, 1992.

[94] B. G. Beaman and G. M. Rao, "Hybrid battery and flywheel energy storage system for LEO spacecraft," in *Thirteenth Annual Battery Conference on Applications and Advances. Proceedings of the Conference*, 1998, pp. 113–116.

[95] O. Briat, J. M. Vinassa, W. Lajnef, S. Azzopardi, and E. Woirgard, "Principle, design and experimental validation of a flywheel-battery hybrid source for heavy-duty electric vehicles," *IET Electr. Power Appl.*, vol. 1, no. 5, pp. 665–674, 2007.

[96] H. Lee, B. Y. Shin, S. Han, S. Jung, B. Park, and G. Jang, "Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 5701904, 2011.

[97] G. N. Prodromidis and F. A. Coutelieris, "Simulations of economical and technical feasibility of battery and flywheel hybrid energy storage systems in autonomous projects," *Renew. energy*, vol. 39, no. 1, pp. 149–153, 2012.

[98] M. A. M. Ramli, A. Hiendro, and S. Twaha, "Economic analysis of PV/diesel hybrid system with flywheel energy storage," *Renew. Energy*, vol. 78, pp. 398–405, 2015.

[99] J. Hou, J. Sun, and H. Hofmann, "Control development and performance evaluation for battery/flywheel hybrid energy storage solutions to mitigate load fluctuations in all-electric ship propulsion systems," *Appl. Energy*, vol. 212, pp. 919–930, 2018.

[100] "Schwungrads success in EU Horizon 2020 programme | Schwungrad Energie - Flywheel energy storage." [Online]. Available: https://schwungrad-energie.com/schwungrads-success-eu-horizon-2020-programme/. [Accessed: 10-Dec-2020].

[101] "Add Hystor | Add Hystor." [Online]. Available: https://add-hystor.com/. [Accessed: 10-Dec-2020].

[102] "Solar is now 'cheapest electricity in history', confirms IEA." [Online]. Available: https://www.carbonbrief.org/solar-is-now-cheapest-electricity-in-history-confirms-iea. [Accessed: 10-Dec-2020].

[103] "Europe's largest hybrid flywheel battery project to help grid respond to energy demand - Archive - News archive - The University of Sheffield." [Online]. Available: https://www.sheffield.ac.uk/news/nr/flywheel-europe-energy-1.704921. [Accessed: 10-Dec-2020].

[104] "World Energy Outlook 2020 – Analysis - IEA." [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2020. [Accessed: 10-Dec-2020].

[105] "HOMER Products." [Online]. Available: https://www.homerenergy.com/products/index.html. [Accessed: 10-Dec-2020].

[106] T. Lambert, P. Gilman, and P. Lilienthal, "Micropower system modeling with HOMER," *Integr. Altern. sources energy*, vol. 1, no. 1, pp. 379–385, 2006.

[107] "How HOMER Calculates the PV Array Power Output." [Online]. Available: https://www.homerenergy.com/products/pro/docs/latest/how_homer_calculates_the_pv_array_power_output.html. [Accessed: 11-Dec-2020].

[108] "How HOMER Creates the Generator Efficiency Curve." [Online]. Available: https://www.homerenergy.com/products/pro/docs/latest/how_homer_creates_the_generator_efficiency_curve.html. [Accessed: 11-Dec-2020].

[109] "Converter." [Online]. Available: https://www.homerenergy.com/products/pro/docs/latest/converter.html. [Accessed: 13-Dec-2020].

Appendix A: Cash Flow Beacon Power FESS vs eCAMION BESS

Appendix A presents the discounted cash flow of all the scenarios of Chapter 3. Table 22 and Table 23 present the lifecycle cost assessment of Scenario 1. Table 24 and Table 25 present the lifecycle cost assessment of Scenario 2 while Table 26 and Table 27 present the lifecycle cost assessment of Scenario 3.

Table 22. Discounted cash flow based on max. theoretical energy available (BESS).

BESS										
Year	**Investment**	**Demand Charge Benefit**	**Maintenance**	**Salvage Value**	**Energy Savings Compared to Diesel**	**PV of Costs**	**PV of Benefits**	**Net Cash Flow**	**Cumulative Cash Flow**	**Present Value**
0	($8,881,224)	$0	$0	$0	$0	($8,881,224)	$0	($8,881,224)	($8,881,224)	($8,881,224)
1	$0	$27,093	($140,000)	$0	$1,087,353	($127,272.73)	$1,013,132.73	$974,446	($7,906,778)	$885,860.00
2	$0	$27,093	($140,000)	$0	$1,087,353	($115,702.48)	$921,029.75	$974,446	($6,932,332)	$805,327.27
3	$0	$27,093	($140,000)	$0	$1,087,353	($105,184.07)	$837,299.77	$974,446	($5,957,886)	$732,115.70
4	$0	$27,093	($140,000)	$0	$1,087,353	($95,621.88)	$761,181.61	$974,446	($4,983,440)	$665,559.73
5	$0	$27,093	($140,000)	$0	$1,087,353	($86,928.99)	$691,983.28	$974,446	($4,008,994)	$605,054.30
6	($500,000)	$27,093	($140,000)	$0	$1,087,353	($579,026.35)	$629,075.71	$474,446	($3,534,548)	$267,812.40
7	$0	$27,093	($140,000)	$50,000	$1,087,353	($71,842.14)	$597,544.92	$1,024,446	($2,510,102)	$525,702.78
8	$0	$27,093	($140,000)	$0	$1,087,353	($65,311.03)	$519,897.28	$974,446	($1,535,656)	$454,586.25
9	$0	$27,093	($140,000)	$0	$1,087,353	($59,373.67)	$472,633.89	$974,446	($561,210)	$413,260.23
10	$0	$27,093	($140,000)	$0	$1,087,353	($53,976.06)	$429,667.18	$974,446	$413,236	$375,691.12
11	$0	$27,093	($140,000)	$0	$1,087,353	($49,069.15)	$390,606.52	$974,446	$1,387,682	$341,537.38
12	($500,000)	$27,093	($140,000)	$0	$1,087,353	($544,608.31)	$355,096.84	$474,446	$1,862,128	$151,173.12
13	$0	$27,093	($140,000)	$0	$1,087,353	($40,553.01)	$322,815.31	$974,446	$2,836,574	$282,262.30
14	$0	$27,093	($140,000)	$50,000	$1,087,353	($36,866.38)	$306,635.03	$1,024,446	$3,861,020	$269,768.65
15	$0	$27,093	($140,000)	$0	$1,087,353	($33,514.89)	$266,789.51	$974,446	$4,835,466	$233,274.62
16	$0	$27,093	($140,000)	$0	$1,087,353	($30,468.08)	$242,535.92	$974,446	$5,809,912	$212,067.84
17	$0	$27,093	($140,000)	$0	$1,087,353	($27,698.25)	$220,487.20	$974,446	$6,784,358	$192,788.95
18	($500,000)	$27,093	($140,000)	$0	$1,087,353	($525,180.23)	$200,442.91	$474,446	$7,258,804	$85,333.28
19	$0	$27,093	($140,000)	$0	$1,087,353	($22,891.12)	$182,220.83	$974,446	$8,233,250	$159,329.71
20	$0	$27,093	($140,000)	$50,000	$1,087,353	($20,810.11)	$173,087.48	$1,024,446	$9,257,696	$152,277.37
					Total PVs	($11,573,122.92)	$9,534,163.68		**NPV**	($1,070,441.00)

Table 23. Discounted cash flow based on max. theoretical energy available (FESS).

