OPTIMAL MANAGEMENT OF MOBILE ENERGY GENERATION AND STORAGE SYSTEMS

by

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Dedication

To my husband, Mahmoud: My rock in life

To my son, Faris: My motivation and my joy

Abstract

As the global demand for energy increases, new technologies are needed to satisfy the necessity for the electrical network growth. As part of a Smart Grid (SG), Distributed Energy Resources (DERs) are adopted to enhance the efficiency, stability, reliability, and the power quality of the electric grid, in addition to, deferring the need for network upgrades. However, in many cases, there is a temporary need for a DER supply such as during peak grid prices, planned outages, and forced outages. Thus, a mobile energy resource can be utilized in these cases to serve several customers. The research presented in this thesis proposes a new approach to optimally dispatch and schedule a Mobile Energy Generation and Storage System (MEGSS) fleet of electric trucks that encompass three types of DER, namely photo-voltaic (PV) panels, dispatchable generator, and battery energy storage system (BESS). The aim of the proposed approach is to maximize the profit of the MEGSS while meeting customers' requirements. The outcomes of the proposed approach are the day-ahead optimal decisions regarding the customers to be served, the route to be followed by each MEGSS in the fleet, and the onboard resources scheduling. To develop these optimal decisions, the proposed approach utilizes traffic information, customers’ requests, PV generation forecast, and offered energy and demand charges. The MEGSS dispatch problem is formulated as a mixed-integer non-linear programming (MINLP) problem, which is decomposed into two sub-problems: an outer problem and an inner problem. The outer problem decides on the customers to be served and the route to be followed, while the inner problem decides on the onboard resources scheduling. The resulted optimal decisions will be used by the dispatch center to mobilize and schedule the fleet of MEGSS units.The proposed approach has been tested on a typical set of 19 industrial customers to optimally dispatch a sample fleet of two trucks. Results show a maximum daily profit of $945 by using two trucks. The suggested method successfully achieved the anticipated goal of the system of attaining maximum profits by reducing daily operation costs.

Keywords: ***Genetic Algorithm, Mobile Energy Storage System, Dispatch, Scheduling, MINLP***

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List of Abbreviations

Abbreviation:	***Description:***
API	Application Program Interface
BARON	Branch And Reduction Optimization Navigator
BESS	Battery Energy Storage System
DG	Distributed Generation
DER	Distributed Energy Resources
DSM	Demand Side Management
ESS	Energy Storage System
EV	Electric Vehicle
GA	Genetic Algorithm
ICE	Internal Combustion Engine
MEGSS	Mobile Energy Generation and Storage System
MINLP	Mixed Integer Non-Linear Programming
MT	Micro Turbine
PV	Photo-Voltaic
RES	Renewable Energy Resources
SG	Smart Grid
V2G	Vehicle-to-Grid
WT	Wind Turbine

Nomenclature

Sets:

$\mathbb{I}$	Set of stops
$\mathbb{C}$	Subset of customers, $\mathbb{C} \subset \mathbb{I}$
$\mathbb{V}$	Set of trucks
$\mathbb{T}$	Set of time segments

Indices

i and j	Indices of stops
t	Index of time segments
v	Index of trucks

Parameters

Δ_t	Time step in minutes
T_i^{start}	Serving start time for customer i
T_i^{end}	Serving end time
$T_{t,i,j}^{travel}$	Travel time between customers
$T_i^{duration}$	Serving duration
T^{cnn}	System connecting time
T^{dcnn}	System disconnecting time
$D_{i,j}$	Distance between customers
k_{PV}	Factor of PV array extension while stationary
p_{t}^{kWh}	Price of sold energy in \$/kWh
p^{kW}	Demand charges in \$/kW
p_v^{fuel}	Diesel fuel price in \$/L
p_t^{grid}	Price of energy from the grid in \$/kWh

$\eta_{v,t}^{BAT-ch}$	Efficiency of charging the battery
$\eta_{v,t}^{BAT-dis}$	Efficiency of discharging the battery
$\eta_{v,t}^{disp}$	Efficiency of the diesel generator
E^{truck}	Energy consumed in kWh/km
E_{max}^{BAT}	Maximum stored energy of the battery
P_{max}^{grid}	Maximum allowed power to be drawn from the grid
P_{max}^{BAT-ch}, $P_{max}^{BAT-dis}$	Maximum battery charging and discharging power, respectively
SOC_0	Initial battery state of charge
SOC_{max}	Maximum battery state of charge
$MDOD$	Battery maximum depth of discharge
P_{min}^{disp}, P_{max}^{disp}	Minimum and maximum output power of diesel generator, respectively
$P_{t,i}^{req}$	Required real power by customer i
$Q_{t,i}^{req}$	Required reactive power by customer i

Variables:

R_i^{kWh}	Revenue of sold energy in $
R_i^{kW}	Revenue of demand charges in $
C_v^{opr}	Total operation cost of the proposed system
C_v^{fuel}	Cost of fuel
C_v^{grid}	Cost of real power purchased from the grid
C_v^{Deg}	Cost of components degradation
$p^{no-load}$	Cost associated with running the dispatchable unit at no-load
$P_{i,t}^{\mathrm{Customer}}$	Real power of chosen customer i
$P_{v,t}^{PV}$	Output power of the PV array
$P_{v,t}^{disp}$	Dispatchable unit output power in kW

$P_{v,t}^{truck}$	Power consumed by the truck in kW
$P_{v,t}^{BAT-dis}$	Battery discharging power
$P_{v,t}^{BAT-ch}$	Battery charging power
$P_{v,t}^{grid}$	Real power consumed from the grid
$SOC_{v,t}$	Battery state of charge
$x_{v,t}^{disp-on}$	Binary decision of turning on the dispatchable unit
$X_{i,v}^{selection}$	Binary decision for selecting customer i to be served by truck v

Chapter - 1 Introduction

Due to the increase of the global population and cities' expansion, in addition to the rapid advancement in technology, the dependency on electricity is rapidly increasing. Future power grids will witness a shift in focus to Renewable Energy Sources (RES) and Energy Storage Systems (ESS) to accommodate the expansion requirements of power without compromising on the minimization of CO_2 emissions. The State of California has placed a mandate to have more than 1300 MW of its power from storage units [1]. Due to multiple beneficial factors, the use of lithium-ion battery ESS (BESS) has significantly increased, lowering its prices [2], making it more attractive for utilities to incorporate such technologies in their systems. The importance of ESS has arisen from the increased penetration of RES to the grid. Due to their intermittent nature, RES units can be problematic to the stability and reliability of the network. Utilizing ESS on conjunction with RES will 1) provide an efficient way to store energy while it is not being used, 2) contribute to an almost stable power output, and 3) provide voltage support through VAR compensation [3].

The focus of mobile ESS research in recent years have been in the form of Electric Vehicles (EV). To use EV's as mobile storage units, the vehicle would participate in grid activities where it would supply power to the grid in times of on-peak selling prices, while charging its batteries during off-peak hours, thus minimizing power drawn from the grid, and capitalizing on the storage capacity of the EV [4]. This concept, however, known as Vehicle-to-Grid or V2G, is not the focus of this thesis. Alternatively, mobile energy storage systems discussed here refer to systems whose main objective is to operate as a Distributed Generation (DG) unit providing power to the grid or directly to the load as required.

The need for such units stems from the increased black-outs caused by various reasons: operational faults, natural disasters, events of war or terrorist attacks [5] – [6]. During those unfortunate events, parts of or the entire grid might be compromised, leaving people disconnected for days. In the presence of vital facilities, such as hospitals, having a power supply is an essential factor in the survival of human beings and the welfare of the community.

On the other hand, the advantage of mobility has proven its worth during such events, as well as during normal operation hours or scheduled outages for maintenance. Therefore, it is beneficial to have a generation or ESS unit that is capable of being transported from one location to another, supplying multiple customers throughout a short period of time.

Various global energy companies have realized the importance of the factor of mobility on power generation resources and are starting to put more emphasis on their production in that area. General Electric, a world-leading company in the field of energy generation, has launched several solutions with different capacities, 31 MW – 203 MW, and different installation time that can serve in a number of ways [7]. This fast, portable power plant can be useful in several cases to clients who required a temporary source of power on-site. Additionally, those units can be flexible in terms of fuel used. Some might require traditional fuels only, while others can accommodate a range of 52 different types of fuels [7].

Another company, Solar Turbines, also offer a range of mobile power plants that were successful in providing solutions to several customers in North and South America. In one case in Venezuela, the company sent multiple mobile natural gas turbine power plants to provide energy in the event of an emergency. A drought that hit the country had caused generation loss from their hydroelectric plants, effecting 65% of the country's total power production. 16 15-MW units were shipped to cover the requirement of almost 1 GW of continuous, stable, uninterrupted power supply [8].

Another world-leading company in the energy sector, Siemens, has also introduced it's 44 MW gas turbine portable power plant that can be delivered, set up, and installed in a span of two weeks. The unit is one of the most powerful and highly efficient portable units available on the market [9].

1.1 Thesis Motivation

The work done in this thesis was motivated by the absence of research related to the dispatch/scheduling of Mobile Energy Generation and Storage Systems (MEGSS). The services of the proposed system can be used to supply customers in the following conditions:

- *Peak demand periods:* Due to short-time peak demand power, typically for industrial customers, utilities often implement very high charges on consumers, requiring them to look for an economically lucrative alternative source of power. The proposed MEGSS in this thesis presents an ideal solution for the various events discussed.
- *Planned Outages:* In times of expected power outage, as in scheduled maintenance, the proposed system can provide power to the location or bus effected by the maintenance.
- *Forced outages:* In times of an emergency, when power is disconnected from one or more busses on the grid, using the proposed system can compensate for the lost power for few hours. The advantage of mobility makes it possible to serve multiple busses/customers during the same day, or until grid power is re-connected.

1.2 Thesis Objectives

The work done in this thesis aims at completing the following:

- Modelling and designing of the proposed MEGSS that encompasses PV panels, a dispatchable generation unit, and a lithium-ion BESS.
- Developing an optimal day-ahead management approach for a single MEGSS unit that would serve multiple customers based on their requirement, traffic, and available resources to maximize the profit of the MEGSS.
- Expanding the proposed approach to manage a fleet of MEGSS trucks.

In correspondence with the thesis's objectives, and the global emphasis on protecting the environment from harmful emissions, the truck used for this system is an electric truck that uses power stored in the BESS for its consumption. The BESS is charged by the mounted PV panels and, when needed, by a dispatchable generator. The work starts with determining the components required for the system. This includes the size and type of PV Panels, electric truck, diesel generator, bi-directional inverter, and the batteries. Upon deciding on those factors, all these components can be put together as one unit, keeping in mind space and weight limitations. Based on the developed optimal decision of the proposed management approach, the MEGSS truck will have instructions from a dispatch center or the hub to move between chosen customers and to deliver their required amount of energy during a specified time of the day. The process of work done in this thesis is shown in Figure 1-1.

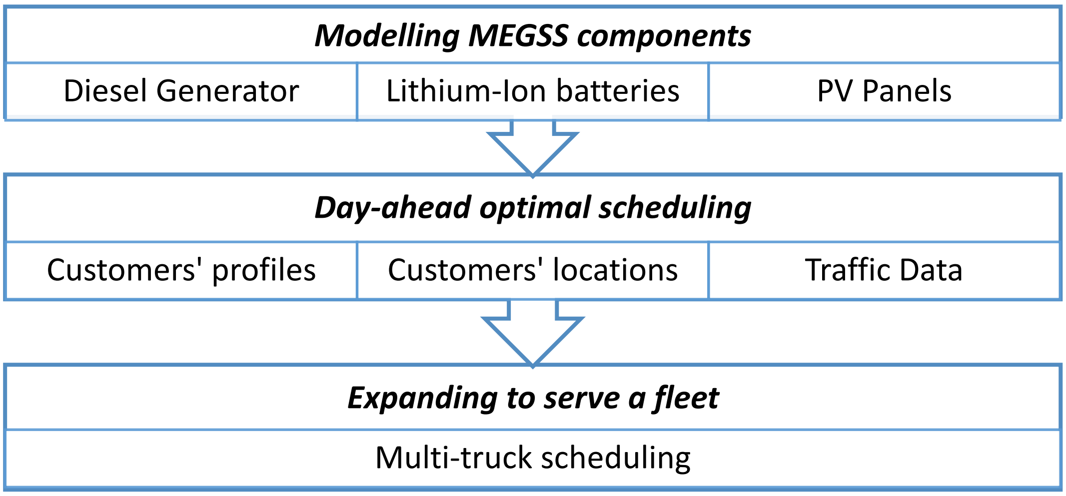

Figure 1-1 Process of proposed work

1.3 Thesis Organization

This thesis is organized as follows. Chapter 2 presents background information about the topic. Similar work done in the field is also presented in Chapter 2. Chapter 3 discuss the proposed system in detail including the proposed approach and the system components. The problem formulation will also be discussed in more details in Chapter 3 of this document. Different case studies and their results will be discussed in Chapter 4. The conclusion and suggested future work are discussed in Chapter 5.

Chapter - 2 Background & Literature Review

To fully understand the motivation, and the objectives of the work done in this thesis, we must clearly identify the components or the technologies that have emerged which led to the necessity of designing and modelling the MEGSS unit discussed. In this section, an overview of Smart Grids (SG) and demand side management (DSM) will be summarized in order to give the readers a better understanding of the full system. The definitions, benefits and types of distributed generation (DG) will be discussed. Light must be shed on ESS and their benefits, specifically mobile energy storage systems which is the main topic of this research.

2.1 Smart Grid (SG)

An important upgrade that has been affecting our power generation and consumption is the shift of the currently existing traditional energy networks to the concept of SG. The traditional grid relies on central generation units and delivers the power to its customers through transmission and distribution networks. However, the SG is characterized by a bi-directional flow of power and information to create an advanced network that has a number of traits [10],[41]:

- It's an intelligent, digital network that has the capability of self-monitoring and self-healing techniques.
- It is adaptive to demand needs and to events effecting the power supply.
- It uses two-way communication to improve the efficiency and reliability of the grid.
- It uses smart devices, such as sensors and smart meters, throughout the network to enhance its capabilities.
- It allows the integration of DG units and controls their behavior to avoid any disturbances.
- It optimizes the grid operations and resources to avoid power losses and minimize CO_2 emissions.

The SG relies on various smaller systems to carry out its functionality. Three subsystems are responsible for crucial aspects of the SG and are categorized as follows [18]:

- *Smart Infrastructure system*: considered as the fundamental layer of communication, energy and information in the SG, the smart infrastructure system supports 1) advanced power generation, delivery, and consumption; 2) advanced metering, monitoring, and management of information; and 3) innovative communication tools.
- *Smart management system*: is the layer responsible for advanced monitoring and control of various components of the SG.
- *Smart protection system*: a crucial layer of the SG, which provides the grid with reliability analysis, failure protection, as well as privacy and security measures.

One of the very important features of a smart grid mentioned is the integration and support of DG units that have a set of desirable features vital to the enhancement of the power generation behavior of the grid.

2.2 Distributed Generation (DG)

DG or DER can be defined as a small electrical generation or storage unit connected to the power grid at any point in the transmission or distribution network, typically at the demand side. Though it is not a new concept in planning electrical grid and networks, it has become very popular and beneficial for various countries as their electrical demand has increased.

The need for such a concept arose from several demanding factors. Major international global blackouts have resulted in interrupted power for several days and effected millions of people. In 2012, more than 600 million people in India suffered from interruption of power due to a sudden in load. The blackout was one of the world's worst blackouts at the time and had gone on for several days, effecting various important facilities such as transportation (Metro service) and hospitals, resulting in a significantly turn down of the economy in India. In developed countries, such as U.S. and Canada, power outages are inevitable. In 2003, a blackout effecting nearly 55 million Americans and Canadians slowed down basic life activities for hours [11]. The effects of those blackouts could have been significantly reduced by using DER units [12]. These effects and a set of other benefits have supported the use of DG technologies in most developed countries. To increase the production of green energy, and to improve its power grid, Dubai's government have initiated a program that targets using renewable energy resources, mainly PV, as part of the DG program for its network. The initiative aims to encourage consumers to install PV panels on rooftops and use the electricity on-site. Any surplus power will be exported on DEWA's grid [13].

In most recent years, the increasing demand for energy has introduced a new set of economic, technical and environmental issues. Building new generation plants has become very costly and unnecessary at times where it is only needed for peak times, as well as harmful to the environment in the continuous generation of CO_2. Today, a lot of power systems have adapted DG unit's installation for various reasons. DER technologies offer numerous economic benefits, which can be summarized as follows [14]:

- Reduction in costs of transmission and distribution networks. Since DG units can actually be installed anywhere on the network, and typically on the load side, upgrading the T&D lines can be deferred or totally avoided as the load increases [15].
- Some DG types can be assembled alone as modules, which makes it easy to install them independently. They can be part of the system but do not require a whole set to be available. When upgrading is required, separate modules can be easily added. This helps in saving costs, as well as cutting down on installation time [14].
- Due to the flexibility of installation location, DG units can influence energy prices. This assumption is based on renewable resources such as wind, solar, and hydro, which are actually geographically constrained [14].
- The continuous advancement of DG units have made them more efficient and less costly, which are important factors for expecting them to be the preferred choice for power generation [16].
- The diversity of technologies and types used doesn't restrict the usage of a certain fuel and thus keeps its demand and consecutively its price from increasing [14].

Moreover, several technical advantages can be offered by DER to the grid and the customers. Some of these main advantages are [14]:

- DG units can improve the reliability of the system. In the case of islanding, which occurs in case of a disconnection from the main grid power, the DG unit will be able to supply power to the local network. Under those circumstances, fewer people will be effected by a blackout [14].

- Since DG units are typically installed at the load side, the transmission losses of the system will significantly drop, which leads to a better voltage profile for the whole system [16].
- Significant reduction in CO_2 emission can be achieved by encouraging the penetration of renewable DG units [17].

