

ENERGY MANAGEMENT SYSTEM FOR PV-BESS-  
DIESEL GENERATOR ISLANDED MICROGRID USING  
MODEL PREDICTIVE CONTROL

BY

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## ABSTRACT

Islanded microgrid is identified as a cost-effective solution to provide electricity to the off-grid areas which are far from the main electricity grid. However, intermittent nature of renewable energy source (RES) and unpredictable nature of load demand can cause an imbalance in the islanded microgrid. In islanded microgrid, components such as battery energy storage system (BESS) and diesel generator can compensate this problem. Diesel generator, especially, can provide auxiliary energy and act as the main grid in the islanded microgrid. Nonetheless, the inefficient utilisation of diesel generator can lead to unnecessary operation cost, shorten the life span and most importantly, contributing to the environmental pollution. Hence, energy management system (EMS) is employed to operate and manage the microgrid efficiently. Model predictive control (MPC) which has grown in popularity in recent years will be integrated with the EMS. The focus of this research is to reduce the use of diesel generator through efficient microgrid management utilising MPC-based EMS. It is proposed that load curtailment and greenhouse gas emissions cost function are included in the EMS to reduce the cost of the diesel generator operation. Two test cases are designed. The first test case compares the performance MPC-based EMS with and without load curtailment to evaluate the diesel generator cost savings. The second test case will observe the impact of the cost functions especially diesel fuel consumption cost and greenhouse gas emission cost influence the cost saving of diesel generator. The MPC-based EMS is simulated using MATLAB software. The optimisation problem of the MPC-based EMS is formulated using mixed integer quadratic programming (MIQP) and is solved using CPLEX. The results shows that the reduction of diesel fuel cost and consumption by 52.21% in MPC-based EMS utilising load curtailment compared to without load curtailment. In the second test case, it is found the second order polynomial diesel fuel consumption cost function is sufficed in reducing fuel cost by 34% compared to combining both diesel fuel consumption cost function and greenhouse gas emission cost function. In contrast, diesel fuel cost and consumption increased dramatically by 178%, despite a trivial improvement in greenhouse gas emission cost. Hence, it can be concluded that MPC-based EMS with load curtailment is able to improve the cost saving of the diesel generator. In addition, second order polynomial diesel fuel consumption cost function is sufficed to drive down the usage of diesel generator. However, load curtailment, particularly demand side management strategies, must be enhanced for islanded or standalone microgrids where incentive-based method cannot be applied.

## ملخص البحث

تم تحديد الشبكة الكهربائية الصغيرة المعزولة كحل فعال من حيث التكلفة لتوفير الكهرباء للمناطق خارج الشبكة والتي تقع بعيداً عن شبكة الكهرباء الرئيسية. ومع ذلك، فإن الطبيعة المتقطعة لمصدر الطاقة المتجددة (RES) والطبيعة غير المتوقعة لطلب الحمل يمكن أن تسبب خللاً في الشبكة الكهربائية الصغيرة المعزولة. في الشبكة الكهربائية الصغيرة المعزولة، يمكن لمكونات مثل نظام تخزين طاقة البطارية (BESS) ومولد الديزل تعويض هذه المشكلة. يمكن لمولد الديزل، على وجه الخصوص، توفير الطاقة المساعدة والعمل كشبكة رئيسية في الشبكة الكهربائية الصغيرة المعزولة. ومع ذلك، فإن الاستخدام غير الفعال لمولد الديزل يمكن أن يؤدي إلى تكلفة تشغيل غير ضرورية، وتقصير عمر الخدمة والأهم من ذلك، المساهمة في التلوث البيئي. وبالتالي، يتم استخدام نظام إدارة الطاقة (EMS) لتشغيل وإدارة الشبكة الكهربائية الصغيرة بكفاءة. سيتم دمج التحكم التنبئي بالنموذج (MPC) الذي اكتسب شعبية في السنوات الأخيرة مع نظام إدارة الطاقة. يركز هذا البحث على تقليل استخدام مولد الديزل من خلال إدارة الشبكة الكهربائية الصغيرة الفعالة باستخدام نظام إدارة الطاقة القائم على MPC. تم اقتراح تضمين تقليص الحمل ووظيفة تكلفة انبعاثات غازات الاحتباس الحراري في نظام إدارة الطاقة لتقليل تكلفة تشغيل مولد الديزل. تم تصميم حالتين اختبار يقيان حالة الاختبار الأولى بين أداء نظام إدارة الطاقة المستند إلى MPC مع وبدون تقليص الحمل لتقييم

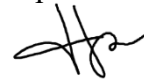
وفورات تكلفة مولد الديزل. ستلاحظ حالة الاختبار الثانية تأثير وظائف التكلفة وخاصة تكلفة استهلاك وقود الديزل وتكلفة انبعاثات غازات الاحتباس الحراري التي تؤثر على توفير تكلفة مولد الديزل. ويتم محاكاة نظام إدارة الطاقة المستند إلى MPC باستخدام برنامج MATLAB. تمت صياغة مشكلة التحسين لنظام إدارة الطاقة المستند إلى MPC باستخدام البرمجة التربيعية الصحيحة المختلطة (MIQP) وتم حلها باستخدام CPLEX. تظهر النتائج أن انخفاض تكلفة وقود الديزل واستهلاكه بنسبة 52.21% في نظام إدارة الطاقة المستند إلى MPC باستخدام تقليص الحمل مقارنة بعدم تقليص الحمل. في حالة الاختبار الثانية، وجد أن دالة تكلفة استهلاك وقود الديزل متعددة الحدود من الدرجة الثانية كافية لتقليل تكلفة الوقود بنسبة 34% مقارنة بالجمع بين كل من دالة تكلفة استهلاك وقود الديزل ودالة تكلفة انبعاثات غازات الاحتباس الحراري. وعلى النقيض من ذلك، ارتفعت تكلفة وقود الديزل واستهلاكه بشكل كبير بنسبة 178%، على الرغم من التحسن الطفيف في تكلفة انبعاثات الغازات المسببة للانحباس الحراري العالمي. وبالتالي، يمكن الاستنتاج أن نظام إدارة الطاقة القائم على MPC مع تقليص الحمل قادر على تحسين توفير التكاليف لمولدات الديزل. بالإضافة إلى ذلك، فإن دالة تكلفة استهلاك وقود الديزل متعددة الحدود من الدرجة الثانية كافية لخفض استخدام مولدات الديزل. ومع ذلك، يجب تعزيز تقليص الحمل، وخاصة استراتيجيات إدارة جانب الطلب، للشبكات الصغيرة المعزولة أو المستقلة حيث لا يمكن للطريقة القائمة على الحوافز.

## APPROVAL PAGE

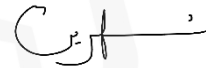
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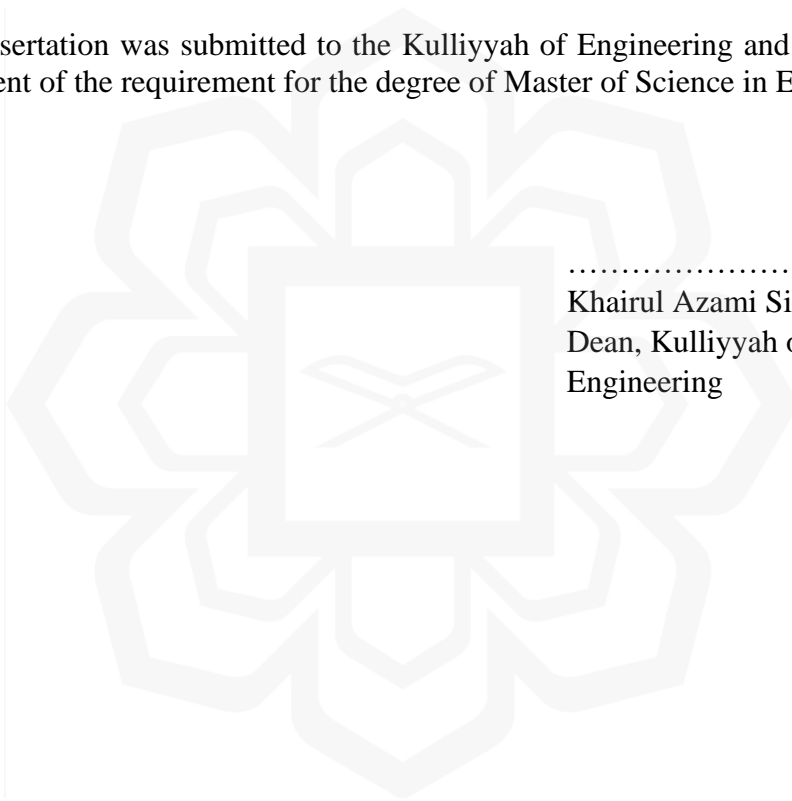
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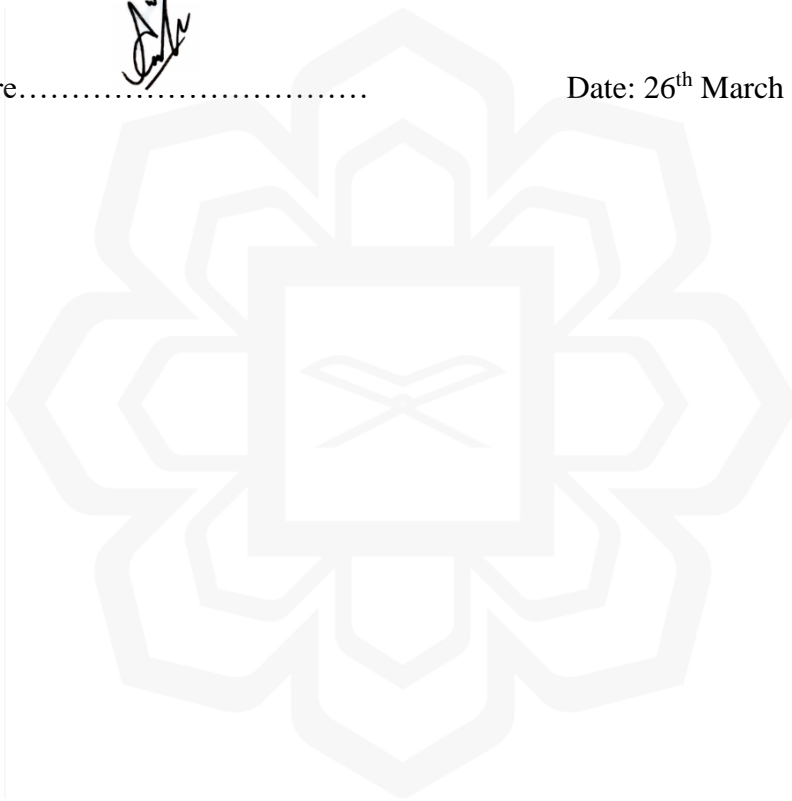
## DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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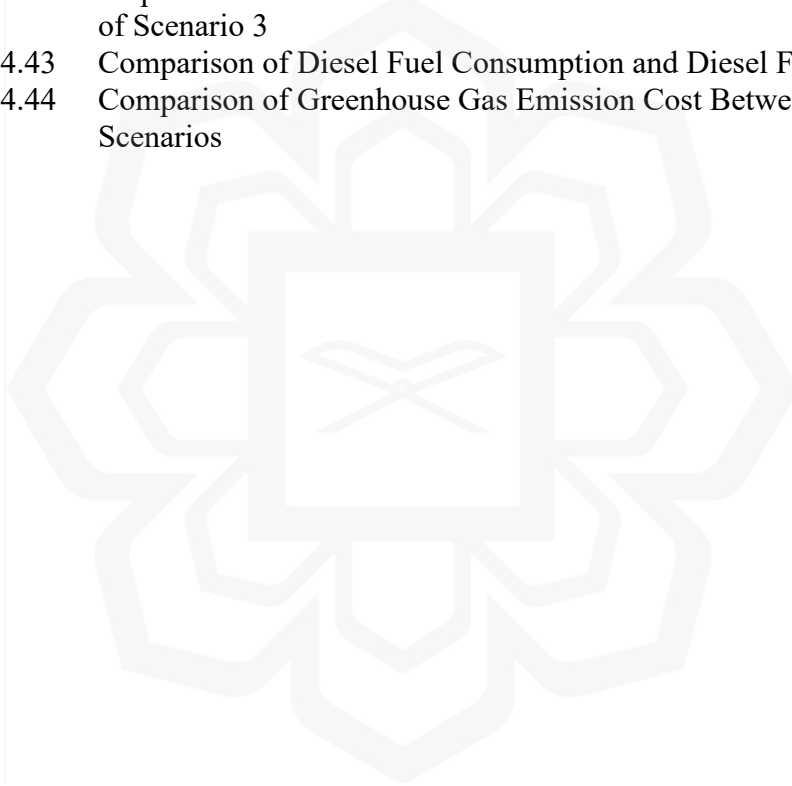


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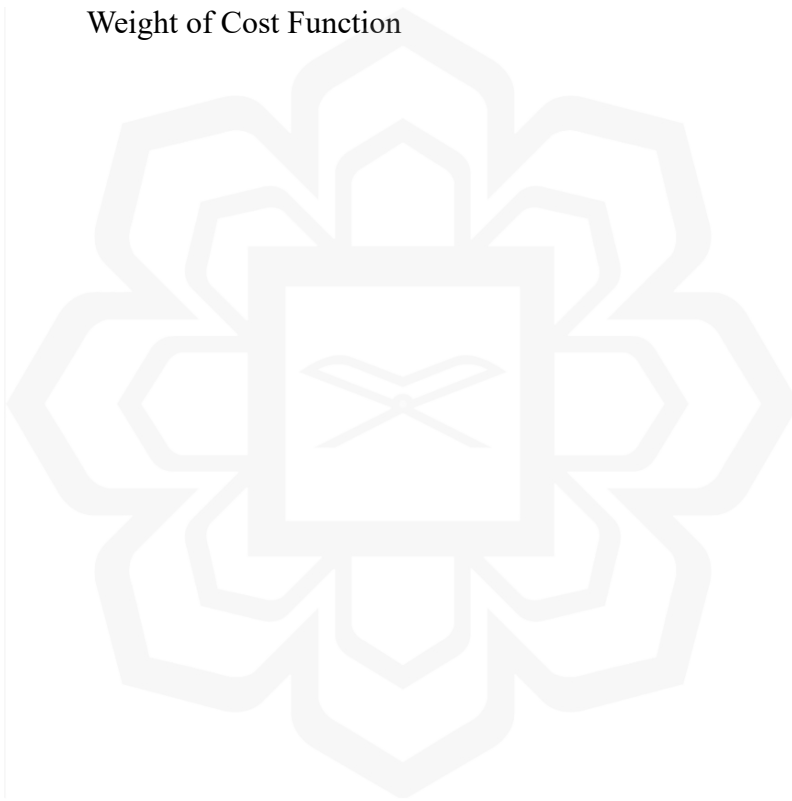
## LIST OF ABBREVIATIONS

RES	Renewable Energy Source
BESS	Battery Energy Storage System
EMS	Energy Management System
MPC	Model Predictive Control
SoC	State of Charge
MIQP	Mixed Integer Quadratic Programming
PV	Photovoltaics
DER	Distributed Energy Resources
ESS	Energy Storage System
PCC	Point of Common-Coupling
DG	Distributed Generation
DC	Direct Current
AC	Alternate Current
MG	Microgrid
MGCC	Microgrid Central Controller
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
ECC	Energy Control Centre
DMS	Distribution Management System
LC	Load Control
DSM	Demand Side Management
GHG	Greenhouse Gas
MLD	Mixed Logical Dynamic
QCC	Quadratic Cost Curve

## LIST OF SYMBOLS

$N_c$	Control Horizon
$N_p$	Prediction Horizon
$SoC$	SoC of the BESS
$C_{bat}^{max}$	Maximum Capacity of the BESS
$I_{bat}$	BESS Current
$P_{bat}$	BESS Power
$p_{bat}^{discharging}$	BESS Discharging Power
$p_{bat}^{charging}$	BESS Charging Power
$T_s$	Sampling Time
$\eta_{discharging}$	BESS Discharging and Power Ponverter Efficiency
$\eta_{charging}$	BESS Charging and Power Ponverter Efficiency
$SoC_{min}$	Minimum SoC of the BESS
$SoC_{max}$	Maximum SoC of the BESS
$p_{bat}^{min}$	BESS Maximum Charging Power
$p_{bat}^{max}$	BESS Maximum Discharging Power
$Z_{bat}$	BESS Auxiliary Variable
$\delta_{bat}$	BESS Binary Variable
$P_{DG}$	Diesel Generator Power
$p_{DG}^{min}$	Diesel Generator Minimum Power
$p_{DG}^{max}$	Diesel Generator Maximum Power
$\delta_{DG}$	Diesel Generator Binary Variable
$P_{CURTAIL}$	Load Curtailment Power
$p_{CURTAIL}^{min}$	Load Curtailment Minimum Power
$p_{CURTAIL}^{max}$	Load Curtailment Maximum Power
$J_{Global}$	Global Cost Function
$J_{BESS}$	BESS Cost Function
$J_{GHG}$	Greenhouse Gas Emission Cost Function
$C_{DG}$	Diesel Cost

$a, b, c$	Fuel Cost Coefficients
$SoC_{ref}$	Reference SoC of the BESS
$NO_x$	Nitric Oxide & Nitrogen Dioxide
$CO_2$	Carbon Dioxide
$CO$	Carbon Monoxide
$SO_2$	Sulphur Dioxide
$\alpha$	Emission Factor of Greenhouse Gas
$\mu$	Environmental Damages Cost Due to Greenhouse Gas Emission
$U$	Decision Variables
$\lambda$	Weight of Cost Function



# CHAPTER ONE

## INTRODUCTION

### 1.1 BACKGROUND

It is approximated 770 million people in this world are currently living without the access to the electricity (SDG7: *Data and Projections*, 2022). In addition, the increasing population has led to the increase of the burning of fossil fuels to meet the ever-increasing energy demand. This consequently raise environmental concern due to the release of greenhouse gases from the energy supply especially for the remote and off-grid areas (Raya-Armenta et al., 2021).

Renewable energy sources such as photovoltaics (PV), wind energy, hydro energy and others have become a first choice to overcome this problem. Due to their uncertainty, microgrids is introduced to properly manage the RESs (Raya-Armenta et al., 2021). According to (Zahraoui et al., 2021), microgrid incorporates distributed energy resources (DER) either renewable or non-renewable energy sources with energy storage systems (ESS) to support loads. Microgrid can be grid-connected or in island mode. In islanded mode, microgrid is disconnected from the grid at the point of common-coupling (PCC) (Raya-Armenta et al., 2021).

Islanded microgrid is seen as a suitable solution to provide electrical supply to the remote and off-grid areas. Islanded microgrid comprises of PV, BESS, diesel generator and loads can provide a cost effective and efficient solution to meet the load demand in remote areas (Batiyah et al., 2022; Nair & Costa-Castelló, 2020). PV alone cannot be made as a reliable system due to its dependence on the stochastic nature of the environment. Hence, integrating ESS such as battery to the system allows the energy

to be stored when in excess and supplied to the load when the generation is lower than demand (Batiyah et al., 2022; Batiyah et al., 2020). The utilization of the BESS is to counter the effect of abrupt disturbances and daily profile of PV power (Batiyah et al., 2022).

The key to efficient management of DER in the microgrid is the energy management system (EMS). The EMS is responsible for managing and coordinating the energy sharing in the microgrid. The optimized management of the DER through EMS can help in maintaining the balance of demand and supply, improving microgrid reliability in addition to reduce the cost of energy production (Rathor & Saxena, 2020).

Various EMS techniques and optimization techniques for microgrid have been proposed, however, model predictive control (MPC) have garnered wide attention among the researchers. This is due to its capabilities to forecast the power generation capability of each DER by using the dynamic model of the microgrid. This can reduce the uncertainty in managing the microgrid hence improving the reliability of the microgrid (Rathor & Saxena, 2020; Raya-Armenta et al., 2021).

The proposed study aims to improve MPC-based EMS for islanded PV, BESS and diesel generator microgrid by focusing specifically on improving the cost saving for the diesel generator in terms of fuel consumption cost. Utilizing load curtailment and greenhouse gas emissions cost function, the study seeks to reduce the reliance on the diesel generator in the islanded microgrid. Hence, contributing to cost-efficient operation of the islanded microgrid and reducing the greenhouse gas emission to the environment.

## 1.2 PROBLEM STATEMENT

The intermittent nature of RES and the unpredictable nature of load can cause imbalances in the microgrid. The imbalance can occur when output power from RES may not be adequate to meet the demand at certain times or at other times, the generated power may be more than the demand. The stability of the microgrid is necessary especially for the islanded microgrid or standalone microgrid. This is due to the unavailability of the main grid to support and aid the stability of the microgrid (Badawi et al., 2019; Batiyah et al., 2022; Raya-Armenta et al., 2021).

In PV, BESS and diesel generator islanded microgrid, diesel generator able to provide the necessary support by acting as a main grid. However, inefficient usage of diesel generator can lead to high diesel fuel consumption, which can lead to high operation cost and also contributing to the environmental pollution (Nair & Costa-Castelló, 2020). With efficient EMS, the operation of the DER, especially diesel generator, can be optimized. Consequently, improving the operation cost of the diesel generator and the microgrid system entirely.

To overcome this problem, MPC-based EMS is proposed to improve the cost saving of the diesel generator in PV, BESS, diesel generator islanded microgrid. As mentioned, EMS is used to maintain stability in the microgrid by efficiently managing the operation of the components in the microgrid. MPC, which has been seen rising in popularity in recent years, is integrated in the EMS due to its capabilities to support multiple inputs and multiple outputs systems such as microgrid.

The EMS is crucial in islanded microgrid which relies solely on the RES without the support of the main grid. The islanded microgrid is crucial especially for the people who live in remote areas far from the main grid. The PV, BESS and diesel generator islanded microgrid can provide efficiency in terms of cost and reliability (Batiyah et al., 2022; Nair & Costa-Castelló, 2020). With the proposed MPC-based EMS, PV, BESS and diesel generator islanded microgrid can become effective, long-term solutions for

electrifying rural areas by reducing operational costs through efficient diesel generator usage, which in turn can also minimize environmental impact by the greenhouse gas emission.

Most of the current systems are complex and exhibit nonlinear characteristics, including the diesel fuel consumption cost function. Previous studies on MPC-based EMS have primarily utilized a linear fuel consumption cost function (Basantes et al., 2023; Salazar et al., 2021).. This is important as MPC-based EMS relies on accurate models to generate optimized control strategies for microgrids. The more precise the model, the more effective optimization of control inputs, eventually improving the cost savings associated with diesel generator operation.

Although the effects of diesel generators on the environment are widely known, the economic analysis of diesel generator operations does not fully incorporate greenhouse gas (GHG) cost functions. Most of the previous research has been concentrated on conventional cost functions that do not take into consideration the external costs related to greenhouse gas emissions. The capacity to completely evaluate the financial effects of using diesel generators is limited by this mistake. It could be feasible to find more efficient methods for cutting operating expenses and minimizing environmental impact by integrating GHG cost functions. To provide comprehensive energy management systems that improve cost savings and encourage sustainability in diesel generator applications, this gap must be filled.

Load curtailment is a key strategy within demand side management (DSM), which is a branch of energy management system (EMS). While numerous studies, such as those by (He et al., 2021) and (Ryu et al., 2021), have demonstrated the effectiveness of load curtailment in reducing reliance on diesel generators in islanded microgrid, these investigations predominantly focus on industrial settings. There is a notable gap in research addressing the application of load curtailment in residential and rural areas islanded microgrid, where unique challenges and opportunities may exist. to reduce the reliance on the diesel generator in islanded microgrid.

Hence, there are research gaps that need to be addressed to improve the cost savings of the diesel generator in PV, BESS and diesel generator islanded microgrid. To conclude those gaps are the usage of more accurate models of the diesel fuel consumption cost function, inclusion of GHG cost function and the implementation of load curtailment under residential or rural environments.

### **1.3 RESEARCH OBJECTIVES**

The main objective of this research is to design an improved MPC-based EMS for islanded PV, BESS, diesel generator islanded microgrid for residential and rural areas by incorporating an accurate model of fuel consumption cost function, inclusion of GHG cost function and implementation of load curtailment to improve the cost saving of the diesel generator.

1. To design an optimized MPC-based EMS to improve the cost saving for diesel generator.
2. To evaluate the performance of the proposed MPC-based EMS under various load curtailment scenarios and different weight of cost functions.

## **1.4 RESEARCH SCOPE**

This research focuses on the development of the MPC-based EMS for the islanded microgrid. The microgrid consists of solar PVs, BESS, diesel generator and loads. The MPC-based EMS is simulated in MATLAB software. The performance of the proposed EMS is evaluated of the power continuity, power balance and the operation cost especially diesel fuel consumption cost. Computational performance, information and communication systems, weather forecasting and load forecasting are out of scope of this research.

## **1.5 THESIS ORGANISATION**

This thesis is organized into five chapters. Chapter 1 elaborates on the introduction of this research. The introduction discusses the background, problem statement, research objectives and research scopes. Chapter 2 describes the literature review on the MPC-based EMS especially in the islanded/standalone microgrid. Chapter 3 explains the research methodology. Meanwhile, chapter 4 demonstrates the results and its discussion. Finally, this thesis is concluded in chapter 5 in which it elaborates on the research contribution and future work for this research.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 INTRODUCTION

This chapter will provide the background studies of the microgrid. This will cover microgrid definition, operating mode, topology and control. The microgrid's distributed generation will then be explored. Next, the review on microgrid energy management is considered. In addition, MPC is addressed. Finally, prior works for the MPC-based EMS are investigated.

##### 2.1.1 Microgrid Definition and Operation Mode

Microgrids have been defined in many ways by different authors. According to (Zia et al., 2018), microgrid is a low-voltage distribution network that is comprised of DERs, controllable loads, and critical loads. Additionally, (Anderson & Suryanarayanan, 2020) defined a microgrid as a small scale version of an electric power system that include its own generation, distribution, and loads integrated into a decentralised structure with several DERs, ESS, controllable loads, reconfigurable topology and control. Department of Energy of United States of America defines microgrid as “a group of interconnected loads and DERs within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid and can operate in grid- connected and island mode (Zia et al., 2018). Figure 2.1 shows the typical structure of microgrid.

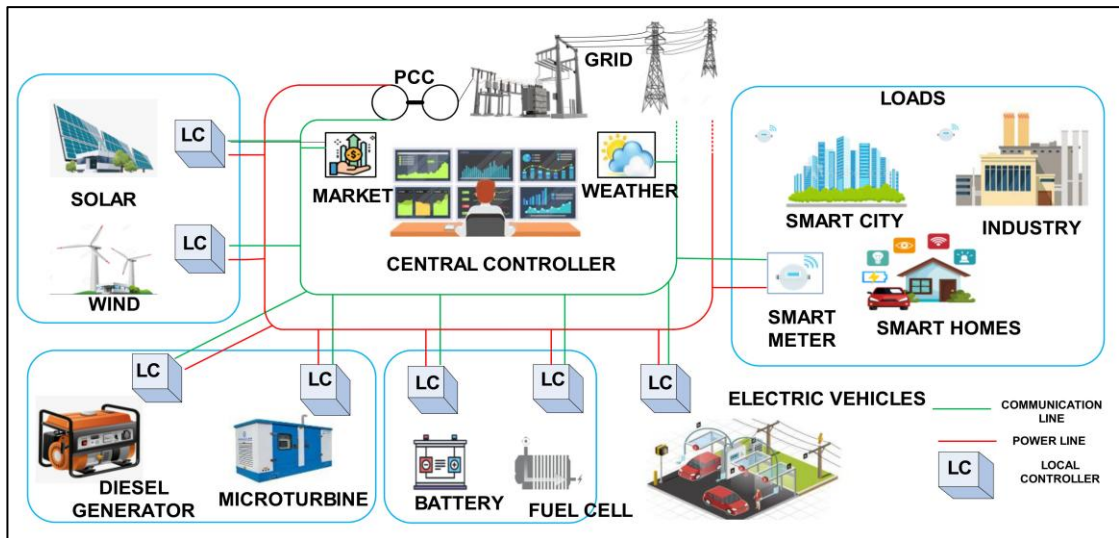


Figure 2.1 Typical structure of Microgrid (Battula et al., 2021)

In figure 2.1, it can be observed that the microgrid consists of multiple generation sources either renewable energy source or non-renewable energy sources, energy storage system such as battery and fuel cell, and various kinds of loads. It also can be observed that the microgrid can have controllers and can be connected to the main grid through point of common coupling (PCC). Hence, it can be concluded that the microgrid can be described as a scaled down version of standard electrical network which is comprised of interconnected generations and loads with its own control and management system.

As mentioned, microgrid can operate in grid-connected mode or island mode (Battula et al., 2021). In island mode, the microgrid disconnected from the main grid at the point of common coupling (PCC). This is beneficial as the microgrid able to isolate itself from the grid in the case of blackouts or faults in the grid (Ahmad et al., 2023; Zahraoui et al., 2021). Moreover, microgrid can also act as a standalone microgrid. Standalone microgrid is self-operated and relies only on the DGs inside the microgrid to maintain the stability and protection. Standalone microgrid can be an effective solution to electrify rural areas where the main grid is not presence (Jamal et al., 2021; Raya-Armenta et al., 2021).

## 2.1.2 Microgrid Topology

Microgrid can be categorised into three categories depending on the type of the network bus: Direct Current (DC) microgrid (DC MG), Alternate Current (AC) microgrid (AC MG) and hybrid microgrid.

Figure 2.2 depicts an AC MG architecture. In AC microgrid, all the DGs and loads are connected to the AC bus. The power is sent by the power generation sources through AC bus to fulfil the load demand. The DC sources and loads are interfaced via an inverter to convert from DC to AC or vice versa. Most of power systems are operating on AC system. Therefore, AC MG effortlessly simple to be integrated into the existing system with no additional, specialised control mechanisms (Uddin et al., 2023). Despite that, AC MG suffers from low efficiency and low reliability in addition to difficult synchronization with the main grid (Raya-Armenta et al., 2021; Uddin et al., 2023).