FESS										
Year	**Investment**	**Demand Charge Benefit**	**Maintenance**	**Salvage Value**	**Energy Savings Compared to Diesel**	**PV of Costs**	**PV of Benefits**	**Net Cash Flow**	**Cumulative Cash Flow**	**Present Value**
0	($8,250,000)	$0	$0	$0	$0	($8,250,000)	$0	($8,250,000)	($8,250,000)	($8,250,000)
1	$0	$27,093	($10,000)	$0	$1,087,353	($9,090.91)	$1,013,132.73	$1,104,446	($7,145,554)	$1,004,041.82
2	$0	$27,093	($10,000)	$0	$1,087,353	($8,264.46)	$921,029.75	$1,104,446	($6,041,108)	$912,765.29
3	$0	$27,093	($10,000)	$0	$1,087,353	($7,513.15)	$837,299.77	$1,104,446	($4,936,662)	$829,786.63
4	$0	$27,093	($10,000)	$0	$1,087,353	($6,830.13)	$761,181.61	$1,104,446	($3,832,216)	$754,351.48
5	$0	$27,093	($10,000)	$0	$1,087,353	($6,209.21)	$691,983.28	$1,104,446	($2,727,770)	$685,774.07
6	$0	$27,093	($10,000)	$0	$1,087,353	($5,644.74)	$629,075.71	$1,104,446	($1,623,324)	$623,430.97
7	$0	$27,093	($10,000)	$0	$1,087,353	($5,131.58)	$571,887.01	$1,104,446	($518,878)	$566,755.43
8	$0	$27,093	($10,000)	$0	$1,087,353	($4,665.07)	$519,897.28	$1,104,446	$585,568	$515,232.21
9	$0	$27,093	($10,000)	$0	$1,087,353	($4,240.98)	$472,633.89	$1,104,446	$1,690,014	$468,392.92
10	$0	$27,093	($10,000)	$0	$1,087,353	($3,855.43)	$429,667.18	$1,104,446	$2,794,460	$425,811.74
11	$0	$27,093	($10,000)	$0	$1,087,353	($3,504.94)	$390,606.52	$1,104,446	$3,898,906	$387,101.59
12	$0	$27,093	($10,000)	$0	$1,087,353	($3,186.31)	$355,096.84	$1,104,446	$5,003,352	$351,910.53
13	$0	$27,093	($10,000)	$0	$1,087,353	($2,896.64)	$322,815.31	$1,104,446	$6,107,798	$319,918.67
14	$0	$27,093	($10,000)	$0	$1,087,353	($2,633.31)	$293,468.46	$1,104,446	$7,212,244	$290,835.15
15	$0	$27,093	($10,000)	$0	$1,087,353	($2,393.92)	$266,789.51	$1,104,446	$8,316,690	$264,395.59
16	$0	$27,093	($10,000)	$0	$1,087,353	($2,176.29)	$242,535.92	$1,104,446	$9,421,136	$240,359.63
17	$0	$27,093	($10,000)	$0	$1,087,353	($1,978.45)	$220,487.20	$1,104,446	$10,525,582	$218,508.75
18	$0	$27,093	($10,000)	$0	$1,087,353	($1,798.59)	$200,442.91	$1,104,446	$11,630,028	$198,644.32
19	$0	$27,093	($10,000)	$0	$1,087,353	($1,635.08)	$182,220.83	$1,104,446	$12,734,474	$180,585.75
20	$0	$27,093	($10,000)	$50,000	$1,087,353	($1,486.44)	$173,087.48	$1,154,446	$13,888,920	$171,601.04
					Total PVs	($8,335,136)	$9,495,339.21		**NPV**	**$1,160,204**

Table 24. Discounted cash flow based on energy consumption (BESS).

BESS										
Year	**Investment**	**Demand Charge Benefit**	**Maintenance**	**Salvage Value**	**Energy Savings Compared to Diesel**	**PV of Costs**	**PV of Benefits**	**Net Cash Flow**	**Cumulative Cash Flow**	**Present Value**
0	($8,881,224)	$0	$0	$0	$0	($8,881,224)	$0	($8,881,224)	($8,881,224)	($8,881,224)
1	$0	$27,093	($140,000)	$0	$68,000	($127,272.73)	$86,448.18	($44,907)	($8,926,131)	($40,824.55)
2	$0	$27,093	($140,000)	$0	$68,000	($115,702.48)	$78,589.26	($44,907)	($8,971,038)	($37,113.22)
3	$0	$27,093	($140,000)	$0	$68,000	($105,184.07)	$71,444.78	($44,907)	($9,015,945)	($33,739.29)
4	$0	$27,093	($140,000)	$0	$68,000	($95,621.88)	$64,949.80	($44,907)	($9,060,852)	($30,672.09)
5	$0	$27,093	($140,000)	$0	$68,000	($86,928.99)	$59,045.27	($44,907)	($9,105,759)	($27,883.71)
6	($500,000)	$27,093	($140,000)	$0	$68,000	($579,026.35)	$53,677.52	($544,907)	($9,650,666)	($307,585.80)
7	$0	$27,093	($140,000)	$50,000	$68,000	($71,842.14)	$74,455.65	$5,093	($9,645,573)	$2,613.51
8	$0	$27,093	($140,000)	$0	$68,000	($65,311.03)	$44,361.59	($44,907)	($9,690,480)	($20,949.45)
9	$0	$27,093	($140,000)	$0	$68,000	($59,373.67)	$40,328.71	($44,907)	($9,735,387)	($19,044.95)
10	$0	$27,093	($140,000)	$0	$68,000	($53,976.06)	$36,662.47	($44,907)	($9,780,294)	($17,313.59)
11	$0	$27,093	($140,000)	$0	$68,000	($49,069.15)	$33,329.52	($44,907)	($9,825,201)	($15,739.63)
12	($500,000)	$27,093	($140,000)	$0	$68,000	($544,608.31)	$30,299.56	($544,907)	($10,370,108)	($173,624.16)
13	$0	$27,093	($140,000)	$0	$68,000	($40,553.01)	$27,545.05	($44,907)	($10,415,015)	($13,007.96)
14	$0	$27,093	($140,000)	$50,000	$68,000	($36,866.38)	$38,207.52	$5,093	($10,409,922)	$1,341.15
15	$0	$27,093	($140,000)	$0	$68,000	($33,514.89)	$22,764.51	($44,907)	($10,454,829)	($10,750.38)
16	$0	$27,093	($140,000)	$0	$68,000	($30,468.08)	$20,695.01	($44,907)	($10,499,736)	($9,773.07)
17	$0	$27,093	($140,000)	$0	$68,000	($27,698.25)	$18,813.64	($44,907)	($10,544,643)	($8,884.61)
18	($500,000)	$27,093	($140,000)	$0	$68,000	($525,180.23)	$17,103.31	($544,907)	($11,089,550)	($98,006.31)
19	$0	$27,093	($140,000)	$0	$68,000	($22,891.12)	$15,548.47	($44,907)	($11,134,457)	($7,342.65)
20	$0	$27,093	($140,000)	$50,000	$68,000	($20,810.11)	$21,567.15	$5,093	($11,129,364)	$757.04
					Total PVs	($11,573,122.92)	$855,836.96		**NPV**	**($9,748,768)**

Table 25. Discounted cash flow based on energy consumption (FESS).