Understanding the types of DG units and technologies is important for deciding which type to use, the environmental impacts, or economical restrictions. DG units can be categorized according to their output power: dispatchable vs. un-dispatchable. They can also be classified according to the interface, or their energy sources used as shown in

Figure 2-1.

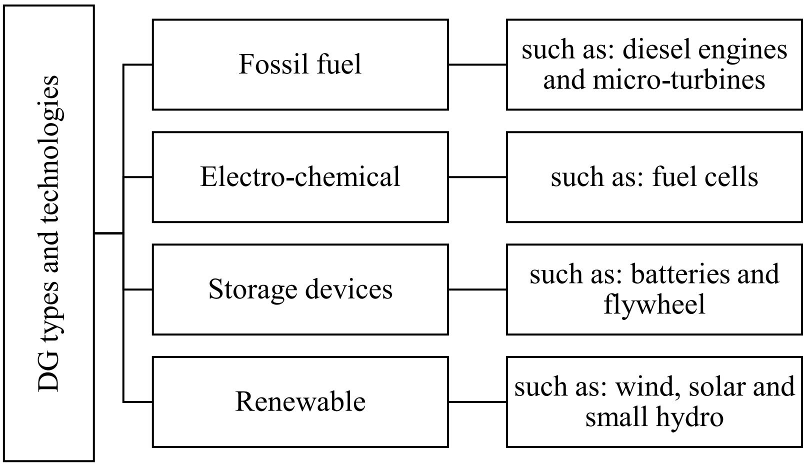

Figure 2-1 DG types according to energy sources [14]

The types of DG units are classified below according to their energy sources:

2.2.1 Fossil fuels. Those generators are considered traditional and are usually micro-turbines or diesel generators. Although the green impact of those generators is not very significant, their cost makes them very attractive to use. Internal Combustion Engine (ICE) is the cheapest DG technology available. Piston-driven ICE’s have been the leading DG type installed today. They have a size range of 0.5kW to 6.5MW and can use multiple fuels to run on [18, 19]. Most of those ICE’s are four-stroke, conventional, reciprocating engines like the one shown in Figure 2-2. Those engines work by an initial ignition spark that causes combustion inside the engines. The gases released from this process push the piston causing the motion required to produce power from a generator [18]. The four-stroke ICE requires four piston strokes to complete a cycle, which includes intake, compression, combustion, and exhaust.

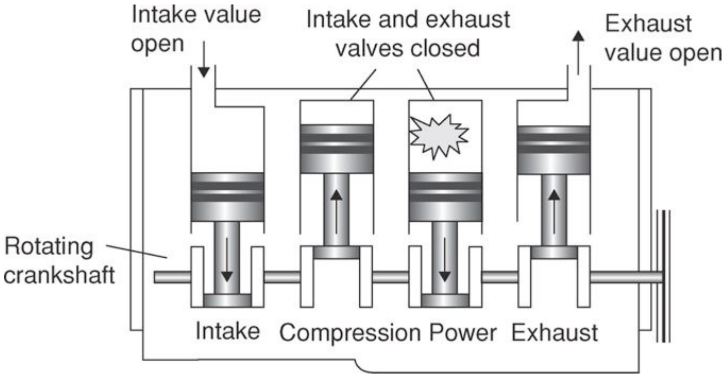

Figure 2-2 Basic four-stroke ICE, [19]

Two major types are available from ICE, and they are based on the type of fuel used for running the engine:

- *Spark-ignited engines (Otto Cycle engine-Nikolaus Otto)*: used with easily ignitable fuels, like natural gas and propane, this type of engines initiates combustion by an external spark, igniting the fuel-air mixture.
- *Compression-ignition engines (Diesel engines)*: this type of engines uses heavier fuels, like diesel and petroleum extracts. Here, only air is inducted into the engine and then compressed. The fuel used will then be sprayed into the hot compressed air at a suitable rate letting it ignite and cause combustion.

Using ICE's have the benefits of:

- Fuel flexibility
- They are the cheapest DG technology available.
- Can be made clean when using natural gas as a fuel source.

Another type of fossil fuel DG is the Micro-turbine (MT). These MTs are small combustion turbines that can come in various sizes, producing anything from 20kW up to 500kW [14]. They can use natural gas, propone, or fuel for combustion but they run at faster speeds, and lower temperatures than normal combustion turbines [14]. They consist of a compressor, recuperator, combustor, turbine, and a generator. The basic operation of a micro turbine is illustrated in Figure *2-3*. As the air enters the compressor, pressure is applied and thus air becomes hotter. The hot air is mixed with the fuel in the combustor, resulting in the release of gas from air that moves the turbines to speeds up to 70,000 rpm. The rapid movement of the turbine's blades will cause the shaft of the generator to rotate creating a magnetic field that then induces an electrical current [14]. MTs are classified as per the arrangement of their components. Single shaft turbines are the ones that have the compressor and the turbines connected on the same shaft. The split shaft MT has a gearbox connected to the shaft, which is used to generate power at nominal frequency.

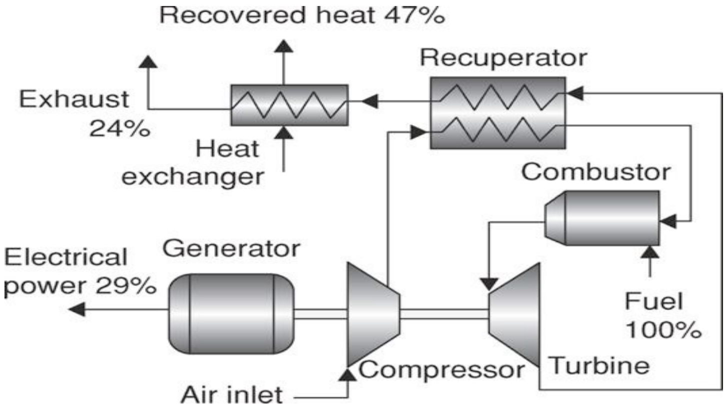

Figure 2-3 Working mechanism of microturbines [19]

Split shaft MT's are ideally used where AC power is required since it eliminates the need for an inverter [20]. MT's are classified as follow:

- *Simple-cycle gas turbines:* can come as a single shaft or split shaft [14].
- *Recuperated gas turbines:* contain a recuperator component which uses the output thermal energy to add efficiency to the system by pre-heating the compressed air as it reaches the combustor [20].
- *Combined cycle gas turbine:* uses the recuperator to recover the wasted heat and convert it to steam. This MT comes with a heat recovery steam engine (HRSE) that produces electrical power from the wasted energy [14].

Some advantages of using micro-turbines are:

- Their running and capital costs are lower than most other DG units.

- Their efficiency can reach up to 80%.
- They are easy flexible to install at site location, which makes them ideal for emergencies.
- People are usually familiar with MT's, which makes them easy to start up and use [14].

2.2.2 Electro-chemical.

The major power source in this category is Fuel Cells. This old technology, invented around 1840, is made of two electrodes separated by an electrolyte. Various materials can be used as the latter, and this is what differentiates fuel cells types. A basic construction of a single fuel cell is shown in Figure *2-4*. The electrolyte has a trait of passing the protons only, leaving the electrons on the anode plate of the cell. Hydrogen is introduced on one side of the cell, while oxygen is introduced on the other. A chemical reaction takes place, producing H_2O, and a small current passed by a resistor resulting with a potential difference of around 0.5 V. Stacking up cells will result in a higher voltage unit, but a good spacing has to be maintained between fuel cells to allow proper interaction of air and hydrogen [19].

As mentioned earlier, different types of fuel cells exist each with its own characteristics. The basic operation is the same, but the electrolyte material is what defines them. The types are as follow [19]:

- *Polymer Electrolyte Fuel Cells (PEMs)*: often called proton exchange membrane fuel cells. They need pure hydrogen (H_2) for their operation.
- *Direct Methanol Fuel Cells (DMFCs)*: use the same electrolyte as PEMs but allow the usage of liquid fuel instead of hydrogen gas.
- *Phosphoric Acid Fuel Cells (PAFCs)*: The electrolyte used is phosphoric acid. They are more expensive than PEM's, but they operate at higher temperatures (around 200° C) improving their efficiency.
- *Alkaline Fuel Cells (AFCs)*: The electrolyte used is potassium hydroxide. They require pure hydrogen, H_2.
- *Molten-Carbonate Fuel Cells (MCFCs)*: The electrolyte used can be molten lithium, potassium, or sodium carbonate. Their operating temperatures are around 650°C, which makes the waste heat good enough to produce electrical power through an additional steam turbine.

- *Solid Oxide Fuel Cells (SOFCs)*: The electrolyte used is a solid material made of zirconia and yttria. It usually uses natural gas as a fuel. The gas is internally converted to H_2, which makes it possible to have other biofuel types as inputs. They operate at very high temperatures (750°C - 1000°C) but are smaller in size than the MCFCs.

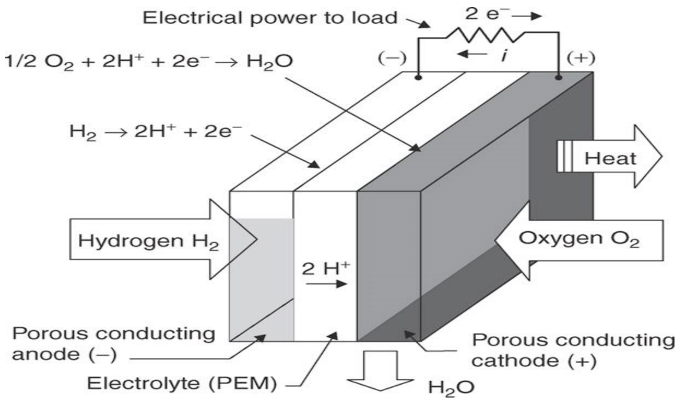

Figure 2-4 Working mechanism of a fuel cell [19].

Some advantages of using Fuel cells are [14]:

- Since no combustion is present, harmful compounds such as carbon monoxide CO, sulfur oxide SOx, and nitrogen oxide NOx will not be produced.
- They have a high efficiency in comparison with the heat-based engines.
- Due to their size and noise-free nature, they can be placed in a variety of places, such as close to residential areas or offices.
- Can be used in conjunction with renewable resources to eliminate the release of CO_2.

2.2.3 Renewables. Renewable resources have become the focus of so many governments and companies due to their zero-emissions criteria and their sustainability. Because of the rising concerns of global warming, this type of energy has become the target goal of major developed countries. In the UAE, the emirate of Dubai has an initiative to have 7% of the city's total generation from clean resources by the year 2020, 25% by 2030, and 75% by 2050 [13]. Various types of power generators fall under this category, but each has its own benefits and challenges. Solar energy is the most common renewable resource used. The electrical energy generated from PV panels is the most popular in the region due to the great exposure to sunlight. As seen in Figure 2-5, PV cells are made of semiconductor material consisting of n and p types brought together to form a junction. As light hits the cell, photons give energy to electrons causing them to move freely. The electrical contacts are used to make sure those electrons don't recombine with the holes and thus are pulled towards the load causing a current to flow. A single PV cell typically gives a current in the range of 2-4 AM and a voltage of 0.5 V. Various arrangements of cells can be set up to form panels or arrays which provide a range of different powers as required.

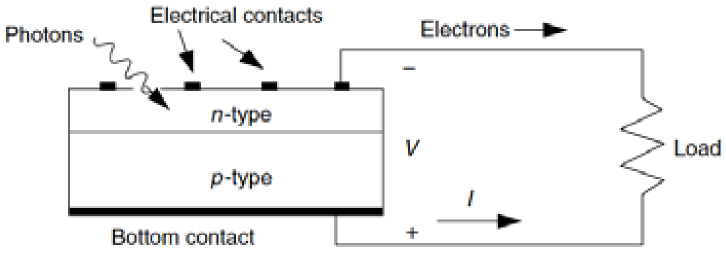

Figure 2-5 Working mechanism of solar cell [19].

The different types of PV cells are due to the material used as a semiconductor, and there are a lot of materials being used. However, the most common ones are described below and are shown in Figure 2-6:

- *Monocrystalline silicon PV cell*: The most popular, and most efficient type of cells currently being used, this type of PV cell can convert up to 26.7% of the sun's energy to electricity [21]. The cell is made up of thin slices of silicon cut from a cylindrical crystal of silicon. Although this type of material is more efficient and performs better in low light conditions than other types of cells, the time consumed to produce them is higher and thus they are more expensive. Since the crystalline in this cell is homogenous, it can be recognized by its even color.
- *Polycrystalline silicon PV cell*: Also made from silicon, this type of cell is composed of multiple small silicon crystals. This can be recognized from the appearance as a wavy-like metallic structure. Those cells are cheaper to produce than Mono-Si cells, but they have efficiencies around 22.3% [21].
- *Thin-film silicon PV cells*: this type of cells is composed of a thin layer of semiconductor material on a substrate such as plastic or glass. The thin film layer varies from a few nanometers to micrometers, which gives them the

advantage of flexibility and avery light weight. Although those cells have started as inefficient cells with a short lifetime, their potential has been focused on in recent years and is expected to thrive in the future. Their efficiencies have increased reaching 21.7% [21], and they are much cheaper to produce than other types of solar cells. However, Cadmium, which is the material used for producing thin films is highly toxic, and thus researches have been conducted to study its long-term effects.

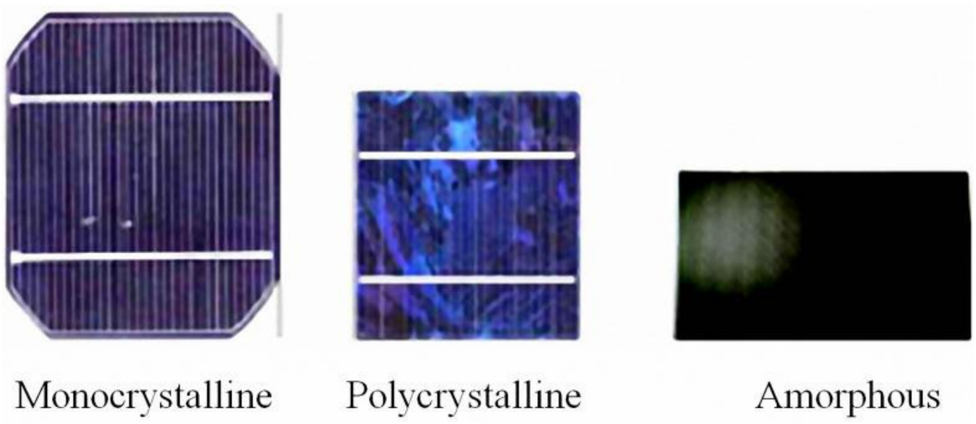

Figure 2-6 Different types of Solar cells [22]

The advantages of solar energy systems are:

- Sustainable and renewable
- Almost zero operational cost since sun radiation is free
- Can be installed in various modules arrangement as a variation of output power
- Zero CO_2 emissions [19].

Another common type of renewable resources is wind energy. Wind turbine technology is not necessarily new, but it has been advancing rapidly. In countries with a stable wind flow, wind turbines are the focus of renewable resources. By the end of 2015, China had 145 GW of wind power installed [23]. In 2017, Denmark has generated 44% of its total generated power from wind turbines [24]. The wind turbine mainly consists of the turbine blades, a slow speed shaft, and a generator. A gear box is an optional part of the system, and with the development of important technologies in power electronics, an inverter has recently become part of the system too. The operation of a wind turbine involves rotating blades that move by the energy of wind. The rotating blades are connected to a shaft that in turn is connected to a generator. The latter produces energy from the movement of its stator caused by the movement of the shaft. The mechanism is represented in Figure 2-7.

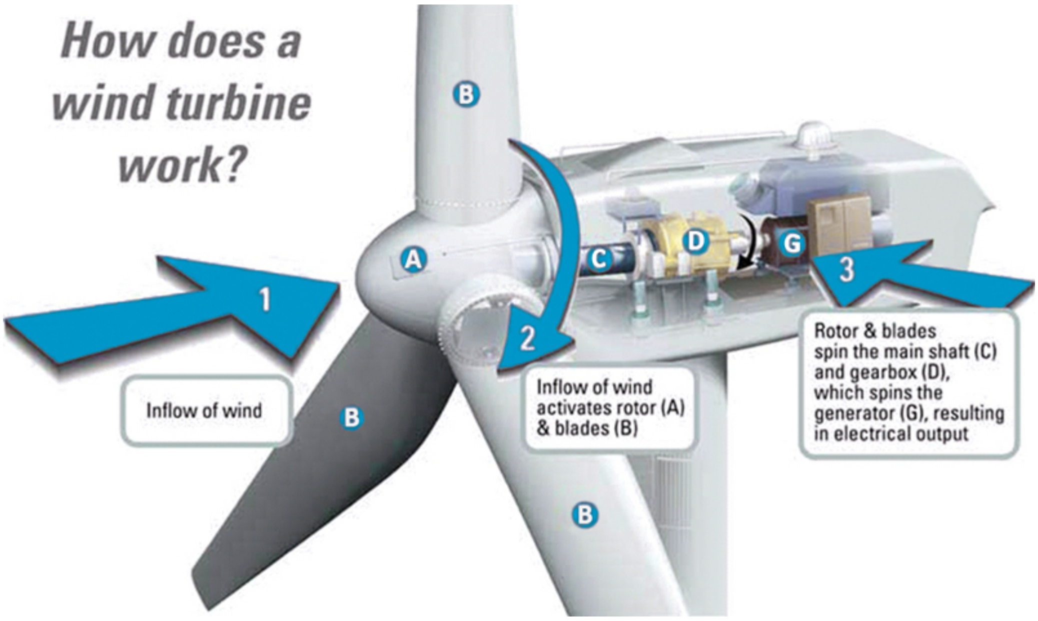

Figure 2-7 Working mechanism of wind turbines [18]

Different types of wind turbines are present as different component modules of the system. They are designed to accommodate different wind speeds, and thus locations. Another factor that differentiates WT classes is turbulence intensity. They are classified as classes:

- *Class A*: used a lot in the 80's, this type on WT consist of a squirrel cage induction generators (SCIG) with a gearbox to maintain the speed above the synchronous speed of the generator. A capacitor bank is used in this configuration for reactive power compensation. Aside from this WT being almost a constant speed turbine, a disadvantage would also be the robust mechanical requirement of its structure to support high winds [19].
- *Class B*: used by Denmark since the mid 1990's, this WT configuration has a wound rotor inductor generator (WRIG) connected directly to the grid. The rotor winding of the generator is connected in series to a variable resistor that controls the range of the variable speed. Like Class A WT, the reactive power compensation is done by a capacitor bank, and a soft starter is used for smooth

grid connection. Since the size of the variable resistor can be controlled, thus controlling the speed, the output power of the whole system can be controlled. This serves a s a major advantage of this class of wind turbines [19].