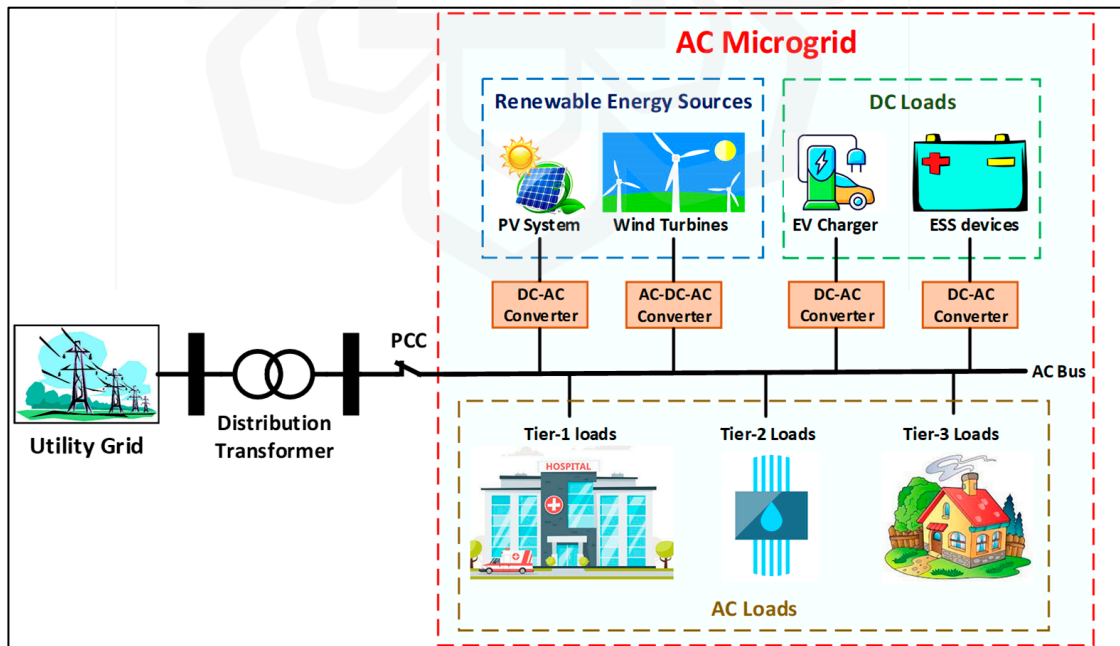


Figure 2.2 AC Microgrid (Abbasi et al., 2023)

Figure 2.23 depicts a DC MG architecture. All DGs and loads in a DC microgrid are connected to a shared DC bus. As a result, the power transfer is in DC form to cater the load demand. The DC MG is being used because several DG, such as solar PV and ESS, generate DC electricity at their outputs. Furthermore, some loads, such as electronic appliances and LED lamps also runs on DC. AC to DC converter is needed for the AC DG and loads to be connected to the DC bus. Some advantages of DC MG are high efficiency due to less power conversion and enhanced grid stability due to the absence of reactive power in the grid (Abbasi et al., 2023). However, the DC microgrid needs a specialised protection scheme (Uddin et al., 2023).

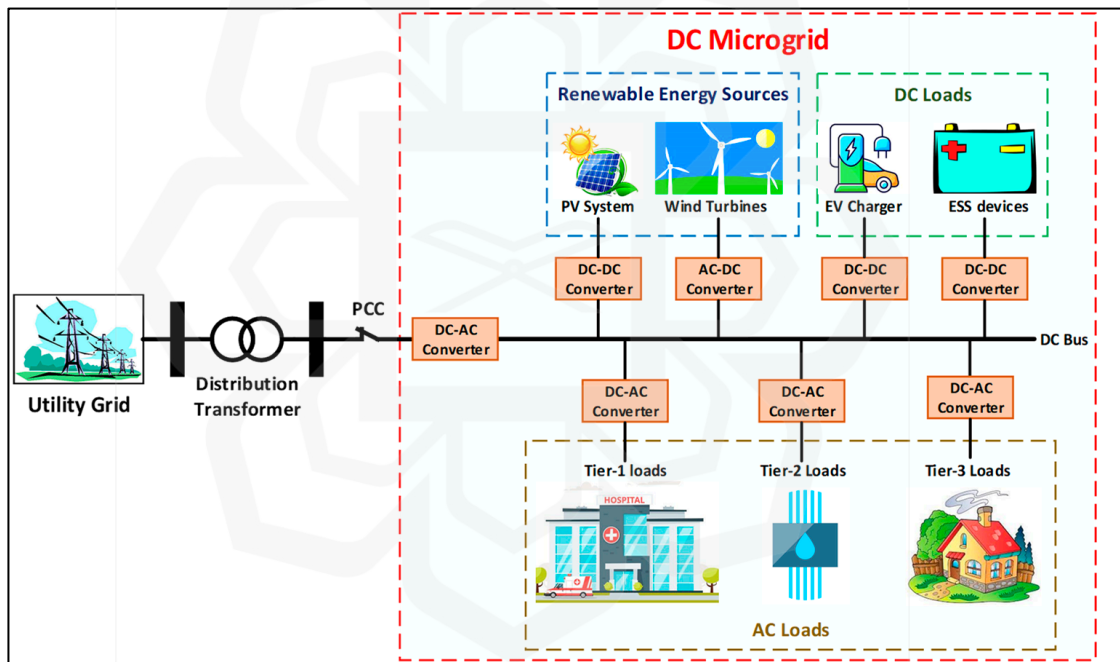


Figure 2.3 DC Microgrid (Abbasi et al., 2023)

Figure 2.4 shows a typical example of hybrid MG architecture. The hybrid MG or hybrid AC/DC MG is the combination of both AC and DC MG concepts. The hybrid AC/DC microgrid is intended to minimise the energy conversion stages (Uddin et al., 2023). AC DG and loads can be linked to the AC bus directly, whereas DC DG and loads can be connected directly to the DC bus. Hence, the advantages of hybrid AC/DC

microgrid are improvement in the reliability, efficiency, and economic operation. However, because of the combination of the AC and DC bus, the hybrid AC/DC suffers from several limitations, including protection and energy management issues.

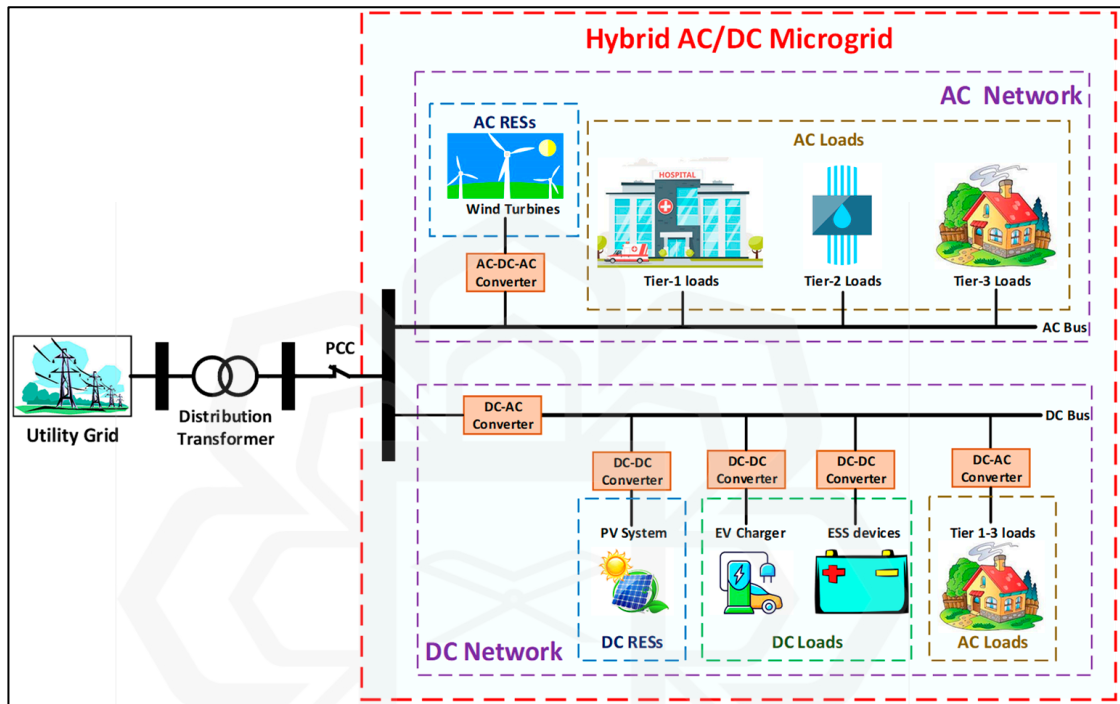


Figure 2.4 Hybrid Microgrid (Abbasi et al., 2023)

### 2.1.3 Microgrid Control Architecture

Complex system such as microgrid relies on the reliable control system to ensure the smooth operation of the microgrid. The main objective of the microgrid control system is to ensure reliable and stable power deliver to meet the demand under normal and abnormal scenarios (Carlos Bordons et al., 2020). Some of the example of the control systems in the microgrid are power balance, power sharing, current and voltage control of DGs units, voltage and frequency regulation and others(Ahmad et al., 2023; Carlos Bordons et al., 2020). Figure 2.5 shows the control architecture of microgrid.

There are 4 types of microgrid control system architecture which are centralised, decentralised, distributed and hierarchical. Centralised control system employs only single controller that collects data from the microgrid, process the information and transmit control signals to the controllable components (Ali et al., 2021). The most compelling aspect of centralised control system is that it offers a global optimum control to the optimisation problem. Depending on the control objectives, this can lead to cost efficient and reliable operation of the microgrid. However, centralised control system can suffers from the scalability problem and computational complexity (Abbasi et al., 2023). Hence, centralised control system is suitable for small microgrid where less components are available subsequently less information to handle.

In decentralised control, each component is controlled by its own local controller, instead of being controlled by a central controller (Ali et al., 2021). The idea of this control is to increase the autonomy of the microgrid. The control decision is made by using the local measurement of each component. The decentralised control system enhanced the scalability and the reliability of the microgrid since it eliminates the single point of failure that exist in centralised control (Uddin et al., 2023). However, the operation of the microgrid ay not optimised since decentralised control tend to have no global optimal solution (Abbasi et al., 2023; Uddin et al., 2023).

Distributed control is the combination of the centralised and decentralised control. This is to leverage the ability of the centralised control of generating global optimum control and the scalability and the reliability of decentralised control. Hence, improving the operation of the microgrid. Nonetheless, the communication network of distributed control can be complex compared to centralised and decentralised control. This may can affect the stability of the microgrid (Uddin et al., 2023).

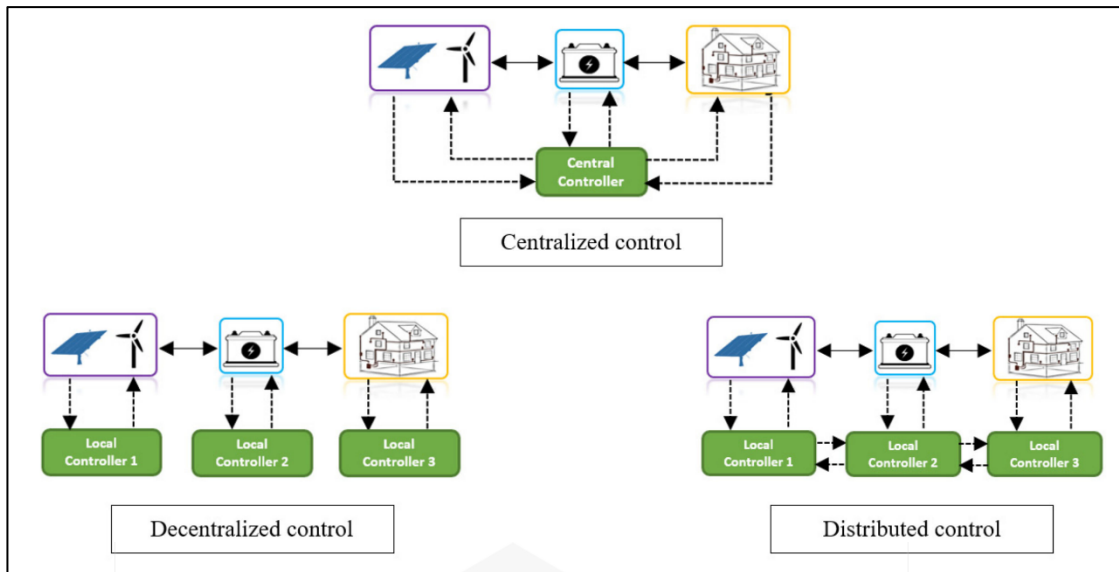


Figure 2.5 Control Architectures of Microgrid (Uddin et al., 2023)

### 2.1.4 Microgrid Hierarchical Control

Figure 2.6 shows the hierarchical control structure of a microgrid. Generally, control of a microgrid can be done established hierarchically. The hierarchical control structure is classified into three levels: primary, secondary, and tertiary. Each level has their own unique characteristics in response time, communication speed and operation (Zahraoui et al., 2021; Zia et al., 2018).

1. Primary control: The lowest level and the fastest response, also known as local control. Primary control is responsible for ensuring power quality (e.g. voltage and frequency within acceptance limit) and coordinating the power sharing among DG.
2. Secondary control: the intermediate level and slower than primary control due to complex mathematical calculation. This level utilises Microgrid Central Controller (MGCC) to optimise economical operation and reliability of the microgrid. It also refers to the Energy Management System (EMS). It can be in centralised or decentralised mode.

3. Tertiary control: the highest level to maintain power flow control and security of the entire system. The tertiary control has a large timescale in order of minutes.

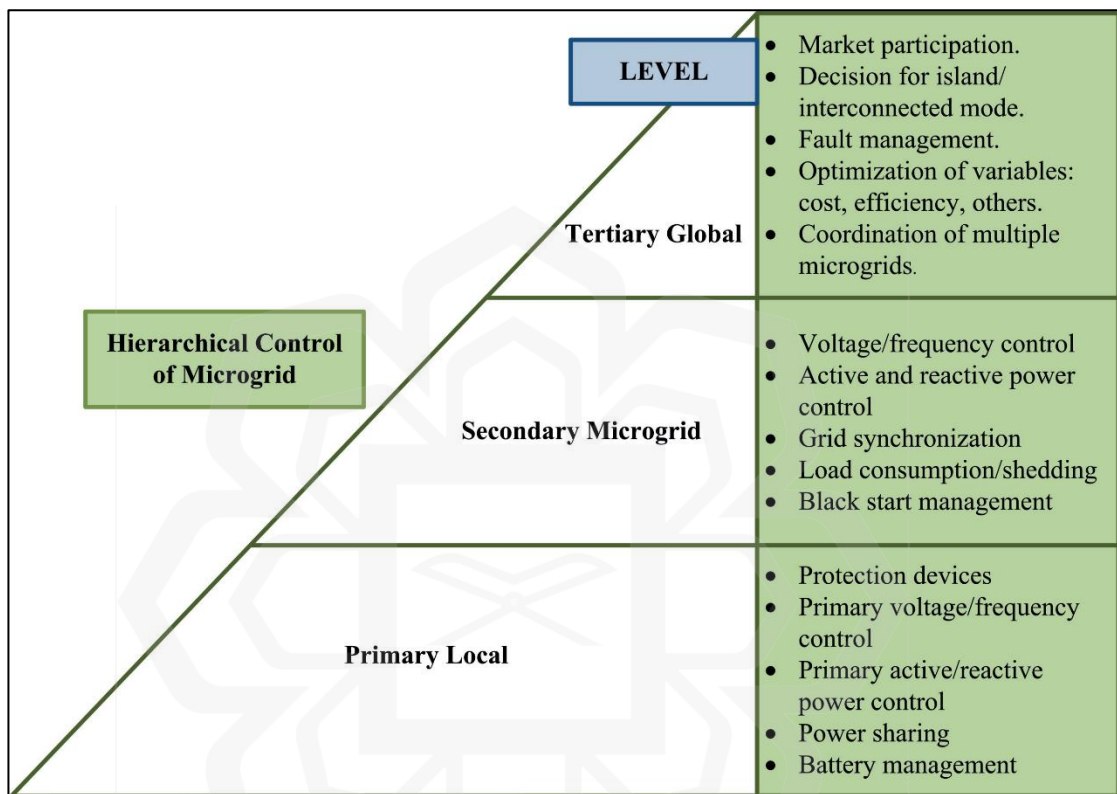


Figure 2.6 Hierarchical Control Structure of Microgrid

## 2.2 DISTRIBUTED GENERATIONS IN MICROGRID

Distributed generations system in microgrid are decentralised, modular and more flexible technologies which are located close to the consumers. This shows the differences between the microgrid and the conventional power generation such as coal plants which are often located far away from the consumers. A highly sophisticated,

complex distribution system is needed to deliver electricity from the generation plant to the consumers.

A distributed generation system can be renewable energy sources and non-renewable sources. Most common renewable energy sources including wind energy, solar energy, hydro, geothermal and biomass. Distributed generation system allows the collection of multiple sources, hence, improving the energy security in the microgrid. Wind energy, solar energy and energy storage system are discussed in the following sections.

### **2.2.1 Solar Energy**

Solar energy is one of the sustainable energy sources and abundantly available. Electricity can be produced by converting sunlight using the solar PV array. The solar power, however, have difficulty to be harvested due to a couple of environmental factors. The solar PV unable to generate electricity during the night due to the absence of sunlight. Hence, limiting the operation of the solar PV during the day when the sunlight is present. Nonetheless, bad weathers such as rain and cloudy also can hinder the production of the electricity from solar PV (Tumeran et al., 2023).

Figure 2.7 shows the solar PV array. Solar PV is made up of semiconductor materials that are coated with a thin layer of metal. The solar PV is comprising of a collection of solar PV module. In addition, solar PV module is made up of a group of solar cells (C. Bordons et al., 2020). The principle working of the solar PV is when the sunlight hits the surface of the semiconductor, the electron gains energy and the semiconductor become conduction state. The movement of the electrons generate current which in result producing electricity (Vodapally & Ali, 2023).



Figure 2.7 Solar PV Array (Duranay, 2023)

Solar PV panel can be categorised according to the used semiconductor. Those are Monocrystalline, Polycrystalline and thin film (Al-Ezzi & Ansari, 2022). Figure 2.8 shows the comparison between monocrystalline and polycrystalline. A comparison between Monocrystalline, polycrystalline, and thin film are shown in Table 2. 1. Monocrystalline has a longer life cycle, higher efficiency, and a smaller form factor than polycrystalline and thin film. However, it performs poorly at high temperatures. In addition, Monocrystalline panel tend to be expensive due the utilisation of crystalline wafer-based technology (Al-Ezzi & Ansari, 2022).

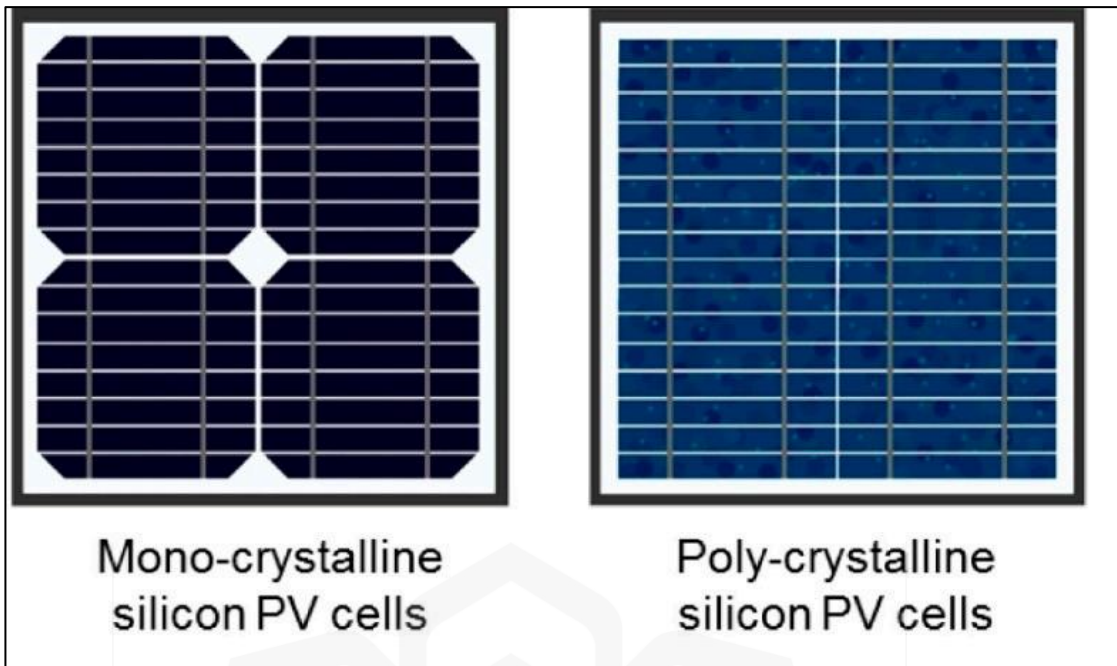


Figure 2.8 Comparison Between Monocrystalline and Polycrystalline Panel  
(Samsudin, 2023)

Table 2.1 Comparison between monocrystalline, polycrystalline and thin film panel  
(Tumeran et al., 2023)

<b>Comparison</b>	<b>Polycrystalline</b>	<b>Monocrystalline</b>	<b>Thin Film</b>
Material	Pure Silicon	Melted Silicon Crystals	Variety of Materials
Life Span	Moderate	Longest	Shortest
Efficiency	~15%	~20%	~7-10%
High Temperature Performance	Poor	Poor	Better
Cost	Least Expensive	Moderate Cost	Most Expensive
Glass Colour	Blue	Black	Brown, Black, Grey
Size	Large	Small	Large

### 2.2.2 Energy Storage System

Renewable energy resources such as solar energy and wind energy suffers are intermittent. As previously discussed, solar PV panel and wind turbine may produce less energy due to cloudy condition and calm condition respectively. Some of the time, they may generate excess energy than demand needed. Hence, Energy Storage Systems is a perfect choice to overcome this problem (Mitali et al., 2022). Energy Storage Systems play an important role in addressing difficulties related to the intermittent nature of renewable energy sources by increasing the efficiency and consumption, improving system continuity and reliability, and lowering reliance on dispatchable generation (Tumeran et al., 2023).

Not only may ESS help to mitigate the intermittent nature of renewable energy resources, but it can also benefit other areas. ESS able to maintain the power flow and prevent power interruption to the microgrid when other distributed generations unable to meet the demand. Next, ESS can be used to store energy during the low-price periods and used the energy to supply to the loads during high-price periods. Furthermore, the fast response of ESS can effectively minimise the power quality issues such as voltage drop, voltage transients, flicker and harmonics (Georgious et al., 2021).

ESS can be categorised into kinetic, potential, chemical, electrochemical and thermal (Georgious et al., 2021). Most commonly ESS used in the microgrid is the batteries which are part of electrochemical ESS category. There is many different type of batteries such as Lead-acid batteries, Sodium-sulphur batteries, Lithium-ion, and others. Figures 2.9 until 2.11 shows the chemical working of Lithium-ion battery, lead acid battery and sodium-sulphur battery. A comparison between batteries is shown in Table 2.2.

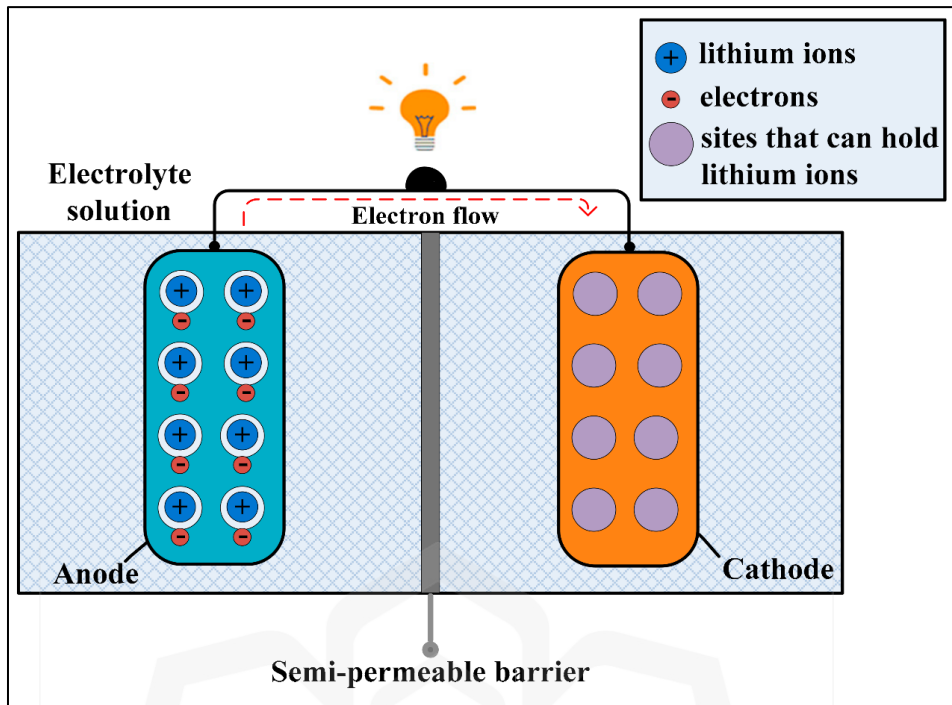


Figure 2.9 Chemical Working of Lithium-Ion Battery (Riaz et al., 2021)

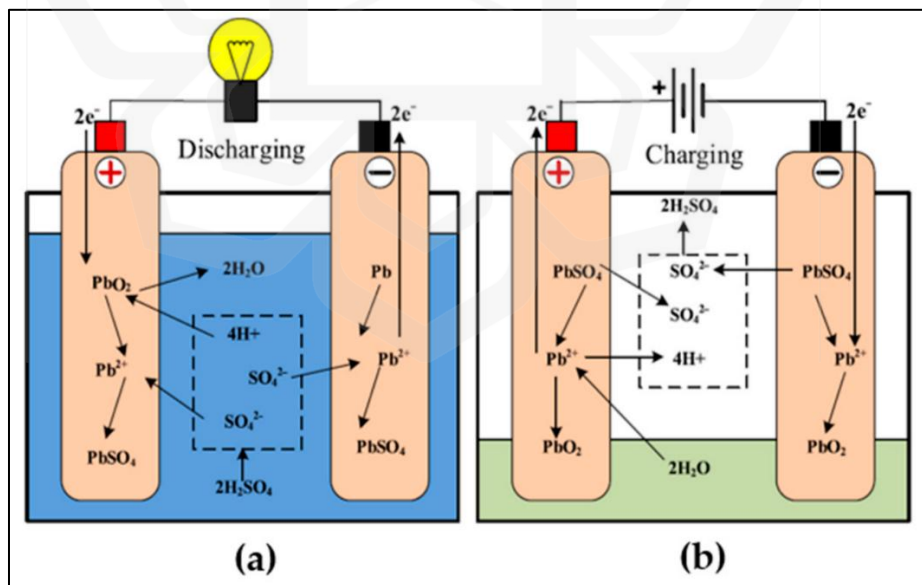


Figure 2.10 Chemical Working of Lead Acid Battery (Riaz et al., 2021)

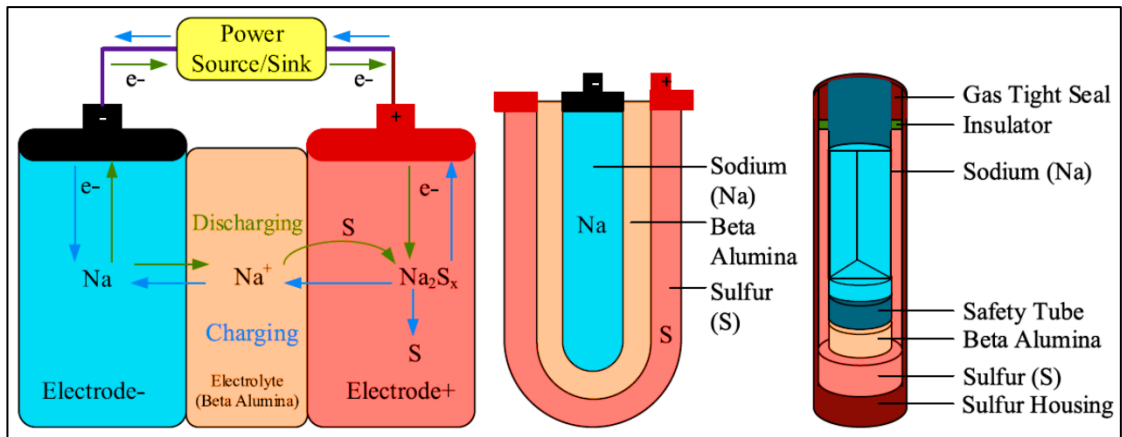


Figure 2.11 Chemical Working of Sodium-Sulphur Battery (Riaz et al., 2021)

Table 2.2 Comparison of different types of batteries

Comparison	Lithium-ion	Lead Acid	Redox Flow	Sodium Sulphur	Zinc Bromine Flow
Cost	High	Low	High	High	Low
Energy Efficiency	High	70-90%	~85%	80-90%	65-80%
Cycle	500-2000	200-2000	>1600	2500	1000
Toxicity	Non-toxic	Highly corrosive	No fire hazard	Highly corrosive	Low toxicity

Another type of ESS is supercapacitor. Figure 2.12 shows the chemical working of supercapacitor. The difference between supercapacitor and the batteries is that the supercapacitor can generate a very high output with a fast response allowing them to respond fast to the variations in the grid. However, it has a very small capacity compared to batteries. Generally, supercapacitor is used to maintain the power quality (Georgious et al., 2021). It also can be used to meet the load demand for a very short time when the

other generations unable to generate a sufficient energy (Tumeran et al., 2023). Table 2.3 shows the comparison between the batteries and supercapacitor.

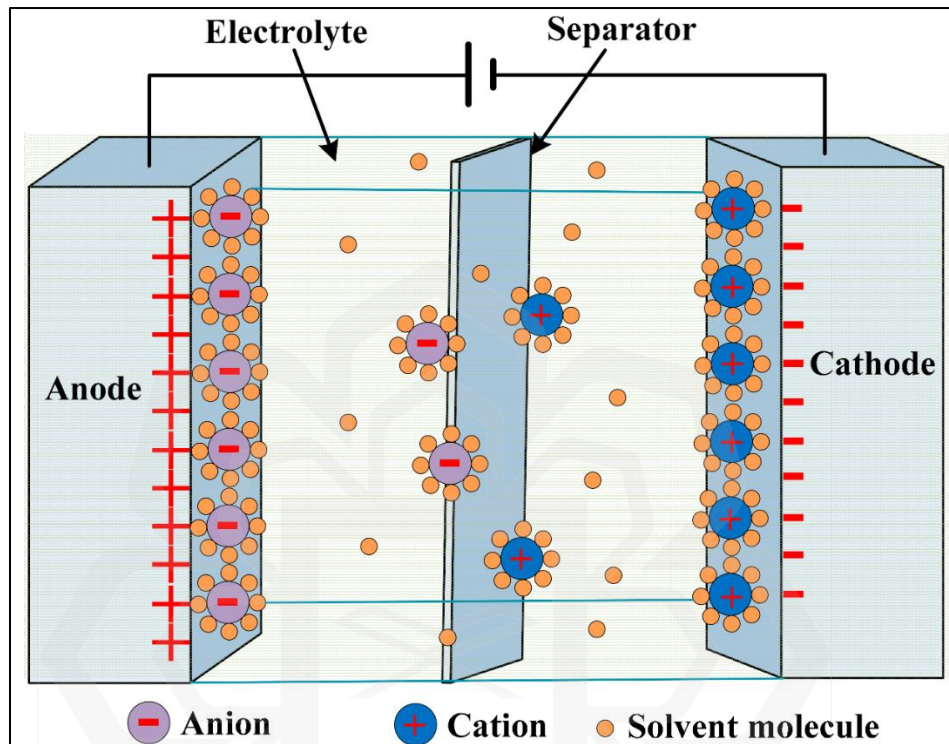


Figure 2.12 Chemical Working of Supercapacitor (Riaz et al., 2021)

Table 2.3 Comparison between batteries and supercapacitor (Tumeran et al., 2023)

<b>Parameter</b>	<b>Batteries</b>	<b>Supercapacitors</b>
Operational Life	Long operational life with the ability to charge and discharge many cycles	Long operational life with the ability to charge and discharge many cycles
Power Density	Linear discharge of energy	Very rapid discharge of energy
Unit	Watt-hour	Watt-sec
Charge Method	Current and voltage	Voltage across terminals
Charge/Discharge Time	1-10 hours	Milliseconds - seconds
Energy Density	8-600 Wh/kg	1-5 Wh/kg
Lifetime	150 – 1500 Cycles	> 100,000 Cycles
Operational Temperature	-20 to +65°C	-40 to +85°C
Form Factor	Large	Small

Table 2.4 shows the advantages and disadvantages of the batteries and supercapacitors. It is preferred that batteries are to be used as a main energy storage to store and supply energy during the excess and lack of energy in the microgrid respectively. On the other hand, supercapacitor can be utilised to deter the power quality issues in the microgrid such as voltage flickering, sagging and others (Raya-Armenta et al., 2021).