FESS										
Year	**Investment**	**Demand Charge Benefit**	**Maintenance**	**Salvage Value**	**Energy Savings Compared to Diesel**	**PV of Costs**	**PV of Benefits**	**Net Cash Flow**	**Cumulative Cash Flow**	**Present Value**
0	($8,250,000)	$0	$0	$0	$0	($8,250,000)	$0	($8,250,000)	($8,250,000)	($8,250,000)
1	$0	$27,093	($10,000)	$0	$39,520	($9,090.91)	$60,557.27	$56,613	($8,193,387)	$51,466.36
2	$0	$27,093	($10,000)	$0	$39,520	($8,264.46)	$55,052.07	$56,613	($8,136,774)	$46,787.60
3	$0	$27,093	($10,000)	$0	$39,520	($7,513.15)	$50,047.33	$56,613	($8,080,161)	$42,534.18
4	$0	$27,093	($10,000)	$0	$39,520	($6,830.13)	$45,497.58	$56,613	($8,023,548)	$38,667.44
5	$0	$27,093	($10,000)	$0	$39,520	($6,209.21)	$41,361.43	$56,613	($7,966,935)	$35,152.22
6	$0	$27,093	($10,000)	$0	$39,520	($5,644.74)	$37,601.30	$56,613	($7,910,322)	$31,956.56
7	$0	$27,093	($10,000)	$0	$39,520	($5,131.58)	$34,183.00	$56,613	($7,853,709)	$29,051.42
8	$0	$27,093	($10,000)	$0	$39,520	($4,665.07)	$31,075.46	$56,613	($7,797,096)	$26,410.38
9	$0	$27,093	($10,000)	$0	$39,520	($4,240.98)	$28,250.41	$56,613	($7,740,483)	$24,009.44
10	$0	$27,093	($10,000)	$0	$39,520	($3,855.43)	$25,682.20	$56,613	($7,683,870)	$21,826.76
11	$0	$27,093	($10,000)	$0	$39,520	($3,504.94)	$23,347.45	$56,613	($7,627,257)	$19,842.51
12	$0	$27,093	($10,000)	$0	$39,520	($3,186.31)	$21,224.95	$56,613	($7,570,644)	$18,038.65
13	$0	$27,093	($10,000)	$0	$39,520	($2,896.64)	$19,295.41	$56,613	($7,514,031)	$16,398.77
14	$0	$27,093	($10,000)	$0	$39,520	($2,633.31)	$17,541.28	$56,613	($7,457,418)	$14,907.97
15	$0	$27,093	($10,000)	$0	$39,520	($2,393.92)	$15,946.62	$56,613	($7,400,805)	$13,552.70
16	$0	$27,093	($10,000)	$0	$39,520	($2,176.29)	$14,496.93	$56,613	($7,344,192)	$12,320.64
17	$0	$27,093	($10,000)	$0	$39,520	($1,978.45)	$13,179.03	$56,613	($7,287,579)	$11,200.58
18	$0	$27,093	($10,000)	$0	$39,520	($1,798.59)	$11,980.93	$56,613	($7,230,966)	$10,182.35
19	$0	$27,093	($10,000)	$0	$39,520	($1,635.08)	$10,891.76	$56,613	($7,174,353)	$9,256.68
20	$0	$27,093	($10,000)	$50,000	$39,520	($1,486.44)	$17,333.78	$106,613	($7,067,740)	$15,847.34
					Total PVs	($8,335,136)	$574,546.20		**NPV**	**($7,760,589)**

Table 26. Discounted cash flow based on average power consumption (BESS).

BESS										
Year	**Investment**	**Demand Charge Benefit**	**Maintenance**	**Salvage Value**	**Energy Savings Compared to Diesel**	**PV of Costs**	**PV of Benefits**	**Net Cash Flow**	**Cumulative Cash Flow**	**Present Value**
0	($8,881,224)	$0	$0	$0	$0	($8,881,224.00)	$0.00	($8,881,224)	($8,881,224)	($8,881,224)
1	$0	$27,093	($140,000)	$0	$467,562	($127,272.73)	$449,686.36	$354,655s	($8,526,569)	$322,413.64
2	$0	$27,093	($140,000)	$0	$467,562	($115,702.48)	$408,805.79	$354,655	($8,171,914)	$293,103.31
3	$0	$27,093	($140,000)	$0	$467,562	($105,184.07)	$371,641.62	$354,655	($7,817,259)	$266,457.55
4	$0	$27,093	($140,000)	$0	$467,562	($95,621.88)	$337,856.02	$354,655	($7,462,604)	$242,234.14
5	$0	$27,093	($140,000)	$0	$467,562	($86,928.99)	$307,141.84	$354,655	($7,107,949)	$220,212.85
6	($500,000)	$27,093	($140,000)	$0	$467,562	($361,263.32)	$279,219.85	($145,345)	($7,253,294)	($82,043.46)
7	$0	$27,093	($140,000)	$50,000	$467,562	($71,842.14)	$279,494.13	$404,655	($6,848,639)	$207,652.00
8	$0	$27,093	($140,000)	$0	$467,562	($65,311.03)	$230,760.21	$354,655	($6,493,984)	$165,449.17
9	$0	$27,093	($140,000)	$0	$467,562	($59,373.67)	$209,782.01	$354,655	($6,139,329)	$150,408.34
10	$0	$27,093	($140,000)	$0	$467,562	($53,976.06)	$190,710.92	$354,655	($5,784,674)	$136,734.86
11	$0	$27,093	($140,000)	$0	$467,562	($49,069.15)	$173,373.56	$354,655	($5,430,019)	$124,304.41
12	($500,000)	$27,093	($140,000)	$0	$467,562	($203,923.72)	$157,612.33	($145,345)	($5,575,364)	($46,311.40)
13	$0	$27,093	($140,000)	$0	$467,562	($40,553.01)	$143,283.93	$354,655	($5,220,709)	$102,730.92
14	$0	$27,093	($140,000)	$50,000	$467,562	($36,866.38)	$143,424.68	$404,655	($4,816,054)	$106,558.31
15	$0	$27,093	($140,000)	$0	$467,562	($33,514.89)	$118,416.47	$354,655	($4,461,399)	$84,901.59
16	$0	$27,093	($140,000)	$0	$467,562	($30,468.08)	$107,651.34	$354,655	($4,106,744)	$77,183.26
17	$0	$27,093	($140,000)	$0	$467,562	($27,698.25)	$97,864.85	$354,655	($3,752,089)	$70,166.60
18	($500,000)	$27,093	($140,000)	$0	$467,562	($115,109.63)	$88,968.05	($145,345)	($3,897,434)	($26,141.58)
19	$0	$27,093	($140,000)	$0	$467,562	($22,891.12)	$80,880.05	$354,655	($3,542,779)	$57,988.93
20	$0	$27,093	($140,000)	$50,000	$467,562	($20,810.11)	$80,959.50	$404,655	($3,138,124)	$60,149.39
					Total PVs	($10,604,604.69)	$4,257,533.51		**NPV**	($6,347,071.18)