- *Class C*: with variable speed control similar to that of Class B WT, this configuration consists of a double fed induction generator (DFIG) and a partial scale power electronics converter. The stator winding of the generator is directly connected to the grid, while the rotor is connected through the partial-scale power electronics converter, which controls the frequency and thus the rotor's speed. The PE converter maintains the speed range at ±30% around synchronous speed. In this configuration, the PE serves as a soft starter, as well as a compensator for reactive power. The existence of this converter makes this class more efficient than class B since no resistive component is connected to the rotor's windings [19].
- *Class D*: This class corresponds to a full variable speed wind turbine. A full-scale power electronic converter is used for a smooth connection to a grid, and reactive power compensation for the full speed range. The power electronics circuit connects the stator winding of the generator to the transformer directly. Various generators can be used with this configuration, which is greatly adopted by manufacturers such as Siemens, and Enercon [19].

The advantages of wind energy systems include:

- Lowest cost in comparison to other renewable resources.
- Sustainable source of power

One of the oldest renewable sources used is hydropower, the concept of generating power from falling water was introduced in the mid-1700s. Various developments were made to the concept in the next 100 years, resulting in the production of the first hydro power plant in Wisconsin, USA in 1881. One of the largest waterfalls in the world, Niagara Falls, was used to produce electricity in 1881, when a dynamo connected to a turbine in a flour mill was used to provide street lighting [18].

The basic operation of hydropower involves a turbine, generator, and falling water. A portion of running water is diverted through a pipeline that delivers it to a waterwheel. The potential energy in the falling water rotates the turbine, which is connected to a generator through the shaft [22].

The advantages of hydropower include:

- Well established technology with life-time up to 100 years.
- Sustainable source of power.
- A very clean energy source since it mainly depends on flowing water.

2.3 Energy Storage Systems (ESS)

As a very important addition to the electric network, especially in the case of implementing smart grid technologies, energy storage systems (ESS) have a variety of types and benefits. As seen in Figure *2-8* the costs associated with various types of battery energy storage systems (BESS) have decreased significantly and are expected to even drop further [25]. This, along with several operational and environmental benefits, have brought a lot of attention to ESS technologies. According to [26], ESS can be categorized according to:

- *The Storage Medium:* In this category, ESS are divided into subcategories based on the form of energy in which it is stored; i.e. mechanical, electrical, or chemical. The mechanical storage can also be divided into two parts: potential energy storage, and kinetic energy storage. Similarly, the electrical storage is also divided into two parts: electrostatic storage, and magnetic energy storage [26].
- *The Charging/Discharging time:* ESS can also be categorized with respect to their charging time. The long-term ESS units, also known as centralized bulk units, can store high amounts of energy ranging from a few to a hundred megawatts, with a duration for more than 8 hours. On the other hand, the short-term ESS units are used for transient periods providing smaller energy amounts [26].

Some types of ESS are briefly discussed below:

- *Battery Energy Storage System (BESS)*: used as the most common form of ESS [19], batteries can vary in their composition and storing capabilities as well as other important factors for different applications. Some examples of BESS are Lithium-Ion batteries, Lead Acid Battery, and Nickel Oxy-Hydroxide (NIMH) batteries [1].
- *Compressed Air Energy Storage (CAES)*: while using electricity during off-peak hours, energy is compressed in the form of air in this technique. When

power demand peaks, the compressed air is heated to release the energy stored to move a turbine which generates the required power [1].

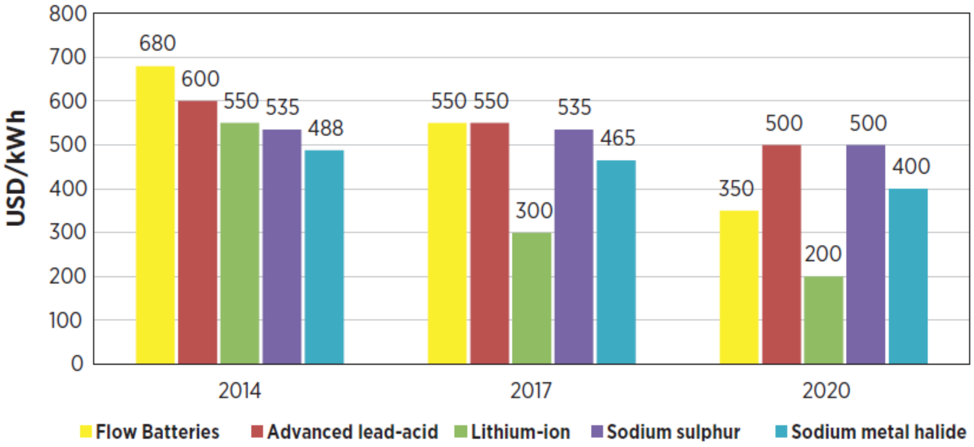

Figure 2-8 Current and forecasted price drop for different types of batteries [25]

- *Flywheel Energy Storage System (FESS)*: used to store energy in the form of kinetic (mechanical) energy, the flywheel consists of a large rotating wheel. The amount of energy stored changes linearly with the moment of inertia of the flywheel and with the square of the rotational speed. This means that the higher the speed, the more the energy stored [1].

The mentioned ESS types, and a few others have certain applications based on their power storage capacity, and their charging time. A summary of their characteristics is presented as shown in Table *2-1*. Some advantages of ESS are [27]:

- Maximizing the use of existing generation units, specifically renewable energy units.
- Reducing dependency on fossil fuels as back-up capacity.
- Aiding in stabilizing the transmission and distribution networks by using stored energy.
- Participating in cost reduction by storing energy during off-peak hours which in turn avoids the extra requirement of generation during peak hours.
- Participating in lowering harmful gas emissions.

2.4 Electric Vehicles (EV)

The emerging technologies of smart grids all over the world will enhance the utilization of electric vehicles as part of the grid. Through the concept of vehicle-to-grid (V2G) the electric vehicle will act as a part of the ESS connected to the network, providing local power where the vehicle is located. The V2G concept will allow the EV to receive and send power to the grid during suitable hours of the day [29]. For example, a vehicle can charge through the night during off-peak hours and discharge its power back to the grid during peak hours of the day. It is important to note that this cycle depends greatly on the behavior of the driver. This concept in literature review works under the assumption that EV owners are willing to participate in grid activities, and that the presence of the EV is more common on the road. The EV acts as a mobile energy storage system, which will be discussed in more details in the next section of this chapter, providing a transportable source of energy that can supply power at different busses on the grid over the period of few hours or a day. The data in Figure *2-9* show the rapid rise of EV sales in the last 10 years, in comparison with the price drop of batteries installed in those cars.

Table 2-1 Characteristics of different ESS types, [28]

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle life (cycles)	Self-Discharge
Pb-Acid	70-80	20-35	25	200-2,000	Low
Ni-Cd	60-90	40-60	140-180	500-2,000	Low
Ni-MH	50-80	60-80	220	<3,000	High
Li-ion	70-85	100-200	360	500-3,000	Med
Li-polymer	70	200	250-1,000	>1,200	Med
NaS	70	120	120	2,000	-
VRB	80	25	80-150	>16,000	Negligible
EDLC	95	<50	4,000	>50,000	Very high
Pumped hydro	65-80	0.3	-	>20 years	Negligible
CAES	40-50	10-30	-	>20 years	-
Flywheel (steel)	95	5-30	1,000	>20,000	Very high
Flywheel (composite)	95	>50	5,000	>20,000	Very high

Electric vehicles can be categorized into three groups: Battery electric Vehicle (BEV), Hybrid Electric Vehicle (HEV), and Fuel Cell Electric Vehicle (FCEV). The major differences and characteristics of those models of EV will be discussed as follows [30]:

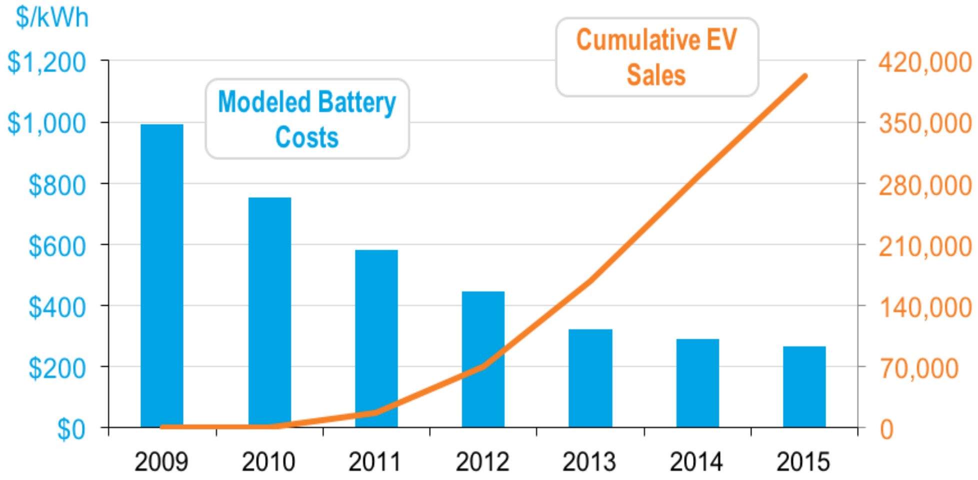

Figure 2-9 Modeled battery costs relation to increasing of EV sales [18]

- *Hybrid Electric Vehicle (HEV)*: the basic idea of a hybrid vehicle is the combination of an electric machine, a battery as a storage unit, and a fossil fuel internal combustion engine that serves as the main source of power [30]. Different levels of HEV’s are discussed below:
  - Micro Hybrid Vehicle (MHV): In this level, a limited power electric machine is used as a starter alternator, helping the internal combustion engine to realize a better startup. Fuel economy has improved from 2% to 10% in this type of HEV. MHV’s have a stop-and-go function, meaning that the engine of the car can be stopped when the vehicle is not moving [30].
  - Mild Hybrid Vehicle (MHEV): In addition to the function of MHV, this level adds a boost function to the vehicle, resulting in a supplementary torque during acceleration or braking. This vehicle allows the charging of a battery through regenerative braking. Fuel economy of this vehicle has shown a 10% to 20% improvement [30].
  - Full hybrid vehicle (FHEV): In this type of HEV, a full electric traction system exists in the vehicle, ensuring full propulsion by the electric component, resulting in a zero-emission vehicle. The propulsion of the car can be done by the ICE alone, or by both the ICE and EM together. The

    improvement of fuel economy for this type of cars have reached the range of 20% to 50% [30].

  - Plug-in Hybrid Vehicle (PHEV): This vehicle can use external charging station to charge its battery, which in turn could make it as a zero-emission vehicle. In some cases, a limited power ICE unit is used, and the vehicle acts mainly as a battery electric vehicle (BEV). On the other hand, the ICE can be used to charge the batteries. In case the ICE is not used to charge the battery, the fuel economy could reach 100% [30], making this type of vehicle an important topic to focus on in the current market.

- *Battery Electric vehicle (BEV)*: Unlike the PHEV, the BEV has a fully electrical propelling system replacing the ICE, which satisfies the power demanded by all functions of the vehicle. The capacity of the battery pack in this vehicle should be increased to accommodate the extension of the energy drive. The battery pack of this vehicle is charged externally using designated charging stations. A popular example of this vehicle is developed by Tesla Motors, which consists of a Li-ion battery pack providing a driving range of 300 mi per charge [31].
- *Fuel Cell Electric Vehicle (FCEV)*: This type can be considered as a BEV since it can be equipped with a battery pack or a super-capacitor [30]. In this case, the fuel cells act as a generator using hydrogen as their fuel and oxygen as the oxidant and storing the produced energy in the battery. Although hydrogen is preferred due to its high energy density, and the byproduct is just water, other fuels could include hydrocarbons and alcohols, and the oxidants could include chlorine and chlorine dioxide [31].

A summary of the major characteristics of the different types of EV is presented in Table 2-2.

2.5 Mobile Energy Storage Systems

As a type of an Energy Storage System (ESS), a Mobile Energy Storage System is a transportable energy system that provides several benefits to the grid. They have energy storage mechanisms, such as a Flywheel, or lithium ion battery as well as other components which could include the following:

- Generation Sources: Such as Diesel Generators, PV panels, or Fuel cells.

Table 2-2 Summary of EV specifications [30]

	Energy Source	ESS	Characteristics
HEV	Gas Stations Electric grid charging stations	Fuel Tank Battery	Low emissions High fuel economy
BEV	Electric grid charging stations	Battery	Zero emissions Independent of fossil fuels
FCEV	Hydrogen Other possible fuels	Hydrogen Tank Battery	Zero emissions Independent of fossil fuels (if not using gasoline to produce H_2)

- Power Electronic Circuits: Converters and Inverters are needed to transform the DC current produced by the RES to AC to serve the required loads.
- Energy Management System: In case more than one source is used to store energy, an EMS is useful in directing the power flow, maximizing power usage from clean resources, leading to less CO_2 emissions and less costs.
- Means of Mobility: mobile energy storage system could simply be a Plug-In Electric Vehicle (PEV). However, a mobile energy storage system could be a normal ESS fixed on a truck trailer or in a shipping container to give it mobility.

Commercial mobile energy storage system units are available in the market with an output power of 100, 1000, and 5000 kW ratings. Various projects around the globe have implemented mobile energy storage systems: In 2013, the Japanese company Toshiba, along with the Spanish Company Gas Natural Fenosa have partnered to test Toshiba's Battery Energy Storage System (BESS). The system consists of lithium ion batteries providing 500 kW of power with 766 kWh and will be used to study the effects of the system on peak shaving, voltage and frequency stability on the grid at different sites [32].

2.5.1 Benefits of mobile energy storage system. A mobile energy storage system is a transportable energy storage system that can be plugged into the grid at different locations and at different times, which gives the advantage of providing different localized grid services. A few benefits serve the purpose of using a mobile energy storage system unit:

2.5.1.1 *Voltage support.* Maintaining a stable voltage level in the grid is a very crucial aspect of keeping a healthy power supply. The compensation of the required reactive power needed by inductive or capacitive equipment in the load has been supplied by the centralized generation sources. Capacitor banks are usually used locally to perform power factor correction, but they withdraw a huge amount of current seen as power loss. The installation of various ESS units in the grid aids in the reactive power concentration [3]. However, this can be a costly addition to the system. A single mobile energy storage system unit can be a cheaper replacement of the various ESS unit but doesn't compromise on the local VAR correction since the mobile energy storage system can change its location and act as the needed ESS in times of grid instability [32].

2.5.1.3 *RES balancing.* RES units, though provide a clean source of energy, face some problems when being part of the system. Though the output of those units can be predicted or modeled, it can't be controlled [29]. PV panels output could vary a lot due to the effect of shading, and wind turbine generation can be highly effected by strong winds [3]. This causes a problem of a constant power supply provided by those units. As a solution to this problem, RES units often come with ESS units to store their unused generated power. The combination of the stored generation with the directly generated power can almost be considered constant, solving the problem of an intermittent RES unit [3]. However, with the increased penetration of renewable energy generators, providing a suitable high capacity ESS can add to the costs of the systems. The increased demand for mobile energy storage systems and PEV will reflect in a price drop of those units, making them more economically attractive than multiple stationary ESS units [2]. Mobile energy storage systems can be located on the network buses with RES units facing variable output to offset their production. Having the advantage of mobility, the mobile energy storage system can serve more than one bus during the same day.

2.5.2 Applications of mobile energy storage systems. There are quite a few scenarios that can benefit from the services of a mobile ESS unit.

2.5.2.1 *Peak shaving.* One of the main reasons to have a DG unit would be the ability to supply high industrial loads. Peak shaving refers to the technique used to reduce power consumption during peak hours. Prior to the penetration of DG units, utilities would have to construct a new power plant to provide this short-time demand. Instead, as an energy management practice, the utility would force consumers to cut down on their loads to avoid the increase in demand, and consequently eliminates the need for a new generation. However, this causes a problem for the consumers, specifically industrial ones. A mobile DG unit can be very helpful in this scenario where the unit will be able to travel to the customer site during this time and provide the cut-down required energy to satisfy the total demand.

2.5.2.2 ***Natural disaster crisis.*** In the last 40 years, the number of natural disasters has increased steadily; hurricanes, cyclones, floods, earthquakes, wildfires [33]. The occurrence of those events can cause severe damage to the generation grid and infrastructure, leaving millions of people in a black-out. A mobile generator, in this case, will help supply parts of the load back until main grid works again. The mobility aspect of the unit is very beneficial in this case since it can aid several areas during the day, providing multiple locations with the necessities of survival and safety.

2.5.2.3 ***Remote areas or refugee camps.*** Due to the unfortunate events of war, more people are seeking refuge in UN camps built to accommodate thousands of people. Though those camps are built for the intention of temporary occupation, unfortunately in many occasions the camps become a permanent residence for a lot of people. Those camps are usually located in remote areas, where the grid transmission and distribution lines are not provided. Construction sites, on the other hand, can also be in remote areas and have the demand of power 24 hours, 7 days a week [34]. A standalone mobile energy system is an excellent solution to provide such areas with the power needed for short periods of construction or during an expansion or a power outage in refugee camps.