Table 2.4 Advantages and disadvantages of batteries and supercapacitors (Tumeran et al., 2023)

<b>Parameter</b>	<b>Batteries</b>	<b>Supercapacitor</b>
Advantages	<ul style="list-style-type: none"> <li>- Low self-discharge rate</li> <li>- Inexpensive</li> <li>- High energy per unit weight</li> </ul>	<ul style="list-style-type: none"> <li>- Much higher recharge cycle life</li> <li>- Longer lifetime</li> <li>- Low internal resistance</li> <li>- Environmentally friendly</li> <li>- High performance in low temperature</li> </ul>
Limitations	<ul style="list-style-type: none"> <li>- Lower lifetime</li> <li>- Lower recharge cycle life</li> </ul>	<ul style="list-style-type: none"> <li>- Expensive</li> <li>- Low per cell voltage</li> <li>- High dielectric absorption</li> <li>- High self-discharge rate</li> </ul>

BESS is one of the important components in microgrid as it able to compensate the intermittency of the RES. To guarantee the effective energy management of the microgrid with a high penetration of RES, it is critical to have a precise and real time information of the battery's available capacity at any given time. State of Charge is the commonly used parameter to estimate a BESS's capacity.

In MPC-based EMS, the SoC model of the BESS can serve as the base for predicting the future state of the BESS and other components in the microgrid. SoC models can be classified into 5 categories which are conventional, adaptive filter, learning algorithms, non-linear observer and advanced algorithms. Figure 2.13 shows the categorizations of methods for SoC estimation.

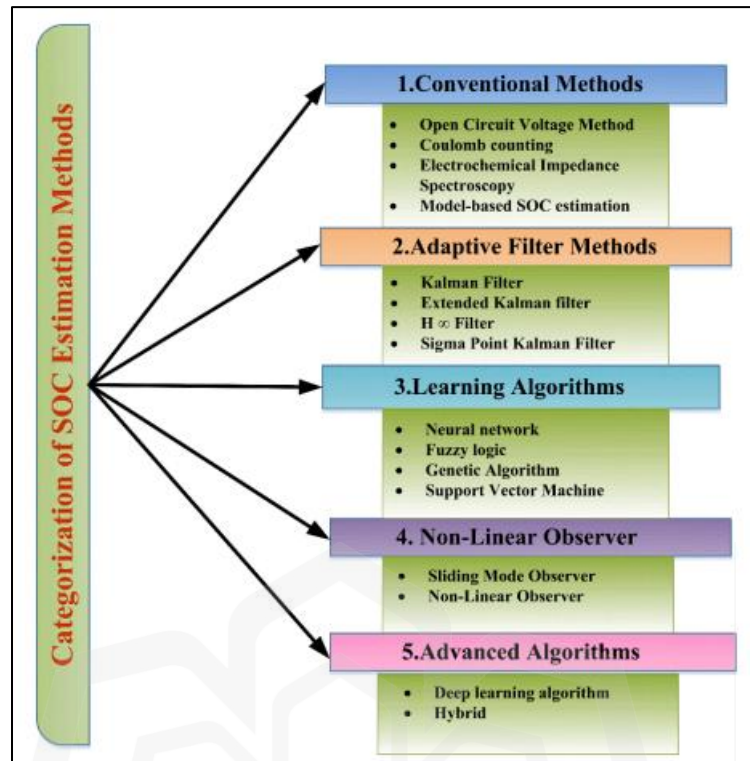


Figure 2.13 Categorizations of Methods for SoC Estimation (T & C, 2022)

Some of the models under conventional methods are open circuit voltage (OCV) method, coulomb counting, electrochemical impedance spectroscopy (EIS) and model-based EMS estimation. OCV is a method that uses measurement of the OCV of the battery. This is due to the consistently increasing relationship between the OCV of a battery with its SoC (Pillai et al., 2022). On the other hand, EIS utilises the impedance measurement of the battery. According to (Wu et al., 2023), a special excitation of varying frequencies are superimposed on the charging/discharging current of the battery and the results are processed to calculate the impedance. In coulomb counting method, the SoC can be estimated as the ratio of the remaining coulombs over the battery capacity (Movassagh et al., 2021).

Some of the models under adaptive filter methods are Kalman filter, extended Kalman filter and Sigma point Kalman filter. Adaptive filter-based methods use estimation algorithms that integrates measurements with system predictions to achieve

a more precise estimate of the system's state. This method consists of two phases which are prediction phase and correction phase. In prediction phase, the algorithm will predict the state of the battery while in the correction phase, the real state of the battery and the prediction are compared. The algorithm will be improved according to the error (Dini et al., 2024). Extended Kalman filter and Sigma point Kalman filter are improvement of the traditional Kalman filter to handle more complex nonlinear system (Dini et al., 2024).

In non-linear observer method, there are sliding mode observer (SMO) model and non-linear observer (NLO) model. This method uses battery model such as RC equivalent model, Thevenin model and Rint model to estimate the SoC of the battery (Marques et al., 2023). Neural network, fuzzy logic and support vector machine are part of the intelligent or learning algorithm method. In the hybrid method, two or more models are combined to leverage their advantages and address their disadvantages, improving the accuracy of the battery's SOC estimation. Table 2.5 shows the advantages and disadvantages of these methods.

Table 2.5 Advantages and disadvantages of SoC estimation method (Marques et al., 2023)

<b>SoC Estimation Method</b>	<b>Advantages</b>	<b>Disadvantages</b>
Conventional	<ul style="list-style-type: none"> <li>• Simple</li> </ul>	<ul style="list-style-type: none"> <li>• Battery must not in used and rest for a long period</li> </ul>
Kalman Filter-Based	<ul style="list-style-type: none"> <li>• Good accuracy under noisy environment</li> </ul>	<ul style="list-style-type: none"> <li>• Need accurate model</li> <li>• High computational</li> </ul>
Nonlinear Observer	<ul style="list-style-type: none"> <li>• Good accuracy</li> <li>• Robust against uncertainties</li> </ul>	<ul style="list-style-type: none"> <li>• High computational</li> </ul>
Learning-Based	<ul style="list-style-type: none"> <li>• Able to predict complex non-linear effectively</li> </ul>	<ul style="list-style-type: none"> <li>• Requires a lot of data to train</li> <li>• Requires expertise</li> </ul>
Hybrid	<ul style="list-style-type: none"> <li>• Good accuracy</li> </ul>	<ul style="list-style-type: none"> <li>• Complex</li> <li>• High computational</li> </ul>

### 2.3 NON-RENEWABLE GENERATIONS

The intermittent nature of renewable energy sources such as solar and wind can lead to power stability issues in microgrids. As previously noted, ESS can be used to address this issue. Backup generators are sometimes required to maintain power security in microgrids, particularly islanded microgrids (Boucekara et al., 2023). Non-renewable generation sources, such as diesel generators and microturbines, can be used as a backup to complete this duty. Figure 2.14 shows the diesel generator and its components (Liu

et al., 2023). They can play an essential role in meeting load demand when RESs and ESS are unable to do so.

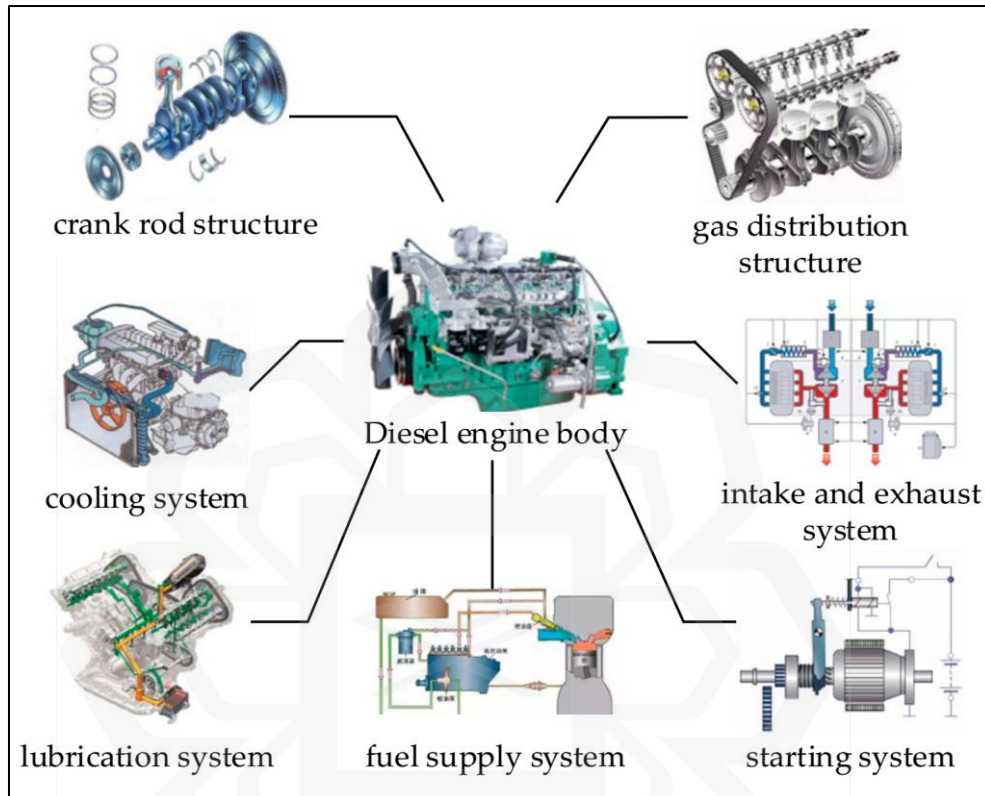


Figure 2.14 Diesel Generator and Its Components

Non-renewable generation can be categorised into reciprocating engines, microturbines, combustion gas turbine and Stirling engine (Raju P & Jain, 2019). Except for reciprocating engines, microturbines, and combustion gas turbines, Stirling engine is not discussed. Developed almost 100 years ago, reciprocating engines use can use diesel or natural gas as their fuel to generate electricity when coupled with a generator (Raju P & Jain, 2019). Figure 2.15 until 2.17 show the schematic operation diagram of reciprocating engine, microturbine and combustion gas engine.

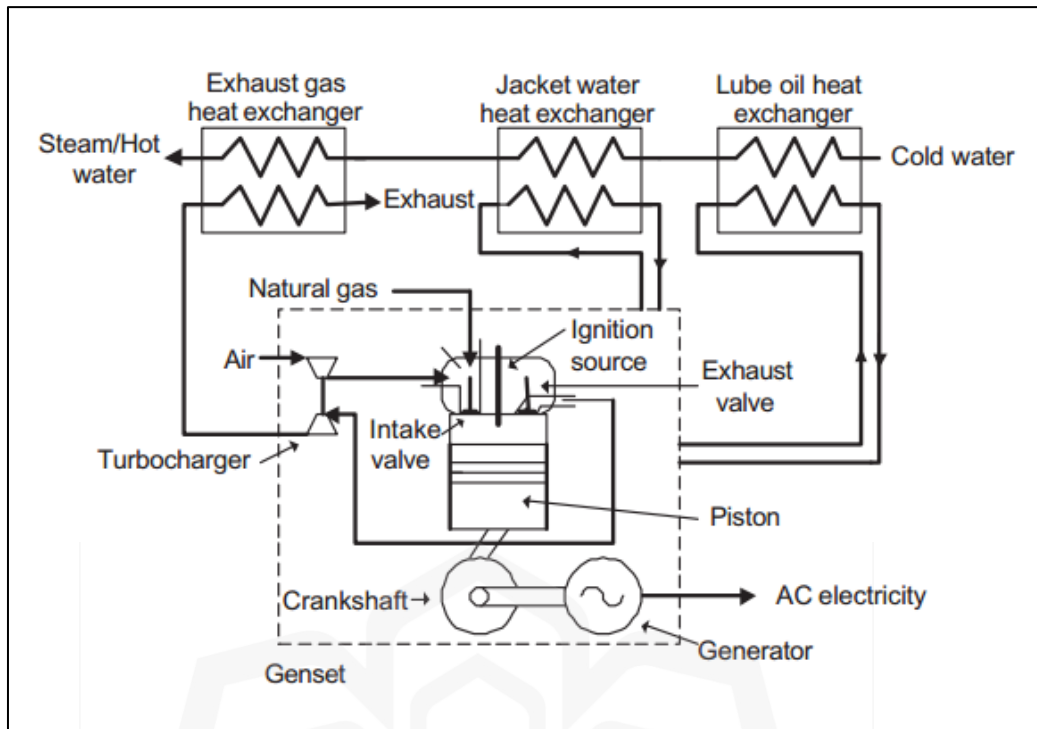


Figure 2.15 Schematic Operation Diagram of Reciprocating Engine (Raju P & Jain, 2019)

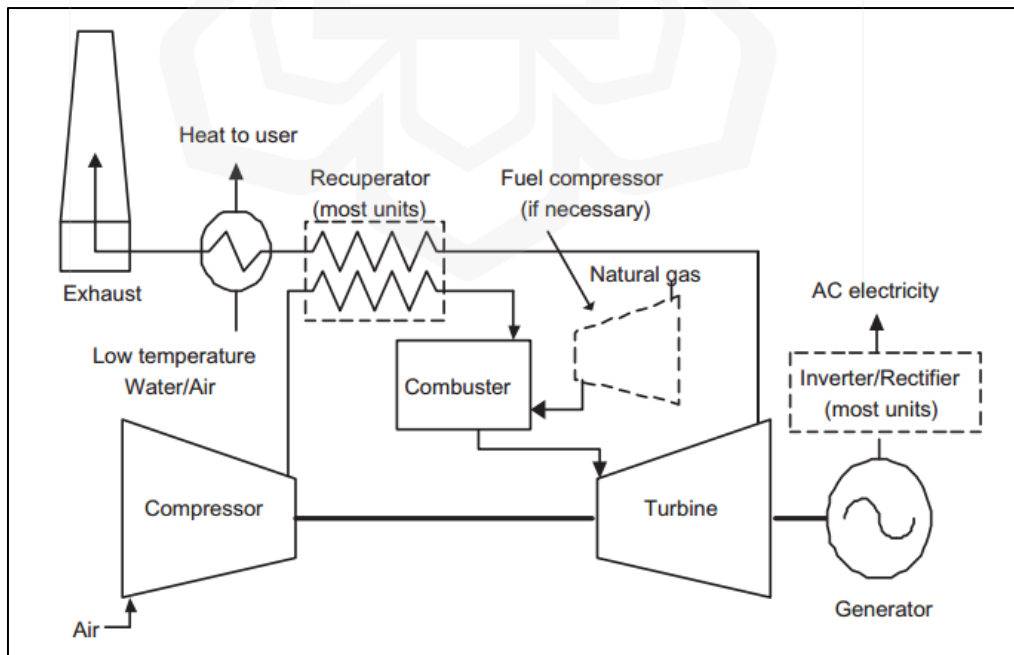


Figure 2.16 Schematic Operation Diagram of Microturbine (Raju P & Jain, 2019)

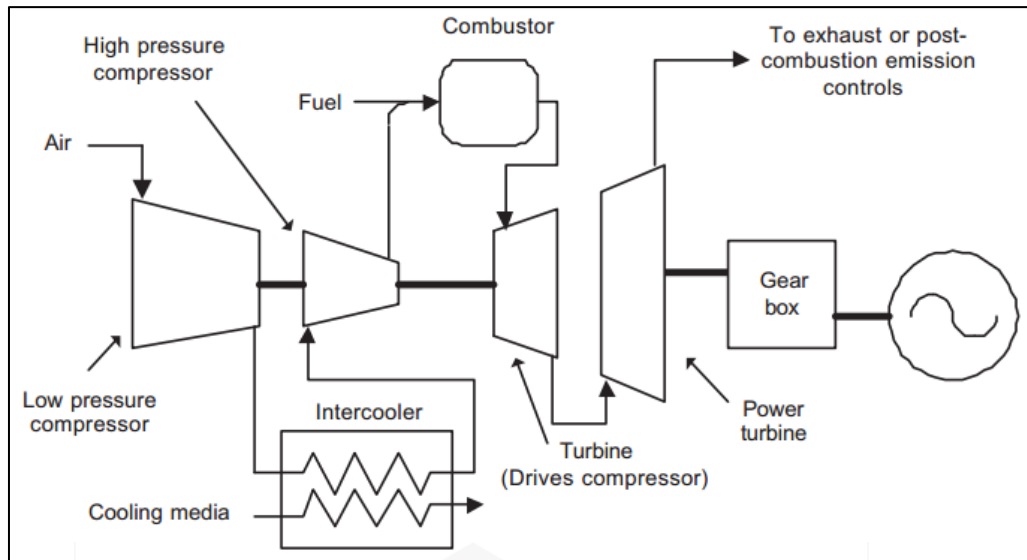


Figure 2.17 Schematic operation Diagram of Combustion Gas Turbine (Raju P & Jain, 2019)

Microturbines convert the thermal energy to mechanical energy through the flow of gas. Generally, it consists of compressor, combustor, turbine and generator. Meanwhile, combustion gas generator is designed to be a stationary power generation in contrast to reciprocating engines and microturbines, which are portable and can be transferred around. Table 2.6 shows the comparison between reciprocating engines, microturbines and combustion gas turbines.

Table 2.6 Comparison between reciprocating engines, microturbines and combustions gas turbines (Raju P & Jain, 2019)

<b>Comparison</b>	<b>Reciprocating Engines</b>	<b>Microturbines</b>	<b>Combustion Gas Turbine</b>
Application	<ul style="list-style-type: none"> <li>- Mainly used for cogeneration, backup power and peaking power operation</li> </ul>	<ul style="list-style-type: none"> <li>- Used primarily for continuous operation</li> </ul>	<ul style="list-style-type: none"> <li>- Used in aiding cogeneration and peaking power application</li> </ul>
Advantages	<ul style="list-style-type: none"> <li>- Low operation cost</li> <li>- Good efficiency</li> </ul>	<ul style="list-style-type: none"> <li>- Low greenhouse gas emissions</li> <li>- Good efficiency</li> </ul>	<ul style="list-style-type: none"> <li>- Low capital cost</li> <li>- Low greenhouse gas emissions</li> <li>- Less maintenance</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>- High maintenance cost</li> <li>- High emissions of greenhouse gas</li> </ul>	<ul style="list-style-type: none"> <li>- High maintenance cost</li> </ul>	<ul style="list-style-type: none"> <li>- Less efficient</li> </ul>

## 2.3 ENERGY MANAGEMENT SYSTEM

### 2.3.1 EMS Definition

In the 1960s, the evolution of the energy management system started, and it was called the "Control Center," then, during the 1970s, the name changed to "Energy Control Center (ECC)." During the 1990s, the name finally changed to real-time, known till now as Energy Management System (EMS). EMS has many control techniques such as distribution management system (DMS), load control (LC), and Demand side management (DSM) (Zia et al., 2018).

The definition of EMS was set in International Electrotechnical Commission standard IEC 61970. EMS is a "computer system containing software platform to provide fundamental support services and applications to deliver the functionality needed for the effective operation of electrical generation and transmission facilities to assure adequate security of energy supply at minimum cost." The idea of EMS is to develop a system that can optimally collect different energy sources for consumers while including sustainable power sources without sacrificing the system's security, reliability, and safety. EMS can monitor, optimise, supervise, and manage the customers, transmission, distribution, and generation facility (Raya-Armenta et al., 2021). And so, the main function of EMS relies on creating a system that can provide a balance between demand and supply in an efficient way (Ahmad et al., 2023). In other words, it should be cost-effective while working under operational restrictions and uncertainties.

Figure 2.18 shows an example of microgrid with centralised EMS. EMS can work on control, energy scheduling, and transmission security management. It is becoming more sophisticated as the grid evolves with the integration of RES, ESS, PEV, high power requirement buildings, and other factors. EMS for smart grid will help maintain supply-demand balance while maintaining the system constraints to achieve

reliable, secure, and economic operation of the power system. Another part integrated with EM is optimization. Optimisation in EMS guarantees that the cost of energy generation is reduced (Thirunavukkarasu et al., 2022). Finally, an energy management system can minimise and control the amount and the cost of the energy required to perform specific applications by integrating all systematic techniques (Hu et al., 2024).

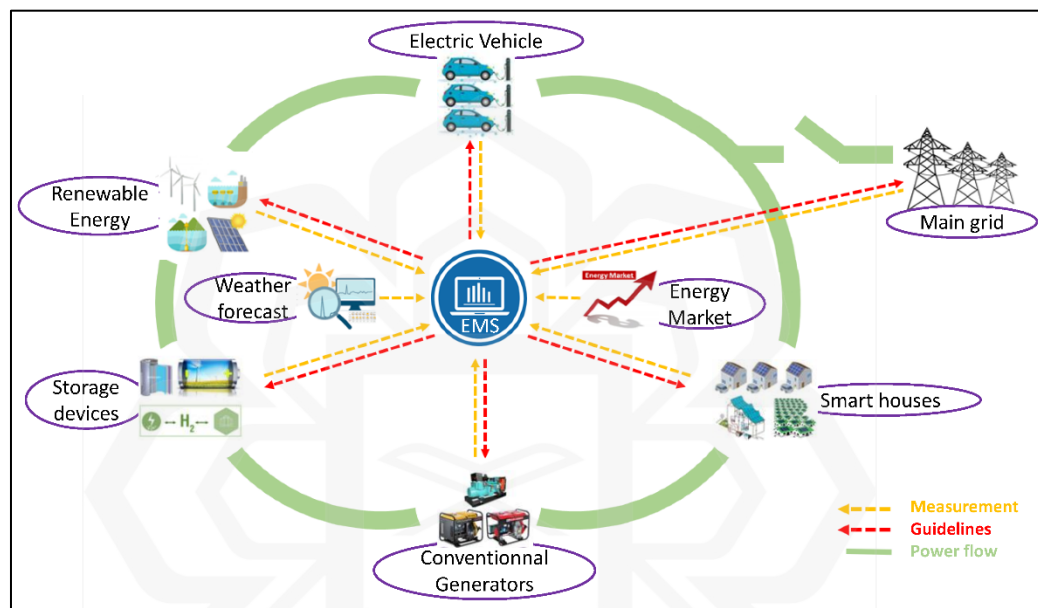


Figure 2.18 Microgrid with Centralised EMS (Ouramdane et al., 2021)

### 2.3.2 Microgrid Energy Management System Objectives

Energy management systems address a range of objectives, including economic, technical, socio-economic, and environmental goals. However, most researchers primarily focus on economic objectives, either using a single objective or multi-objective approach that combines other goals (Raya-Armenta et al., 2021). In islanded microgrids, common objective functions include cost minimization/profit maximization, minimization of voltage and frequency deviations, maximization of load

served, minimization of emissions, reduction of renewable energy curtailment, and improvement of system reliability (Anderson & Suryanarayanan, 2020).

In the study by (Basantes et al., 2023), the authors focused on economic and socio-economic goals, aiming to minimize diesel generator costs and unsupplied power from renewable energy sources and diesel generators. Conversely, (Nair & Costa-Castelló, 2020) concentrated on minimizing fuel cell usage, maintaining the state of charge (SoC) of the supercapacitor at a reference value, preventing high battery SoC, and avoiding steep charging and discharging of the battery.

(Pippia et al., 2020) took a single-objective approach, minimizing diesel generator costs by optimizing fuel usage when fuel prices are low. Similarly, both (Novickij & Joós, 2019) and (Ryu et al., 2021) targeted diesel generator operating costs. (Ryu et al., 2021) enhanced the cost function by factoring in fuel, maintenance, and startup costs, also aiming to prevent high battery SoC and mitigate steep charging and discharging rates.

(Polimeni et al., 2021) sought to minimize fuel costs, unmet demand costs, curtailment penalties, and tracking costs. (He et al., 2021) focused on minimizing the maintenance costs of battery energy storage systems (BESS) and reducing the opening, operation, and maintenance costs of diesel generators. Additionally, (Ndwali et al., 2021) worked to minimize diesel fuel costs and grid purchase costs. Lastly, (Salazar et al., 2021) aimed to minimize diesel generator power costs, regulate water temperature, reduce penalty costs for wasted power, and maintain the SoC of the battery at the desired level.

## 2.4 MODEL PREDICTIVE CONTROL

### 2.4.1 MPC Definition

MPC does not relate to a specific control strategy, but rather to a group of control approaches that take full use of the system model under certain constraints to generate control signals or directives by minimising predetermined cost functions or objective functions (Hu et al., 2021). Figure 2.19 shows the structure of MPC (Konneh et al., 2022). MPC uses the dynamic model of the system to predict the next state of the system by generating optimal control signals according to the defined objective functions and constraints.

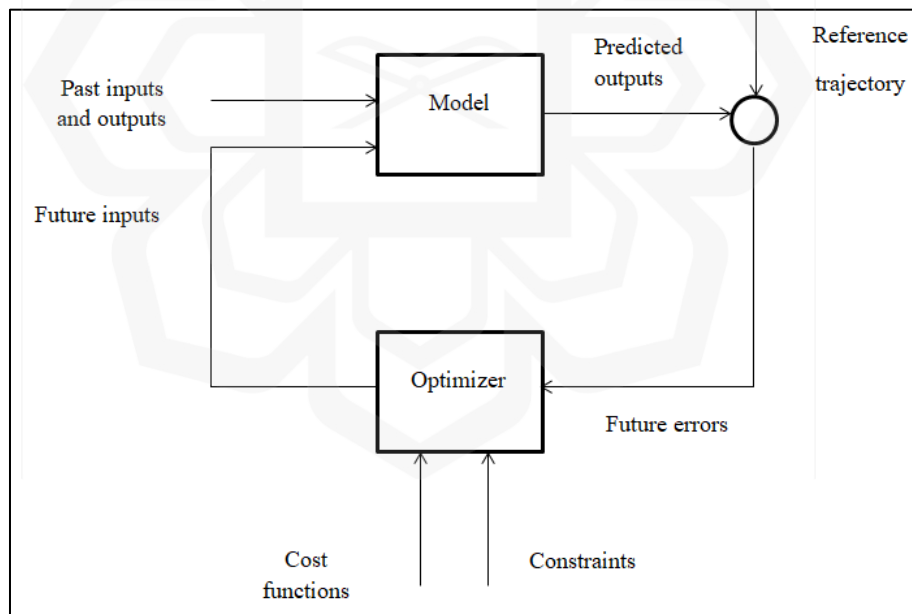


Figure 2.19 MPC Structure

## 2.4.2 MPC Advantages and Disadvantages

The advantages of MPC (Joshua & Gupta, 2023) compared to the traditional control are the capability in handling multiple inputs and multiple outputs (MIMO) system. Traditional controller such as PID unable to handle MIMO system effectively compared to MPC. Next, MPC also able to consider constraints into its formulation. This is important for many systems where constraints such as physical limitation of the system can be included into the control systems.

MPC, however, has several drawbacks. MPC necessitates a precise system model. A thorough understanding of the system is required to create an accurate model of the system. While tiny systems are relatively easy to mimic, most real-world systems are sophisticated and non-linear. Furthermore, MPC is computationally expensive. MPC, unlike other controllers, requires powerful processing. However, recent advancements in processing units may be able to overcome this issue. Table 2.7 listed the advantages and disadvantages of MPC.

Table 2.7 Advantages and disadvantages of MPC

<b>Advantages</b>	<b>Disadvantages</b>
Multiple inputs and multiple outputs capabilities	Require expertise in modelling of the system
Constraints consideration	Computationally expensive
Able to handle disturbances	Complexities increases with the number of control variables

### 2.4.3 MPC Strategy

As mentioned, MPC uses the system model to generate optimal solution for the defined cost functions or objective functions. Figure 2.20 shows the strategy of MPC with  $t$  denoted as present sampling time,  $y(t)$  is the past outputs,  $u(t)$  is the past inputs,  $y(t + k|t)$  is the predicted outputs and  $u(t + k)$  is the future input actions.

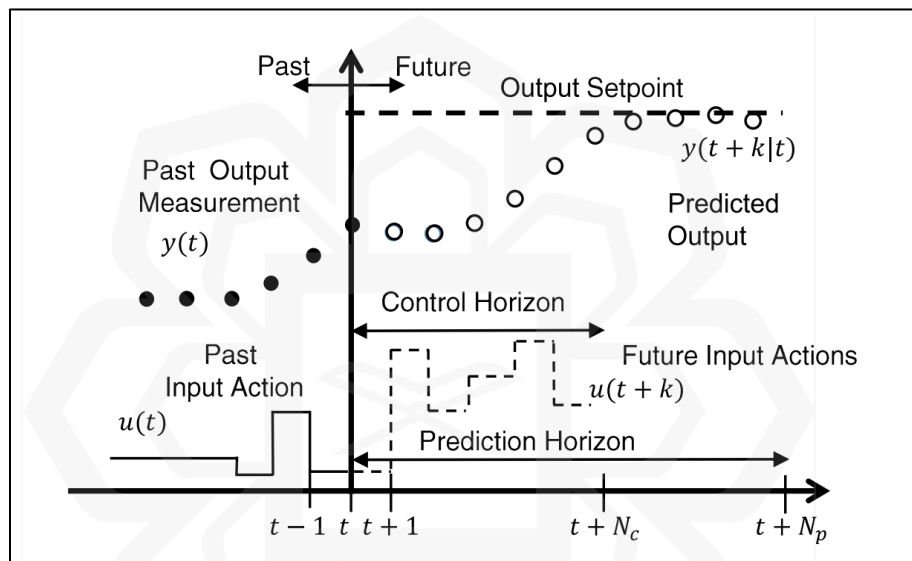


Figure 2.20 MPC Strategy

MPC solves the optimisation problem by calculating a set of future input actions  $u(t + k), k = 0, 1, \dots, N_c$ .  $N_c$  is the control horizon. From Figure 2.19, these future input actions are calculated to keep the output as close as possible to the reference output value. The future outputs  $y(t + k|t), k = 0, 1, \dots, N_p$ , are predicted using dynamic model of the system and depends on the predicted input actions.  $N_p$  is the prediction horizon. The input action  $u(t)$  is sent to the system while future input actions are discarded. The steps are repeated for sampling time  $t + 1$  with the updated values and a new sequence of control moves is calculated.

## **2.5 MPC-BASED EMS MODELS FOR ISLANDED MICROGRIDS**

In recent years, extensive research has focused on the development of MPC-based EMS tailored to islanded microgrids (Anderson & Suryanarayanan, 2020). These EMS solutions play a critical role in islanded microgrids by compensating for the absence of a main grid, carefully balancing resource to maintain stability and efficiency. Due to their similar operational requirements, this study treats islanded and standalone microgrids as equivalent. The primary objective of EMS is to manage the components effectively to ensure power stability in the microgrid.

This work specifically aims to enhance the MPC-based EMS by implementing strategies that reduce the fuel cost of diesel generators, subsequently decreasing greenhouse gas emissions such as carbon dioxide. The sections that follow delve into essential aspects of this objective, including the optimisation algorithms that drive EMS decisions, cost functions diesel generation and greenhouse gases, and considerations for load curtailment. Together, these components support the primary goal of achieving efficient, cost-effective and environmentally responsible microgrid management.