Table 27. Discounted cash flow based on average power consumption (FESS).

FESS										
Year	**Investment**	**Demand Charge Benefit**	**Maintenance**	**Salvage Value**	**Energy Savings Compared to Diesel**	**PV of Costs**	**PV of Benefits**	**Net Cash Flow**	**Cumulative Cash Flow**	**Present Value**
0	($8,250,000)	$0	$0	$0	$0	($8,250,000)	$0	($8,250,000)	($8,250,000)	($8,250,000)
1	$0	$27,093	($10,000)	$0	$532,231	($9,090.91)	$508,476.36	$549,324	($7,700,676)	$499,385.45
2	$0	$27,093	($10,000)	$0	$532,231	($8,264.46)	$462,251.24	$549,324	($7,151,352)	$453,986.78
3	$0	$27,093	($10,000)	$0	$532,231	($7,513.15)	$420,228.40	$549,324	($6,602,028)	$412,715.25
4	$0	$27,093	($10,000)	$0	$532,231	($6,830.13)	$382,025.82	$549,324	($6,052,704)	$375,195.68
5	$0	$27,093	($10,000)	$0	$532,231	($6,209.21)	$347,296.20	$549,324	($5,503,380)	$341,086.98
6	$0	$27,093	($10,000)	$0	$532,231	($5,644.74)	$315,723.82	$549,324	($4,954,056)	$310,079.08
7	$0	$27,093	($10,000)	$0	$532,231	($5,131.58)	$287,021.65	$549,324	($4,404,732)	$281,890.07
8	$0	$27,093	($10,000)	$0	$532,231	($4,665.07)	$260,928.77	$549,324	($3,855,408)	$256,263.70
9	$0	$27,093	($10,000)	$0	$532,231	($4,240.98)	$237,207.98	$549,324	($3,306,084)	$232,967.00
10	$0	$27,093	($10,000)	$0	$532,231	($3,855.43)	$215,643.61	$549,324	($2,756,760)	$211,788.18
11	$0	$27,093	($10,000)	$0	$532,231	($3,504.94)	$196,039.65	$549,324	($2,207,436)	$192,534.71
12	$0	$27,093	($10,000)	$0	$532,231	($3,186.31)	$178,217.86	$549,324	($1,658,112)	$175,031.56
13	$0	$27,093	($10,000)	$0	$532,231	($2,896.64)	$162,016.24	$549,324	($1,108,788)	$159,119.60
14	$0	$27,093	($10,000)	$0	$532,231	($2,633.31)	$147,287.49	$549,324	($559,464)	$144,654.18
15	$0	$27,093	($10,000)	$0	$532,231	($2,393.92)	$133,897.72	$549,324	($10,140)	$131,503.80
16	$0	$27,093	($10,000)	$0	$532,231	($2,176.29)	$121,725.20	$549,324	$539,184	$119,548.91
17	$0	$27,093	($10,000)	$0	$532,231	($1,978.45)	$110,659.27	$549,324	$1,088,508	$108,680.82
18	$0	$27,093	($10,000)	$0	$532,231	($1,798.59)	$100,599.34	$549,324	$1,637,832	$98,800.75
19	$0	$27,093	($10,000)	$0	$532,231	($1,635.08)	$91,453.94	$549,324	$2,187,156	$89,818.86
20	$0	$27,093	($10,000)	$50,000	$532,231	($1,486.44)	$90,572.13	$599,324	$2,786,480	$89,085.69
					Total PVs	($8,335,135.64)	$4,769,272.70		**NPV**	($3,565,862.94)