2.5.2.4 ***Short-term events.*** During New Year's Eve, many cities around the world decide to celebrate the upcoming of a new year with fireworks and light shows. Those events last for a few hours but required a good amount of power to be constant. The current practice in many cities is to use multiple generators to supply the required load. In the presence of a mobile energy storage system unit, the demand of power could be supplied by a single unit avoiding unnecessary costs and having a better impact on the environment.

2.6 Literature Review

To understand the work being done in the field now and has a positive contribution that would expand the findings of this topic, a search was conducted to compare the work done previously with the proposed work in this thesis.

As a part of ESS research topics, the work presented in [32] models an Energy Management System (EMS) that decides on which grid bus to position the mobile ESS in order to minimize day-ahead costs of grid power and to give reactive power support to critical loads. The mobile energy storage system consists of two parts, the ESS components which is an array of lithium-ion batteries, and the truck. The EMS represents the network as a radial feeder system with several RES units at certain buses and a number of dispatchable units, such as micro turbines located at different buses. To operate the mobile energy storage system, the EMS needs to perform three main tasks:

- Design the transit delay model that gives the travelling time between stations.
- Design the power flow model that studies bus voltages, currents, and power losses and decided where the position of the mobile energy storage system should be
- Design the ESS model representing the dynamic of the batteries.

In addition, an economical model was included to define the costs of all resources, to accurately model the savings of the suggested system. The objective function of this work was to minimize costs of energy by reducing the amount of power drawn from the grid. The results of the work done in this paper have been summarized in Table *2-3*. First, it can be concluded that the mobile energy storage system has a major impact on improving the voltage level of the system achieved by providing localized reactive power at various buses. Second, the proposed system had a 5.5% reduction in power losses. This was caused by the reduction of power demanded from the grid. Finally, the work presented shows an increased profit of approximately 3.1%.

Table 2-3 Summarized results from studied paper, [32]

	Without mobile ESS	**With mobile ESS**
Voltage Level	Vmax = 1.062, Vmin=0.89	Vmax=1.04, Vmin-0.956
Power losses	8.1863 MWh	7.7277 MWh
Profit	14,320 $	14,760$

Likewise, [35] proposes an approach that utilizes a mobile energy storage unit connected to the transmission grid to reduce investment costs and load losses associated with the occurrence of a natural disaster. The proposed approach considers a 15-bus radial feeder solved by a two-stage optimization technique. Considering only stationary units, the first stage optimizes the location and size of each unit, while stage 2 decides the amount of power they will provide. The next step includes the contribution of mobility, with increases the complexity of the problem, and thus uses the Progressive Hedging Algorithm (PH) to solve it.

The problem stated in the work presented in this paper targets finding a feasible solution while keeping low investment costs, and low lost load. This leads to a compromise done between the economic value, and the proposed system's success in providing the required services to the distribution system in case of emergencies. To solve this problem, the PH algorithm divides it into various scenarios, assigning a weight or probability of occurrence to each scenario. The effect of the natural event is assumed to appear on a certain transmission line. Six scenarios are simulated under different conditions:1) no storage units are present on the grid, 2) only stationary ESS units are present, and 3) mobile ESS units are connected to the grid.

Shown in Table *2-4* are the proposed 6 scenarios, and their corresponding lost load resulting from the occurrence of a natural disaster. Table *2-5* shows the amount of investment required for each of the mentioned conditions.

For Case 1, which represents the normal operation of the line and thus has the probability of occurrence of 0.9, the same operation and financial benefits can be concluded from having an ESS, stationary or mobile.

Table 2-4 Problem scenarios and reduced lost loads, [35]

	Scenarios	**Probability**	**Effected**	**Total Lost load (MWh)**		
		ws	**Distribution Line**	**No ESS**	**ESS**	**Mobile ESS**
Case 1	s1	0.9	-	0	0	0
	s2	0.1	4	0.44	0	0
Case2	s1	0.9	-	0	0	0
	s2	0.02	1	3.47	2.89	2.18
	s3	0.02	12	6.82	6.82	5.42
	s4	0.02	4	0.44	0	0
	s5	0.02	8	0	0	0
	s6	0.02	9	0	0	0

In Case 1, a natural disaster event is predicted to occur at t=6. While the mobile energy storage unit is located at Bus 1 during normal operation, it will relocate to bus 4 in anticipation of the emergency event. The suggested mobile ESS unit starts supplying buses 5 and 6, shown in Figure 2-10.

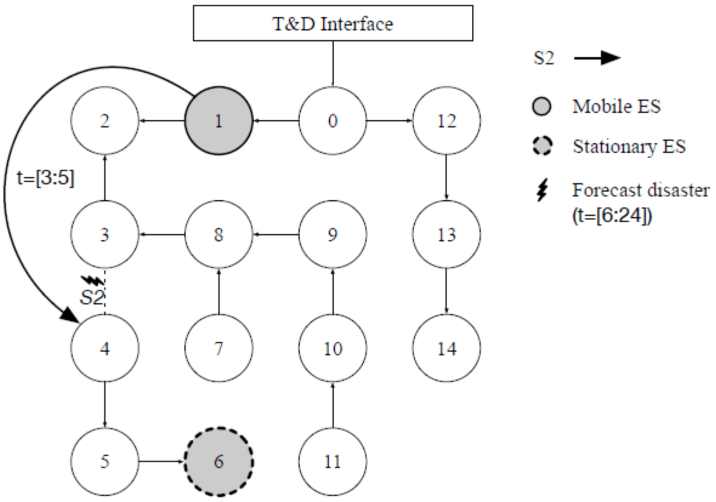

Figure 2-10 15-bus feeder for suggested system, [35]

Simulation results show that the stored energy in the mobile ESS is enough to avoid load shedding until t=24. In Case 2, the emergency event is modelled on 5 different scenarios, and the resultant optimized relocation of the proposed mobile energy storage unit can be seen in [35]. The resulting effects of having a mobile storage unit in case of an emergency on the load shedding or investment costs are shown in Table 2-4 and Table 2-5 respectively.

Table 2-5 Reduced Investment ($) in case of a mobile ESS unit, [35]

	No ESS	ESS	Mobile ESS
Case 1	1,185.62	1,032.51	1,032.07
Case2	2,036.2	1,997.95	1,788.41

The proposed system in [36] is a standalone hybrid emergency supply system (EPS) that consists of various generation units: PV array, Wind Turbine, a diesel generator, and a gas turbine, in addition to an energy storage system (ESS). The proposed approach optimizes the type, size and quantity of the various components while minimizing the costs of the entire system including capital investment costs, maintenance and operation costs, environmental and fuel costs. The system proposed is designed to support the grid by providing power to critical loads in case of an emergency, in addition to supporting the grid's stability and resilience. Shown in Figure *2-11* is the hybrid portfolio containing the mentioned components, as well as a set of converters/inverters required for stepping up/down the DC voltage, or for AC/DC bi-conversion.

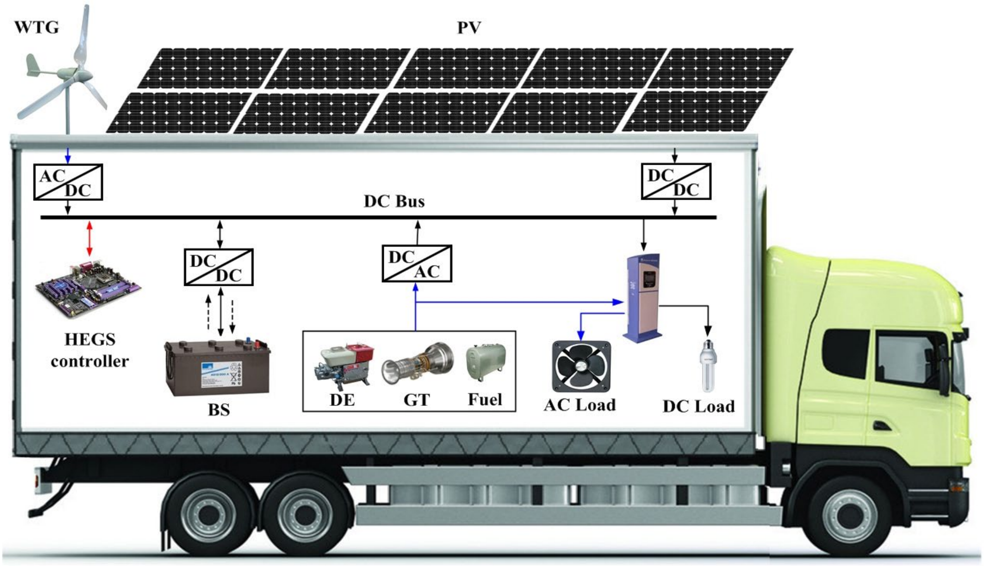

Figure 2-11 System components of suggested hybrid portfolio, [36]

To solve the proposed problem, Multi-Objective Differential Evolution (MODE) Algorithm is used with two main objectives: economic and mobility. In the economic objective, total costs associated with the systems are minimized, while the mobility objective's purpose is to ensure the truck is available on required location in the shortest time possible. This is affected by the mass and volume of components in the truck, amount of fuel in tanks and the weight of the truck itself.

To analyze this proposed solution, different schemes were constructed as follows:

- *Scheme 1:* Consists of all the energy generation resources suggested in the proposed system.
- *Scheme 2:* A mix of diesel generators and gas turbines is assumed.

- *Scheme 3:* Only diesel generators are used as an EPS.

Table 2-6 Size and quantity of different schemes suggested in [36]

Scheme	PV (kW)	WTG (kW)	DG (kW)	GT (kW)	BESS (kW)	Diesel (L)
1	463×0.083	0	1×200	0	30×2.5	9×35
2	0	0	1×60+1×200	1×65	0	9×35
3	0	0	2×60+1×200	0	0	7×35

The results of running the MODE algorithm to minimize the costs and weight of the entire system are summarized in Table *2-6* and Table *2-7*, respectively. The first set of results represent how big the selected generation resources should be, and how many units of each size should be part of the system to achieve the minimum investment costs and minimum truck weight.

Table 2-7 Costs and weight of different schemes suggested in [36]

Scheme	Cost ($)	Weight (kg)	Environmental Cost ($)
1	68,794	7,115	1,138
2	76,378	7,264	1,560
3	77,040	7,380	1,821

The environmental costs shown in Table *2-7* are calculated by enforcing a penalty on pollutants emitted from thermal power resources. [36] concludes that scheme one, the proposed hybrid system, provides the least costs and the lowest weight of the system. In addition, it is also concluded that the use of wind turbines was not considered due to its difficult transportability, while on the other hand PV serves the best in this area. Also, the initial cost, as well as maintenance and operation costs of renewable energy resources are very minimal, which makes them very effective in the proposed system since they have zero emissions and fuel consumption.

Based on the previous discussion and the limited work in this area, it is obvious that the research in the field of mobile energy storage systems is still in its early stages. All the previous work didn't consider the scheduling and dispatch of a fleet of MEGSS to serve multiple customers considering traffic information. Accordingly, this research proposes to develop a new approach to schedule and dispatch a fleet of MEGSS.

Chapter - 3 Proposed research

This chapter discusses the problem at hand and provides the proposed research as a suitable solution. The problem statement is first discussed in more details. Then the system proposed is presented, shedding more light on the system components and the data required to formulate the problem. The last section of this chapter includes the equations and constraints required to run the optimization tool for the targeted objective.

3.1 Problem Statement

In the previous section, various occasions where discussed giving the need for a mobile energy and storage system. The more traditional method of dealing with such circumstances is to rent diesel generators or micro turbines to provide required energy. In cases where the power requirement is fixed over a long period of time, for example, more than two weeks, other techniques might be more efficient or profitable than using the system proposed in this thesis. Although some types of mobile energy storage units can be transported to rural area and used for a long period of time as a stationary unit, this thesis proposes a mobile energy generation and storage system that would be efficient in cases of varying loads and short period of times. The goal of this work is 1) to design and model a MEGSS that would perform energy transactions to multiple customers or locations throughout the day, and 2) to dispatch and schedule the proposed system in order to maximize the profit generated by serving those customers using by minimizing operation costs.

As suggested in Figure 3-1, the proposed MEGSS unit will be operated from a monitoring HQ hub. Prospect clients will send their power profiles to the monitoring HQ office, where they will be negotiated. Through using an optimization tool to maximize profits, the HQ will decide which customers to serve. The truck will be dispatched from the hub where it will return after serving all clients. It is important to mention that the proposed system is optimized based on location data from real customers allocated in York, Toronto, Canada, as shown in Figure 3-2.

3.2 Proposed MEGSS

The problem being discussed here involves supplying customers with high demand power during certain hours of the day their requirmenet while achieving the maximum profits possible. The system being studied is a Mobile Energy Generation and Storage System (MEGSS) that can serve power using variousgeneration/storage resources:

Figure 3-1 Overall system concept

- A diesel generator
- PV panels
- Lithium Ion batteries.
-

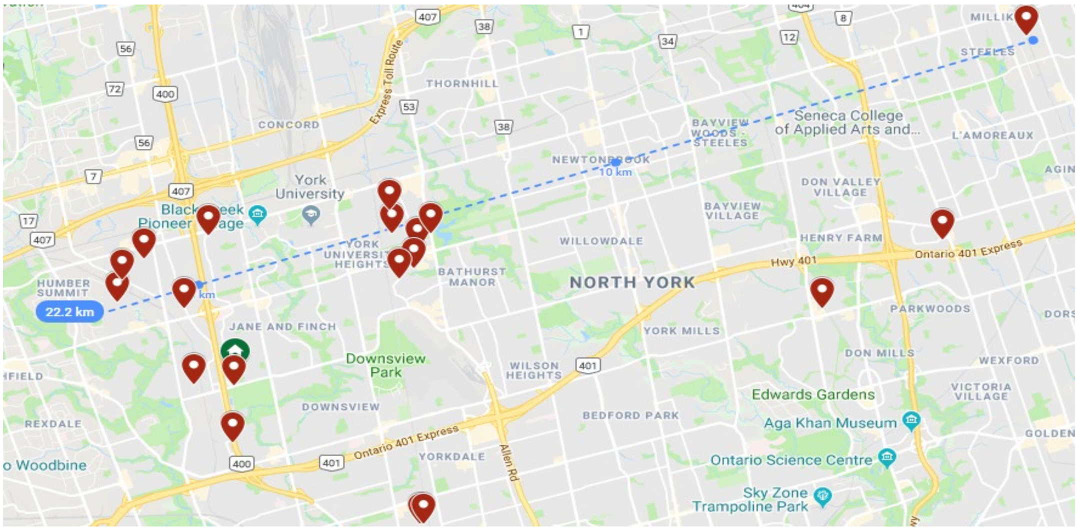

Figure 3-2 Customers' locations in North York, ON, Canada

The overall system is shown in Figure *3-3* consisting of a truck connected to a flatbed trailer and a shipping container. The latter contains a diesel generator, an inverter, and an array of lithium ion batteries. The PV panels cover the area on the surface of the shipping of the container, and while stationary, can extend to three times that size to increase power production. The components of the proposed unit will be discussed in more details in the following sections.

3.2.1 Electric truck. As a major part of the MEGSS unit, the truck intended for the proposed system should be able to meet a certain design requirement.

Figure 3-3 MEGSS truck overall unit with components

The truck should be able to tow the total weight of all the components of the system installed in a shipping container of 40 ft. In addition, the truck should, ideally, be an electric truck to minimize the CO_2 emissions and fuel consumption in correspondence to the goal of the thesis, and to the global demand of lowering or eliminating emissions. Finally, the truck should be an economically feasible option for the utility to maximize its profits. The Nikola One [37] Truck has been chosen to fulfil the intended job mentioned in this thesis. The truck will be modified to include the following components.

3.2.2 Solar panels. As part of the generation system, an array of solar panels will be mounted on the surface of the truck. To maximize the power generated from the PV panels, the whole surface area of the truck will be used for the panels' installation. The surface area to be used, as calculated on the top of the shipping container is

$$12\,m \times\ 2.3\,m\ =\ 27.6\ m^2 \tag{3-1}$$

SunPower Solar Panels from UK were chosen to be used as part of our system. Each panel has a length of 1.56m, and a width of 1.05 m [38], resulting in an area of

$$1.56\,m \times\ 1.05\,m\ =\ 1.638\,m^2 \tag{3-2}$$

Based on the previous calculations, it is approximated that an array of 14 panels is required to cover the entire surface area of the truck. Keeping in mind that each panel produces 320 W, the total array will be capable of producing 4.58 kW of power. To maximize the power generation as much as possible, the PV array is designed to extend while stationary to three times its moving size of 14 panels. This will result in two new arrays cascaded on top of the original panel and thus cover it partially. It is assumed that 20% of the primary panel is covered during stationary time due to the extension of the other 2 PV arrays. The new calculations will lead to

$$(2 \times\ 4.58\,kW)\ +\ (0.8 \times\ 4.58\,kW)\ =\ 12.8\,kW \tag{3-3}$$

3.2.3 Diesel generator. As a main source of generation, we are using a dispatchable DG unit. A fuel cell would be the best option from the environmental perspective. However, from an economic perspective, a diesel generation set would be the best option. In this work, without losing generality, a traditional diesel engine-generator set is utilized. The Caterpillar C9 ATAAC 200 kW diesel generator was chosen to be part of the system with a generating capacity of 250 kVA and a weight of 2,021 kg [39]. The generator is supplied by diesel which is stored in the truck in a tank with a capacity of 600 liters to be used as a back-up.

3.2.4 Lithium-ion battery array. To store all this generated energy, lithium ion batteries are used. Although li-ion batteries have come widely available in the market and at attractive prices, the 12V Meslen Lithium battery from China was used mainly due to the advantage of having them customized as per the requirements of the system. To match the generated power of the truck, the lithium ion string should be of a capacity of 480 kWh [40].