### **2.5.1 Optimisation Algorithm**

The core of the energy management is the optimisation algorithm (Thirunavukkarasu et al., 2022). Microgrids are made up of many sources of generation, ESS, and loads, each with their own unique operational and technical limitations. As a result, it is critical that these components perform efficiently to ensure supply and demand balance and cost effectiveness.

Optimisation algorithms in the energy management of the microgrid can be categorised into traditional, heuristics, artificial intelligence, and hybrid methods (Raya-Armenta et al., 2021; Ziabina et al., 2023). Traditional optimisation algorithms utilise

mathematical programming to solve objective function with subject to the given set of constraints. Traditional optimisation algorithms use branch and bound method to solve the optimisation problem through an iterative process (Battula et al., 2021). Some of the traditional optimisation algorithm are linear programming, quadratic programming, non-linear programming, and mixed integer programming.

On the contrary, metaheuristics algorithms are a method uses random search to find optimal solution of an optimisation problem. Key concepts in metaheuristics optimisation are intensification and diversification (Battula et al., 2021). Intensification is defined as the search of the search region in which the best solution may be available, whereas diversification is the random search of the search area. This is to achieve the global optimal rather than staying in the local optimum. Figure 2.21 shows the classification of optimisation algorithms and their examples. Some of the heuristic optimisation algorithm are particle swarm optimisation, genetic algorithm, and others.

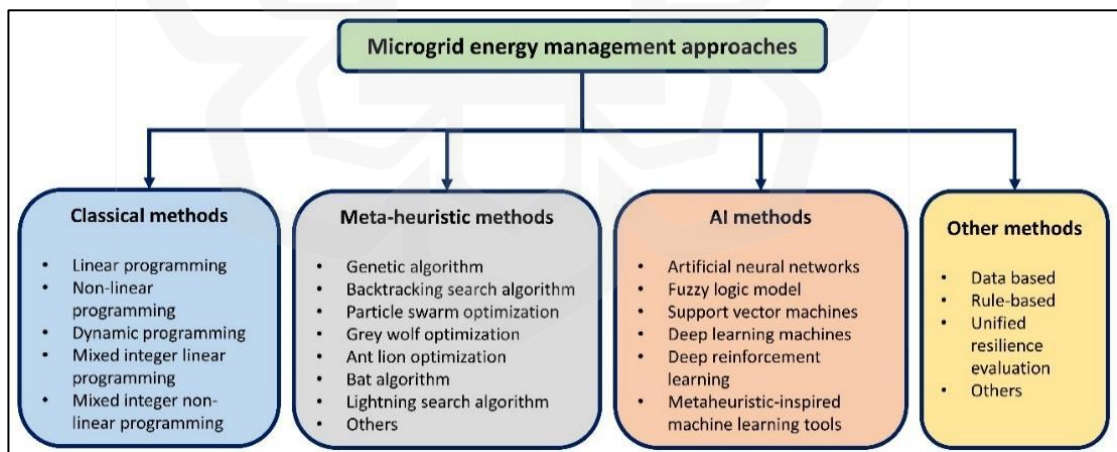


Figure 2.21 Classification of Optimisation Algorithms

Based on the review, traditional optimisation is widely utilised in the MPC framework for islanded microgrid EMS application (Raya-Armenta et al., 2021). This is due to traditional method offers a balance between simplicity and convergence to the

solution. Heuristics optimisation offers a low computational problem solving; however, the solution may not be a global optimal. Hybrid and artificial intelligence optimisation require expertise in utilising them for the EMS application. The complex nature of the artificial intelligence needs a powerful computation processing capability in return of accurate and optimised solution (Raya-Armenta et al., 2021; Thirunavukkarasu et al., 2022). Hence, this project considered traditional optimisation for the MPC-based EMS implementation.

### **2.5.2 Diesel Generator Cost Function**

Diesel generator is important and have been used extensively especially in islanded and standalone microgrid due to their low cost and fast response (Adefarati et al., 2021). Some of the cost function of the diesel generator are fuel consumption cost, start-up cost and maintenance cost (Thirunavukkarasu et al., 2022). By defining cost function of the fuel consumption cost, the diesel generator usage could be optimised hence, reducing the fuel consumption in which relate to the releases of the greenhouse gases such as CO<sub>2</sub> to the atmosphere. However, papers such as (Nair & Costa-Castelló, 2020) and (Pippia et al., 2020) does not include fuel consumption in their EMS objective functions.

Papers such as (Salazar et al., 2021), (He et al., 2021) and (Basantes et al., 2023) proposed a linear fuel consumption cost to allow a simple computation. The result shows a satisfactory energy management of the microgrid. However, the use of the linear fuel consumption cost function in EMS for the microgrid can lead to suboptimal usage of the diesel generator. A comparison is made between second order polynomial function and first order polynomial of fuel consumption in (Djelailia et al., 2019). This shown in Figure 2.22. The result shows that a significant less error in second order polynomial fuel consumption cost to the experimental values compared to the first order polynomial.

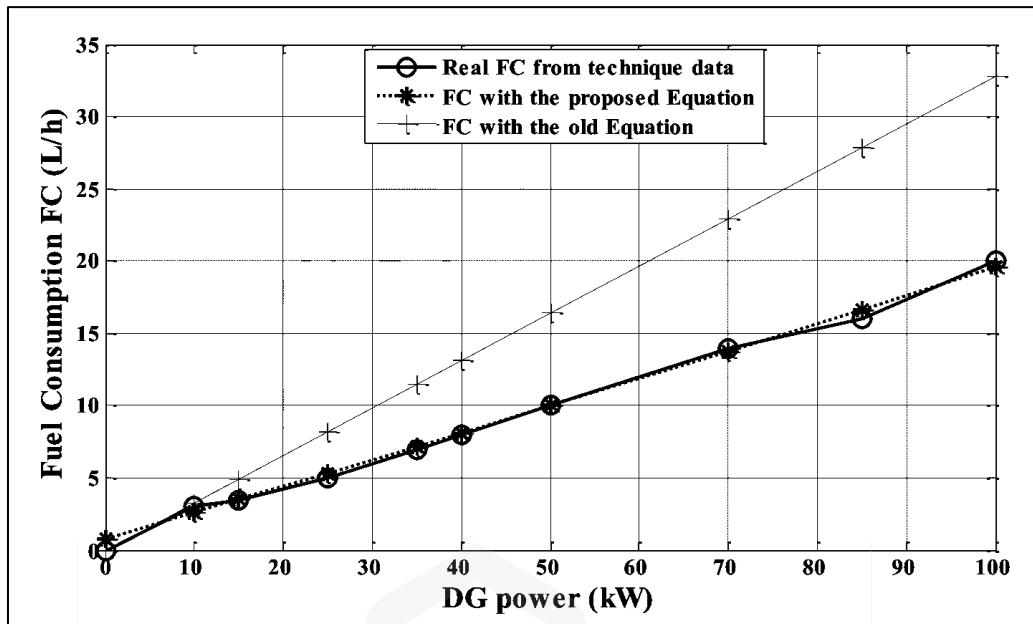


Figure 2.22 Comparison Between First Order and Second Order Polynomial of Fuel Consumption (Djelailia et al., 2019)

The application of linear programming, nonlinear programming and quadratic programming optimisation is not sufficient to consider the on and off operation of the microgrid. As extension of this, mixed integer programming which considers binary variables is introduced. (Ryu et al., 2021) proposed MPC-based EMS which considers the mixed integer linear programming. The diesel generators are minimally used and the power generation for the PV is used optimally to charge more EVs compared to without using the proposed EMS. In (Nair & Costa-Castelló, 2020), the author proposed the application of mixed integer quadratic programming in the MPC-based EMS formulation. However, the author does not consider any cost function for the diesel generator.

### 2.5.3 Greenhouse Gas Cost Function

The utilisation of diesel generator in islanded microgrid able to aid the microgrid during the high demand. However, greenhouse gas releases each time the diesel generator is used, raising environmental concern. One of the effects is greenhouse effect. Figure 2.23 shows the infographics of the greenhouse effect (*Energy and the environment explained: Greenhouse gases*, 2022). Hence, an efficient usage of diesel generator can reduce the environmental impact. Greenhouse gas emission cost function can be introduced in the objective functions of the EMS. This is proposed in papers such as (Adefarati et al., 2021) and (Hleihel et al., 2022). Nonetheless, based on the reading, it was found that there is very little paper that considers emission cost in the optimisation problem especially in MPC-based EMS islanded or standalone microgrid. This might be since fuel consumption cost function is sufficed to reduce the usage of diesel generator. This, indirectly, reduces the greenhouse gas emission.

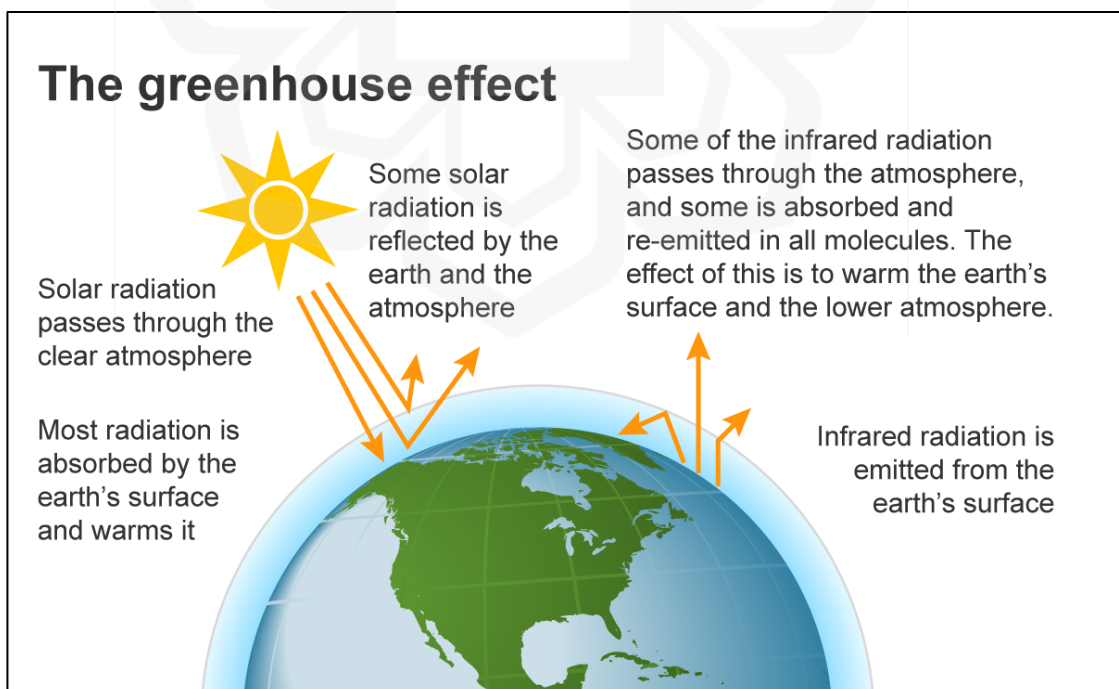


Figure 2.23 The Greenhouse Effect

## 2.5.4 Demand Side Management

Demand Side Management or load management is one of the strategies under the EMS (Ahmad et al., 2023). Some of the benefits of DSM programs are able to relax the optimisation of the energy management problem, reducing peak load demand and reshaping load profiles (Essayeh et al., 2021). Figure 2.24 shows some of the demand side management techniques (Jasim et al., 2023). Load curtailment is one of the programs of DSM and is used to overcome problems of overloads by reducing the “distance” between the generation and load demand. Efficient load curtailment able to reduce the cost of the operation in microgrid (Ahmad et al., 2023).

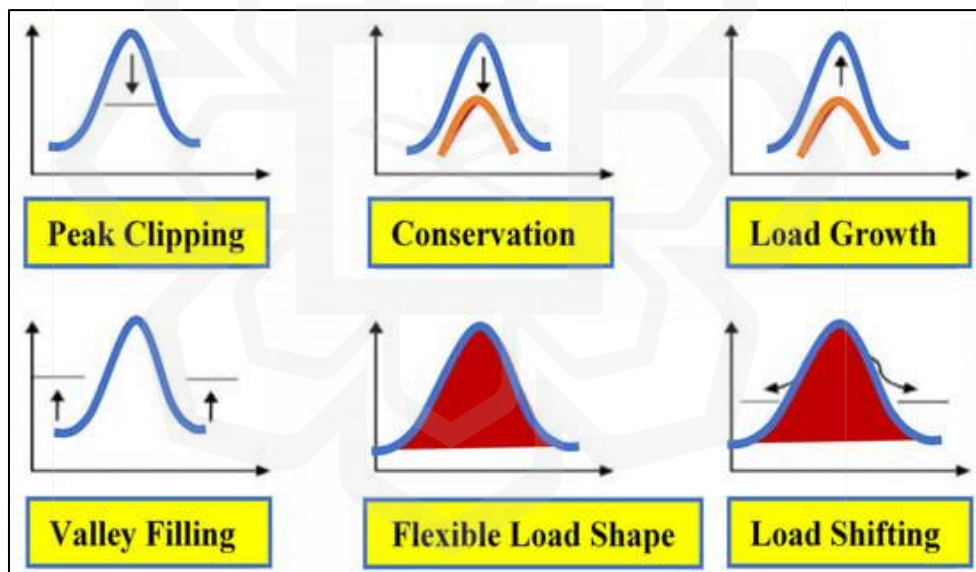


Figure 2.24 Demand Side Management Techniques

Load curtailment implementation has been observed in paper such as (He et al., 2021) and (Ryu et al., 2021). In (He et al., 2021), author’s proposed MPC-based EMS employed load curtailment to ensure the cost of the diesel generator being kept minimum. Conversely, load curtailment is utilised in (Ryu et al., 2021) to maintain the

power balance while reducing the use of diesel generator. On the contrary, no load curtailment strategy is observed in (Nair & Costa-Castelló, 2020), (Pippia et al., 2020), (Novickij & Joós, 2019), (Ndwali et al., 2021) and (Salazar et al., 2021).

While not implementing load curtailment strategy, (Polimeni et al., 2021) penalised the unmet demand and employs RES curtailment. The downside of RES curtailment is that the power generated by the RES is not fully utilised defeating the purpose of the microgrid which to improve the consumption of the RES (Nair & Costa-Castelló, 2020). The unmet demand and RES curtailment can be avoided by proper sizing of the microgrid during the design stage. The proper sizing of the microgrid components allow the energy to be supplied to the demand adequately under all scenarios (Abbasi et al., 2023). The summary of the past researches on the MPC-based EMS on islanded microgrid is shown in Table 2.8

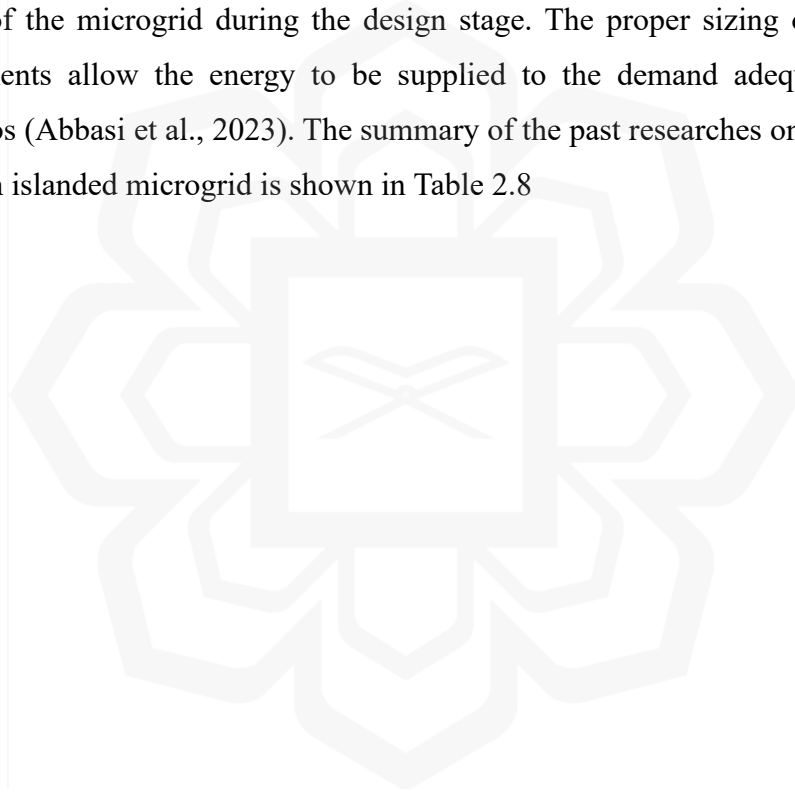


Table 2.8 Summary of the past researches on the MPC-based EMS in islanded microgrid

<b>Paper (Year)</b>	<b>Description</b>	<b>Contribution</b>	<b>Limitation</b>
(Basantes et al., 2023)	This research proposes MPC-based EMS for a standalone DC microgrid. The EMS objectives are to ensure optimise power flow distribution and operation at minimum cost while extending the lifespan of the BESS.	<ul style="list-style-type: none"> <li>• Implementation of hierarchical control allows for identifying the impact that each level has on the EMS and how the disturbances affect optimal operation.</li> </ul>	<ul style="list-style-type: none"> <li>• Linear cost function of the diesel generator is considered.</li> </ul>
(Nair & Costa-Castelló, 2020)	The main objective of this research is to develop MPC-based EMS that able to manage the energy among the different ESS to minimise their degradation and increase the consumption among renewable energy sources.	<ul style="list-style-type: none"> <li>• Implementation of slack variables to allow the violation of the non-critical constraints. This help in reduce the difficulty of the problem.</li> </ul>	<ul style="list-style-type: none"> <li>• Cost function for diesel generator is not considered</li> </ul>

(Pippia et al., 2020)	The author proposed a novel rule MPC-based EMS where if-the-else rules is used to decide the on or off status of the ESS and diesel generator. The proposed method can convert the Mixed Integer Linear Programming problem into a simple Linear Programming.	<ul style="list-style-type: none"> <li>• The computational time is reduced notably by around one fourth required by other approach.</li> </ul>	<ul style="list-style-type: none"> <li>• There is no significant cost reduction.</li> <li>• No diesel generator cost function is considered</li> </ul>
(Novickij & Joós, 2019)	The main of the research is to reduce the computational time and the scalability of the MPC-based EMS by decoupling the objectives into unit commitment and economic dispatch.	<ul style="list-style-type: none"> <li>• The computation time is reduced while still respecting the constraints of the microgrid.</li> </ul>	<ul style="list-style-type: none"> <li>• Linear cost function of the diesel generator is used.</li> </ul>
(Ryu et al., 2021)	This research focusses on developing MPC-based EMS to increase the hosting	<ul style="list-style-type: none"> <li>• Second order polynomial of fuel consumption is used for more</li> </ul>	<ul style="list-style-type: none"> <li>• No consideration on the greenhouse gases</li> </ul>

	capacity of the PVs and EVs. The strategy is to allow more EVs to be charged with using certain number of PVs.	accurate estimation; however, it is linearised using piecewise function.	emissions cost function.
(Polimeni et al., 2021)	The research proposed two-layer hierarchical EMS where the first layer is based on deterministic Mixed Integer Linear Programming model while second layer is based on stochastic model predictive model control.	<ul style="list-style-type: none"> <li>Fuel consumption is improved when comparing with PI-based EMS.</li> </ul>	<ul style="list-style-type: none"> <li>The linear cost function of the diesel generator is considered.</li> <li>No consideration on the greenhouse gases emissions cost function.</li> </ul>
(He et al., 2021)	To limit the uncertainty in the microgrid system and forecast, this research proposed a Robust MPC based on interval prediction approach to optimise the real time operation of islanded microgrid.	<ul style="list-style-type: none"> <li>Robust MPC has a low sensitivity to the uncertainty compared to traditional MPC and hard changing method hence able to cope with the uncertainty.</li> </ul>	<ul style="list-style-type: none"> <li>The linear cost function of the diesel generator is considered.</li> <li>No consideration on the greenhouse gases emissions cost function.</li> </ul>

(Ndwali et al., 2021)	The paper proposed an economic MPC EMS to minimise the grid cost and fuel cost while considering the level of fuel in the storage tank.	<ul style="list-style-type: none"> <li>• Significant reduction is observed in the usage of diesel generator and energy imported from the main grid.</li> </ul>	<ul style="list-style-type: none"> <li>• No emission cost is considered.</li> </ul>
(Salazar et al., 2021)	The paper suggested MPC-based EMS which aimed to reduce the microgrid cost while fulfil the user's comfort constraints in an isolated rural area of Ecuador. A domestic hot water system consisting of an electric water heater and water storage tank is considered.	<ul style="list-style-type: none"> <li>• The usage of diesel generators and energy waste is reduced.</li> </ul>	<ul style="list-style-type: none"> <li>• The linear cost function of the diesel generator is considered.</li> <li>• No consideration on the greenhouse gases emissions cost function.</li> </ul>

## 2.6 SUMMARY

This chapter has reviewed overall structure of the microgrid, EMS, MPC as well as past research papers that are related to the project. Based on the past research papers from year 2018 until 2023, it can be concluded that the diesel generator usage can be minimised by considering the fuel consumption cost function. Instead of using a linearised fuel consumption function, an accurate model of fuel consumption must be employed to improve the accuracy of energy management. The greenhouse gas emission cost function can also be included to penalise the usage of diesel generators. This reduces the need for diesel generators, resulting in cost savings.

To achieve further cost-saving improvements and flexibility in energy management, a load-curtailment strategy is also proposed. The load-curtailment strategy is proposed to minimise the power generation by the diesel generator by shedding a pre-defined amount of load. Therefore, this research will implement improved second order polynomial of fuel consumption cost function, greenhouse gas emission cost function and load shedding strategy to improve the energy management and improving the cost saving in the islanded microgrid.

## **CHAPTER THREE**

### **METHODOLOGY**

#### **3.1 INTRODUCTION**

This chapter outlines the systematic approach and specific techniques employed in conducting this research. The methodology was designed to align with the research objectives, ensuring that each method selected provides reliable, reproducible, and relevant data. First, we present the overall research methodology. Next, we explore the microgrid design and its component parameters. Afterwards, we delve into the proposed MPC-based EMS design, which consists of system modelling, objective function, and optimization. The parameters of the MPC-based EMS are also discussed. Subsequently, the simulation parameters and test cases are presented and described.

#### **3.2 OVERALL RESEARCH METHODOLOGY**

The research methodology is developed to achieve all objectives. Figure 3.1 shows the methodology flowchart of this research work.

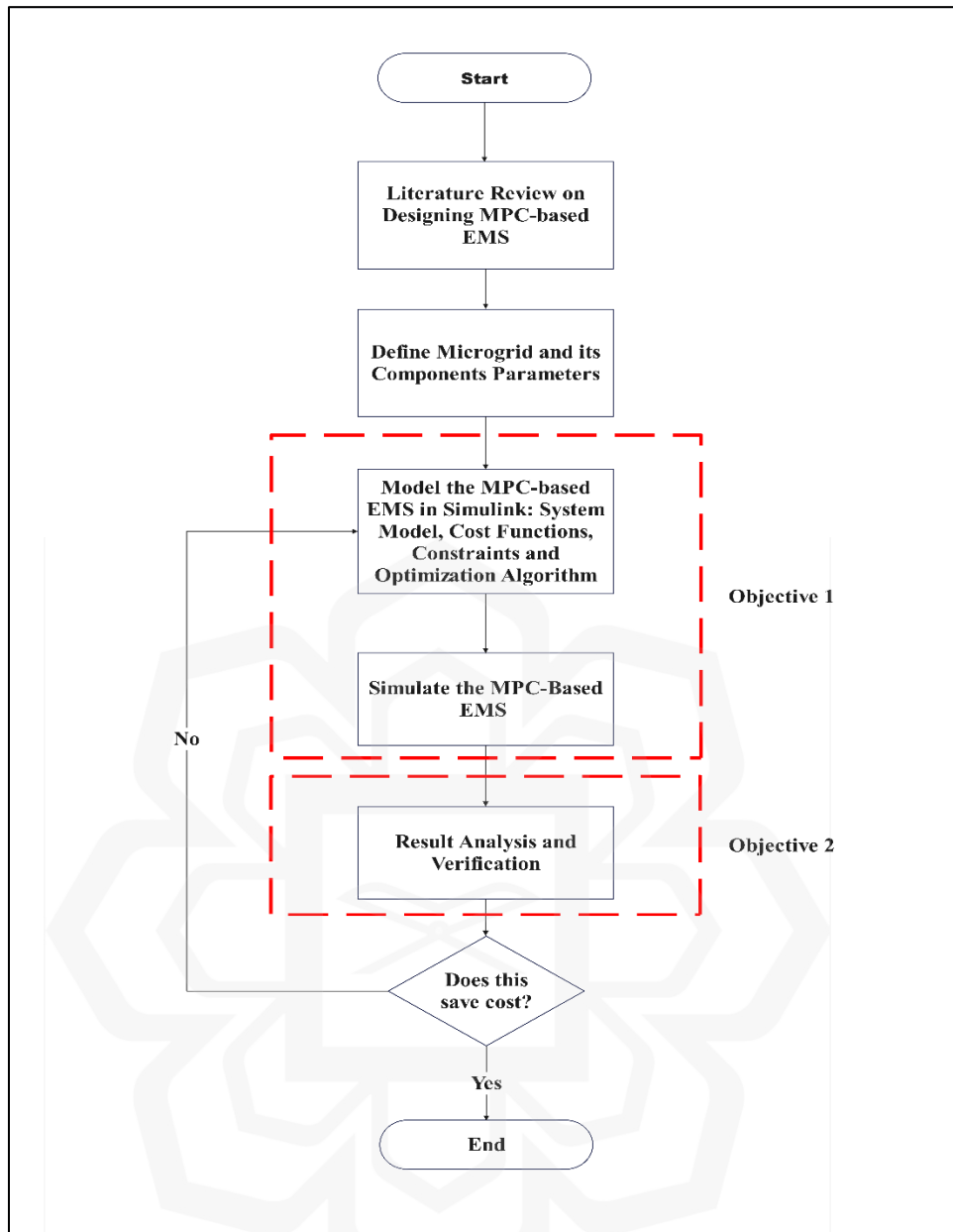


Figure 3.1 Methodology Flowchart

From figure 3.1, the research starts with a literature review of past research on MPC-based EMS. Next, the microgrid and its components are defined. The parameters of each component are needed in modelling the MPC-based EMS. Then, MPC-based EMS is modelled in MATLAB software. The components of the MPC-based EMS are the system model, constraints, objective/cost functions, and optimization functions. Objective 1 is achieved when the MPC-based EMS is successfully simulated in

MATLAB software. The MPC-based EMS result will be analyzed and verified against another MPC-based EMS algorithm to observe its effectiveness in achieving the objectives. Depending on the satisfaction of the result, the process might need to be repeated to achieve a more satisfactory result. If the result is satisfactory, then objective 2 is achieved.

### **3.3 ISLANDED MICROGRID DESCRIPTION**

In this research, an islanded AC/DC microgrid is proposed. The microgrid consists of solar PV panels, BESS, diesel generator and AC loads. The primary generation unit of this microgrid is solar PV. The solar PV is set to operate in maximum power point to extract as much power from the solar energy. Meanwhile, the BESS is utilised to smooth the intermittent nature of the solar PV which can result in stable operation of the microgrid. Diesel generator is utilised in the microgrid to act as backup source for the microgrid whenever the solar PV and BESS unable to provide power to the load. Figure 3.2 shows the proposed AC/DC microgrid structure

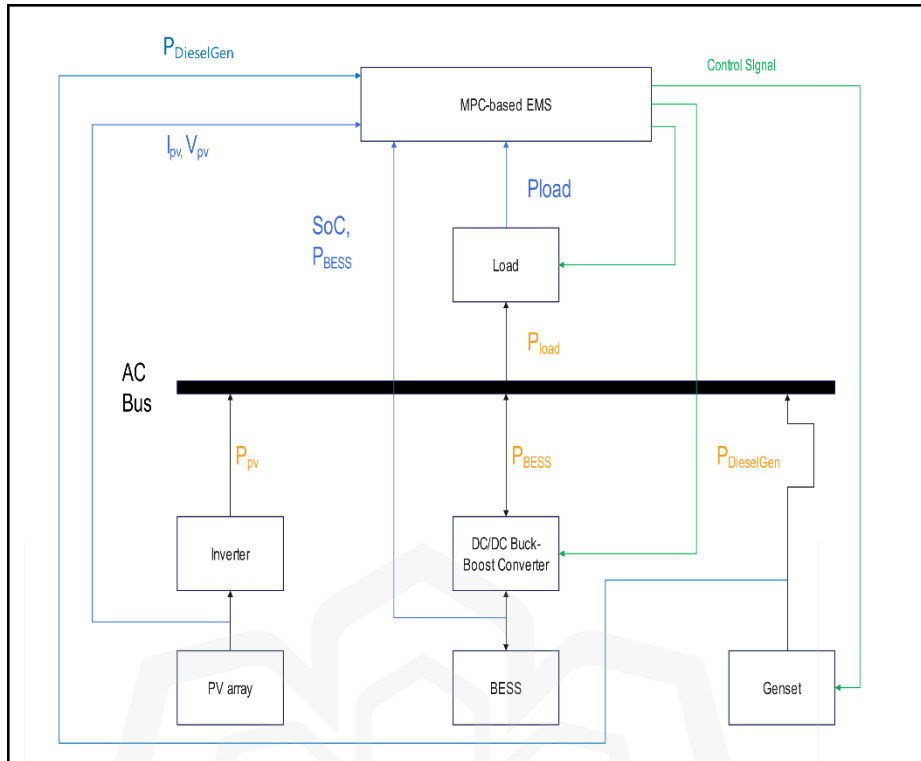


Figure 3.2 Proposed AC/DC Islanded Microgrid

Solar PV and BESS are connected to the main bus through an inverter. The inverter connects the BESS to main grid are bidirectional inverter due to the nature of the BESS that able to charge and discharge power from and to the main bus. The diesel generator is connected to the main bus through an AC-AC converter. It is assumed that there is no power converter load, and the main bus.

The utilisation of many power converters can cause the power efficiency to drop in the microgrid especially in small microgrid (Zhang et al., 2022). However, the design of the microgrid is not the main highlight of this research. Nevertheless, one of the advantages of MPC-based EMS which able to cater these constraints such as physical limitations of the equipment and others (Konneh et al., 2022). Hence, power converter efficiencies can be included in the MPC-based EMS formulation. This is reflected in the next section 3.4, where the detailed design of MPC-based EMS is done.

Information such as the current power output of the PV panel, the current BESS power, the current load power consumption, and the current SoC of the BESS are collected by the MPC-based EMS. The information will be processed to generate the optimal control signals for the BESS and the diesel generator. Due to the small structure of the microgrid, it is preferable to use the centralised architecture of the EMS since there is less information to process, so optimisation can be easily calculated to achieve global optimisation.

### 3.4 MPC-BASED EMS DESIGN

This section discusses the design of the MPC-based EMS. Figure 3.3 shows the step-by-step procedures for designing the MPC-based EMS. The procedures start with system modelling, which shows the derivation of the dynamic model of the microgrid and its components. Here, the constraints are also defined. Next, objective functions are formulated. Lastly, the previously discussed system model, constraints, and objective functions are formulated into optimisation algorithm under the MPC framework.