Appendix B: Community Case Study- Scenario 1

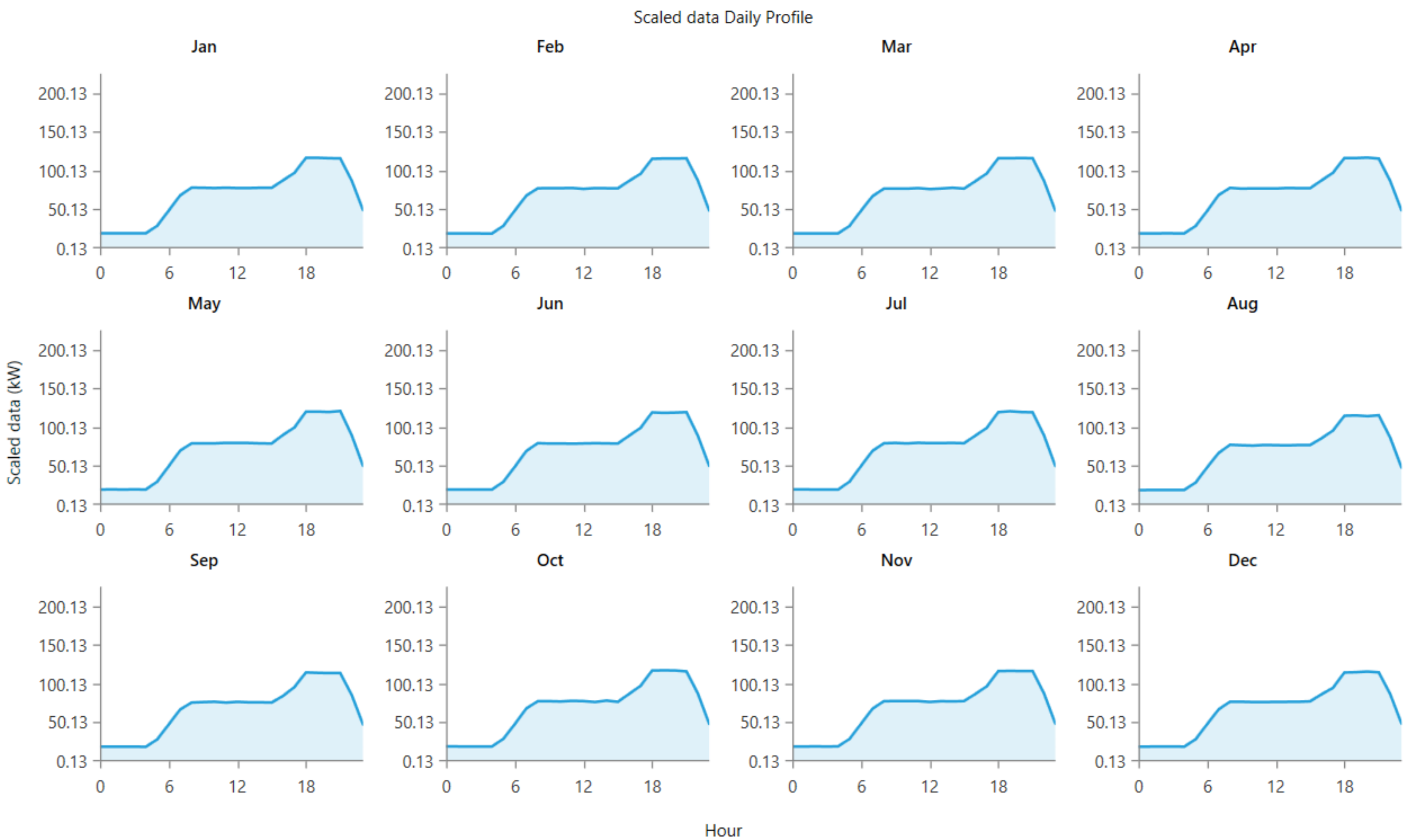


Figure 27. Hourly load profile for community for each month of a year.

Figure 27 depicts the hourly load profile of a community for each month of a year, that is served by the different components and storage systems in different scenarios. Figure 28 presents the schematic of microgrid in Scenario 1 with the load served only by the generator.

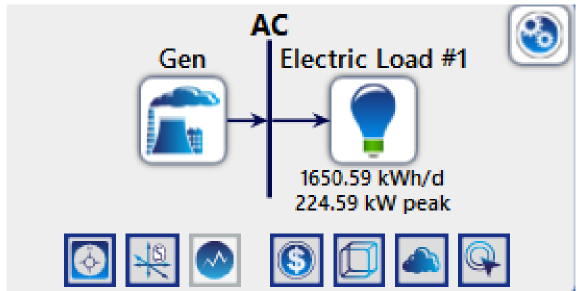


Figure 28. Schematic of standalone microgrid with diesel generator (Scenario 1 – Community microgrid).

Figure 29 presents the power output of the generator for a whole year. The generator produced 711,176 kWh/year with mean electrical output of 81.2 kW. The average fuel consumption by the generator was 0.417 L/hr. When the load was served only by the generator, it resulted in highest GHG emissions when compared to other scenarios. Table 28 indicates the quantity of GHG emissions in a single year. About half a million kilograms of carbon dioxide was released into the atmosphere every year.

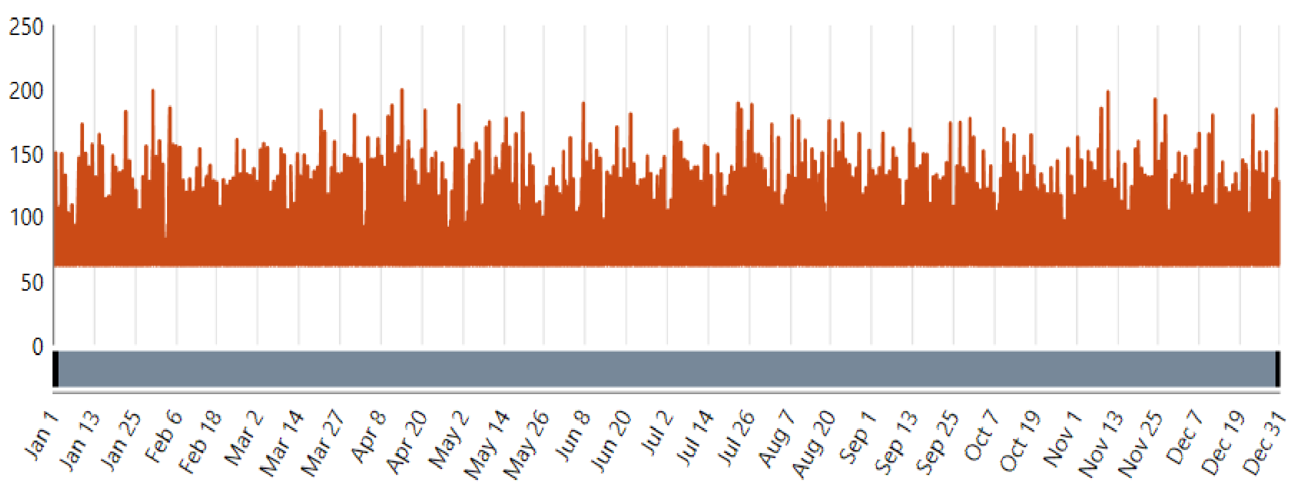


Figure 29. Generator power output (kW) for microgrid with diesel generator (Scenario 1 – Community microgrid).

Table 28. GHG emissions for microgrid with diesel generator (Scenario 1 – Community microgrid).

Emissions	Value	Unit
Carbon dioxide	573,658	kg/yr
Carbon monoxide	3,616	kg/yr
Unburned hydrocarbons	158	kg/yr
Particulate matter	21.9	kg/yr
Sulfur dioxide	1,405	kg/yr
Nitrogen oxides	3,397	kg/yr

Figure 30 presents the discounted cash flow of the generator based microgrid. All costs including capital, replacement, O&M, and fuel costs are presented in the graph.