3.2.5 Power electronics converters. Since the battery and the PV panels will produce DC power, an Inverter is required for DC/AC transformation. It is preferred to use multiple smaller inverter than one bulk unit. This is to avoid system failure; if we have one bulk unit and it stops conducting current, the whole system will not be able to supply power. If, however, there are multiple units and one failed, the other unit can do the job and the system will still run as required. For compatibility requirements with other components of the system, the inverter must be of 200 kVA rating. Combining three units to act as one, JFY iPS 10-60 kVA inverter was chosen to be part of the system.

3.3 Design Requirements

To ensure the Nikola One will be a suitable choice for our purpose, the total weight of the system components was calculated and is presented in Table *3-1*. The Nikola One Truck has a payload capacity of 29,500 kg, which can accommodate the system parts as required. Another advantage for choosing the Nikola One is the energy source: hydrogen fuel cell. The FC charges the batteries which the truck runs on, in correspondence to our purpose of using clean resource and limiting harmful emissions.

Table 3-1 Weight of truck components

Component of System	Mass (kg)
Shipping Container	3,980
Solar PV	1,058
Battery	2,240
Inverter	225
Diesel Engine	2,021
Flatbed Trailer	14,061
Total	23,114

Due to the large number of batteries required to store all the generated power, the charging and discharging cycles will cause some power loss dissipated as heat. This heat shall be dealt with to avoid any harmful effect on the components inside the shipping container. This puts a constraint on placing the devices inside the container, as well as designing ventilation space. A gap for air to flow is required between the racks of the lithium-ion batteries to ensure safe dissipation of heat. This resulted in placing the DC/AC inverter on top of the batteries racks, leaving space between the battery rows of for air to flow, in addition to personnel movement in the case of required maintenance or inspection. Figure *3-4* shows a) top view of the truck with clear ventilation gap and component placement, and b) a side view of the truck. Based on the calculations made in this section, the rating of the proposed devices for the MEGSS system are sumamrized in Table 3-2.

Table 3-2 Ratings of electrical devices in the MEGSS truck

Component	Rating
Solar Panels	12.8 kW
Battery	64,000Ah (200 Ah per unit)
Inverter	200 kVA
Diesel Engine	200 kVA

3.4 Power Flow

A very important scheme to note is the power flow of the system at hand. It is important to label each power source as DC or AC, and to differentiate between the inputs and the outputs. The diagram in Figure 3-5 shows clearly the flow of power in the system. A DC bus is used for the connection of the battery and PV panel as inputs, and to the electric motor of the truck, and the battery as an output. On the other hand, the AC bus is connected to the diesel generator as an input, and to the I/O interface for supplying loads as an output. Since the battery will be used for charging and discharging, then it will be considered as both a load and a generator. The bi-directional

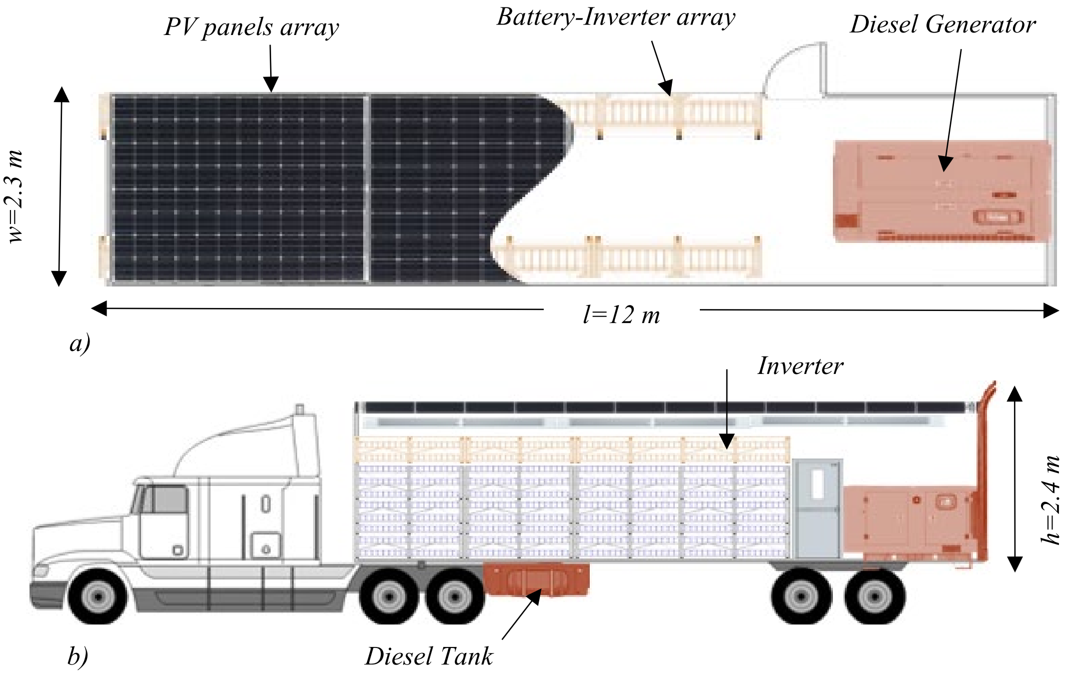

Figure 3-4 Overall system design a) top view, b) side view

inverter is used between the DC and AC busses for current conversion as required.

3.5 Problem Formulation

As mentioned in the problem statement, the purpose of this thesis is to model and dispatch an MEGSS that has the capability to serve various customers throughout the day. The goal is to optimize the customer selection and the route of the truck based on the available information. The requested profiles include the required real power, power fact, duration of demand requirement, and when the power is required. Based on the acquired distances and travelling duration between customers, the optimizer will decide which customers to be served to maximum the profit. Customers are offered three different prices for peak, mid-peak, and off-peak consumption times. Choosing the time-step is a trade-off between accuracy and computational time. Although in a real-time problem like the one at hand, a 1 –minute time-step can be solved, it would take a lot of computational time, especially at later stages as the optimization code increases to accommodate more constraints. Modelling the problem using a time-step of 1 hour will not be very efficient due to travelling times, connecting and disconnecting times being provided in minutes. On the other hand, modelling it as 1 minute will require more computational time. Thus, for this work, we define a time step, Δ_t of 5

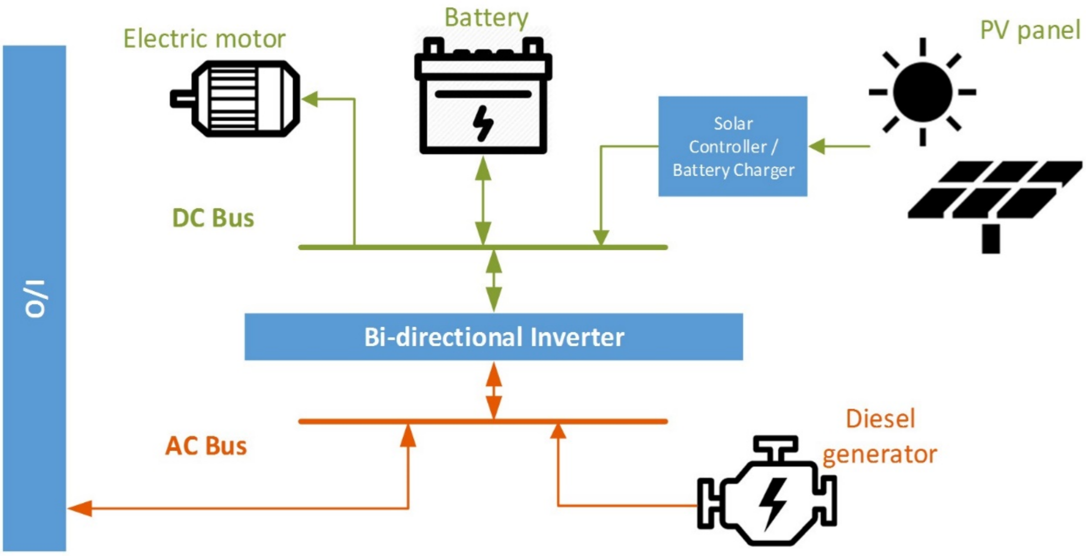

Figure 3-5 Power flow diagram the MEGSS truck

minutes. This time step of 5 minutes yields a total of $N_t = 288$-time segments for the day, i.e. $N_t = 60 \times 24/\Delta_t$.

The index and set of time segments can be defined as $\in \mathbb{T} = \{1,2,\dots,N_t\}$. Similarly, the index and the set of the stops are defined as $i \in \mathbb{I} =$ where N_c is the maximum number of stops. A subset $\mathbb{C} \subset \mathbb{I}$ is defined to differentiate between the customers and the stops, i.e. $\mathbb{C} = \{2,3,4,\dots,N_c\}$. Thus, the system can serve a maximum of $N_c - 1$ customers or requests. For the fleet of MEGSS trucks, v and $\mathbb{V}$ are the index and the set of trucks respectively.

The objective of the proposed approach is to maximize the MEGSS net profit. Therefore, the objective function can be defined as in (3-4).

$$\max \sum_{i\in\mathbb{C}} \left(R_i^{kW} + R_i^{kWh}\right) - \sum_{v\in\mathbb{V}} C_v^{opr} \tag{3-4}$$

where R_i^{kWh} and R_i^{kW} is the revenue made from customer i as energy and demand charges respectively. They are calculated as per (3-5) and (3-6)

$$R_i^{kW} = p^{kW} \times \max_t P_{i,t}^{\text{Customer}} \quad \forall\, i \tag{3-5}$$

$$R_i^{kWh} = \sum_{t\in\mathbb{T}} p_{\text{t}}^{kWh} \times P_{i,t}^{\text{Customer}} \times \frac{\Delta_t}{60} \quad \forall\, i \tag{3-6}$$

where p^{kW} is the demand charge in \$/kW, p_{t}^{kWh} is the price of selling energy in \$/kWh at time t, and $P_{i,t}^{\text{Customer}}$ is the power delivered to the customer i at time t.

The operation cost C_v^{opr} of truck $v \in \mathbb{V}$ is the sum of all the costs associated with that MEGSS. The total operation cost on any MEGSS includes the cost of fuel (if any), the cost of charging from the grid, and the degradation cost of all components of the MEGSS as in (3-7). The cost of fuel includes the no-load cost and the fuel cost, as in (3-8). The cost of charging from the grid, depends on the time of the charging, which is usually off-peak. which is calculated as the sum of (3-9).

$$C_v^{opr} = C_v^{fuel} + C_v^{grid} + C_v^{Deg} \quad \forall\, v \tag{3-7}$$

$$C_v^{fuel} = \frac{P_{v,t}^{disp}}{\eta_{v,t}^{disp}} \times \frac{\Delta_t}{60} \times p_v^{fuel} + x_{v,t}^{disp-on} \times \frac{\Delta_t}{60} \times p^{no-load} \quad \forall\, v \tag{3-8}$$

$$C_v^{grid} = \sum_{t\in\mathbb{T}} p_t^{grid} \times P_{v,t}^{grid} \times \frac{\Delta_t}{60} \qquad \forall\, v \tag{3-9}$$

where $\eta_{v,t}^{disp}$ is the efficiency of the dispatchable unit in truck v,

$P_{v,t}^{disp}$ is the power output of the dispatchable unit in truck v at time t,

p_v^{fuel} is the price of fuel in \$/kWh

$p^{no-load}$ is the cost associated with running the dispatchable unit at no-load,

$x_{v,t}^{disp-on}$ is the binary decision of turning on the dispatchable unit,

p_t^{grid} is the cost associated with buying energy from the grid in \$/kWh, and

$P_{v,t}^{grid}$ is the power consumed from the grid to charge the batteries during off-peak times.

After receiving the customers' requests, the locations of the customers are known. Using Google Maps Application Program Interface (API), the distance between the customers and the next day travel time matrices can be developed, as shown in (3-10*)* and (3-11*)*. w

$$D_{i,j} = \begin{bmatrix} 0 & D_{1,2} & \cdots & D_{1,N_c} \\ D_{2,1} & 0 & \cdots & D_{2,N_c} \\ \vdots & \vdots & \ddots & \vdots \\ D_{N_c,1} & D_{N_c,2} & \cdots & 0 \end{bmatrix}_{N_c \times N_c} \tag{3-10}$$

$$T_{t,i,j}^{travel} = \begin{bmatrix} 0 & T_{t,1,2} & \cdots & T_{t,1,N_c} \\ T_{t,2,1}^{travel} & 0 & \cdots & T_{t,2,N_c} \\ \vdots & \vdots & \ddots & \vdots \\ T_{t,N_c,1} & T_{t,N_c,2} & \cdots & 0 \end{bmatrix}_{N_c \times N_c} \tag{3-11}$$

Moreover, the customers requested service details are input to the proposed approach. Any service request must be accompanied with start time T_i^{start}, end time T_i^{end}, active power profile $P_{t,i}^{req}$, and reactive power profile $Q_{t,i}^{req}$ of power factor. For simplicity, T_i^{start} and T_i^{end} are assumed to be in terms of the time slots, i.e. from 1 to N_t. Then, the duration of the service for customer c can be calculated as $T_i^{duration} = T_i^{end} - T_i^{start}$. Also, the scheduling approach must consider the time required for the

MEGSS truck to disconnect and to turn off the dispatchable unit, which is denoted as T^{dcnn} , and the time to connect and turn on the dispatchable unit, which is denoted as T^{cnn}. Therefore, the following constraint must be fulfilled for each truck v:

$$X_{i,v}^{selection}\left(T_i^{end} + T^{dcnn} + T_{t,i,j}^{travel}\right) \leq T_j^{start} - T^{cnn} \ \forall\, i,j,t,v \quad \text{(3-12)}$$

where $X_{i,v}^{selection}$ is the binary decision for selecting customer i to be served by truck v.

The power balance between generation and consumption must be maintained at all time slots and for all trucks, as in (3-13)

$$P_{v,t}^{PV} + P_{v,t}^{grid} + P_{v,t}^{disp} + P_{v,t}^{BAT-dis} \times \eta_{v,t}^{BAT-dis} = X_{i,v}^{selection}\, P_{i,t}^{\text{Customer}} + \frac{P_{v,t}^{BAT-ch}}{\eta_{v,t}^{BAT-ch}} + P_{v,t}^{truck} \ \forall\, i,j,t,v, \quad \text{(3-13)}$$

where $P_{v,t}^{PV}$ is the output power of the photo-voltaic array and can be calculated as suggested in [19]

$P_{v,t}^{truck}$ is the power consumption of the truck while moving, and can be calculated as per (3-14),

$P_{v,t}^{BAT-ch}$ and $P_{v,t}^{BAT-dis}$ are the battery charging and discharging power respectively,

$\eta_{v,t}^{BAT-ch}$ and $\eta_{v,t}^{BAT-dis}$ are the battery's charging and discharging efficiencies, respectively.

The power consumption of the truck can be defined as

$$P_{v,t}^{truck} = \frac{E^{truck} \times D_{i,j}}{T_{t,i,j}^{travel} \times \Delta t/60} \ \forall\, t,v \quad \text{(3-14)}$$

where E^{truck} is the energy consumed by the truck while moving.

Although the output of the PV modules is independent of other generation units, $P_{v,t}^{PV}$ will vary on v and t due to the extension of the panels that can be calculated as $k_{PV} \times P_{v,t}^{PV}$. While solving for the variables based on (3-15), the optimizer needs to include the state of charge (SOC) of the battery at all times, calculated as

$$SOC_{v,t} = SOC_{v,t-1} + 100 \times (P_{v,t}^{BAT-ch} - P_{v,t}^{BAT-dis}) \times \frac{\Delta_t}{60} \times \frac{1}{E_{max}^{BAT}} \ \forall\, t,v \quad \text{(3-15)}$$

where SOC is the state of charge of the battery, and E_{max}^{BAT} is the energy capacity of the battery in kWh.

A set of constraints governing the model of the components is presented in (3-16) - (3-22). According to (3-16), a limit is set to the power that can be drawn from the grid to charge the batteries. Similarly, (3-17) and (3-18) ensure the battery doesn't charge or discharge beyond the allowed power maximum at any instant t.

$$0 \leq P_{v,t}^{grid} \leq P_{max}^{grid} \;\; \forall\, t, v \tag{3-16}$$

$$P_{v,t}^{BAT-ch} \leq P_{max}^{BAT-ch} \;\;\; \forall\, t, v \tag{3-17}$$

$$P_{v,t}^{BAT-dis} \leq P_{max}^{BAT-dis} \;\;\; \forall\, t, v \tag{3-18}$$

In addition, the battery's SOC should always be maintained within operational limits as governed by (3-19), while constraint (3-20) ensures that the battery doesn't charge and discharge at the same time.

$$(100 - MDOD) \leq SOC_{v,t} \;\leq SOC_{max} \;\;\; \forall\, t, v \tag{3-19}$$

$$P_{v,t}^{BAT-ch} \times P_{v,t}^{BAT-dis} = 0 \;\;\; \forall\, t, v \tag{3-20}$$

On the other hand, the dispatchable unit should also operate within its limits whenever it is on, as suggested in (3-21). Constraint (3-22) ensures that the diesel generator only operates when the truck is stationary. Additionally, the dispatchable unit should not be operated during connecting or disconnecting times, shown in constraint (3-23). To model this constraint, a binary variable $z_{v,t}$ is introduced, which is equal to 1 only when the truck is connecting or disconnecting to/from any stop (customers and hub) and is 0 otherwise.

$$x_{v,t}^{disp-on}\, P_{min}^{disp} \leq P_{v,t}^{disp} \leq x_{v,t}^{disp-on}\, P_{max}^{disp} \;\;\; \forall\, v, t \tag{3-21}$$

$$P_{v,t}^{disp} \times P_{v,t}^{truck} = 0 \;\;\; \forall\, t, v \tag{3-22}$$

$$x_{v,t}^{disp-on} = \; 0 \;\forall\, z_{v,t} = 1 \tag{3-23}$$

where P_{max}^{grid} is the maximum allowed power to be drawn from the grid,

P_{max}^{BAT-ch} is the maximum charging power of the battery,

$P_{max}^{BAT-dis}$ is the maximum discharging power of the battery,

$MDOD$ is the Maximum Depth of Discharge of the battery,

SOC_{max} is the maximum State of Charge of the battery,

P_{min}^{disp} is the minimum output power of the diesel generator,

and P_{max}^{disp} is the maximum output power of the diesel generator,

3.6 Problem Solving

The proposed problem in this thesis is translated from a scheduling problem to a Mixed-Integer Non-Linear Programming (MINLP) optimization problem. However, due to its complexity resulting from the very large number of variables, the problem was decomposed into two sub-problems. The outer sub problem has the objective of maximizing the revenue generated from selling power to the customers. The population generation in the outer problem with Genetic Algorithm (GA) is governed by the constraint in (3-11$)$. Constraint matrix constructed ensures only one customer can be served during time slot t. The connecting time, disconnecting time, and travelling time between customers was also taken in consideration in the outer sub-problem. The inner sub-problem works as an Energy Management System (EMS) and minimizes the costs associated with the system. The exact solver used for this sub-problem is BARON, Brand and Reduction Optimization Navigator, which solves for a global solution in MINLP and takes in consideration the power balance equations of the system to minimize the operating costs. The costs calculated will then be sent back to the outer sub-problem to be considered in the GA fitness function. The steps shown in Figure 3-6 summarize the over-all problem solving, with the objective of maximizing the profits.