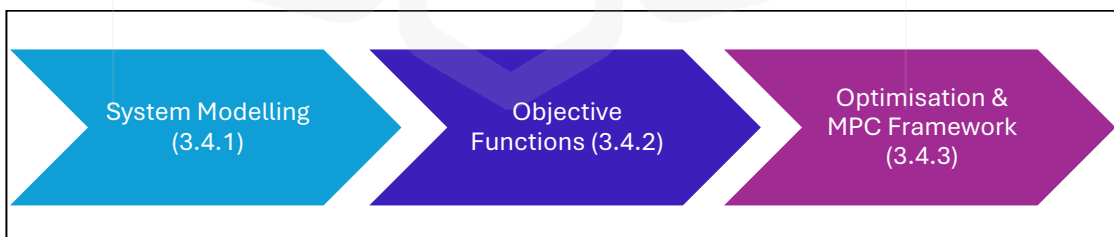


Figure 3.3 Procedures for Designing MPC-Based EMS

### 3.4.1 System Modelling

In this section, the model of the components in the islanded microgrid are discussed. In addition, the constraints of each components are also defined. First, the SoC model of the BESS and its constraints are defined, followed by the diesel generator, load curtailment and power balance.

#### 3.4.1.1 BESS

Lithium-ion (Li-on) batteries are considered for this project. The SoC dynamics of the BESS are modelled using the Coulomb Counting method as the basis for the prediction model within the MPC-based EMS. The model derivation is referenced from (Alarcón et al., 2022) and (Ali et al., 2023).

$$SoC(t) = \frac{C_{bat}(t)}{C_{bat}^{max}(t)} \quad (3.1)$$

Where  $SoC(t)$  is the current SoC of the BESS,  $C_{bat}(t)$  is the current capacity of the BESS in Ah and  $C_{bat}^{max}(t)$  is the maximum capacity of the BESS in Ah. By converting the current capacity of the BESS into the integration of battery current, we obtained as follows.

$$SoC(t) = \frac{\int I_{bat}(t) dt}{C_{bat}^{max}(t)} \quad (3.2)$$

For a large system such as microgrid, it is preferred the unit to be measured in watt, W, and watt-hour, Wh, instead of Ampere, A and Ampere-Hour, Ah. Consequently, (3.2) will take form as follows.

$$SoC(t) = \frac{1}{C_{bat}^{max}} \left( \int P_{bat}(t) dt \right) \quad (3.3)$$

Where  $C_{bat}^{max}$  is maximum capacity of the BESS in Wh and  $P_{bat}(t)$  is the BESS power in W. By further expand the equation (3.3), we obtained as follows.

$$\frac{d(SoC(t))}{dt} = \frac{1}{C_{bat}^{max}} (P_{bat}^{discharging}(t) - P_{bat}^{charging}(t)) \quad (3.4)$$

In (3.4), the  $P_{bat}(t)$  term is divided into two,  $P_{bat}^{discharging}(t)$  and  $P_{bat}^{charging}(t)$ .  $P_{bat}^{discharging}(t)$  is the power discharge by the BESS in W and  $P_{bat}^{charging}(t)$  is the charge power of the BESS.

In MPC framework, the model of the system is utilised to forecast its future dynamics. Previously, we derived the dynamics of the BESS, which represent the dynamic for our island microgrid. By using the Euler method from (Ali et al., 2023), the dynamic model can be discretised, and a prediction model of the BESS can be obtained. The discrete model of the BESS is shown below.

$$\frac{SoC(k+1) - SoC(k)}{T_s} = \frac{1}{C_{bat}^{max}} (P_{bat}^{discharging}(k) - P_{bat}^{charging}(k)) \quad (3.5)$$

$$SoC(k+1) = SoC(k) + \frac{P_{bat}^{discharging}(k) \cdot T_s}{C_{bat}^{max}} - \frac{P_{bat}^{charging}(k) \cdot T_s}{C_{bat}^{max}} \quad (3.6)$$

Where  $SoC(k + 1)$  is the state of charge of the battery at next time step,  $SoC(k)$  is the current state of charge of the battery,  $P_{bat}^{discharging}(k)$  and  $P_{bat}^{charging}(k)$  are the current discharging and charging battery power in W respectively,  $T_s$  is the sampling time in h and  $C_{bat}^{max}$  is the maximum capacity of the battery in Wh.

Since the battery is interacting with the converter, the BESS charging and discharging efficiency as well as the power converter efficiency need to be taken into consideration (Nair & Costa-Castelló, 2020). Furthermore, the BESS's dynamic can be divided to represent the SoC separately for charging and discharging mode.

$$SoC(k + 1) = \begin{cases} SoC(k) - \frac{P_{bat}(k) \cdot T_s \cdot \eta_{charging}}{C_{bat}^{max}} & \text{if } P_{bat}(k) < 0 \\ SoC(k) - \frac{P_{bat}(k) \cdot T_s}{C_{bat}^{max} \cdot \eta_{discharging}} & \text{if } P_{bat}(k) \geq 0 \end{cases} \quad (3.7)$$

Where  $\eta_{charging}$  and  $\eta_{discharging}$  represents the product of BESS charging and discharging efficiency and power converter efficiency respectively. The power flow for the microgrid is that the power is negative when it exits the main bus, and positive when it enters the bus. As a result, from (3.7), the BESS is charging when the  $P_{bat}(k)$  is negative and discharging into the grid when the  $P_{bat}(k)$  is positive. By applying a straightforward mathematical operation, it is possible to infer that the future SoC of the BESS will experience a rise when  $P_{bat}(k)$  is negative and a drop when the opposite is true.

The BESS is a crucial component to the island microgrid. Through BESS, microgrid stability can be achieved by absorbing excess energy or releasing energy needed by the microgrid. However, BESS can be quite expensive and generally does not have a very long lifespan (Tumeran et al., 2023). The lifespan of the BESS can be improved by avoiding deep charging or discharge (Mahendra et al., 2020). This can be defined through the following constraint.

$$SoC_{min} \leq SoC \leq SoC_{max} \quad (3.8)$$

Where  $SoC_{min}$  is the minimum SoC and  $SoC_{max}$  is maximum SoC. In addition, the constraint on the battery power,  $P_{bat}(k)$  needs to be implemented. The constraints represented the actual input and output power limitations of the battery specified by the manufacturer during the charging and discharging process. Based on (Nair & Costa-Castelló, 2020), we need to define two constraints, which are the power range of the battery during the charging and discharging of the battery, respectively. The constraints are defined as follows.

$$P_{bat}^{min} \leq P_{bat}^{charging} \leq P_{bat}^{max} \quad (3.9)$$

$$P_{bat}^{min} \leq P_{bat}^{discharging} \leq P_{bat}^{max} \quad (3.10)$$

Previously, it is defined that the battery is in charging mode when the battery power is negative. Consequently, the range of  $P_{bat}^{charging}$  should also have a negative value, and the range of  $P_{bat}^{discharging}$  must have a positive value. This condition allows the constraints to be simplified.

$$P_{bat}^{min} \leq P_{bat} \leq P_{bat}^{max} \quad (3.11)$$

In this case, the maximum charging power of the battery is represented by the negative value,  $P_{bat}^{min}$ , while the maximum discharging power is represented by the positive value,  $P_{bat}^{max}$ .

It is observed that equation (3.7) is a hybrid dynamical model in that the dynamic of the system changes depending on the power flow from and to the BESS (Nair & Costa-Castelló, 2020). Simply put, the changes in the SoC of the BESS are tightly related to the charging and discharging of the BESS. The hybrid dynamical model cannot be used directly in any optimisation problems (Nair & Costa-Castelló, 2020).

This model needs to be converted into a mixed logical dynamic (MLD) model that supports Boolean variables. The idea is to represent a model in a particular form when the Boolean is zero and another form when the Boolean is one. The formulation of the hybrid dynamical model into the MLD model can be referred to (Bemporad & Morari, 1999).

$$\begin{aligned}
SoC(k+1) = SoC(k) & \\
& + \frac{T_s}{C_{bat}^{max}} \cdot \delta_{bat}(k) \cdot P_{bat}(k) \cdot \left( \eta_{charging} - \frac{1}{\eta_{discharging}} \right) \\
& - \frac{T_s \cdot \eta_{charging}}{C_{bat}^{max}} P_{bat}(k)
\end{aligned} \tag{3.12}$$

Where  $\delta_{bat}(k)$  is the Boolean variable and  $\delta_{bat}(k) \in \{0, 1\}$ . When  $[\delta_{bat}(k) = 1] \leftrightarrow [P_{bat}(k) < 1]$ . The BESS will set to charging mode when  $\delta_{bat}(k)$  is equal to 1 and vice versa. The multiplicative term  $\delta_{bat}(k) \cdot P_{bat}(k)$  term introduces non-linearity in the formulation. Hence, an auxiliary variable,  $Z_{bat}(k)$  which  $Z_{bat}(k) = \delta_{bat}(k) \cdot P_{bat}(k)$  is introduced to ensure the formulation is linear. This is shown below.

$$\begin{aligned}
SoC(k+1) = SoC(k) + \frac{T_s}{C_{bat}^{max}} \cdot Z_{bat}(k) \cdot \left( \eta_{charging} - \frac{1}{\eta_{discharging}} \right) \\
- \frac{T_s \cdot \eta_{charging}}{C_{bat}^{max}} P_{bat}(k)
\end{aligned} \tag{3.13}$$

Moreover, an additional set of linear inequalities need to be defined in order to facilitate the mixed logical dynamic formulation for the BESS (Bemporad & Morari, 1999).

$$-P_{bat}^{min} \cdot \delta_{bat} \leq P_{bat} - P_{bat}^{min} \tag{3.14}$$

$$-P_{bat}^{max} \cdot \delta_{bat} \leq -P_{bat} \tag{3.15}$$

$$z_{bat} \leq P_{bat}^{max} \cdot \delta_{bat} \quad (3.16)$$

$$z_{bat} \geq P_{bat}^{min} \cdot \delta_{bat} \quad (3.17)$$

$$z_{bat} \leq P_{bat} + P_{bat}^{max} \cdot (1 - \delta_{bat}) \quad (3.18)$$

$$z_{bat} \geq P_{bat} + P_{bat}^{min} \cdot (1 - \delta_{bat}) \quad (3.19)$$

### 3.4.1.2 Diesel Generator

Diesel generator is a combination of diesel engine and electrical generator to generate electrical energy. It is used as an auxiliary generation unit in case where the PV and BESS unable to provide required power by the loads. Moreover, DG also can be used to charge the BESS whenever the cost of the fuel is cheaper aside from supplying power to the load (Ahmad et al., 2023). By having DG in microgrid, the reliability of the microgrid is improved since the DG can act as the main grid, supplying electricity whenever the microgrid requires it.

The detailed model of the DG is not considered in this project. It is considered that the diesel generator is fast-acting and has very little start-up time. However, the physical limitation of the diesel generator, which is the maximum amount of power able to be generated by the diesel generator, needs to be defined. The physical limitation can be defined as follows.

$$0 \leq P_{DG}(k) \leq P_{DG}^{max} \quad (3.20)$$

Where  $P_{DG}^{max}$  is maximum power output can be generated by the diesel generator. Since DG is a dispatchable unit, it can be turned on and off whenever it is needed. We need to take this consideration in defining the constraints of the diesel generator. Hence, (3.20) can be transformed into (3.21) and (3.22) by using MLD formulation.

$$P_{DG}^{min} \cdot \delta_{DG} \leq P_{DG} \quad (3.21)$$

$$P_{DG} \leq P_{DG}^{max} \cdot \delta_{DG} \quad (3.22)$$

Where  $\delta_{DG}(k)$  is the Boolean variable and  $\delta_{DG}(k) \in \{0, 1\}$ . The diesel generator is ON when  $\delta_{DG}(k) = 1$ . The diesel generator can operate by generating output power ranging from  $P_{DG}^{min}$  until  $P_{DG}^{max}$ . When  $\delta_{DG}(k) = 0$ , the diesel generator is OFF. Hence, the diesel generator power is zero.

### 3.4.1.3 Load Curtailment

Load curtailment provides a valuable flexibility in the energy management of a microgrid. While it is ideal for generation to fully meet the load demand, ensuring both system stability and cost-efficiency is equally crucial. The load curtailment should be minimised and applied efficiently. In this research, the load curtailed cannot exceeds the maximum value.

$$\delta_{CURTAIL} \cdot P_{CURTAIL}^{min} \leq P_{CURTAIL}(k) \leq \delta_{CURTAIL} \cdot P_{CURTAIL}^{max} \quad (3.23)$$

#### 3.4.1.4 Power Balance in Microgrid

The balance between power generation and consumption must be always met by the MPC-based EMS. This is to ensure a stable operation of the microgrid. This is ensured by always satisfying (3.24).

$$P_{PV}(k) + P_{BESS}(k) + P_{DG}(k) = P_{LOAD}(k) - P_{CURTAIL}(k) \quad (3.24)$$

$P_{PV}(k)$  is the PV output power,  $P_{BESS}(k)$  is the BESS output power,  $P_{DG}(k)$  is the DG output power,  $P_{LOAD}(k)$  is the load consumption power and  $P_{CURTAIL}(k)$  is the load curtailment power. Again, the power flow consideration of this microgrid is that the power is positive when its flow into the main bus while negative when its flow out from the main bus. By this,  $P_{BESS}(k)$  can be a positive or negative depending on the charging or discharging mode.

#### 3.4.2 Objective Function

Objective function is a formulation of mathematical expressions that consists of decision variables that reflect the desired outcome or goals of an optimization problem. There are a few optimization problems that we need to tackle, especially for our proposed microgrid. Given that the BESS and the diesel generator are both units that can be dispatched, the optimization of these two components will be the primary focus. Hence, multi-objective functions are considered where the goal is to generate optimal control actions for the battery and diesel generator. The global cost function can be defined as follows.

$$J_{Global} = J_{DG} + J_{BESS} + J_{GHG} \quad (3.25)$$

Where  $J_{Global}$  is the global cost function which is the summation of the  $J_{DG}$ , diesel generator cost function,  $J_{BESS}$ , BESS cost function and  $J_{GHG}$ , greenhouse gas emission cost function.

### 3.4.2.1 Diesel Generator Cost Function

The first objective is to minimise the fuel cost. The steady-state power output of the diesel generator unit is proportional to its fuel consumption per time. The fuel consumption also is proportional to the fuel costs per time. Hence, steady-state power output of the diesel generator unit is proportional to the fuel costs per time. The fuel cost function of the diesel generator can be approximated by the quadratic function known as quadratic cost curve (QCC) (Ajani, 2020).

$$J_{DG} = C_{DG}[a.P_{DG}(k)^2 + b.P_{DG}(k) + c] \quad (3.26)$$

Where  $P_{DG}(k)$  is diesel generator power output.  $a, b$  and  $c$  are the fuel cost coefficients.  $C_{DG}$  is the cost of the diesel. The equation (3.26) is illustrated in Figure 3.4.

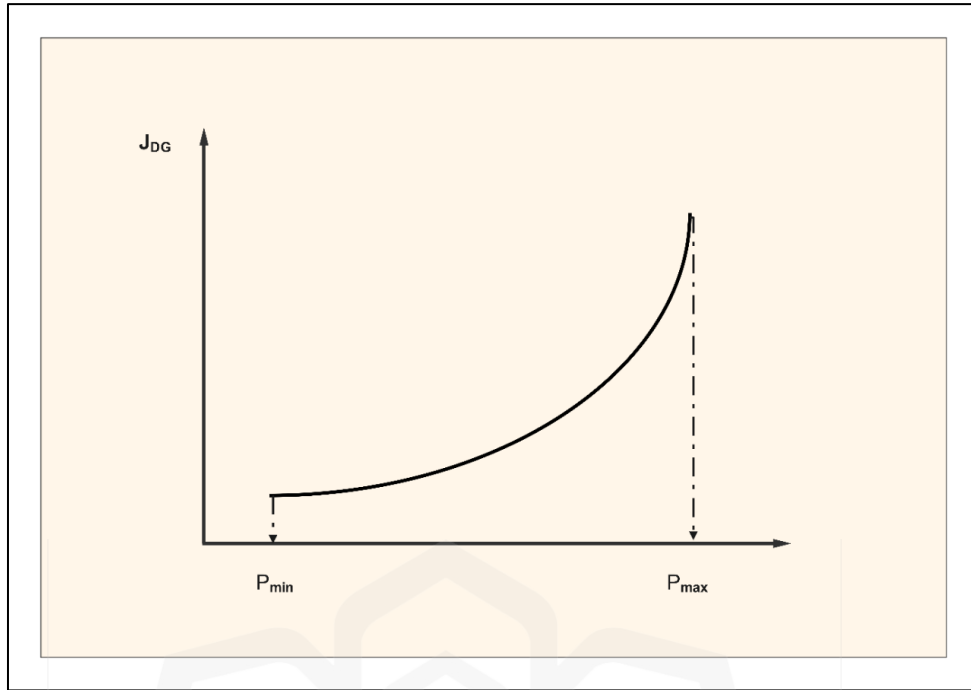


Figure 3.4 Quadratic Cost Curve

Figure 3.4 shows that the lower the diesel generator power supplied to the grid, the lower the fuel cost used during the time when the diesel generator is on. Whenever there is no diesel generator power being supplied to the grid, the fuel cost is zero. It is therefore recommended that the diesel generator be turned off most of the time or that it supplies the grid with the least amount of power possible.

As mentioned, the diesel generator is an important component which able to contribute to the stability of the microgrid. However, the release of the  $\text{CO}_2$  into the atmosphere due to the burning of the fossil fuel can cause environmental concern. It is reasonable for one to assume  $\text{CO}_2$  objective function into consideration. Nevertheless, by using less diesel generator power, we are not only reducing the fuel cost but also the emission of  $\text{CO}_2$  into the atmosphere. The indirect method helps us to simplify and minimise the computation complexity due to the MIQP method.

### 3.4.2.2 BESS Cost Function

The BESS is crucial in maintaining the power balance in the microgrid by absorbing excess energy and release energy when the energy is lacking. The BESS, however, commonly suffers from two common problems: calendar ageing and cycling ageing.

Calendar ageing occurs when the battery is idling, no current flow from in or out of the battery (Redondo-Iglesias et al., 2020). According to (Nair & Costa-Castelló, 2020), calendar ageing occurs when the battery dwell at high SoC for a long time. On the contrary, cycling ageing is due to the excessive charging and discharging cycle of the battery. In this research, however, the focus is on the cost saving of the diesel generator. Hence, the objective function of the BESS below is considered instead.

$$J_{BESS} = [SoC(k+1) - SoC_{ref}]^2 \quad (3.27)$$

Equation (3.27) is defined to ensure that the SoC of the BESS always follows the reference SoC value. Hence, there will always be reserved energy to be supplied to the loads. It is recommended that to set the SoC reference value between the minimum SoC and maximum SoC.

### 3.4.2.3 Greenhouse Gas Emission Cost

The burning of the diesel fuel using diesel generator releases greenhouse gas to the atmosphere. Some of the greenhouse gases produced from the burning of the diesel fuel are carbon dioxide, carbon monoxide, sulphur dioxide, nitric oxide, and nitrogen dioxide (G. P & Saha, 2020; Hleihel et al., 2022; Taha et al., 2018). However, carbon dioxide made up of almost 95% of the total emission (Taha et al., 2018). The greenhouse

gas emission could be reduced by reducing the utilisation of the diesel generator in the islanded microgrid. The cost function is defined as follows.

$$J_{GHG} = [\alpha_{NO_x}\mu_{NO_x} + \alpha_{CO_2}\mu_{CO_2} + \alpha_{CO}\mu_{CO} + \alpha_{SO_2}\mu_{SO_2}].P_{DG}(k) \quad (3.28)$$

$\alpha$  is the emission factor of a greenhouse gas expressed in  $kg/kWh$ .  $\mu$  is the environmental damages cost due to the gas emission expressed in  $RM/kg$ .  $P_{DG}(k)$  is DG power output.

### 3.4.3 Optimisation Using Mixed Integer Quadratic Programming (MIQP) Under MPC Framework

Combining the constraints and the objective function defined in the previous sections, the overall optimization problem can be formulated as:

Minimise  $J_{Global}$  (3.25)

Subject to BESS Model: (3.13)

Storage constraints: (3.8), (3.11) and (3.14) -(3.19)

DG constraints: (3.21) and (3.22)

Load curtailment constraint: (3.23)

Power balance: (3.24)

**Step 1: Formulate the optimization problem.**

At the current point in time, an optimization problem is formulated for a selected prediction horizon,  $N_p$ , based on the current SoC level of the battery, current solar PV generation power, current load consumption as well as forecasts of the future PV production and load demand.

To solve the optimization problem expressed by (3.25), it must be reformulated into a form that can be solved using commercial solvers. This is because MATLAB don't have a specific solver to solve Mixed Integer Quadratic Programming (MIQP) problem. Some of the commercial solvers are CPLEX, Gurobi etc. CPLEX 12.10 is used to solve the optimization problem (3.25) since it is the latest version which have the MATLAB integration.

$$\begin{aligned}
 &\text{Minimise} && \frac{1}{2}U^TQU + U^TP + c \\
 &\text{Subject to} && U \text{ are integers and binary,} \\
 &&& A_{ineq} \cdot U \leq b_{ineq} \\
 &&& A_{eq} \cdot U = b_{eq} \\
 &&& lb \leq U \leq ub
 \end{aligned}$$

(3.28)

Where:

- The decision variables are collected in the vector.

$$U = [P_{BESS}(k) \quad P_{DG}(k) \quad P_{CURTAIL}(k) \quad \delta_{BESS}(k) \quad \delta_{DG}(k) \quad Z_{BESS}(k)]$$

for  $k = 0, \dots, N_p-1$

- The objective function J (3.24) is written as a vector with quadratic coefficients.
- The inequality constraints (3.8), (3.11), (3.14) – (3.19) and (3.21) – (3.22) are represented using the matrix  $A_{ineq}$ , the vector  $b_{ineq}$  and the decision vector U.

- The equality constraint (3.23) is represented using the matrix  $A_{eq}$ , the vector  $b_{eq}$  and the decision vector  $U$ .
- The upper and lower limits of the decision variables are not implemented for the optimization problem since all constraints are defined under inequality constraints.

**Step 2: Solve the optimization problem.**

By solving the MIQP problem in (3.28), the optimal control inputs for the prediction horizon  $N_p$  is obtained as

$$U_{opt}(k) = \left[ \left( (U_{opt}(0)) \right)^T \quad \left( (U_{opt}(1)) \right)^T \quad \dots \quad \left( (U_{opt}(N_p - 1)) \right)^T \right]$$

Where each vector is the current and future optimal control inputs sequences for the sample times  $k = 0, 1, \dots, N_p - 1$ , respectively.

**Step 3: Execute the optimal control.**

Although a complete sequence of  $N_p$  control signals is computed, only the first element,  $U_{opt}(0)$ , which is the optimal control inputs for the current time is applied to the system, the remaining future control inputs are discarded.

**Step 4: Shift the prediction horizon.**

At the next sample time, the prediction horizon is shifted, and a new optimal sequence of control signals is obtained by repeating step 1-3. A new estimate for PV generation and load consumption as well as a new battery SoC are obtained in this process. With

this updated and new knowledge, a new optimization problem is solved. With this strategy, known as receding horizon, a feedback mechanism is developed so that any disturbances that have affected the system in the interim can be compensated for by newly optimal solutions.

### 3.5 MICROGRID PARAMETERS, SOLAR PV POWER OUTPUT AND LOAD DEMAND DATA

#### 3.5.1 Microgrid, Cost Function and Simulation Parameters

The microgrid considered in this research is an AC islanded microgrid which consist of solar PV panel, diesel generator, BESS, and AC loads. The overall microgrid structure has been discussed in previous chapter. The islanded microgrid, cost and simulation parameters are listed in the Table 3.1.

Table 3.1 Islanded Microgrid, Cost and Simulation Parameters

Microgrid Parameters	
Parameter	Value
$C_{bat}^{max}$	9 kWh
$P_{bat}^{min}, P_{bat}^{max}$	-3 kW, 3 kW
$SoC_{initial}, SoC_{min}, SoC_{max}, SoC_{ref}$	50%, 10%, 80%, 50%
$\eta_{charge}, \eta_{discharge}$	0.95, 0.95
$P_{DG}^{min}, P_{DG}^{max}$	1 kW, 5 kW

$P_{CURTAIL}^{min}, P_{CURTAIL}^{max}$	0 kW, 30% of load demand of that interval (kW)
<b>Cost Parameters</b>	
<b>Parameter</b>	<b>Value</b>
$a$	$2.5 \frac{L}{kWh^2}$
$b$	$-1.375 \frac{L}{kWh}$
$c$	$0.7813 \frac{L}{h}$
$C_{DG}$	$2.05 \frac{RM}{L}$
$\alpha_{CO_2}$	$0.232037 \frac{kg}{kWh}$
$\alpha_{NO_x}$	$0.00431 \frac{kg}{kWh}$
$\alpha_{CO}$	$0.00233 \frac{kg}{kWh}$
$\alpha_{SO_2}$	$0.00464 \frac{kg}{kWh}$
$\mu_{NO_x}$	$1.27 \frac{RM}{kg}$
$\mu_{CO_2}$	$0.0057 \frac{RM}{kg}$
$\mu_{CO}$	$0.10 \frac{RM}{kg}$
$\mu_{SO_2}$	$0.57 \frac{RM}{kg}$
<b>Simulation Parameters</b>	
<b>Parameter</b>	<b>Value</b>
Sampling Time, $T_s$	1 Hour
Simulation Duration	72 Hours
Prediction Horizon, $N_p$	24 Hours

The microgrid parameters were obtained and adjusted (Nair & Costa-Castelló, 2020). The efficiency of the power converter for the solar PV and diesel generator is not specified since it is assumed that the efficiency is already considered in the solar PV generation profile and the power diesel generator can provide. The coefficient of the fuel consumption curve of the diesel generator is obtained from the curve fitting of the

general diesel generator fuel consumption curve in (Hleihel et al., 2022). In addition, the emission factor and environmental impact cost of the greenhouse gases are acquired and adjusted based on the data from (Hleihel et al., 2022; Tahmasebi et al., 2021). The cost is converted from US Dollar into Malaysian Ringgit.

The simulation was configured for 72 hours with 1 hour of sampling time. Next, the prediction horizon,  $N_p$  was set for 24 hours. By this, the MPC-based EMS will attempt to optimise the future energy management control according to the objective functions for 24 hours from the current time. The weights for the three objective functions created in the previous chapter were also set. More weight was given to the fuel consumption cost function and the greenhouse gas emission cost function because the goal of this thesis is to increase the diesel generator's cost savings.

### **3.5.2 Solar PV Generation profile and Load Demand Profile**

This thesis considers solar PV generation and load demand as of (Morrow, 2021) is considered in this thesis. The dataset represents a yearly timeseries of residential load and 8 PV systems with a 1-minute resolution. In this thesis, the dataset spanning 72 hours is retrieved and resampled at 1- hour interval. Figure 3.5 and 3.6 show the solar PV generation and load demand profiles, respectively.

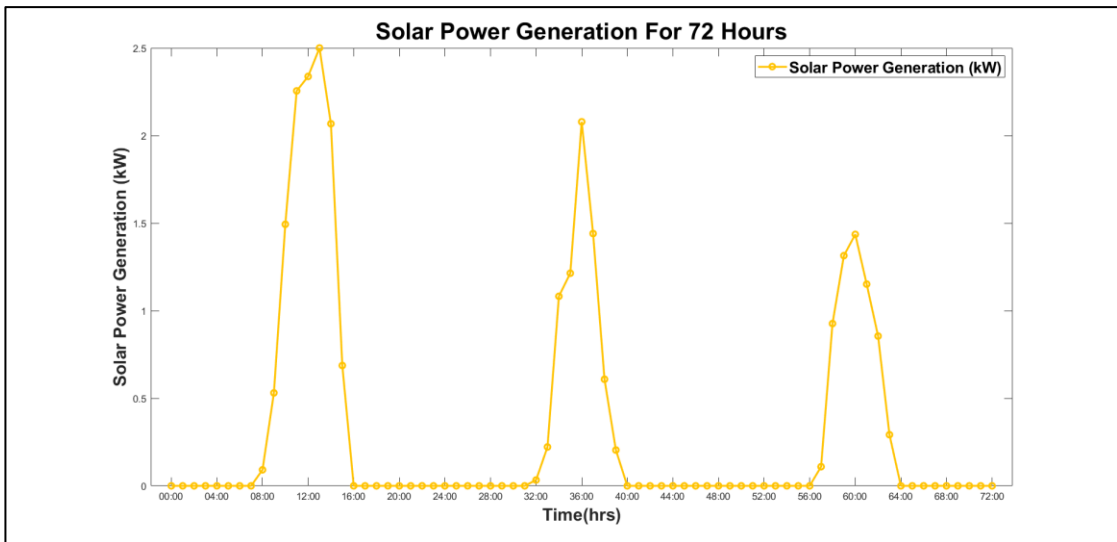


Figure 3.5 Solar PV Generation Profile for 72-Hours

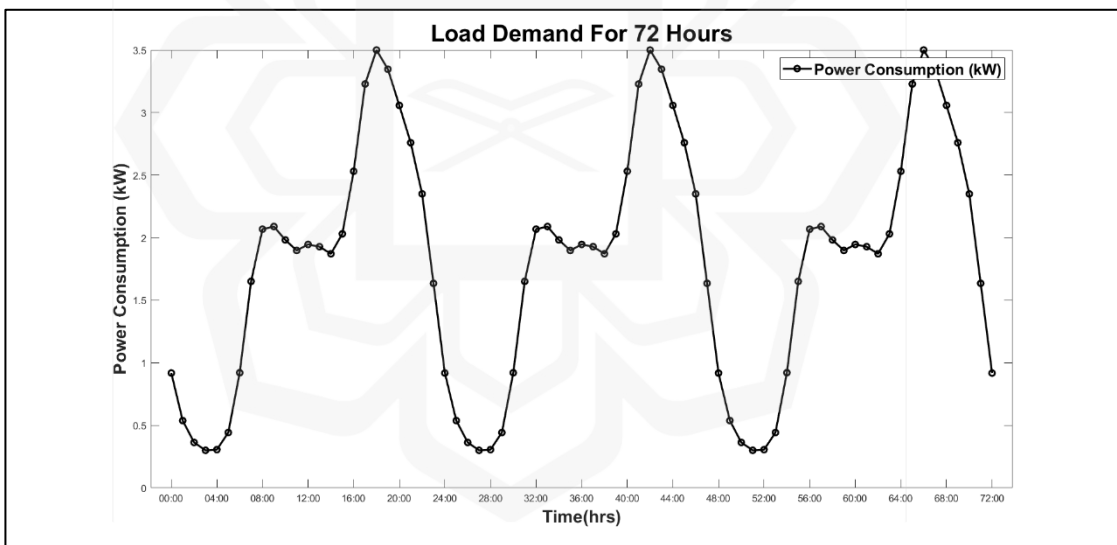


Figure 3.6 Load Demand Profile for 72-Hours

The solar PV generation is assumed to be working under MPPT. Figure 3.5 indicates that the peak solar PV generation decreases from day-1 to day-3. The maximum power generated by the solar PV within the 3-days period is 2.5 kW. Figure 3.6 depicts the traditional residential load demand pattern. The load demand is minimal

in the morning and gradually increases until midday. The load demand peaks during the evening before decreasing until midnight.