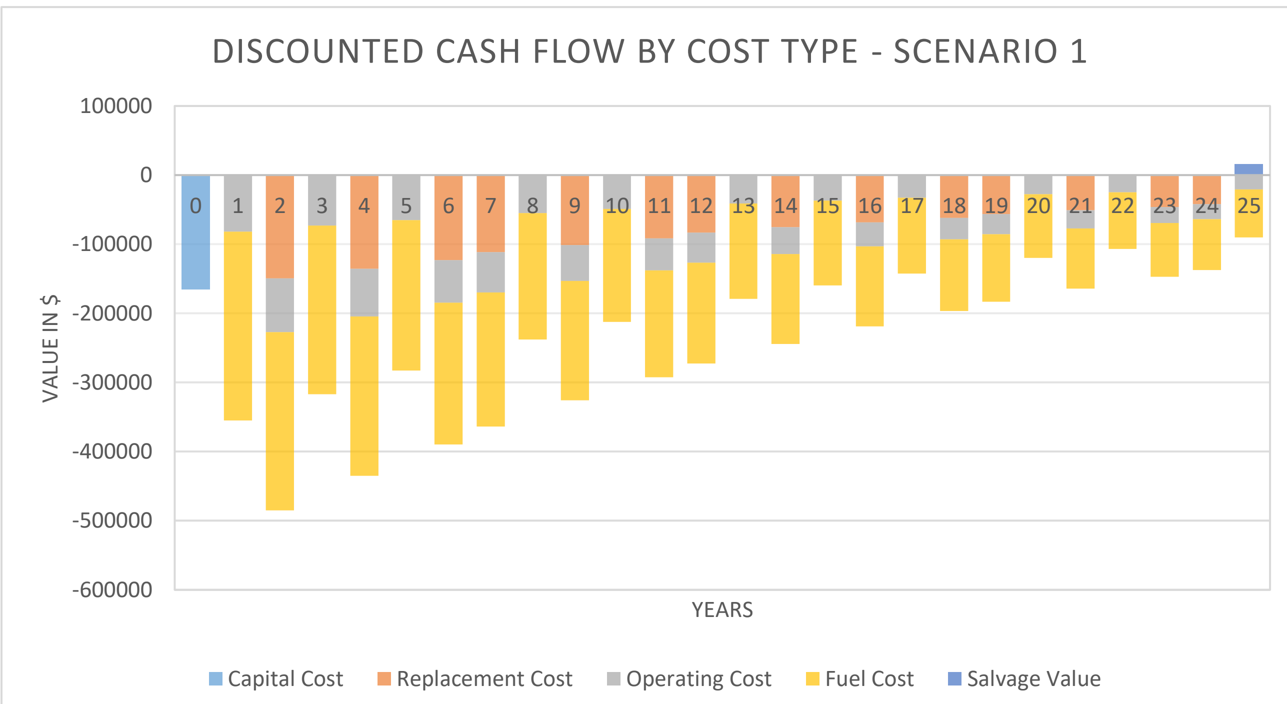


Figure 30. Discounted cash flow by type of cost incurred for microgrid with diesel generator (Scenario 1 - Community microgrid).

Appendix C: Community Case Study- Scenario 2

Figure 31 presents the schematic of a PV array, generator and lithium-ion BESS based microgrid. The microgrid includes only one ESS, that is, a 100 kWh lithium-ion BESS. Solar PV array was used to introduce green energy and minimize the use of generator, to achieve the goal of reduced GHG emissions.

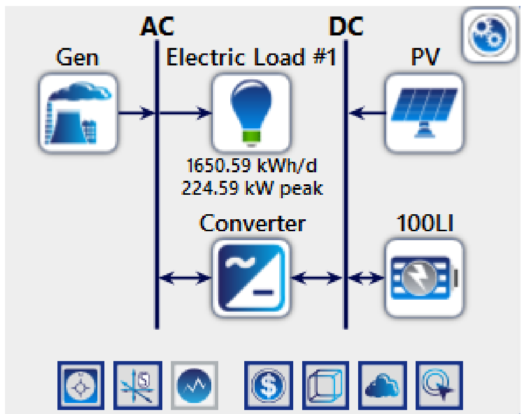


Figure 31. Schematic of standalone microgrid with diesel generator, solar PV, and BESS (Scenario 2 - Community microgrid).

The daily power output of the PV array for a week is shown in Figure 32. The mean output of PV array was 1,364 kWh/day and the annual total produced electricity was 498,008 kWh. The COE of PV array was calculated to be $0.129/kWh and the yearly hours of operation were 4,385.

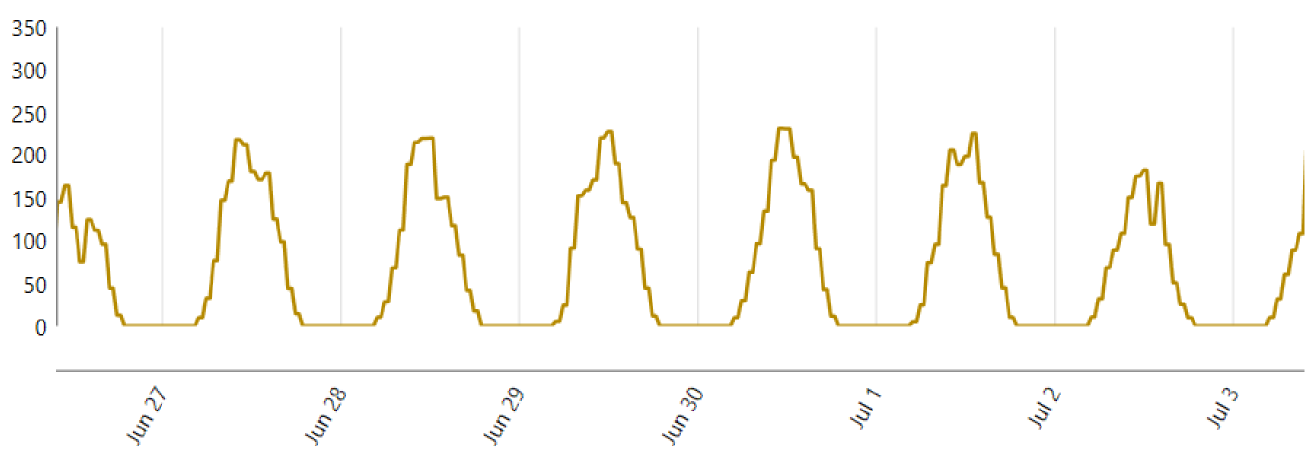


Figure 32. Sample PV array power output (kW) for microgrid with diesel generator, solar PV, and BESS (Scenario 2 – Community microgrid).

Sample generator's power output for a week can be seen in Figure 33. Fuel consumption by the generator was 68,080 L/year with a specific fuel consumption value of 0.306 L/kWh. The fixed generation cost and the marginal generation cost was \$7.23/hr and \$0.273/kWh, respectively. The average operational life of the generator was 4.99 yrs. The gases released are less than Scenario 1 and the emissions information is presented in Table 29.

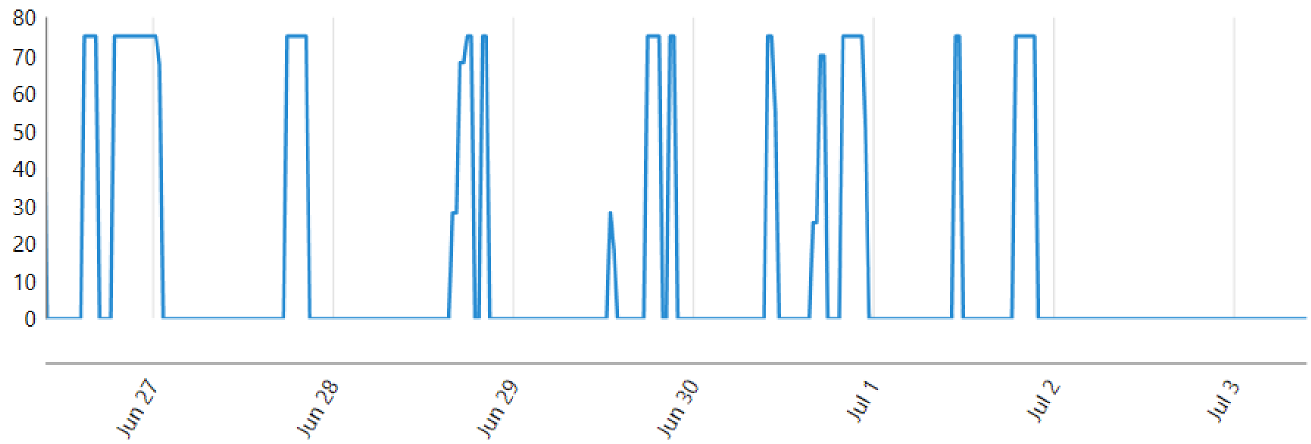


Figure 33. Sample generator power output (kW) for microgrid with diesel generator, solar PV, and BESS (Scenario 2 – Community microgrid).