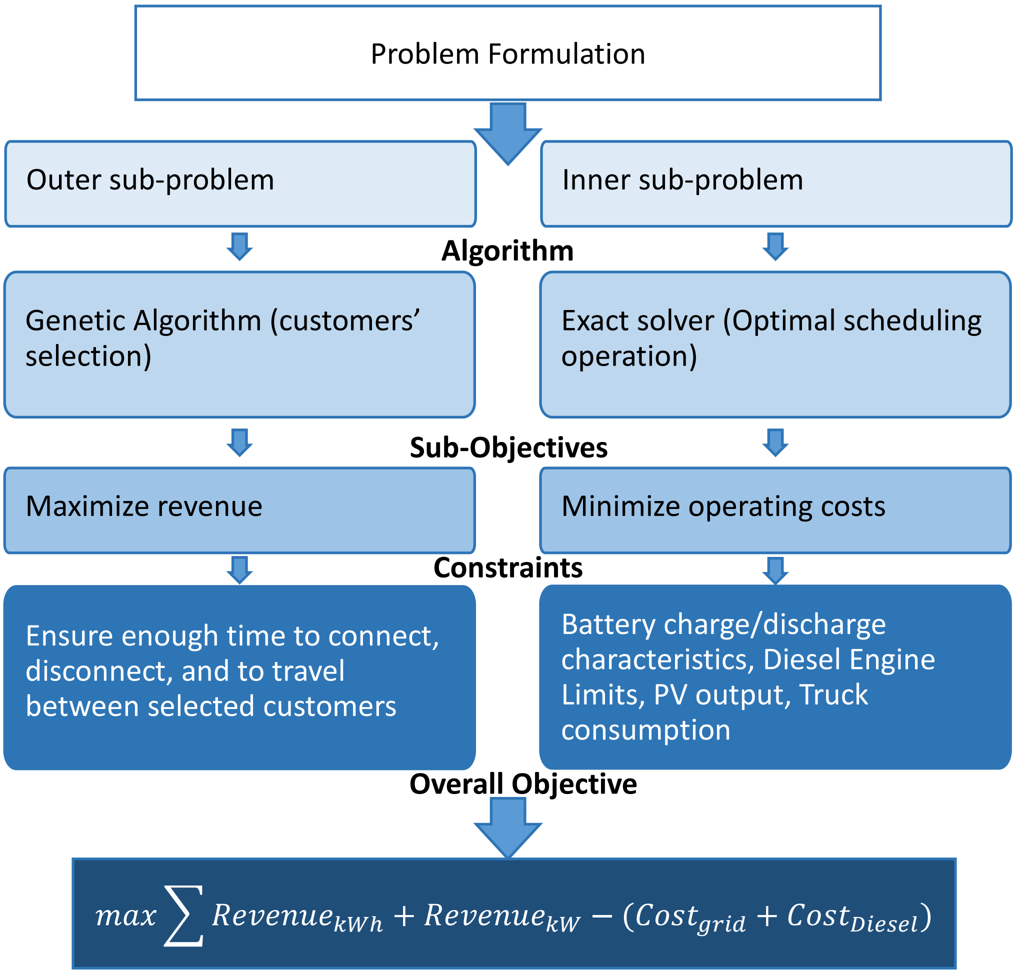

Figure 3-6 Summary of problem formulation

Chapter - 4 Case studies and results

To analyze the effectiveness of the proposed research, different cases were simulated. Table 4-1 and Table 4-2 show the parameters used and customers' requirements in all cases.

Table 4-1 Parameter values in case study

Parameter	Value	Parameter	Value
Δ_t	5 minutes	p_v^{fuel}	0.8677 $/L
v	Case 1 & 2:1, Case 3: 2	$\eta_{v,t}^{disp}$	0.266
k_{PV}	3	p_t^{grid}	0.1 $/kWh
p^{kW}	0.5 $/kW	$\eta_{v,t}^{BAT-ch}$	90%
p_t^{kWh}	0.3 $/kWh	$\eta_{v,t}^{BAT-dis}$	87%
P_{max}^{grid}	100 kW	E_{truck}	1.24 kWh/km
P_{max}^{BAT-ch}	100 kW	E_{max}^{BAT}	480 kWh
$P_{max}^{BAT-dis}$	100 kW	T^{cnn}	2 slots
$MDOD$	80%	T^{dcnn}	2 slots
SOC_0	25%	P_{min}^{disp}	50 kW
SOC_{max}	100%	P_{max}^{disp}	200 kW

4.1 Case 1

In case 1, only one truck is assumed to optimally serve several customers chosen from 19 profiles. In this case, the battery will be charged only from the PV panels throughout the day, or from the diesel generator if required, and as decided by the EMS. The total profit of the system, in this case, is \$395. Table 4-3 summarizes the revenue, costs, and profits for all cases studied. Figure 4-1 presents the consumption of the vehicle, the truck's consumption while moving from one customer to the other, and the customers' consumption, where the MEGSS is stationary and selling power. Figure 4-2 shows the charging and discharging power of the battery, while Figure 4-3 shows that most of the power supplied to the customers was generated from the diesel generator. Comparing those figures, it can be realized that the battery's discharge power was used to supply the truck's required energy for movement. Also, at certain times of the day, the truck-mounted PV panels were supplying some of the required power to the customers resulting in less power produced by the diesel generator.

Table 4-2 Customer Data used in case study

i	T_i^{start}	T_i^{end}	$P_{i,t}^{\text{Customer}}$	pf
1	0	1	0	0
2	96	168	175	0.781
3	204	246	180	0.753
4	240	288	185	0.781
5	36	72	145	0.955
6	84	180	190	0.912
7	156	192	185	0.9
8	276	288	160	0.847
9	264	288	160	0.819
10	234	252	185	0.857
11	264	288	170	0.555
12	186	216	175	0.581
13	108	150	160	0.673
14	96	132	160	0.731
15	216	264	170	0.847
16	132	192	165	0.988
17	156	216	180	0.673
18	156	168	195	0.873
19	84	120	150	0.673
20	12	36	195	0.919

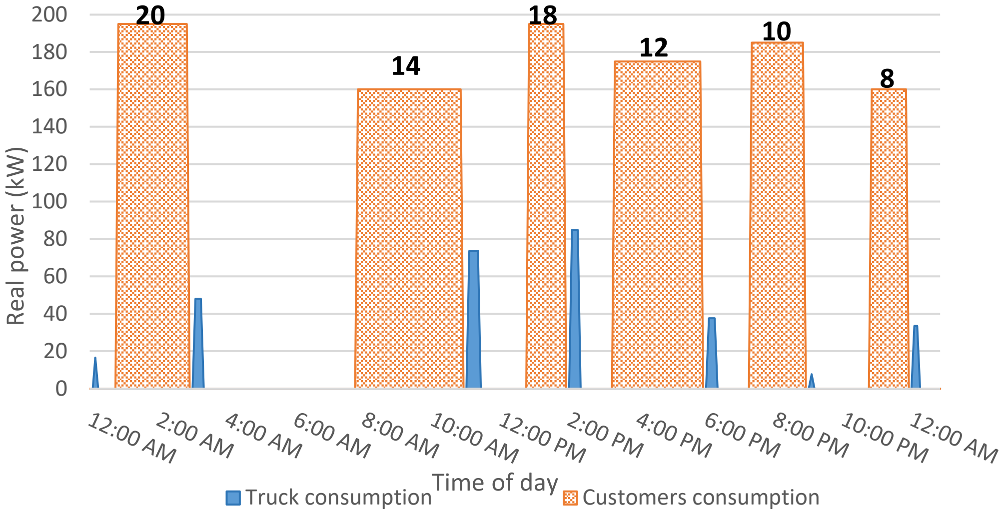

Figure 4-1 Case 1: Truck and customers' power consumption

However, a slight difference can be noted. This is due to two things:

1. During the day, the PV panels are contributing to supplying the power required by the truck.
2. Charging/discharging the battery usually entitles some power loss, represented by the efficiency factors which results in this change.

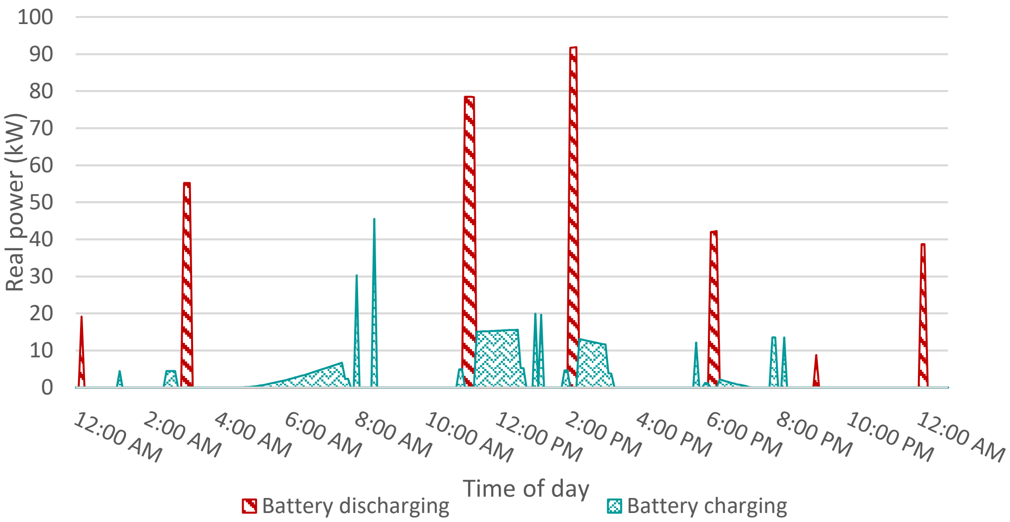

Figure 4-2 Case 1: Battery charging and discharging behavior

The total power generation of the proposed MEGSS is shown in Figure 4-4.

Figure 4-3 Case 1: Diesel generator output vs costumers' consumption

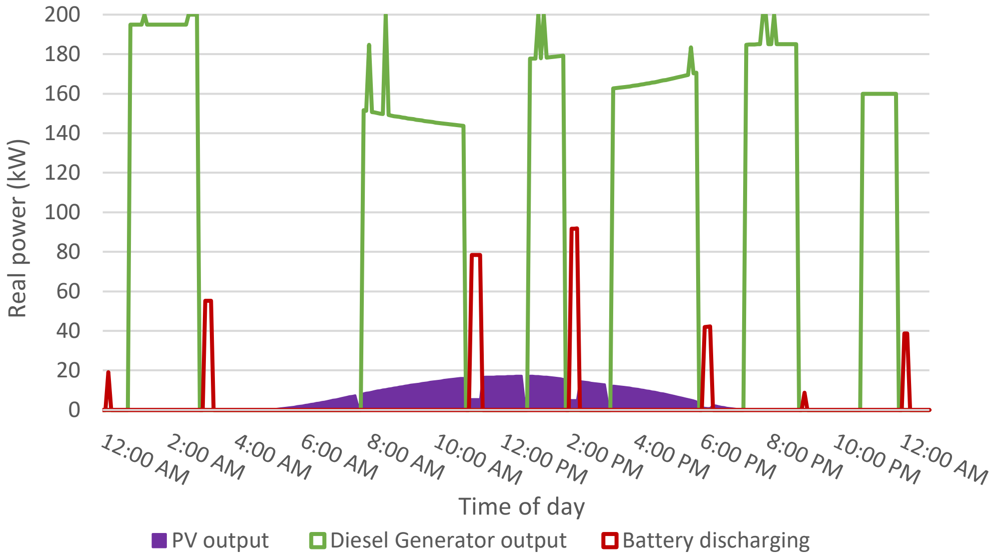

Figure 4-4 Case 1: Total power generation in MEGSS

The slight drops in the PV output power are due to the movement of the truck, where the extended cascaded panels are reduced to one-third.

4.2 Case 2

Case 2 represents a single truck that serves the optimized chosen customers, but in this case, the batteries are charged during off-peak hours from the grid, which can be seen from comparing figures Figure 4-5 and Figure 4-6.

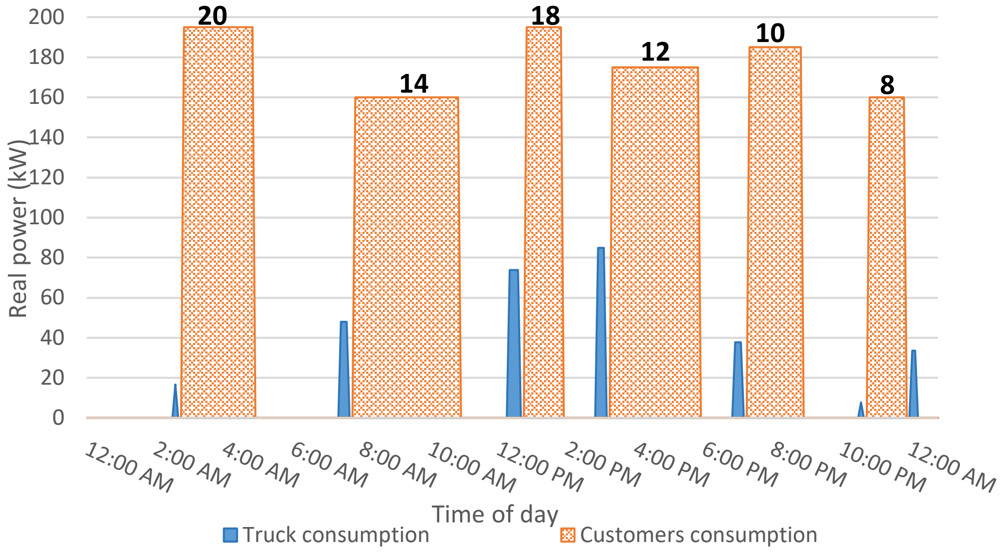

Figure 4-5 Case 2: Truck and costumers' power consumption

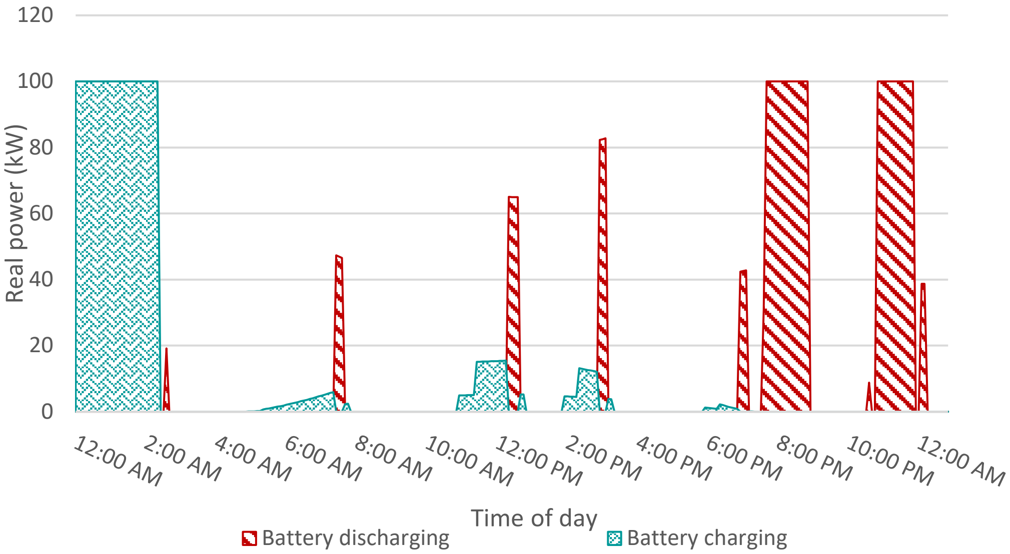

Figure 4-6 Case 2: Battery charging and discharging behavior

To ensure the off-peak hours charging, the MEGSS ensure the discharge of the battery by the end of the day as can be seen in Figure 4-6. This had an effect on decreasing the use of the diesel generator as seen in Figure 4-7. Comparing the results in this case to those in Case 1, it can be concluded that charging the batteries during off-peak hours had an impact on diesel usage, and thus improved the profit to $417.