### 3.6 SIMULATION TEST CASES

In this research, the purpose of the proposed MPC-based EMS is to improve the cost savings of the diesel generator by limiting its usage. The less frequent diesel generator is used, the less diesel fuel is utilised. Subsequently, low cost spent of buying the diesel fuel and low emission of greenhouse gases. The proposed MPC-based EMS integrates load curtailment alongside the more accurate second order polynomial fuel consumption cost function and greenhouse gas emission cost function as part of its strategy in achieving the objectives.

To study the capabilities of the developed MPC-based EMS for diesel generator cost saving, two test cases will be conducted. The first test case is to observe the energy management of the components in the islanded microgrid with and without the load curtailment. In second test case, it is desired to observe the impact of the weight of the defined cost functions to the energy management strategy and the cost saving potential in the microgrid. Table 3.2 shows the breakdown of the test cases.

Table 3.2 Test cases

<b>Test Case</b>	<b>Explanation</b>
Case 1	Impact of load curtailment
Case 2	Impact of weight of the cost functions

The subsequent sections give the simulation results of the proposed test cases. Generally, all simulations follow the simulation parameters listed in Table 3.1. In test case 1, the proposed MPC-based EMS is compared to an MPC-based EMS without load curtailment capabilities. In test case 2, the weights of the cost functions will be adjusted to see how they affect cost savings.

### 3.6.1 Case 1: Impact of Load Curtailment

The simulation is done to compare and observe between the proposed MPC-based EMS and MPC-based EMS without the load curtailment capabilities. The microgrid, cost and simulations parameters will be the same to the one listed in the Table 3.1. However, weight of each cost functions is yet to be listed. Table 3.3 listed the weight of each cost functions.

Table 3.3 Weight of the cost functions

Cost Parameters	
Weight of BESS Cost Function, $\lambda_1$	1
Weight of Fuel Consumption Cost Function, $\lambda_2$	70
Weight of Greenhouse Emission Cost Function, $\lambda_3$	475.17

In Table 3.3, the weight of BESS cost function is set to 1 and weight of fuel consumption cost function and weight of emission cost function is set 70 and 475.17 respectively. The weight for fuel consumption cost function and greenhouse gas emission cost function are given in that way is to level the final value due to the difference in the fixed cost for fuel consumption and greenhouse emission cost. The BESS cost function, which is not the focus of this research, is set to 1 to allow the other two cost functions to stand out

The fixed cost for fuel consumption cost is  $2.05 \frac{RM}{L}$  while  $0.302 \frac{RM}{kWh}$  is the fixed cost for the greenhouse emission cost. By using the weight values in Table 3.3, the final value calculated as the weight multiplied by the fixed cost of each cost function- will be the same. This ensures that both cost functions have an equal impact on the optimization process.

### **3.6.2 Case 2: Impact of Weight of The Cost Function on The Cost Saving and Greenhouse Gas Emission**

This case investigates the effect of the weight of the cost function on the diesel fuel cost saving. The purpose of the weight in the optimisation problem is to give some cost functions more influence or priority than others. Hence, the optimisation problem solving will be more focused on minimising or maximising the cost functions according to their assigned weights.

Previously, the weights were assigned in such a way that the diesel fuel consumption cost function and greenhouse emission cost function were level with each other in case 1. In case 2, some scenarios are designed to observe the impact of the weight of the cost function on the cost reduction on the diesel fuel of the diesel generator. Table 3.4 shows the weight parameters for three scenarios.

Table 3.4 Weight parameters for three scenarios

<b>Scenario</b>	<b>BESS Cost Function Weight</b>	<b>Diesel Generator Cost Function Weight</b>	<b>Greenhouse Gas Emission Cost Function Weight</b>
<b>1</b>	2.05	1	6.8
<b>2</b>	2.05	70	0
<b>3</b>	2.05	0	475.17

Three scenarios are considered to test the impact of the weight of the cost function. The weight values are assigned with the knowledge of the fixed cost of each cost function where the fixed cost of the diesel generator cost function is higher than the cost of greenhouse gas emission cost function and cost of BESS cost function. The greenhouse gas emission cost function is lower than the cost of BESS cost function. Hence,

In the first case, the weight of the BESS cost function, diesel generator cost function and greenhouse gas emission cost function are 2.05, 1 and 6.8. The weights are chosen to ensure the influence of every cost function is the same. This led to the final cost of 2.05 for all the cost functions after the weight is multiplied with the fixed cost. In the second case, the diesel generator cost function weight is set to 70 which led to final cost of 143.5, while the greenhouse gas emission cost function weight is set to 0.

In the third case, the weight of the diesel generator cost function is set to 0 while the weight of greenhouse gas emission cost function is set to 475.17 which led to final cost of 143.5. The weight of the BESS cost function is maintained at 2.05. In the first scenario, the final cost will be the same for all the cost functions. In the second and third scenario, we will observe the impact when the focus is more on the fuel consumption cost functions and disregard the greenhouse emission cost function and vice versa.

### 3.7 SUMMARY

In this chapter, the research approach is discussed. The methodology is defined while considering the study objectives. Next, the structure of the islanded microgrid is defined. The islanded microgrid is an AC microgrid which consist of solar PV, BESS, diesel generator and AC loads. For this research, Lithium-ion BESS is considered due to its effectiveness and capabilities as a storage and backup generator in microgrid.

Moreover, the MPC-based EMS also have been designed and explained. The dynamic model of the microgrid will be represented as the dynamic model of the SoC of the BESS. The main objective of the MPC-based EMS is to reduce the fuel consumption in the islanded microgrid. This is done by considering the second-order polynomial of fuel cost function instead of linearised one. In addition, greenhouse gas function also being considered along with the BESS cost function. To achieve further cost saving, load curtailment is introduced.

Finally, the MPC-based EMS will be developed and simulated using MATLAB software. CPLEX is employed to solve the Mixed Quadratic Programming efficiently.

## **CHAPTER FOUR**

### **RESULTS AND DISCUSSION**

#### **4.1 INTRODUCTION**

In this chapter, the proposed MPC-based EMS is simulated, and the results are analysed. Section 4.2 presents the base case study of the MPC-based EMS without the load curtailment capabilities. Section 4.3 discusses the results of case study 1, which examines the MPC-based EMS with load curtailment. Section 4.4 presents case study 2, analysing the impact of weight functions. Lastly, section 4.5 summarizes the chapter.

#### **4.2 MPC-BASED EMS WITHOUT LOAD CURTAILMENT**

The simulation is done for the MPC-based EMS without the load curtailment capabilities in MATLAB as a base case study and serves as a comparison for the proposed MPC-based EMS in section 4.3. Figures 4.1 shows the energy profile for all components including the solar PV generation and load for the 72- hours period with 1-hour interval. In addition, Table 4.1 listed the power-set point for every components including solar PV generation and load for the first day with 1-hour interval.

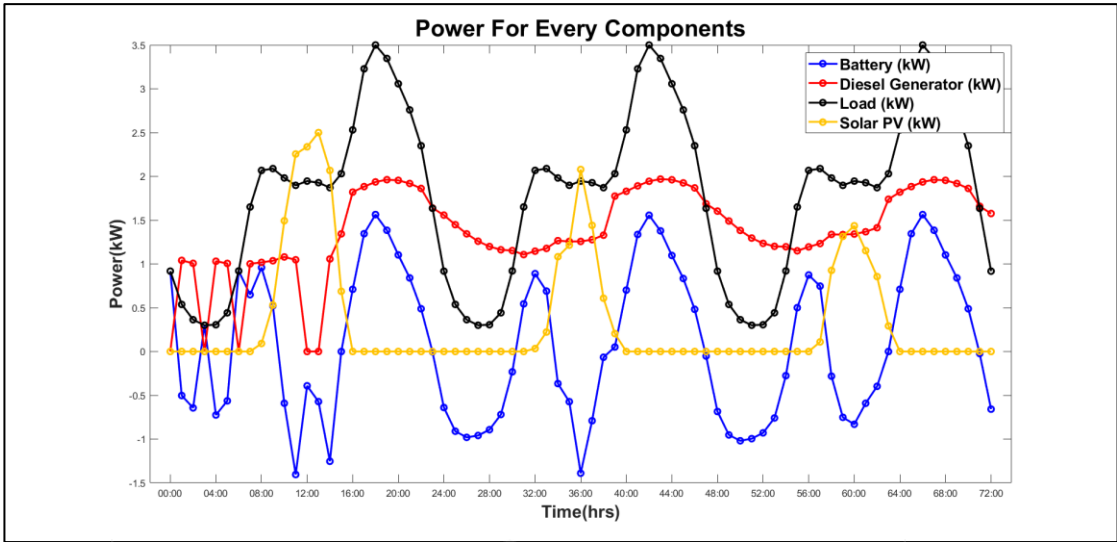


Figure 4.1 Energy Profile for All Components for MPC-Based EMS Without Load Curtailment

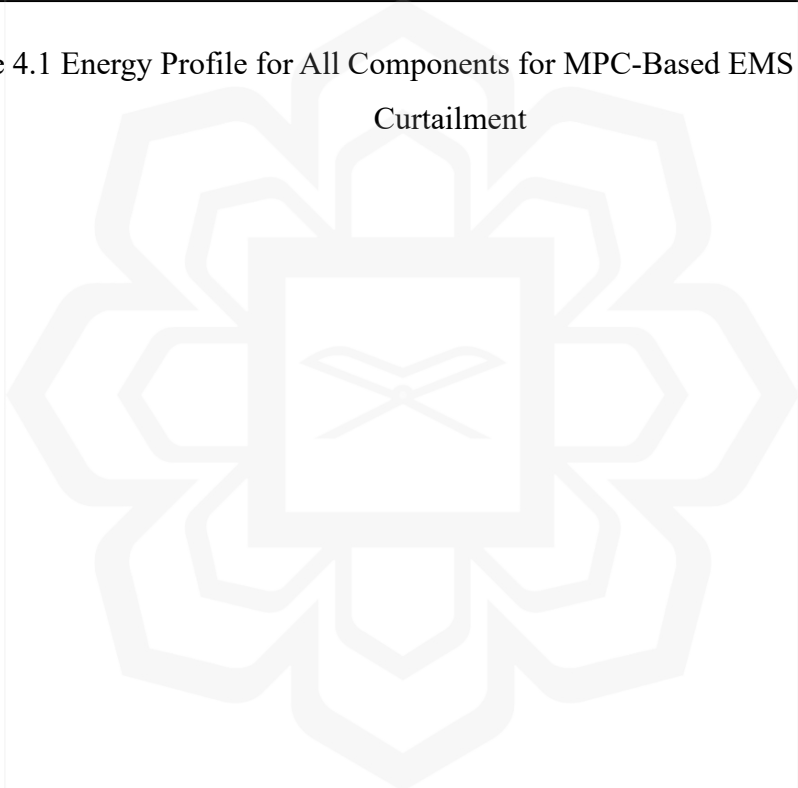


Table 4.1 Power set-point for every components of first day for MPC-based EMS without load curtailment

<b>Time (h)</b>	<b><math>P_{PV}</math> (kW)</b>	<b><math>P_{DG}</math> (kW)</b>	<b><math>P_{BESS}</math> (kW)</b>	<b><math>P_{Loads}</math> (kW)</b>
00:00	0	0	0.9176	0.9176
1:00	0	1.0403	-0.5027	0.5376
2:00	0	1.0069	-0.6438	0.3631
3:00	0	0	0.3	0.3
4:00	0	1.0306	-0.7249	0.3057
5:00	0	1.0057	-0.5636	0.4421
6:00	0	0	0.9202	0.9202
7:00	0	1.0012	0.6492	1.6504
8:00	0.0916	1.0179	0.9587	2.0682
9:00	0.5307	1.0365	0.5216	2.0888
10:00	1.4934	1.0795	-0.5911	1.9818
11:00	2.2552	1.0471	-1.4047	1.8976
12:00	2.3377	0	-0.3919	1.9458
13:00	2.5	0	-0.5723	1.9277
14:00	2.0676	1.0566	-1.2534	1.8708
15:00	0.6872	1.3433	0	2.0305
16:00	0	1.8203	0.7103	2.5306
17:00	0	1.8832	1.3450	3.2282
18:00	0	1.9363	1.5637	3.5
19:00	0	1.9619	1.3846	3.3465
20:00	0	1.9544	1.1030	3.0574
21:00	0	1.9188	0.8402	2.7590
22:00	0	1.8619	0.4880	2.3499
23:00	0	1.6387	-0.0040	1.6347
00:00	0	1.5574	-0.6398	0.9176

From Table 4.1, it is observed that the MPC-based EMS able to the manage the energy in the islanded microgrid. The constraints for all the components especially BES and diesel generator are respected. The BESS charging and discharging power is respected by not reaching maximum 3 kW during discharging and -3kW during charging time. The power generated by the diesel generator also not exceeded the set limit which was 5 kW. Most importantly, the power balance is always met by using the power balance equation in Section 3.4 which is reflected in the Table 4.1. Figure 4.2 and Table 4.2 shows the SoC of the BESS for the 72-hours period. From Table 4.2, it can be observed that the SoC of the BESS also stayed within the SoC limits to protect the BESS from the deep charging and discharging.

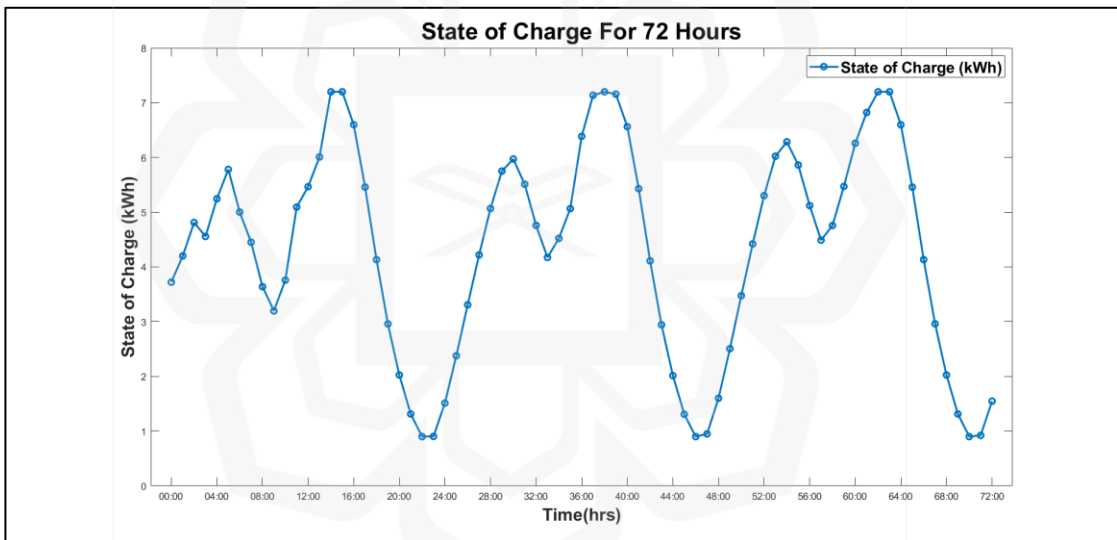


Figure 4.2 SoC of the BESS for MPC-Based EMS Without Load Curtailment

Table 4.2 SoC of the BESS for MPC-based EMS without load curtailment for 24-hour period

<b>Time (h)</b>	<b><math>SoC_{PV}</math> (kWh)</b>
00:00	3.7224
1:00	4.2
2:00	4.8117
3:00	4.5575
4:00	5.2461
5:00	5.7815
6:00	5.0018
7:00	4.4517
8:00	3.6393
9:00	3.1973
10:00	3.7588
11:00	5.0933
12:00	5.4656
13:00	6.0092
14:00	7.2
15:00	7.2
16:00	6.5981
17:00	5.4584
18:00	4.1334
19:00	2.9601
20:00	2.0255
21:00	1.3135
22:00	0.9
23:00	0.9038
00:00	1.5116

From Figure 4.4, it can be observed that the BESS is charged whenever the solar PV generates power from 8:00 AM until 15:00 PM. At this time, the EMS set the BESS to store the excess energy, and the diesel generator can be seen not outputting any power on the first day or outputting low power in the subsequent days. The stored energy eventually be used at 15:00 PM onwards when the solar PV stopped generating power. Hence, it can be observed the BESS start to discharge power along with the diesel generator to meet the demand.

Another moment the BESS was set to charge was after the midnight when the loads were decreasing. It can be noticed that the diesel generator is used to charge the BESS. On top of that, the power generated by the diesel generator was also used to supply the loads. The excessive usage of the diesel generator can subsequently lead to high diesel fuel consumption. Hence, it can result in high operation cost. Figures 4.3 and 4.4 show the diesel fuel consumption and diesel fuel cost for the diesel generator over the 72-hours period.

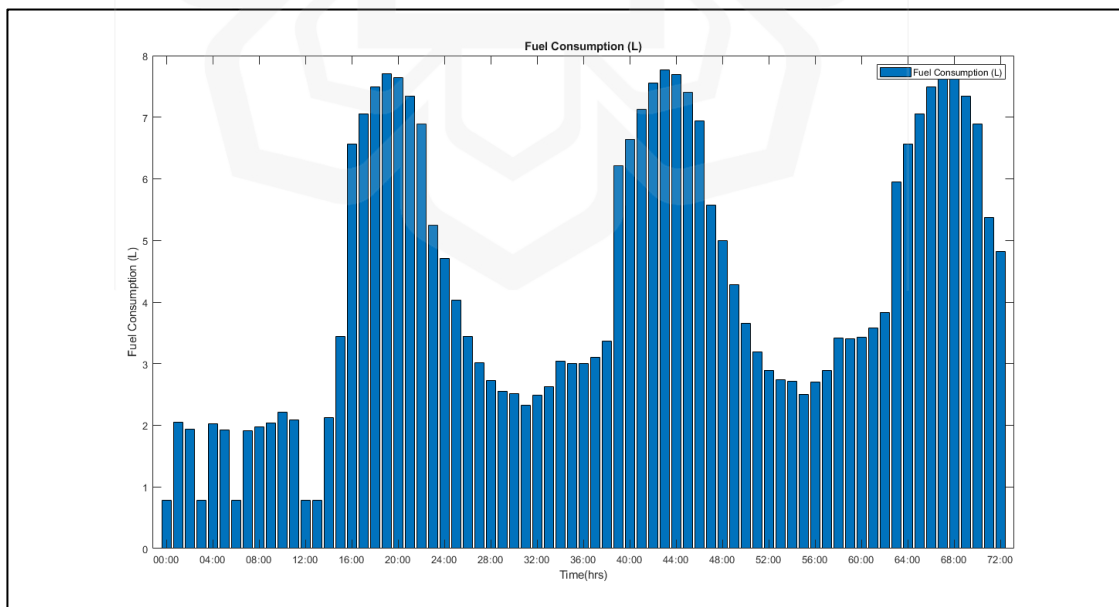


Figure 4.3 Diesel Fuel Consumption Pattern for MPC-Based EMS Without Load Curtailment for 72-Hours Period

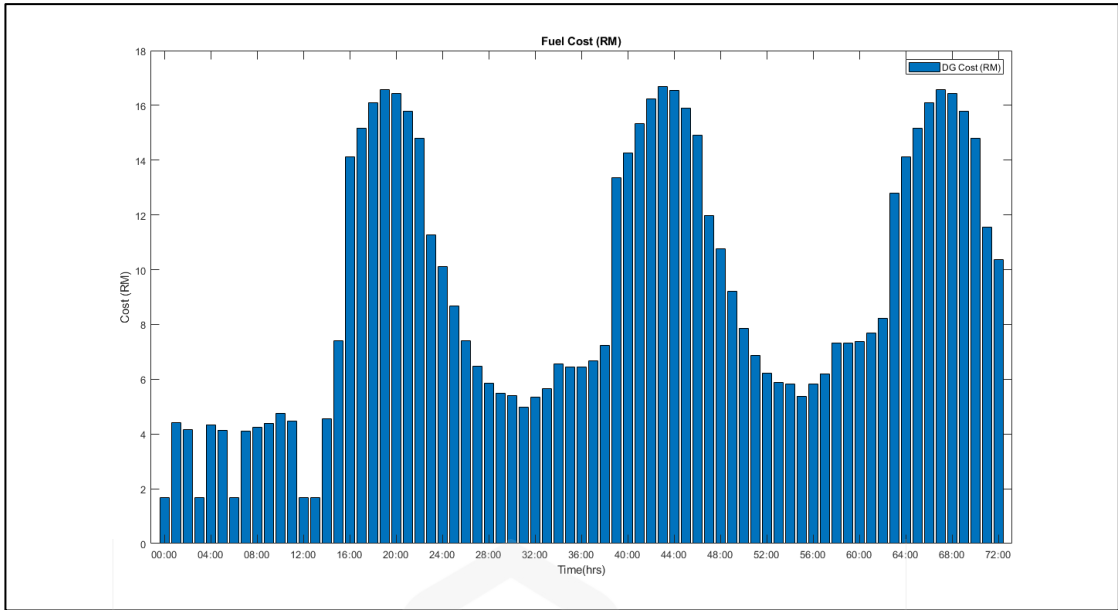


Figure 4.4 Diesel Fuel Cost Pattern MPC-Based EMS Without Load Curtailment for 72-Hours Period

From Figure 4.3, the fuel consumption was at peak from 16:00 PM until early morning of the next day. This continues over the next days. The high fuel consumption is attributed to the extensive use of diesel generator to supply demand. Table 4.3 listed the fuel consumption of the diesel generator and its cost for the 72-hours period.

Table 4.3 Diesel fuel consumption and diesel fuel cost for MPC-Based EMS without load curtailment

<b>Diesel Fuel Consumption</b>	309.50 Litres
<b>Diesel Fuel Cost</b>	RM 665.43

As can be observed in Table 4.3, the diesel generator used 309.50 litres of diesel fuel, which resulted in a total expenditure of RM665.43. Figures 4.5 until 4.8 shows the greenhouse gases emission cost for the duration of 72-hours. Table 4.4 listed the total greenhouse gases emission cost.

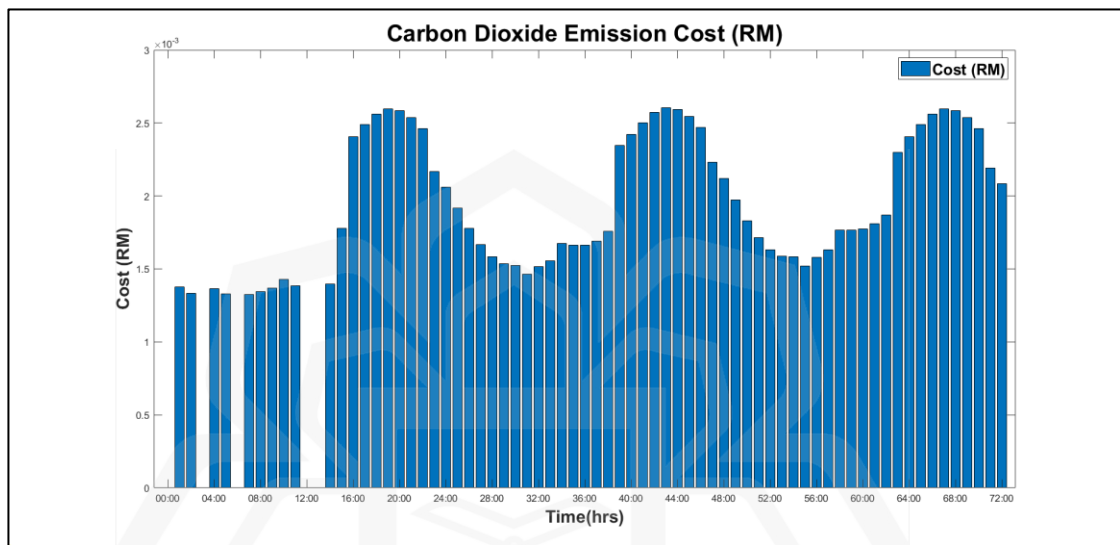


Figure 4.5 Carbon Dioxide Emission Cost Pattern for MPC-Based EMS Without Load Curtailment for 72-Hours Period

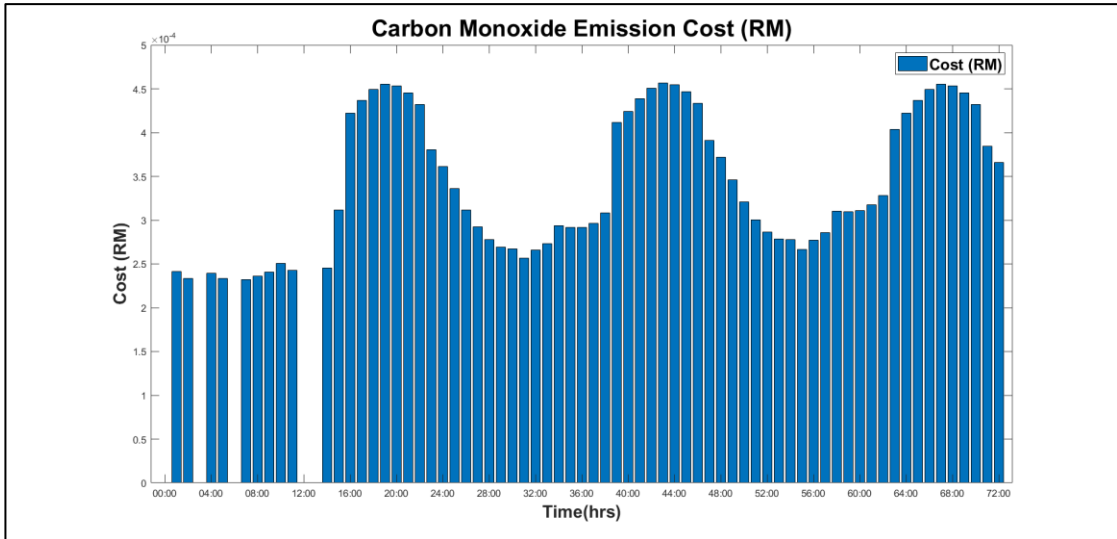


Figure 4.6 Carbon Monoxide Emission Cost Pattern for MPC-Based EMS Without Load Curtailment for 72-Hours Period

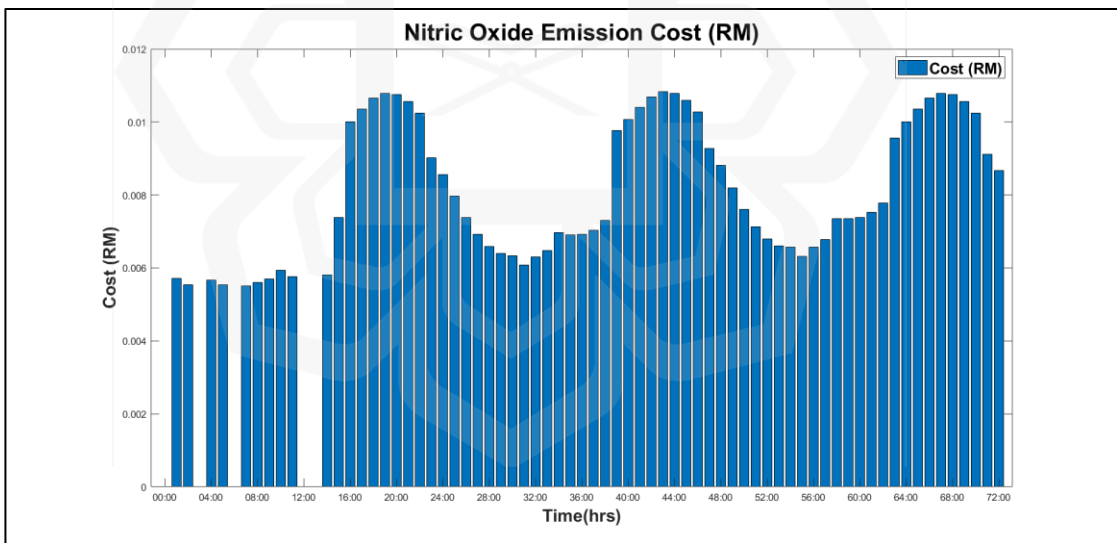


Figure 4.7 Nitric Oxide & Nitrogen Dioxide Emission Cost Pattern for MPC-Based EMS Without Load Curtailment for 72-Hours Period

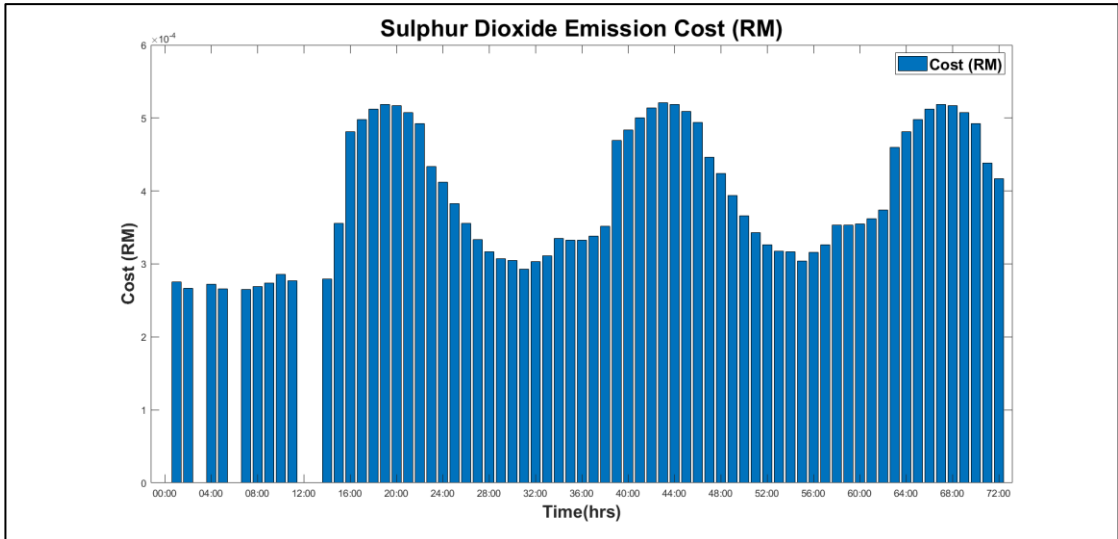


Figure 4.8 Sulphur Dioxide Emission Cost Pattern for MPC-Based EMS Without Load Curtailment for 72-Hours Period

Table 4.4 Greenhouse gas emission cost for MPC-Based EMS without load curtailment

Greenhouse Gas	Cost
Carbon Dioxide	RM 0.1329
Carbon Monoxide	RM 0.0233
Nitric Oxide & Nitrogen Dioxide	RM 0.5528
Sulphur Dioxide	RM 0.0266
<b>Total Emission Cost</b>	<b>RM 0.7356</b>

From Table 4.4, the emission cost for carbon dioxide, carbon monoxide, nitric oxide and nitrogen dioxide and sulphur dioxide are RM 0.1329, RM0.0233, RM0.5528 and RM0.0266 respectively. Hence, the total cost of the greenhouse gas emission is RM0.7356 by using the MPC-based EMS without the load curtailment.

### 4.3 CASE 1: IMPACT OF LOAD CURTAILMENT

The simulation is done for the proposed MPC-based EMS in MATLAB. Figure 4.9 shows the energy profile for all components including the solar PV generations, loads and the net loads for the 72-hours period with 1-hour interval. Net loads are the loads after the load curtailment. In addition, Table 4.5 listed the power set point for every component including solar PV generations, loads and net loads for the first day with 1-hour interval.