Table 29. GHG emissions for microgrid with diesel generator, solar PV and BESS (Scenario 2 – Community microgrid).

Emission	Value	Unit
Carbon dioxide	178,225	kg/yr
Carbon monoxide	1,112	kg/yr
Unburned hydrocarbons	49	kg/yr
Particulate matter	6.67	kg/yr
Sulfur dioxide	436	kg/yr
Nitrogen oxides	1,046	kg/yr

It can be seen from the Figure 34 that highest capital cost is allocated to lithium-ion BESS and PV array. On the contrary, the capital cost of the generator is considerable low but other costs are higher each respective year, compared to other components of the system.

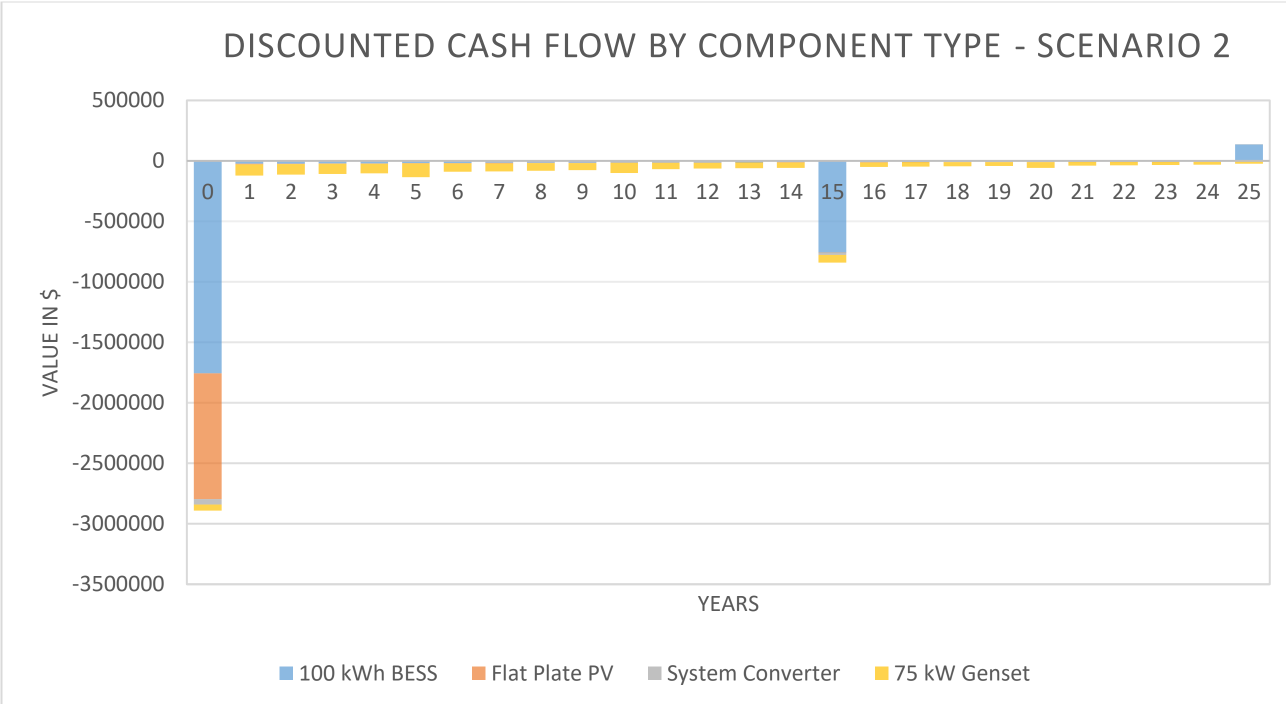


Figure 34. Discounted cash flow by component type for microgrid with diesel generator, solar PV and BESS (Scenario 2 - Community microgrid).

Appendix D: Community Case Study- Scenario 3

Figure 35 shows the schematic of the hybrid micro-grid (PV, generator, lithium-ion BESS, and FESS). Fly160, in the figure represents a 160 kW FESS and 100LI represents 100 kWh lithium-ion BESS.

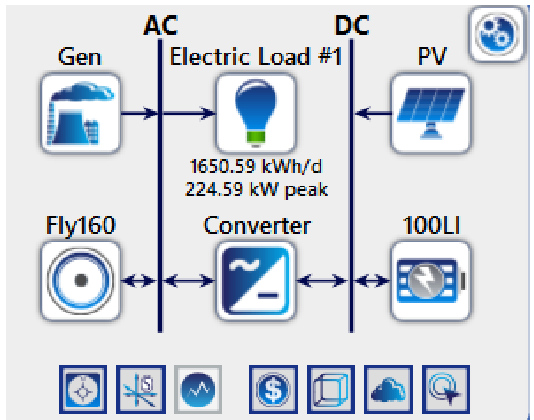


Figure 35. Schematic of standalone microgrid with diesel generator, solar PV, BESS and FESS (Scenario 3 - Community microgrid).

Figure 36 depicts daily power output of PV array over one week. Electricity produced in a single year was 434,884 kWh. The levelized cost of energy of PV array was calculated to be 0.129 \$/kWh and the yearly hours of operation were 4,385.

A one-week section of generator power output is depicted in Figure 37. Generator consumed 107,630 L fuel every year with a specific fuel consumption value of 0.306 L/kWh. The average operational life of the generator was 3.17 yrs. The fixed generation cost was \$7.23/hr and the marginal generation cost was \$0.273/kWh. Table 30 presents the yearly emissions from the generator.