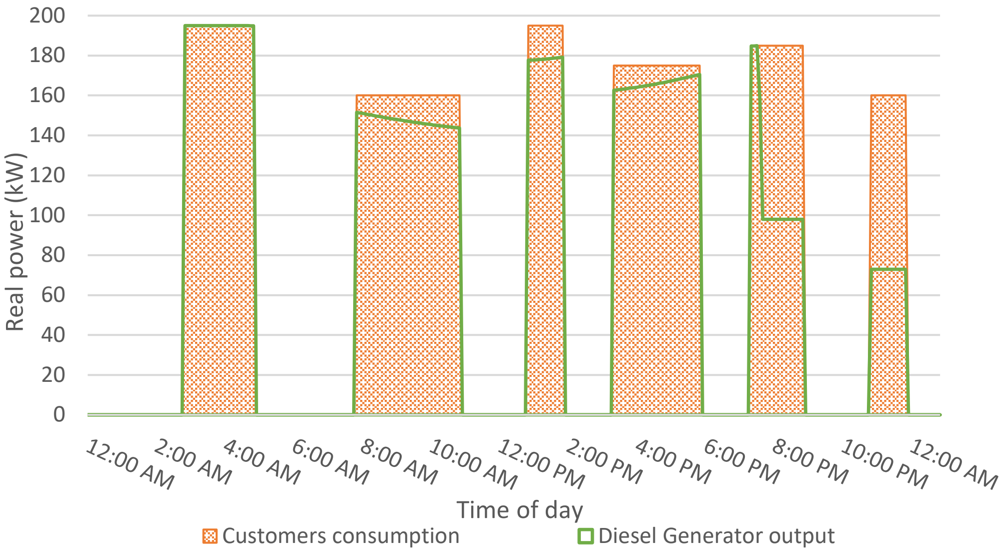

Figure 4-7 Case 2: Diesel generator output vs customers' consumption

The total generation of the system, in this case, is shown in Figure 4-8.

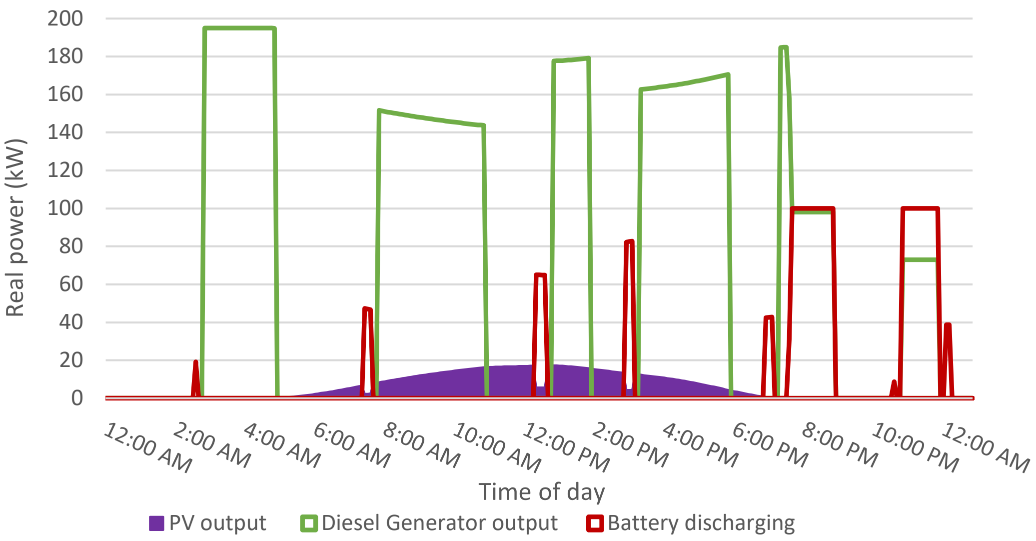

Figure 4-8 Case 2: Total power generation in MEGSS

4.3 Case 3

In Case 3, the problem is slightly expanded to include another MEGSS unit, to serve a new set the customers. The second truck will follow the pattern of the same one. Batteries will charge during off-peak hours before the truck is optimally dispatched to serve a set of customers and return to the hub. The optimizer is written in a way to forbid overlapping between customers, resulting in two different sets of served clients. For Truck 1, the same set of customers chosen in Case 2 will be chosen here.

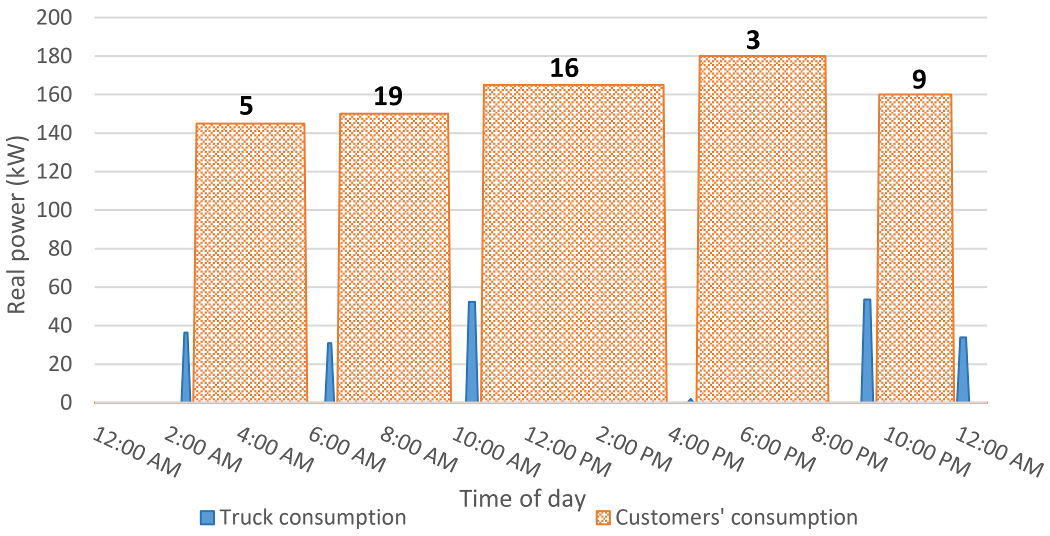

Figure 4-9 Case 3: Truck and customers' power consumption for Truck 2

The second MEGSS truck will serve the customers shown in Figure 4-9. Similar to the previous cases, Figure 4-10 shows the charging and discharging behavior of the battery pack, and Figure 4-11 shows the amount of customers' consumption power was served by the diesel generator. The total profit generated from this case is $945.

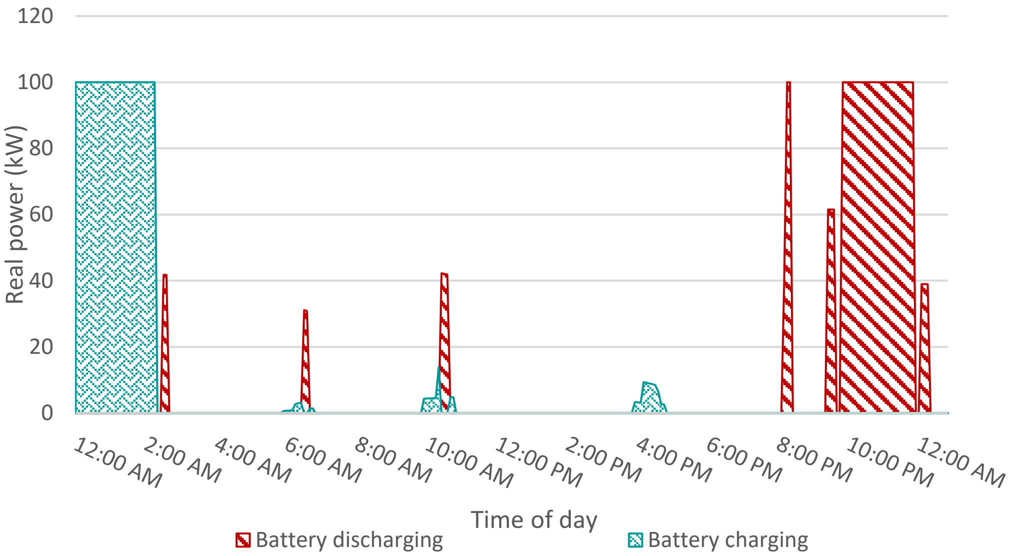

Figure 4-10 Case 3: Battery charging and discharging behavior of Truck 2

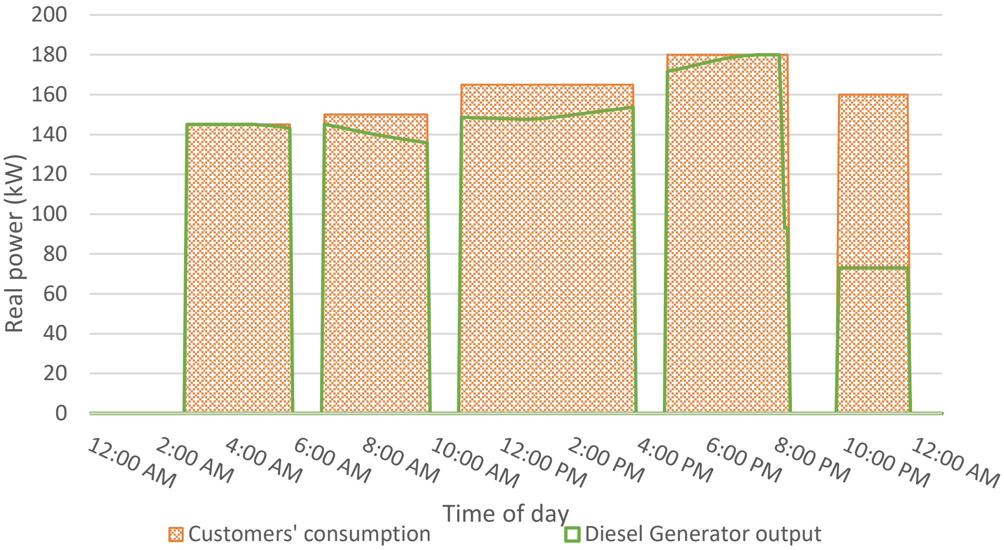

Figure 4-11 Case 3: Diesel generator output vs customers' consumption of Truck 2

Table 4-3 Summarized result for the 3 case studies

Case	Total revenue ($)	Total cost ($)	Total profit ($)
1	847	452	395
2	847	430	417
3	1,893	948	945

The power generation of the whole system for truck 2 is shown in Figure 4-12.

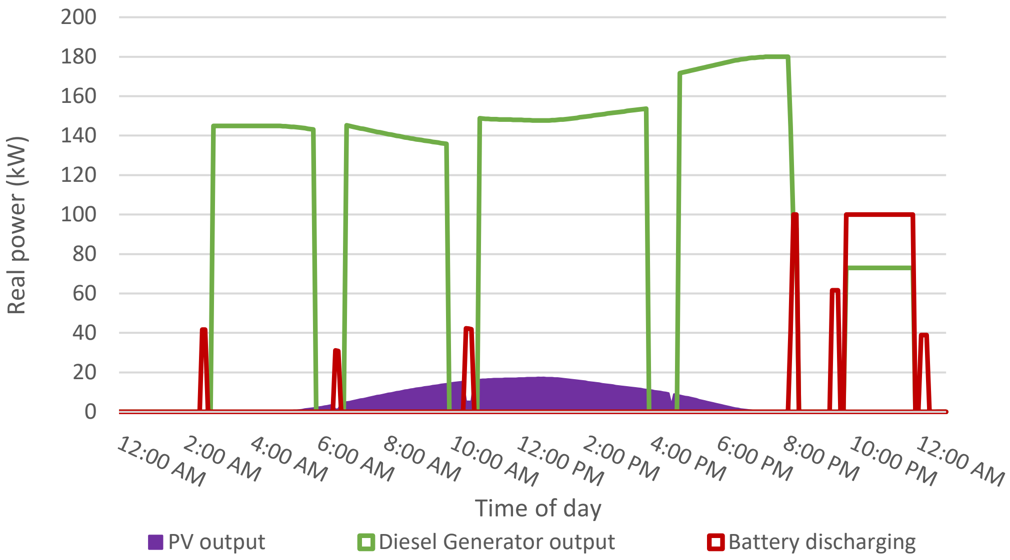

Figure 4-12 Case 3: Total power generation in MEGSS of Truck 2

The resultant route selection for both trucks is shown in Figure 4-13. Each truck leaves from the hub to serve a separate set of allocated customers and returns back to the hub at the end of the day.

A simple comparison can be made to realize the savings customers can make by using the service of the proposed system versus buying power from the grid. If the utility operators impose a demand charge of 5 $/kW, then customer 14, for example, will pay the grid an amount of $5 \times 160 = 800$ $ as demand charges alone. If customer 14 decides to use the services of the proposed system which provides power at 0.5 $/kW, as suggested in the case study, the savings for customer 14 will be $5 \times 160 - (0.5 \times 160) = 720$ $. Other charges from the grid, such as transmission and transmission connection charges, can increase the costs even further, thus making the proposed system a more lucrative option for customers.

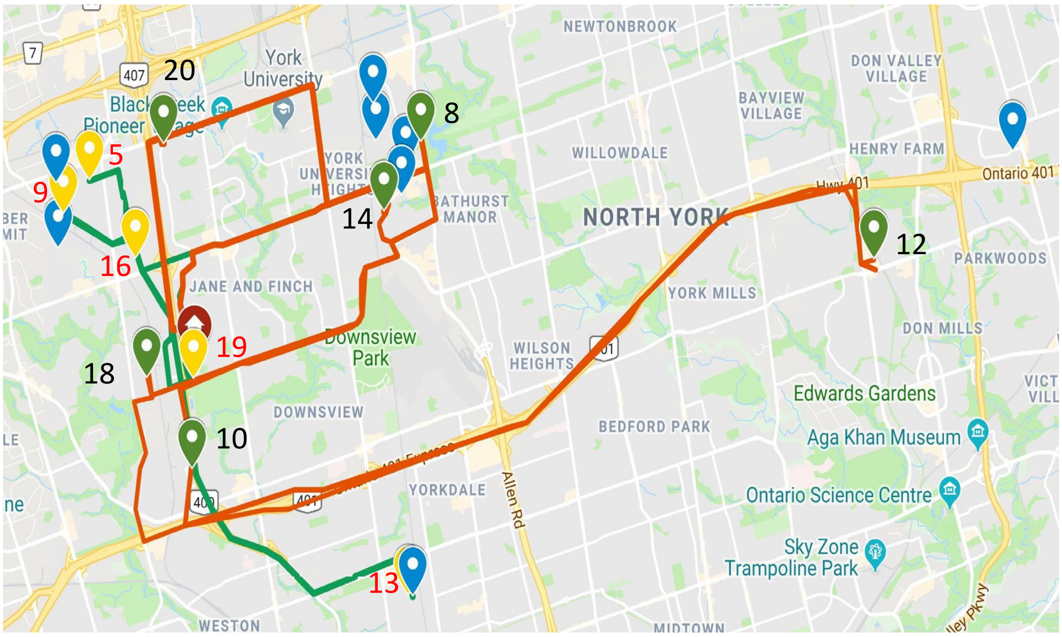

Figure 4-13 Map of North York, ON, Canada with chosen customers of Case 3

On the other hand, CO_2 reductions are achieved by using the battery or the PV panels instead of using the diesel generator, as seen in Case 2. For example, the requirement of customer 8 was served by both the battery pack and the diesel generator, where the larger contribution was made by the battery. In this case, assuming diesel generator supplied the customer with 70kWh, the resultant CO_2 emissions are $2.68\ \frac{kG}{L} \times 0.3\ \frac{L}{kWh} \times 70\ kWh = 64.32\ kG$. However, if the same customer was supplied by the grid power, the CO_2 emissions in that case would be $43\ \frac{kG}{kWh} \times 160\ kWh = 6{,}880\ kG$ which shows a huge reduction in harmful emissions while using the services provides of the proposed MEGSS.

4.4 Sensitivity Analysis

To perform sensitivity analysis on the proposed approach, Case 2 was run twice with a different offered energy price. Shown in Figure 4-14 are the resultant profits, and the served number of customers for three different offered prices. It is worth mentioning here, that trying to serve the customers' set resulting from Case 2 as in Figure *4-5* with an offered price of 0.45 \$/kWh will not result in a higher profit than the customers' set chosen by the proposed approach, given that it is serving fewer customers. The same case also applies for a lower energy price; the optimized solution changes as parameters change.

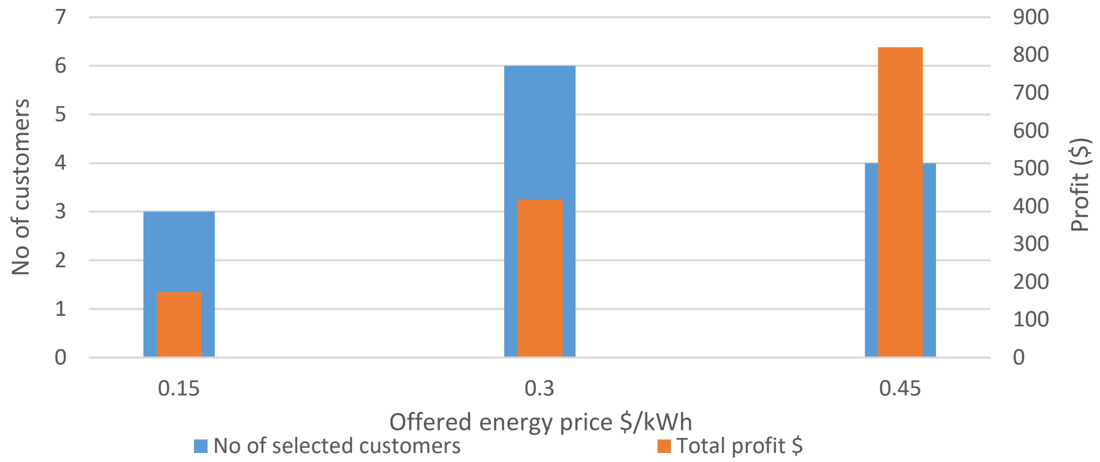

Figure 4-14 Sensitivity analysis with 3 different offered prices

4.5 Computational Time

To understand how different parameters can affect the computational time of the suggested approach, two simulations were tested with different time steps. Table shows

Table 4-4 Computational time changes due to change of parameters

Case tested	Time step Δ_t (min)	Computational time (hours)	No. of customers	Total Profit ($)
Case 2, first run	5	15	6	417
Case 2, second run	10	4	5	448

Both simulations were tested on Inter Core i7-5500U CPU x-64 based processor running at 2,4GHz using 64-bit operating system Windows 8.1 with 8 GB of RAM. The computational time for the second run was highly affected by changing the time step since it significantly reduces the number of variables in the system, in addition to the reduction of number of constraints as well. Figure 4-15 shows the truck and customers' consumption for case 2 with the adjustment of Δ_t to 10 minutes. Although the optimizer selected less customers to serve, the total profit exceeds that with the 5 minutes time step.