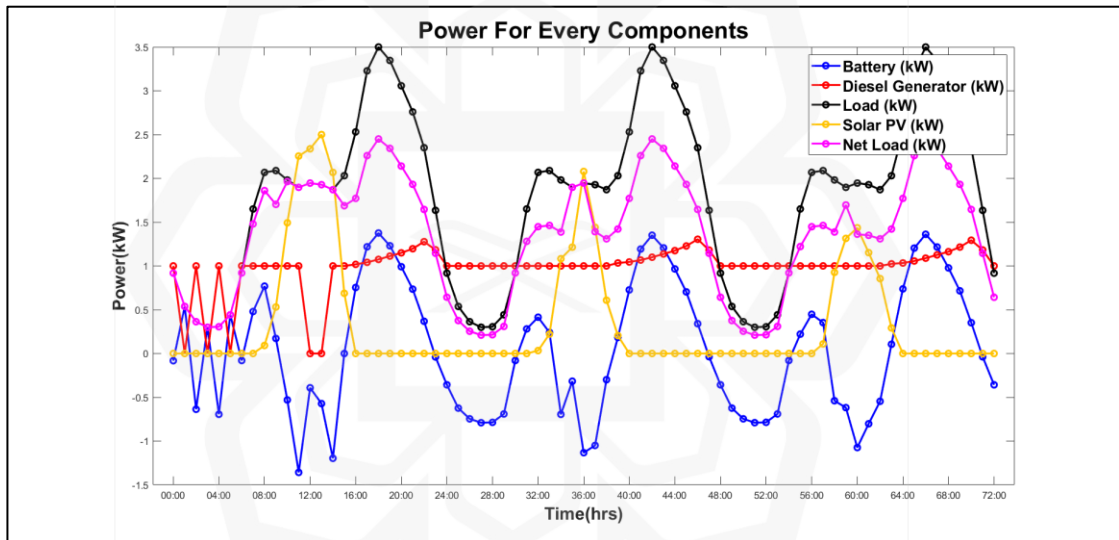


Figure 4.9 Energy Profile for All Components for MPC-Based EMS With Load Curtailment

Table 4.5 Power Set-Point for Every Component of First Day for MPC-Based EMS With Load Curtailment

<b>Time (h)</b>	<b><math>P_{PV}</math> (kW)</b>	<b><math>P_{DG}</math> (kW)</b>	<b><math>P_{BESS}</math> (kW)</b>	<b><math>P_{Loads}</math> (kW)</b>	<b><math>P_{CURTAIL}</math> (kW)</b>
00:00	0	1	-0.0824	0.9176	0
1:00	0	0	0.5375	0.5375	0
2:00	0	1	-0.6369	0.3631	0
3:00	0	0	0.3	0.3	0
4:00	0	1	-0.6943	0.3057	0
5:00	0	0	0.4422	0.4422	0
6:00	0	1	-0.0798	0.9202	0
7:00	0	1	0.4793	1.6505	0.1712
8:00	0.0916	1	0.7689	2.0681	0.2076
9:00	0.5307	1	0.1722	2.0888	0.3859
10:00	1.4934	1	-0.5302	1.9818	0.0186
11:00	2.2552	1	-1.3576	1.8976	0
12:00	2.3377	0	-0.3919	1.9458	0
13:00	2.5	0	-0.5723	1.9277	0
14:00	2.0676	1	-1.1968	1.8708	0
15:00	0.6872	1	0	2.0305	0.3433
16:00	0	1.0180	0.7535	2.5307	0.7592
17:00	0	1.0411	1.2186	3.2281	0.9684
18:00	0	1.0743	1.3757	3.5	1.05
19:00	0	1.1123	1.2302	3.3464	1.0039
20:00	0	1.1494	0.9909	3.0575	0.9172
21:00	0	1.1965	0.7348	2.7590	0.8277
22:00	0	1.2772	0.3678	2.35	0.7050
23:00	0	1.1841	-0.0397	1.6348	0.4904
00:00	0	1	-0.3577	0.9176	0.2753

From Table 4.5, it is observed that the proposed MPC-based EMS able to the manage the energy in the islanded microgrid. The constraints for all the components especially BES and diesel generator are respected. The BESS charging and discharging power is respected by not reaching maximum 3 kW during discharging and -3kW during charging time. The power generated by the diesel generator also not exceeded the set limit which was 5 kW. Most importantly, the power balance is always met. This is reflected in the Table 4.5.

The load curtailment is observed to remain within the specified limit of no more than 30% of the original load. The load curtailment decision and its value are determined by the solving of the optimisation problem defined in the MPC-based EMS in Chapter 3. Without defining the penalty cost for load curtailment, it can be observed that the curtailment decision by the MPC-based EMS does not occur all the time. Most of the curtailment occurs during the high demands and low PV generations which is during the night. Figure 4.10 and Table 4.6 shows the SoC of the BESS for the 72-hours period. From Table 4.6, the SoC of the BESS also stayed within the set boundary to protect it from the deep charging and discharging.

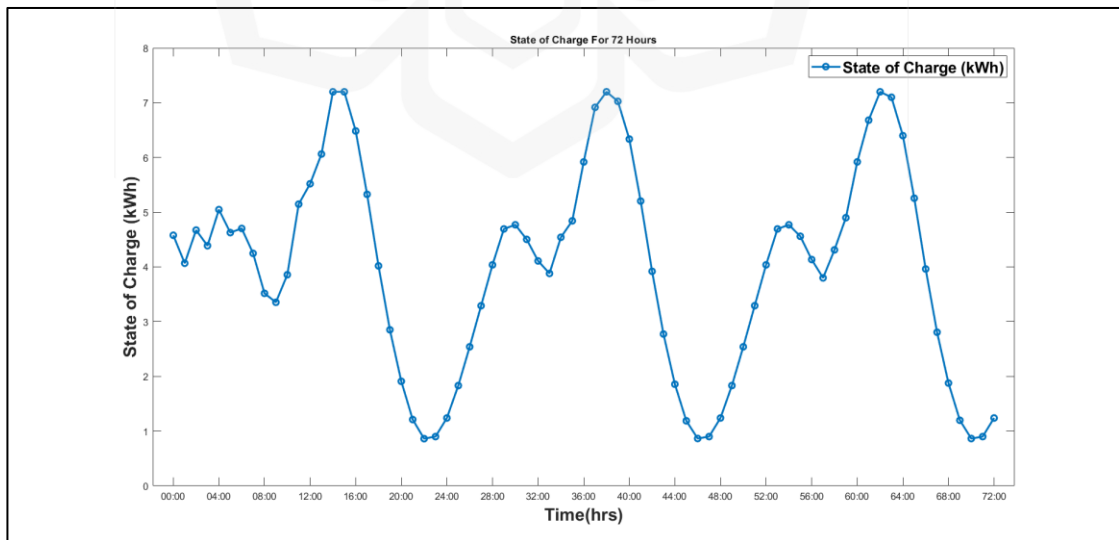


Figure 4.10 SoC of the BESS for MPC-Based EMS With Load Curtailment

Table 4.6 SoC of the BESS for MPC-Based EMS With Load Curtailment for 24-Hours Period

<b>Time (h)</b>	<b><math>SoC_{BESS}</math> (kWh)</b>
00:00	4.5783
1:00	4.0676
2:00	4.6727
3:00	4.3877
4:00	5.0473
5:00	4.6272
6:00	4.7031
7:00	4.2477
8:00	3.5173
9:00	3.537
10:00	3.8574
11:00	5.1471
12:00	5.5194
13:00	6.0630
14:00	7.2
15:00	7.2
16:00	6.4842
17:00	5.3266
18:00	4.0197
19:00	2.8510
20:00	1.9097
21:00	1.2116
22:00	0.8623
23:00	0.9
00:00	1.2398

From Figure 4.9 and Table 4.5, it is observed that the load curtailment was applied by the MPC-based EMS. In Figure 4.9, the load curtailment is observed from the morning until noon and from the evening until the night. As expected, the load curtailment is not exceeding the 30% of the original loads. While the EMS was able to curtail all the loads to 30% of the original loads, it is evident that this was not the case. For an example, the loads curtailed by the EMS during 6:00 AM, 7:00 AM and 8:00 AM were just around 10% to 20% of the original loads. This may be due to the solar PV was generated power; hence, extra energy is available to supply to the demand.

However, this was not true during the evening until night where there was little to no sunlight and solar PV unable to generate power. In Table 4.5, it is noted that from 15:00 PM until 00:00 AM, the loads curtailment is mostly around 30% of the original loads. It is also observed that BESS was discharging to aid in supplying the load alongside the diesel generator. It can be highlighted that from Figure 4.9, the diesel generator pattern is almost in straight line most the time during the 72-hours period. This indicates that the load curtailment able to reduce the supply and demand gap between the solar PV, diesel generator, BESS, and loads. Figure 4.11 until 4.12 shows the fuel consumption and fuel cost graph for the diesel generator over the 72-hours period.

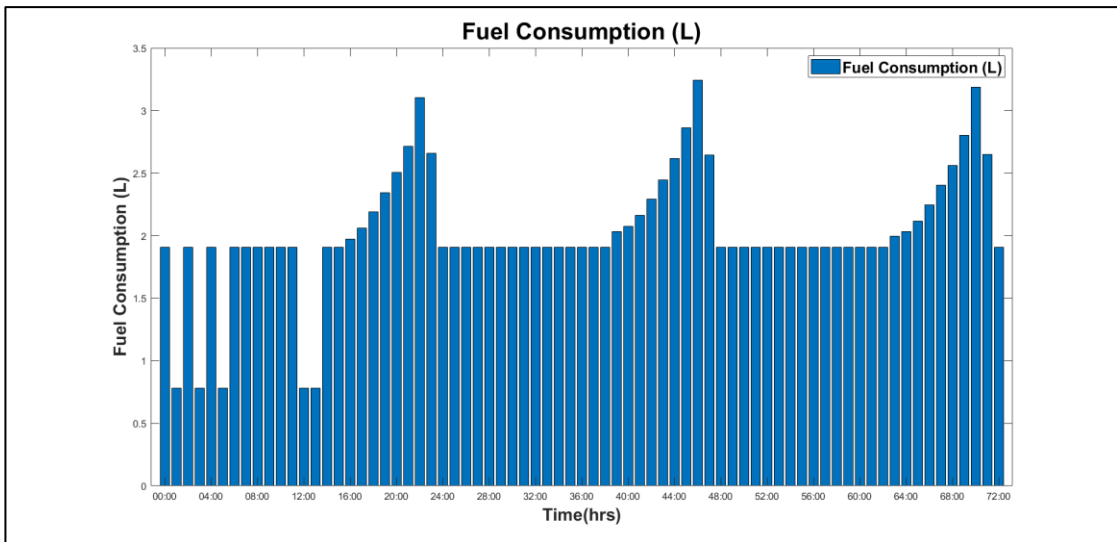


Figure 4.11 Diesel Fuel Consumption Pattern for MPC-Based EMS With Load Curtailment for 72-Hours Period

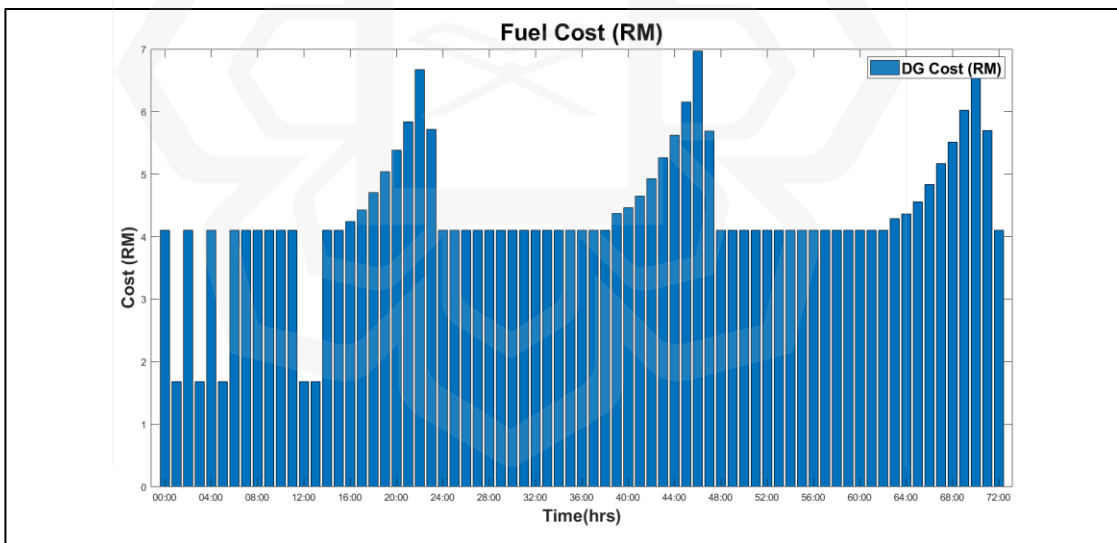


Figure 4.12 Diesel Fuel Cost Pattern for MPC-Based EMS With Load Curtailment for 72-Hours Period

From Figure 4.11, it can be noticed that the fuel consumption for the diesel generator shows a peak between 16:00 PM and 11:00 PM. This is predictable since the loads is at its peak during these hours with the fuel consumption generally constant around 1.9 Litre in other hours. Eventually, the price of the fuel in Figure 4.12 also reflecting the same pattern as in fuel consumption in Figure 4.11. Table 4.7 shows the fuel consumption and fuel cost of the diesel generator over the 72-hours period.

Table 4.7 Diesel Fuel Consumption and Diesel Fuel Cost for MPC-Based EMS With Load Curtailment

<b>Diesel Fuel Consumption</b>	147.88 Litres
<b>Diesel Fuel Cost</b>	RM 317.95

From Table 4.7, the diesel generator consumed 147.88 Litre of diesel fuel which costed RM 317.95 over the 72-hours period. Figure 4.13 until 4.16 shows the greenhouse gas emission cost for over 72-hours period. Table 4.8 summarised the carbon dioxide emission cost, carbon monoxide emission cost, nitric oxide emission cost and the total emission cost.

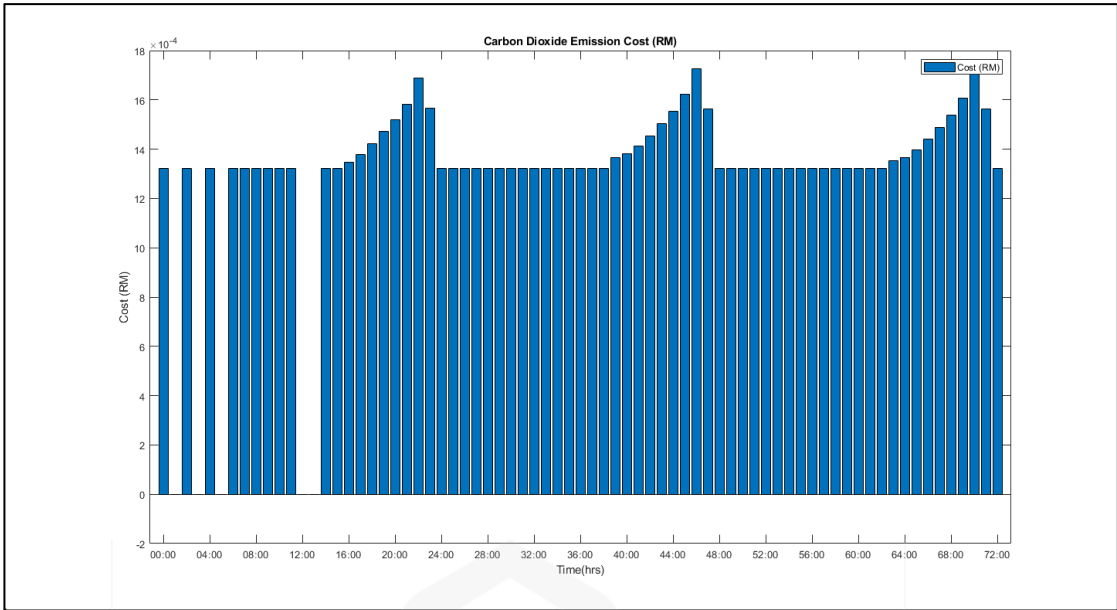


Figure 4.13 Carbon Dioxide Emission Cost Pattern for MPC-Based EMS With Load Curtailment for 72-Hours Period

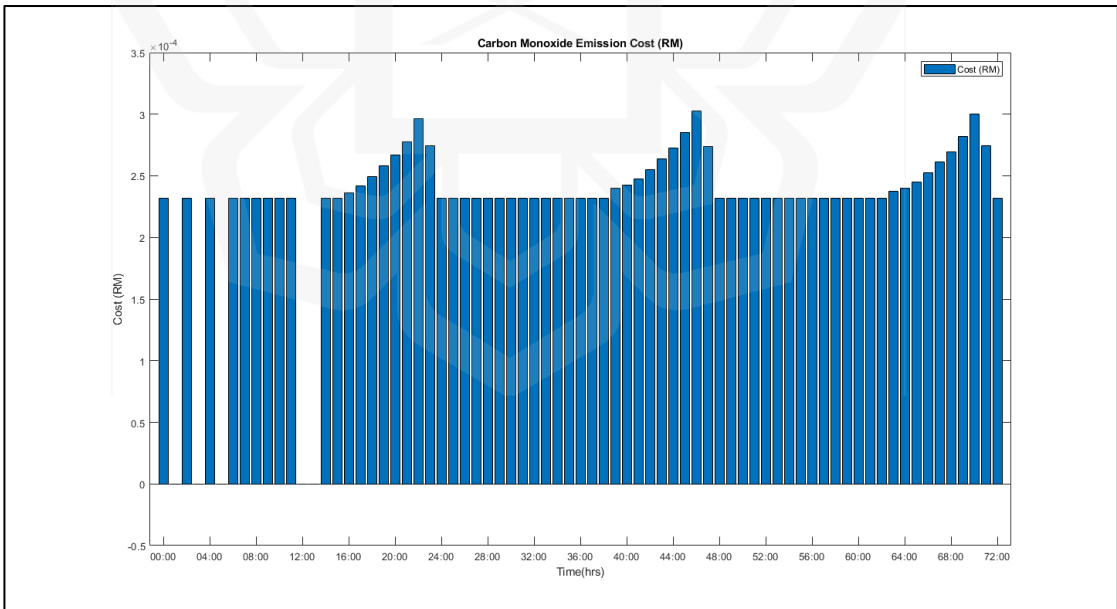


Figure 4.14 Carbon Monoxide Emission Cost Pattern for MPC-Based EMS With Load Curtailment for 72-Hours Period

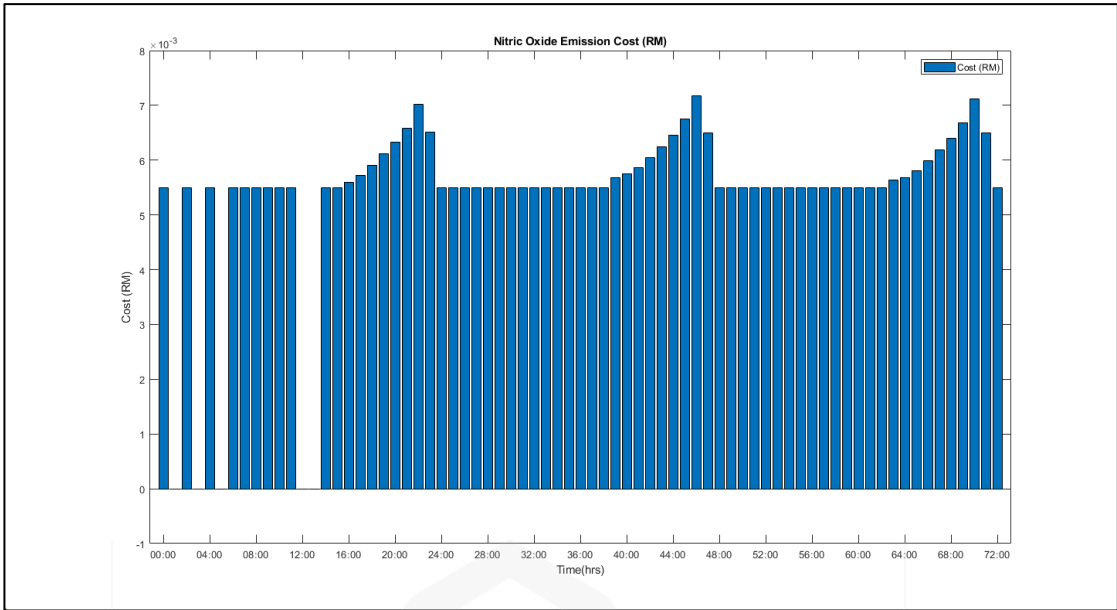


Figure 4.15 Nitric Oxide & Nitrogen Dioxide Emission Cost Pattern for MPC-Based EMS With Load Curtailment for 72-Hours Period

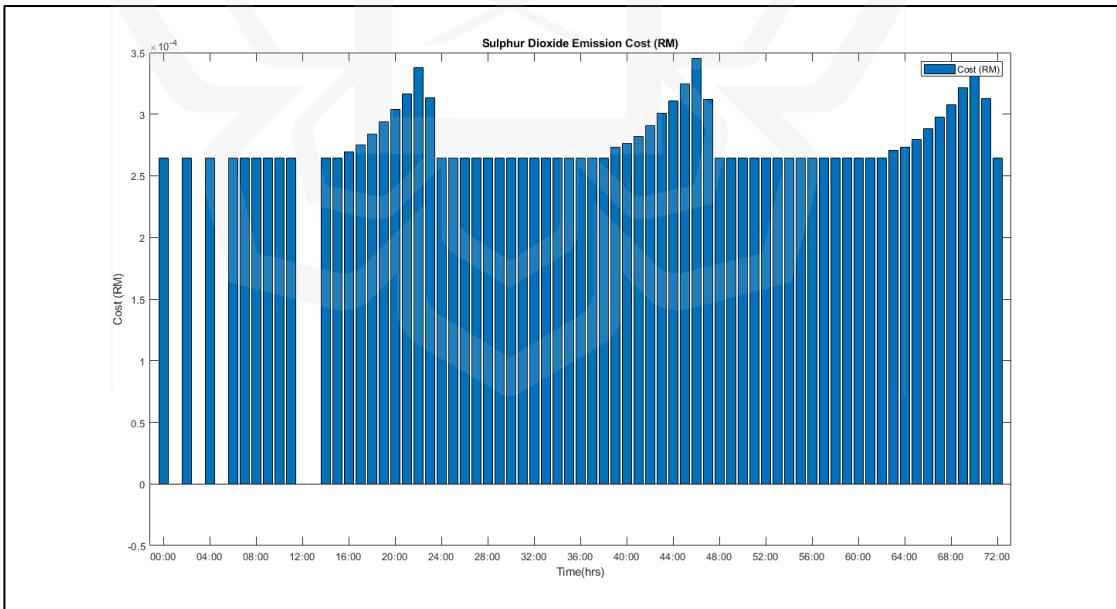


Figure 4.16 Sulphur Dioxide Emission Cost Pattern for MPC-Based EMS With Load Curtailment for 72-Hours Period

Table 4.8 Greenhouse Gas Emission Cost for MPC-Based EMS With Load Curtailment

<b>Greenhouse Gas</b>	<b>Cost</b>
Carbon Dioxide	RM 0.0946
Carbon Monoxide	RM 0.0166
Nitric Oxide & Nitrogen Dioxide	RM 0.3933
Sulphur Dioxide	RM 0.0189
<b>Total Emission Cost</b>	<b>RM 0.5234</b>

Table 4.8 shows that the emission cost for carbon dioxide, carbon monoxide, nitric oxide and sulphur dioxide are RM 0.0946, RM 0.0166, RM 0.3933, and RM 0.0189 respectively. Hence, the total greenhouse gas emission cost is RM 0.5234 for a 72-hours period.

Previously, the results of both MPC-based without load curtailment and load curtailment scenarios are discussed. It is suggested that MPC-based EMS in both cases showed the capabilities in managing the components inside the islanded microgrid. From Table 4.1 and Table 4.5, the MPC-based EMS able to ensure the power balance in the microgrid. As mentioned, the power balance is important in the microgrid as it protects the microgrid from instability. In AC microgrid, power imbalance can lead to voltage and frequency fluctuations.

In addition, it is observed that the MPC-based EMS also able to ensure all components in the microgrid to operate within the defined constraints. For BESS, the MPC-based EMS ensure that the BESS charging and discharging are not exceeding 3 kW. In addition, the SoC of the BESS was also controlled to be no less than 10% and exceed 80% of the capacity of the battery. This was reflected in Table 4.2 and Table 4.6. The SoC of the BESS was set to track the reference SoC. However, the assignment of

weight of the fuel consumption cost function and greenhouse gas cost function was relatively higher than the SoC tracking cost function. Hence, the focus of the MPC-based EMS is more on the reduction of the fuel consumption and the greenhouse gas emission.

The diesel generator in both cases also operated within the specified boundaries which is between 0-5 kW. The diesel generator usage is low and constant in the case of MPC-based EMS with the load curtailment compared to the MPC-based EMS without the load curtailment. In the latter, diesel generator is used excessively to meet the demand which was high especially during the evening until the night. With the load curtailment, the gap between the generation and the demand can be modified and brought closer. This can result in lower fuel consumption, hence, improving the cost saving of the islanded microgrid. Table 4.9 shows the comparison of fuel consumption and fuel cost of both scenarios. Figure 4.17 and 4.18 shows the comparison of the diesel fuel consumption and diesel fuel cost comparison between MPC-based EMS without load curtailment and MPC-based EMS with load curtailment.

Table 4.9 Comparison of Fuel Consumption and Fuel Cost of Both Scenarios

	<b>MPC-based EMS Without Load Curtailment</b>	<b>MPC-based EMS With Load Curtailment</b>
<b>Diesel Fuel Consumption</b>	309.50 Litres	147.88 Litres
<b>Diesel Fuel Cost</b>	RM 665.43	RM 317.95

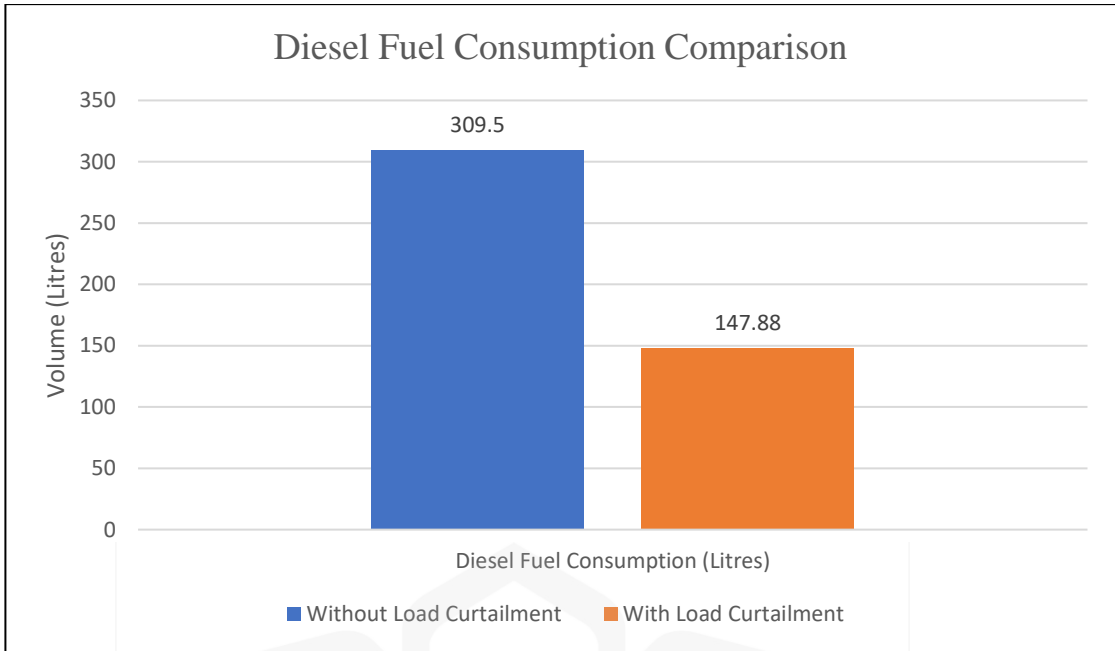


Figure 4.17 Diesel Fuel Consumption Comparison Between MPC-Based EMS Without Load Curtailment and With Load Curtailment

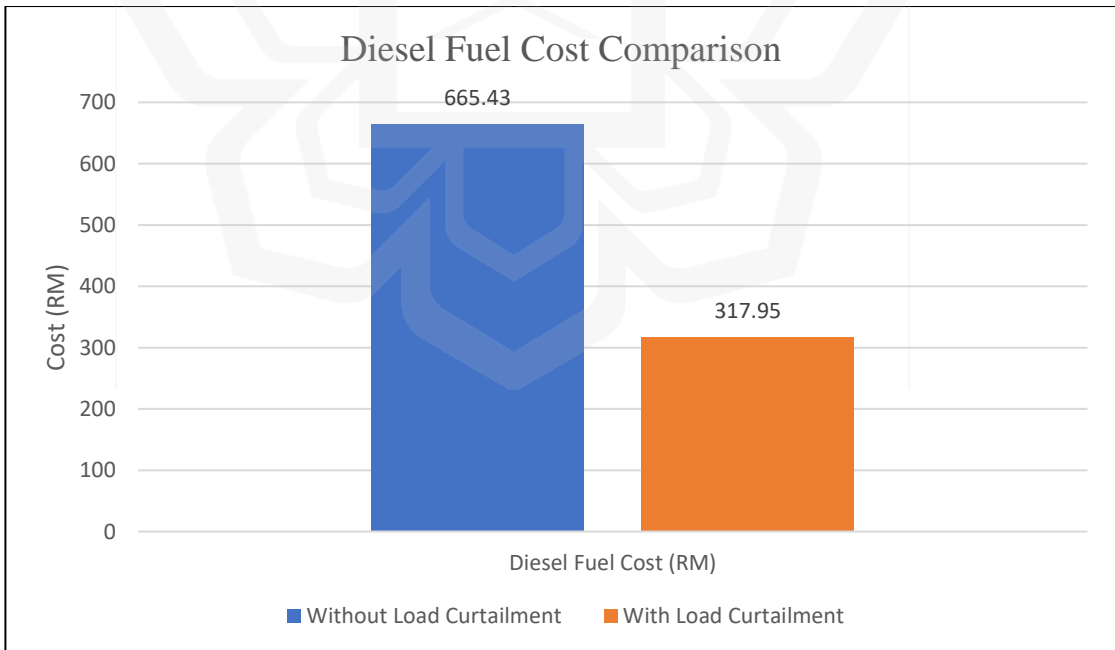


Figure 4.18 Diesel Fuel Cost Comparison Between MPC-Based EMS Without Load Curtailment and With Load Curtailment

Based on Figure 4.17 and 4.18, the diesel fuel consumption reduced from 309.50 Litres to 147.88 Litres when load curtailment is utilized. The reduced diesel fuel consumption also leads to the reduced diesel fuel cost. The diesel fuel cost reduced from RM 665.43 to RM 317.95 by utilising the load curtailment in islanded microgrid. The comparison shows that an improvement of 52.21% is achieved by utilising load curtailment in the MPC-based EMS.