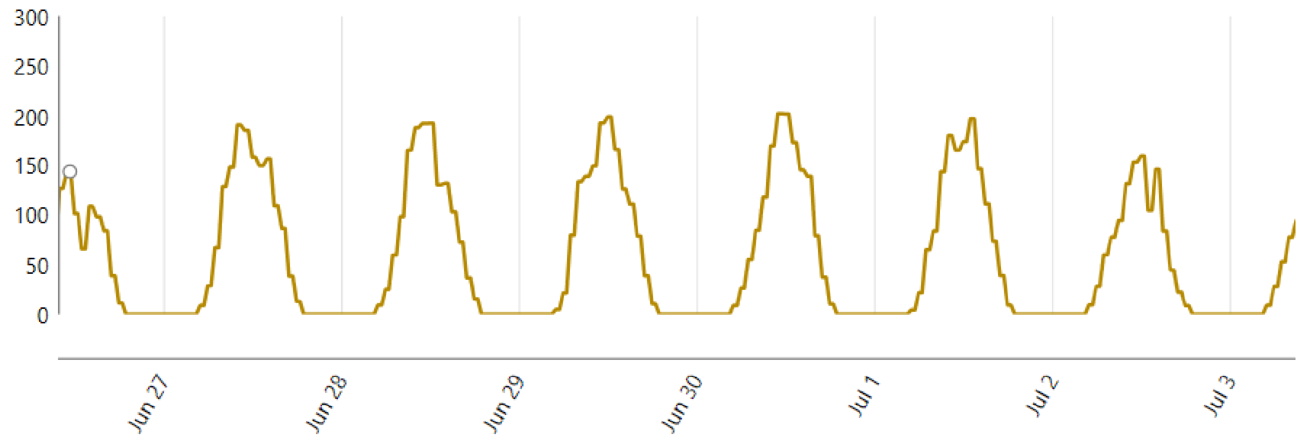


Figure 36. Sample PV array power output (kW) for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 – Community microgrid).

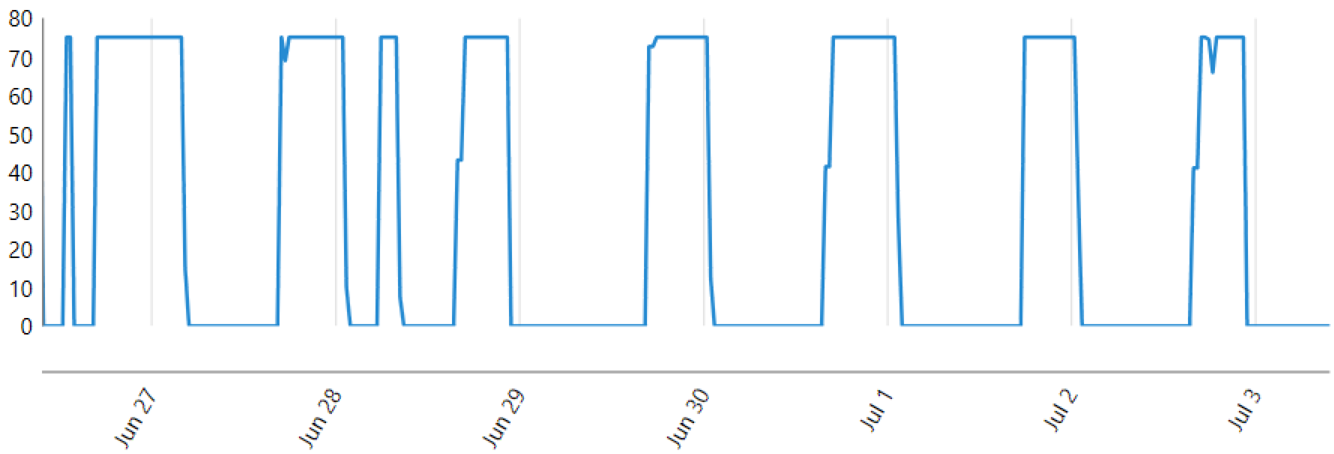


Figure 37. Sample generator power output (kW) for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 – Community microgrid).

Table 30. GHG emissions for microgrid with diesel generator, solar PV, BESS, and FESS (Scenario 3 – Community microgrid).

Emission	Value	Unit
Carbon dioxide	281,762	kg/yr
Carbon monoxide	1,759	kg/yr
Unburned hydrocarbons	77.5	kg/yr
Particulate matter	10.5	kg/yr
Sulfur dioxide	690	kg/yr
Nitrogen oxides	1,653	kg/yr

Yearly costs incurred by PV array, FESS, lithium-ion BESS, generator, and converter are presented in Figure 38. Capital cost of generator is low but the remaining costs are higher when compared to other components.

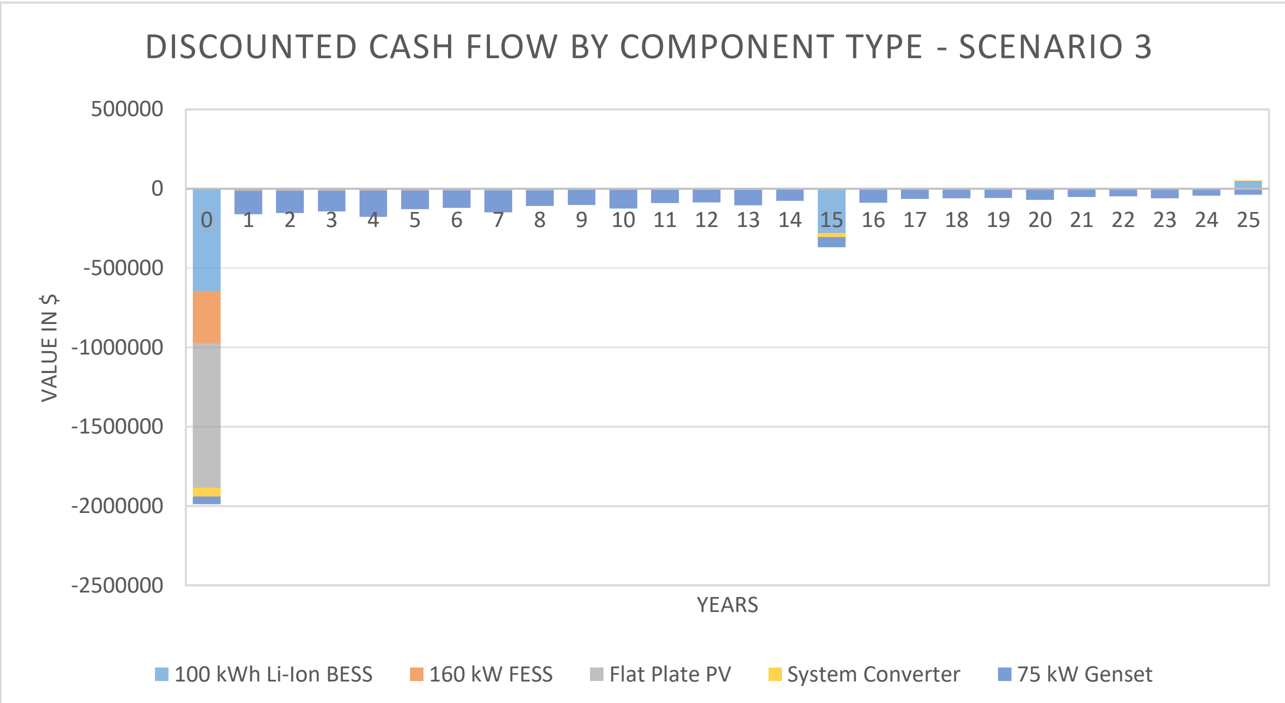


Figure 38. Discounted cash flow by component type for microgrid with diesel generator, solar PV, BESS and FESS (Scenario 3 - Community microgrid).