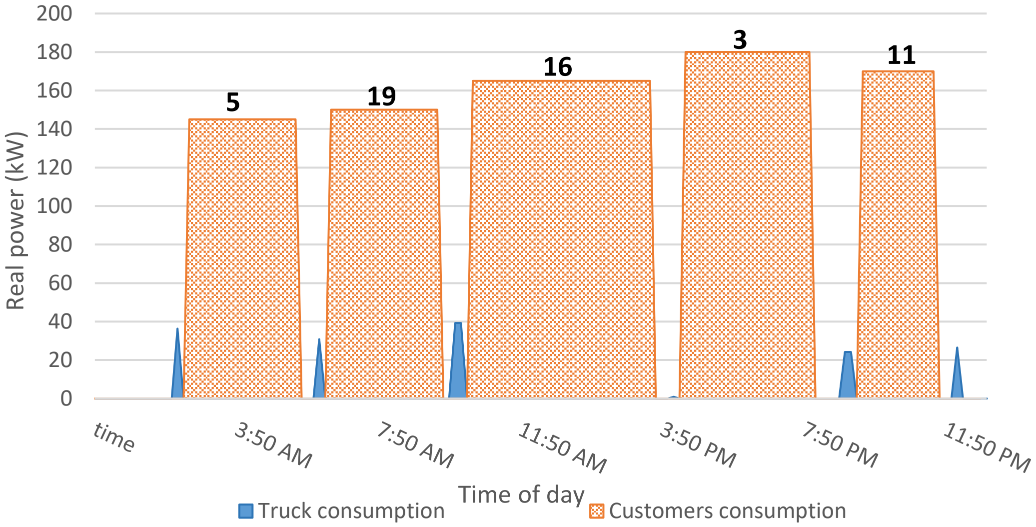

Figure 4-15 Case 2 with 10 minutes Δ_t: Truck and customers' consumption

The charging and discharging behavior in Figure 4-16 shows a similar pattern to the case with 5 minutes time step, as well as the diesel generator's percentage of serving the customers' requirements as suggested in Figure 4-17.

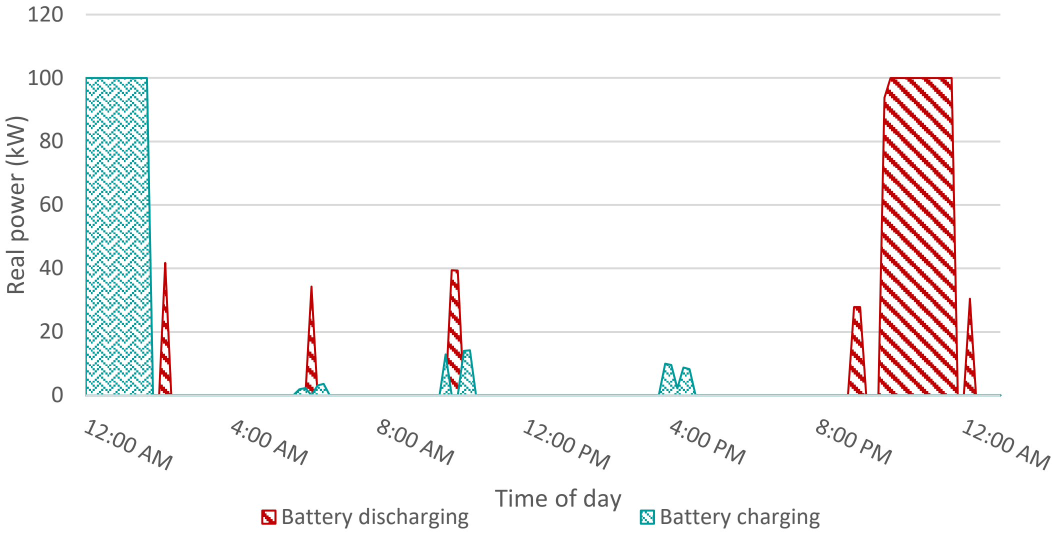

Figure 4-16 Case 2 with 10 minutes Δ_t: battery charging and discharging behavior

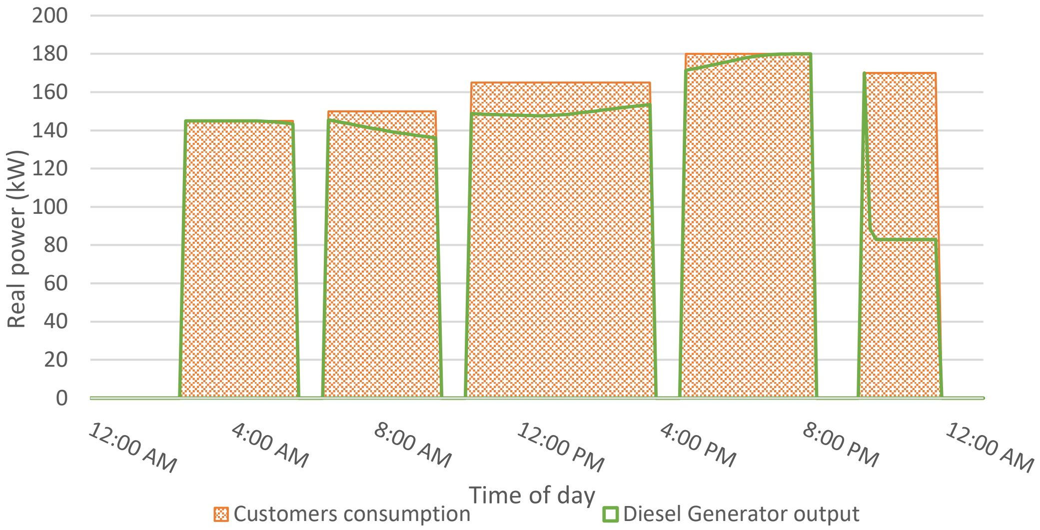

Figure 4-17 Case 2 with 10 minutes Δ_t: Diesel generator output vs customers' consumption

The output power of all generation components of the suggested system is shown in Figure 4-18.

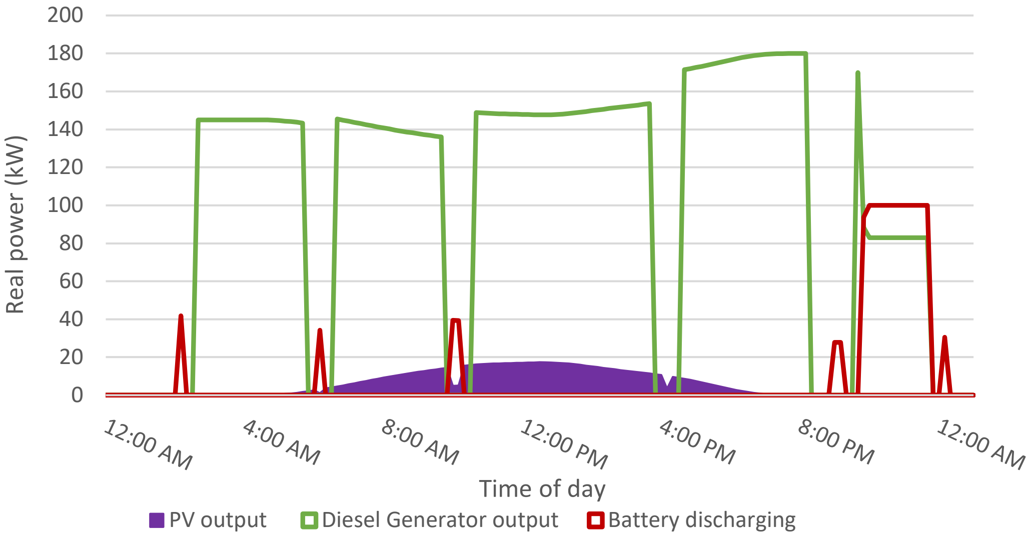

Figure 4-18 Case 2 with 10 minutes Δ_t: Total power generation in MEGSS

As mentioned earlier, a compromise needs to be taken into consideration when deciding on the time step of the problem. Increasing time step results in a small number of variables, and thus reduces the complexity of the problem, resulting in a faster computational time. However, more accuracy can be obtained with a smaller time step.

Chapter - 5 Conclusions and Future Work

This chapter discusses concluded findings of the result of the optimizer, as well as the future work that is needed to be carried out to complete the model of the system.

5.1 Conclusions

A comprehensive model was developed for a MEGSS truck that serves a number of customers in a city requiring power at a certain time throughout the day. The MEGSS model used so far depends on a diesel generator for serving customers, and it considers the time need to travel between customers based on day-ahead forecasted data. The suggested approach was successful in obtaining the required profits, and thus the system functions as targeted. In accordance with the motivation behind this research, the proposed system would provide an alternative source of power to the customer during scheduled maintenances or during times where demand charges are imposed on them. In addition, the proposed system can be effectively used to provide power during short-term maintenance and unforeseen events. The objective to achieve profits generated by choosing customers that provide maximum revenue, and minimizing operating costs was obtained, and the following set of conclusions can be drawn:

- The optimizer proved its effectiveness in solving the problem at hand and acquiring the desired objective.
- Using PV panels and the batteries has a significant effect on reducing the amount of diesel fuel used.
- Using a large battery pack and charging it during off-peak hours was effective in lowering fuel consumption, and in turn, lowering operating costs and CO_2 emissions.
- The offered energy price has a significant impact on the number of customers chosen and thus the profit generated.
- Expanding the serving fleet to include more serving units initially increases the profits. However, the customers' pool must also increase to avoid investment losses, which can happen when a truck is left with 2 or 3 customers to serve. To increase the customers' number, more profiles can be acquired, or different MEGSS units can be allocated to different areas.

To enhance this research even further, some possibilities of expanding the word already done are suggested in the following section.

5.2 Future Work

To further improve the proposed work in this thesis, several points can be added. The addition of the following components can either improve the results of the economic model and thus reflect more accurate financial results or can be used to improve the system technically.

- *Providing ancillary services*: The proposed approach can expand to include connecting the suggested system to the grid to provide technical services such as supporting the voltage on a certain bus, or correction of reactive power due to inductive loads.
- *Include varying truck consumption*: Due to climate limitations, whether it be cooling or heating of the interior of the truck to a threshold suitable for the driver's comfort, A/C power consumption should be considered as it can increase the EV consumption to 100%. In addition, varying speed also effects the power consumption of the vehicle and thus can also be accounted for.
- *Replace the diesel and the BESS with Fuel Cell*: A fuel cell can be used to power the truck and to supply customers at almost zero emissions. However, capital cost analysis should be studied to ensure the economic feasibility of the MEGSS.

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Appendix A: Traffic Data

$T_{i,j}^{travel}$ in time slots

Time required for travelling between customers

i/j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	0	3	3	3	2	2	1	2	3	2	1	2	4	3	2	3	1	4	1	0
2	3	0	4	4	3	4	2	4	1	3	4	1	4	0	1	4	3	4	3	3
3	3	4	0	3	3	3	3	3	3	3	3	3	3	4	3	0	3	4	3	3
4	68	70	69	0	68	69	68	68	70	68	68	70	70	70	69	69	68	70	68	68
5	2	3	3	3	0	1	1	1	3	0	2	3	4	3	3	3	1	4	2	2
6	2	4	3	3	1	0	2	1	4	1	2	3	4	3	3	3	1	5	2	2
7	1	2	3	2	1	2	0	1	2	1	2	2	4	2	2	3	1	4	2	1
8	2	3	3	3	1	1	1	0	4	0	2	3	4	3	3	3	1	4	1	2
9	3	1	3	3	3	4	3	4	0	4	3	1	3	1	1	3	3	4	3	3
10	2	3	3	2	0	1	1	0	3	0	2	3	4	3	3	3	1	4	1	2
11	1	4	3	2	2	2	2	2	4	2	0	3	4	3	3	3	1	4	1	1
12	3	1	3	3	3	3	2	3	1	3	3	0	3	1	0	3	2	4	3	2
13	4	4	4	4	4	5	4	5	4	4	4	4	0	4	4	4	4	2	4	4
14	3	0	4	4	3	3	2	3	1	3	4	1	4	0	1	4	3	4	4	3
15	2	1	3	3	3	3	2	3	1	3	3	0	3	1	0	3	2	3	2	2
16	3	4	0	3	3	3	3	3	3	3	3	3	3	4	3	0	3	4	3	3
17	1	3	2	2	1	1	1	1	3	1	1	2	4	3	2	2	0	4	1	1
18	4	4	3	3	4	4	4	4	3	4	4	3	2	4	3	3	4	0	4	4
19	1	3	3	2	2	1	2	1	3	1	1	3	4	4	2	3	1	4	0	1
20	0	3	3	2	2	2	1	2	3	2	1	2	4	3	2	3	1	4	0	0

$D_{i,j}$ in km

Distance of travelling between customers chosen for case study

i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.0	7.2	11.7	5.8	4.9	4.6	3.6	4.5	6.9	4.6	3.5	6.0	22.6	8.9	6.0	11.9	2.9	25.5	2.3	1.1
2	7.2	0.0	11.6	5.9	7.8	8.8	6.1	8.6	1.2	8.9	10.5	1.6	16.2	0.7	2.2	11.7	7.0	19.1	9.3	8.1
3	11.1	11.9	0.0	5.8	13.9	11.9	12.2	11.8	10.8	11.9	6.5	8.3	15.0	12.7	7.8	0.1	10.2	17.9	10.5	8.2
4	582.3	594.7	581.4	0.0	586.9	588.4	583.4	586.7	587.3	586.3	577.0	587.3	591.4	594.0	586.7	581.5	581.4	594.3	577.6	578.2
5	4.9	7.8	11.8	5.9	0.0	3.1	1.9	1.4	8.4	1.0	6.1	7.8	22.7	7.0	7.8	12.0	2.1	25.6	4.1	5.1
6	4.6	8.8	11.6	5.8	3.1	0.0	5.2	2.0	8.4	2.2	5.9	7.6	22.4	12.5	7.6	11.7	2.4	25.3	3.7	4.8
7	3.6	6.1	12.8	5.8	1.9	5.2	0.0	3.4	6.7	3.0	6.8	6.6	23.6	5.3	6.6	12.9	2.9	26.5	5.6	4.4
8	4.5	12.3	11.5	5.9	1.4	2.0	3.4	0.0	8.3	0.5	5.8	7.5	22.3	11.6	7.4	11.6	2.4	25.2	3.6	4.8
9	6.8	1.1	10.4	5.9	8.1	8.4	6.4	8.3	0.0	8.4	9.8	1.3	15.0	1.9	1.9	10.6	6.6	18.0	8.6	7.4
10	4.6	11.9	11.6	5.9	1.0	2.2	3.0	0.5	12.6	0.0	5.9	7.6	22.4	11.2	7.6	11.7	1.9	25.3	3.8	4.8
11	3.6	10.4	6.5	5.8	6.1	5.9	6.9	5.8	9.9	5.9	0.0	8.8	19.2	14.1	8.3	6.7	4.1	22.1	2.6	2.4
12	6.0	1.6	8.4	5.9	7.8	7.6	6.6	7.5	1.3	7.6	8.8	0.0	15.0	2.4	0.5	8.5	5.8	18.0	7.6	6.4
13	22.2	16.2	15.7	5.9	25.0	23.1	23.3	22.9	15.1	23.0	19.7	15.1	0.0	17.0	14.6	15.9	21.3	5.8	20.4	20.9
14	8.0	0.7	12.3	5.9	7.0	12.8	5.3	8.5	2.0	8.1	14.5	2.4	16.9	0.0	3.0	12.5	8.0	19.8	10.0	8.9
15	7.0	2.2	7.8	5.9	7.8	7.6	6.6	7.4	1.9	7.6	8.3	0.5	14.5	3.0	0.0	8.0	5.8	17.4	7.0	5.9
16	11.3	12.1	0.1	5.8	14.1	12.2	12.4	12.0	10.9	12.2	6.7	8.5	15.1	12.8	7.9	0.0	10.4	18.0	10.6	8.4
17	2.9	7.0	9.8	5.8	2.1	2.4	2.9	2.4	6.7	1.9	4.1	5.8	20.7	8.0	5.8	10.0	0.0	23.6	3.2	3.1
18	24.2	18.2	17.7	5.9	27.0	25.0	25.3	24.9	17.1	25.0	21.7	17.1	5.7	19.0	16.6	17.8	23.3	0.0	22.3	22.9
19	2.3	9.3	10.4	5.8	4.1	3.7	5.6	3.6	8.6	3.8	2.2	7.6	20.5	10.0	7.1	10.5	3.3	23.4	0.0	1.2
20	1.1	8.1	7.9	5.8	5.0	4.8	4.4	4.8	7.5	4.8	2.4	6.5	21.0	9.7	5.9	8.0	3.0	23.9	1.2	0.0

Vita

Sarra Mahmoud Samara was born in Sharjah , UAE in 1987. She completed her elementary and hisgh school education in Sharjah, UAE. She receieved her Bachelor's Degree in Electrical Engineering from the American University of Sharjah, UAE, in 2008. In 2010 she worked for almost a year as a Project Management Office Administrator at Siemens, Dubai. She then took a role as a Systems' Engineer from April 2012 to November 2013 in Innovative Contractors for Advanced Dimensions (ICAD) in Jeddah, KSA.

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