Hence, it can be concluded that the proposed MPC-based EMS with load curtailment capabilities is able to save cost of the diesel generator operation in islanded microgrid. The significant cost saving of 52.21% reduction compared to the MPC-based EMS without the load curtailment can create an opportunity for a further cost optimisation in the islanded microgrid. Besides that, the MPC-based EMS also able to manage efficiently the components in the islanded microgrid. The MPC-based EMS ensures that the power balance is met while respecting the limitations that have been defined.

#### **4.4 CASE 2: IMPACT OF THE WEIGHT OF THE COST FUNCTIONS ON THE COST SAVING AND GREENHOUSE GAS EMISSION**

##### **4.4.1 Scenario 1**

For the first scenario, the weight is set 2.05, 1 and 6.8. The weight distribution is chosen to ensure the final value – calculated as the fixed cost multiplied by the fixed cost - remains same across all the cost functions. Figures 4.19 and 4.20 shows the energy profile for all the components and the SoC of the BESS for the 72 hours period.

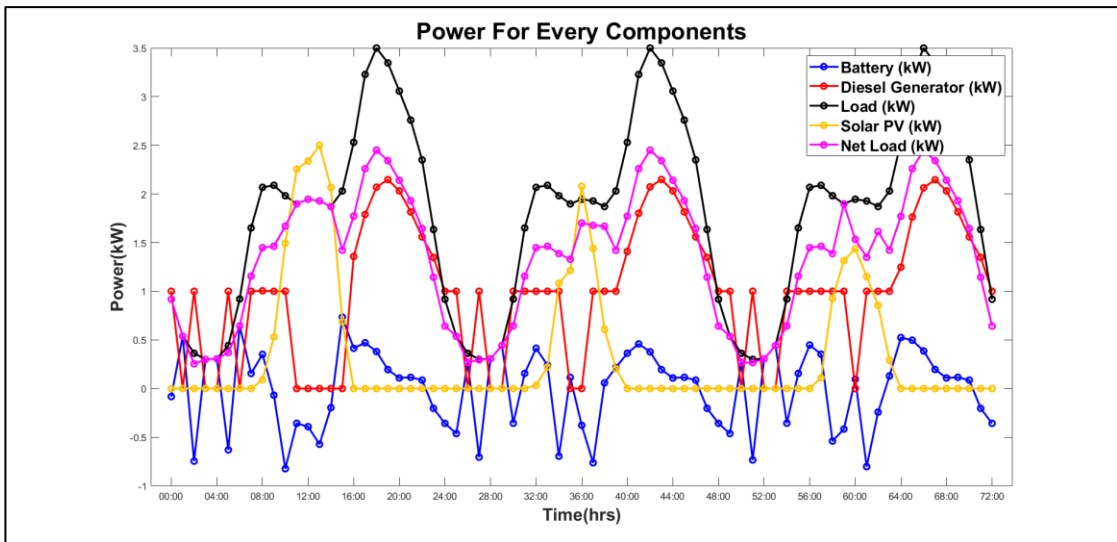


Figure 4.19 Energy Profile for All Components for MPC-Based EMS of Scenario 1

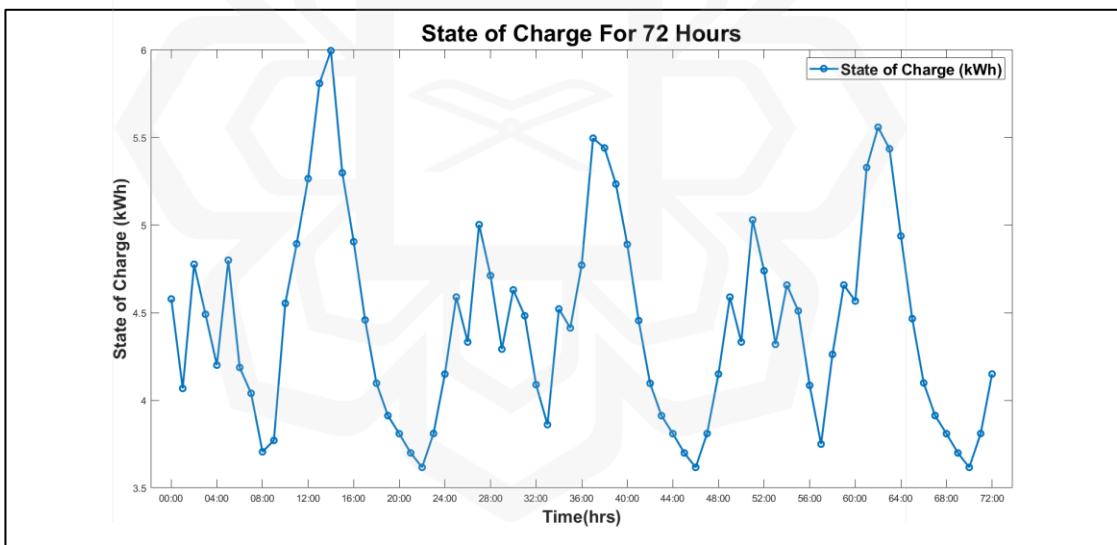


Figure 4.20 SoC of the BESS for MPC-Based EMS of Scenario 1

From Figure 4.19, the power set-point of each components represent equal final value - calculated as the fixed cost multiplied by the fixed cost - across all cost functions. The diesel generator produces more than 1 kW when the load is high, particularly in the evening and night. Otherwise, the diesel generator will produce either 1 kW of power

or no power. The diesel generator's low power output over a 72-hours period is owing to the deployment of load curtailment, which was previously discussed.

The diesel generator meets most of the demand, with the BESS providing support on occasion, particularly from the evening till the night. The BESS is charged mostly in the morning by the diesel engine and anytime the solar PV provides power to be delivered to the loads. This is demonstrated by the SoC pattern of the BESS in Figure 4.20. Figures 4.21 and 4.22 shows the diesel fuel consumption and diesel fuel cost under scenario 1. Table 4.10 shows the total diesel fuel consumption and cost for scenario 1.

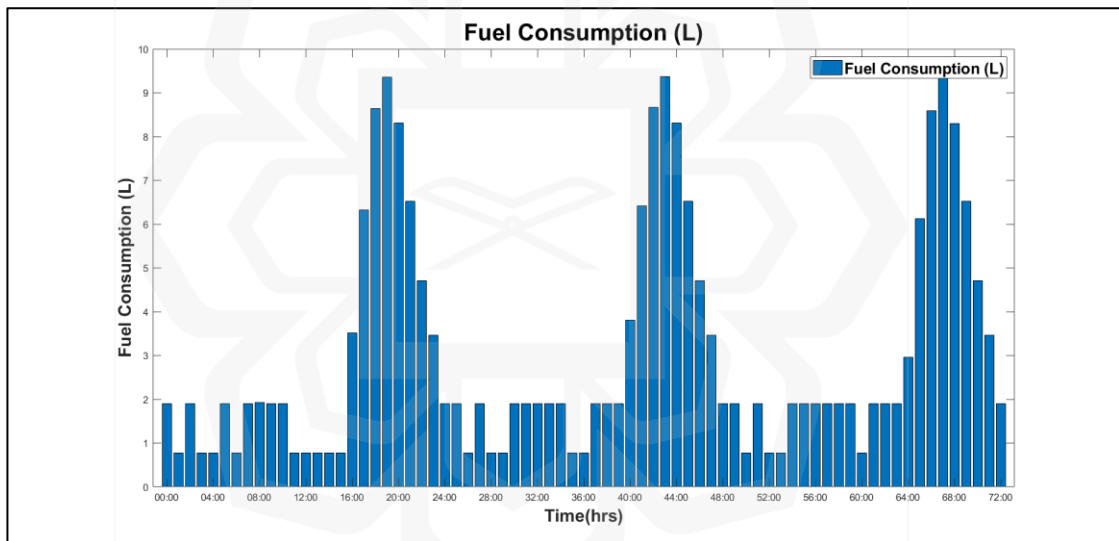


Figure 4.21 Diesel Fuel Consumption Pattern for MPC-Based EMS of Scenario 1

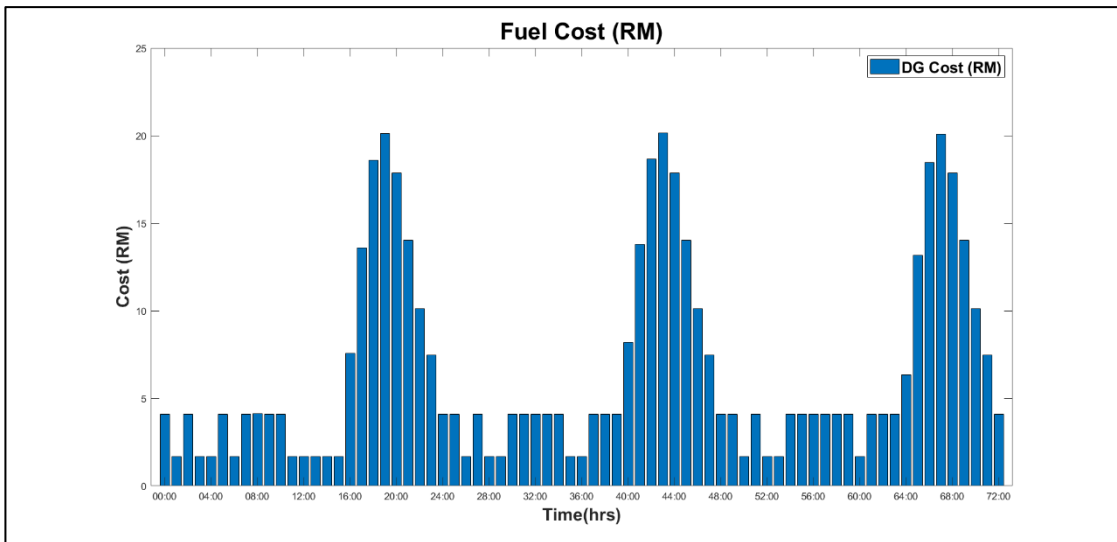


Figure 2.22 Diesel Fuel Cost Pattern for MPC-Based EMS of Scenario 1

Table 4.10 Diesel Fuel Consumption and Diesel Fuel Cost of Scenario 1

<b>Diesel Fuel Consumption</b>	225.34 Litres
<b>Diesel Fuel Cost</b>	RM 484.75

From Table 4.10, the diesel consumption for 72-hours period in scenario 1 is 225.34 litres which costed RM 484.75. Figures 4.23 until 4.26, shows the carbon dioxide emission cost, carbon monoxide emission cost, nitric oxide & nitrogen dioxide emission cost and sulphur dioxide emission cost respectively. Table 4.11 summarised each greenhouse gas emission cost and total emission cost.

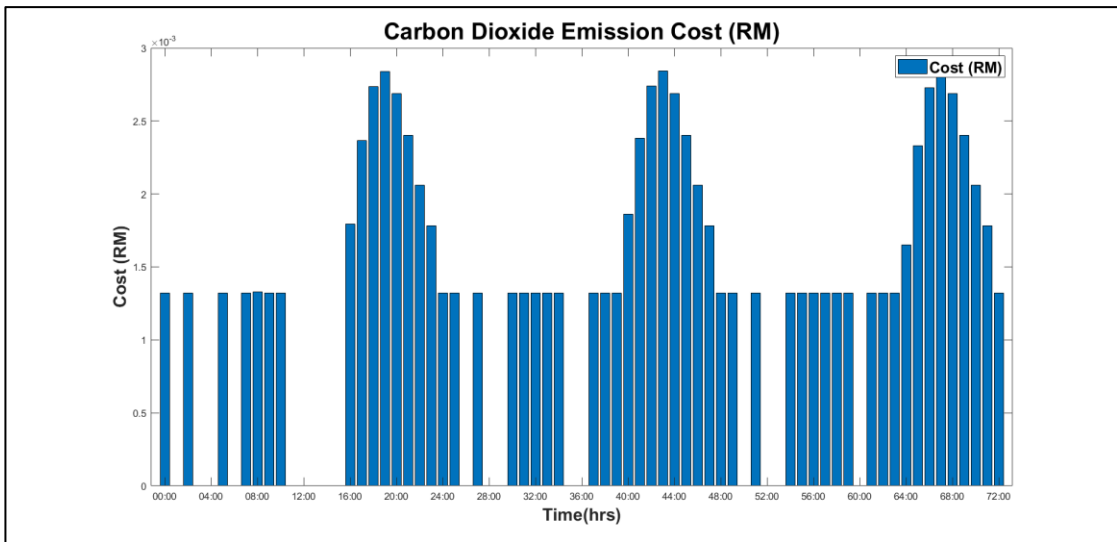


Figure 4.23 Carbon Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario

1

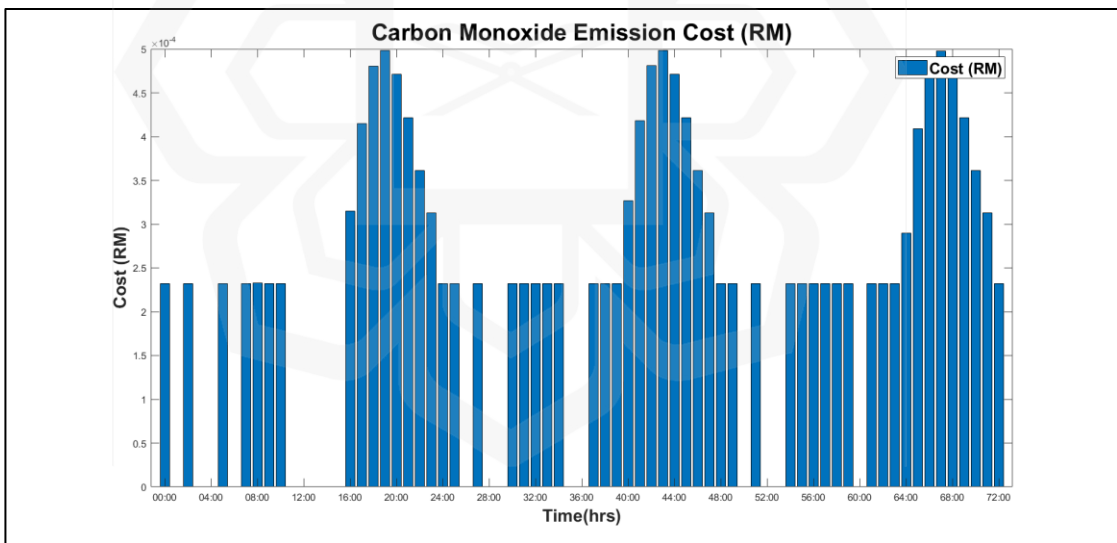


Figure 4.24 Carbon Monoxide Emission Cost Pattern For MPC-Based EMS of

Scenario 1

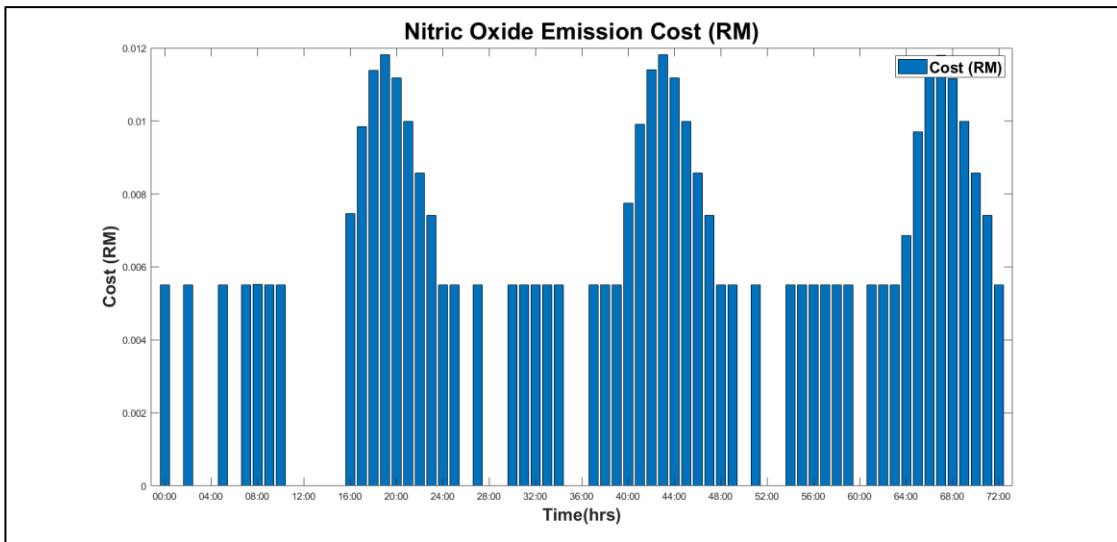


Figure 4.25 Nitric Oxide & Nitrogen Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario 1

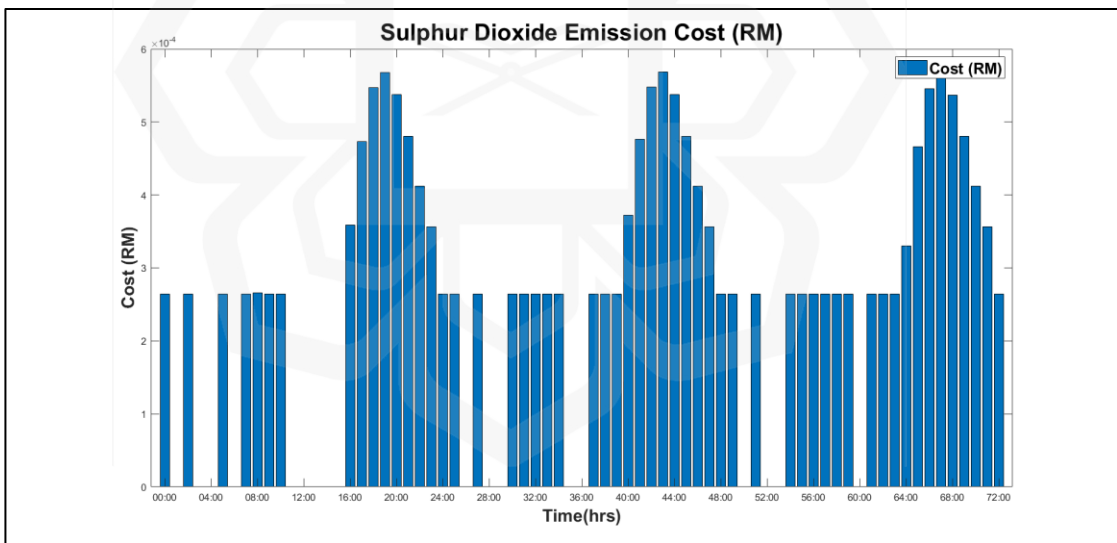


Figure 4.26 Sulphur Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario 1

Table 4.11 Greenhouse Gas Emission Cost for MPC-based EMS of Scenario 1

<b>Greenhouse Gas</b>	<b>Cost</b>
Carbon Dioxide	RM 0.0969
Carbon Monoxide	RM 0.0170
Nitric Oxide & Nitrogen Dioxide	RM 0.4031
Sulphur Dioxide	RM 0.0194
<b>Total Emission Cost</b>	<b>RM 0.5364</b>

From Table 4.11, the total greenhouse emission cost is RM 0.5364 for 72-hours period. The cost of the carbon dioxide emission, carbon monoxide emission, nitric oxide & nitrogen dioxide emission and sulphur dioxide emission are RM 0.0969, RM 0.0170, RM 0.4031, and RM 0.0194 respectively.

#### 4.4.2 Scenario 2

In the second scenario, the weight is assigned more on the diesel generator cost function while the greenhouse gas emission cost function is set to zero. The cost function of the BESS remains constant. By setting the weight of diesel generator cost function higher than the greenhouse gas emission cost function, it is expected that the diesel generator usage will become low. Hence, reducing the fuel consumption and consequently, the diesel fuel cost. Figures 4.27 and 4.28 shows the energy profile for all the components and SoC of the BESS for the 72-hours period.

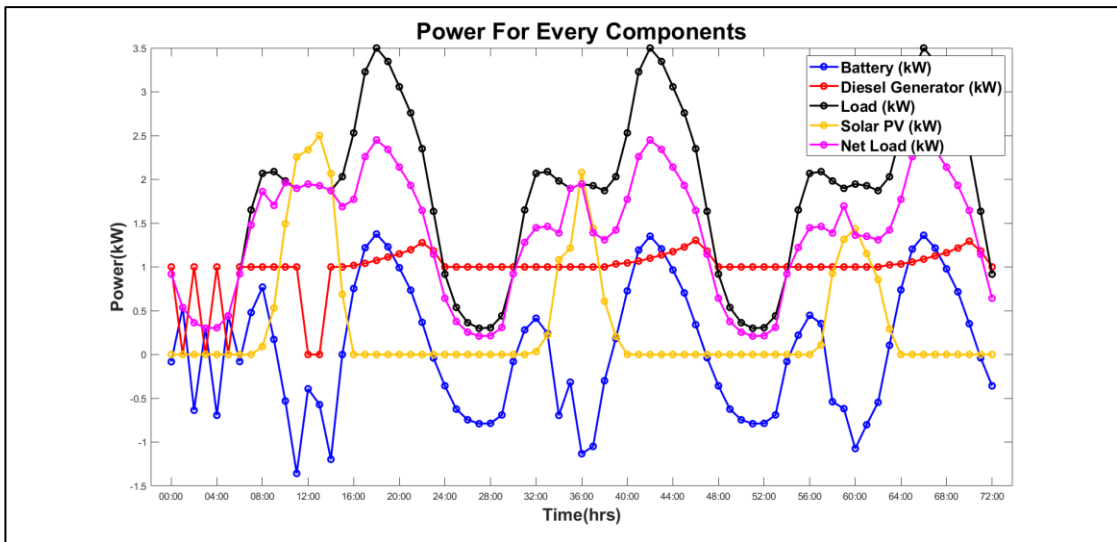


Figure 4.27 Energy Profile for All Components for MPC-Based EMS of Scenario 2

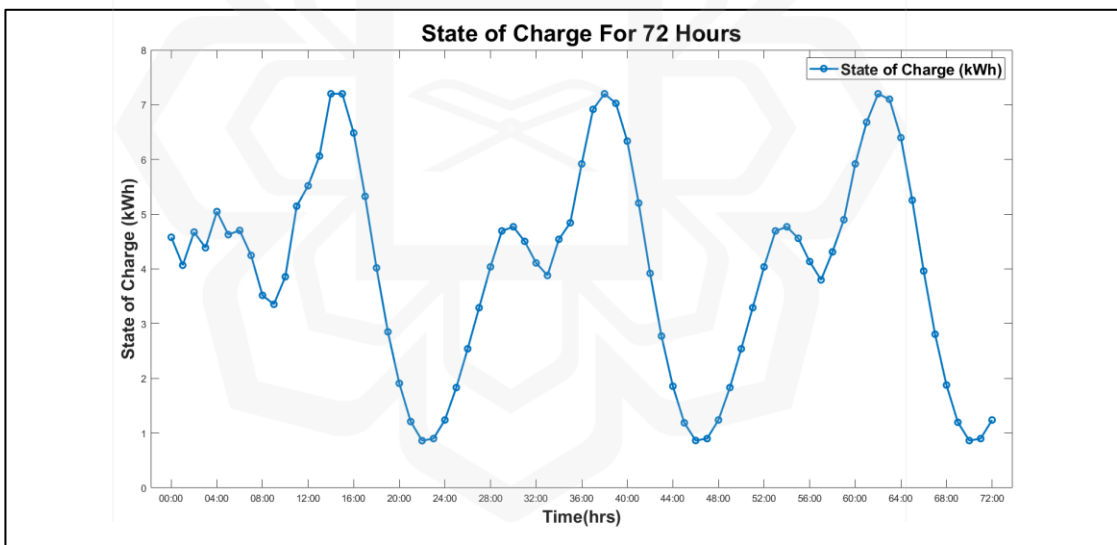


Figure 4.28 SoC of the BESS for MPC-Based EMS of Scenario 2

From 4.27 shows the power set-point of each components by setting the weight more on the diesel generator cost function and less focus on the BESS cost function. The weight of the greenhouse gas emission cost is set to zero to remove the influence of it in determining the optimal power set-point of each components in the islanded

microgrid. It can be observed that the diesel generator power set-point pattern is almost constant at 1 kW during the 72-hours duration. This is due to the BESS and load curtailment ensures the power balance and the demand are met.

The BESS is charged whenever the solar PV generates power. In Figure 4.28, the SoC of the BESS climbed until the solar PV generation was nil before it began to discharge to assist the diesel generator in meeting the demand. Since, the weight is more on the diesel generator cost function, which is a fuel consumption function, the BESS is utilised as much as it can by the MPC-based EMS to minimise the usage of the diesel generator. Figures 4.29 and 4.30 shows the diesel fuel consumption and diesel fuel cost under scenario 2. Table 4.12 shows the diesel fuel consumption and cost for scenario 2.

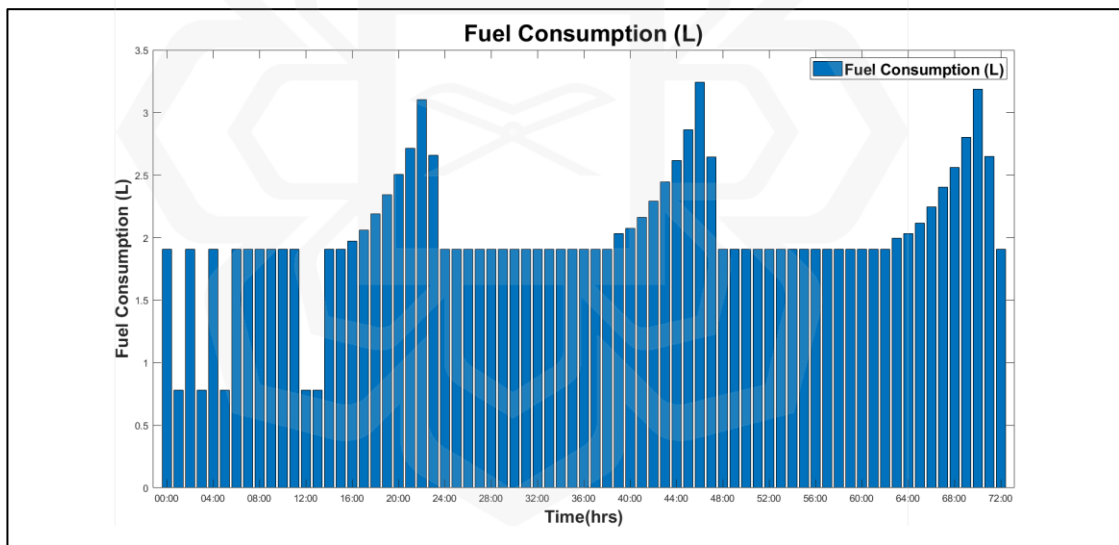


Figure 4.29 Diesel Fuel Consumption Pattern for MPC-Based EMS of Scenario 2

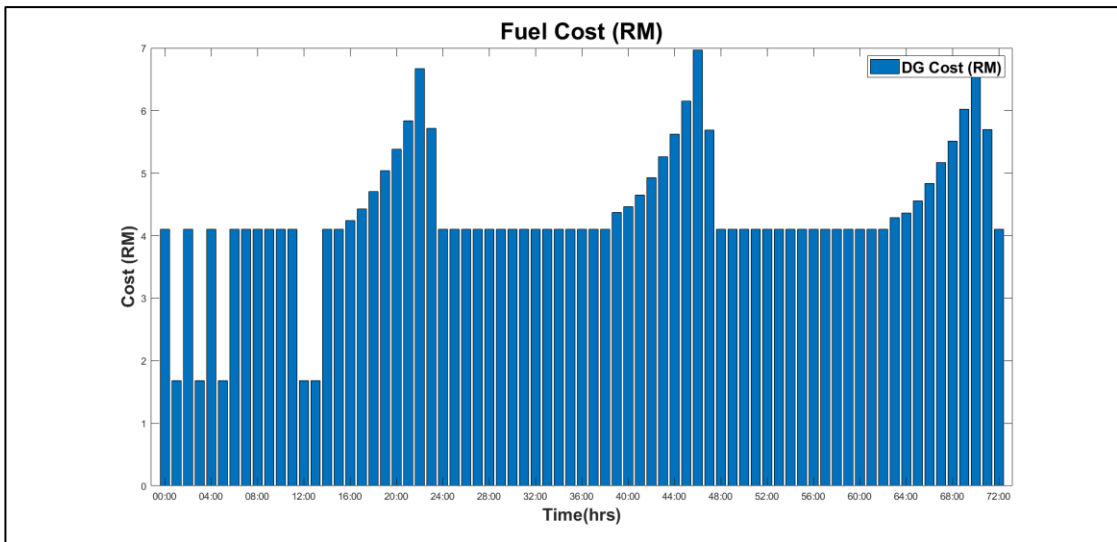


Figure 4.32 Diesel Fuel Cost Pattern for MPC-Based EMS of Scenario 2

Table 4.12 Diesel Fuel Consumption and Diesel Fuel Cost for MPC-Based EMS of Scenario 2

<b>Diesel Fuel Consumption</b>	147.88 Litres
<b>Diesel Fuel Cost</b>	RM 317.95

From Table 4.12, the diesel consumption for 72-hours period in scenario 2 is 147.88 litres which costed RM 317.95. Figures 4.31 until 4.34, shows the carbon dioxide emission cost, carbon monoxide emission cost, nitric oxide & nitrogen dioxide emission cost and sulphur dioxide emission cost respectively. Table 4.13 summarised each greenhouse gas emission cost and total emission cost.

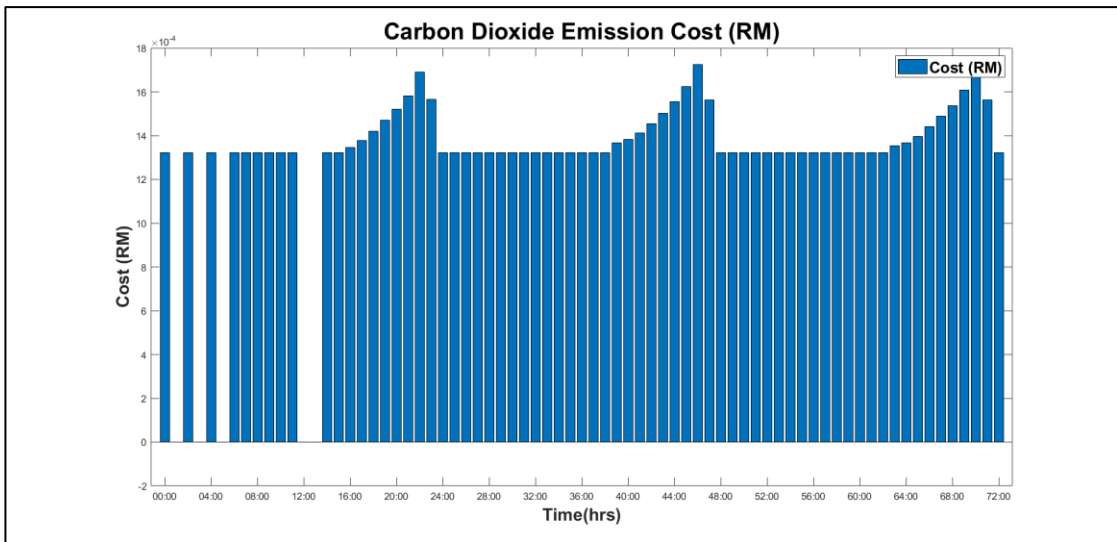


Figure 4.31 Carbon Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario

2

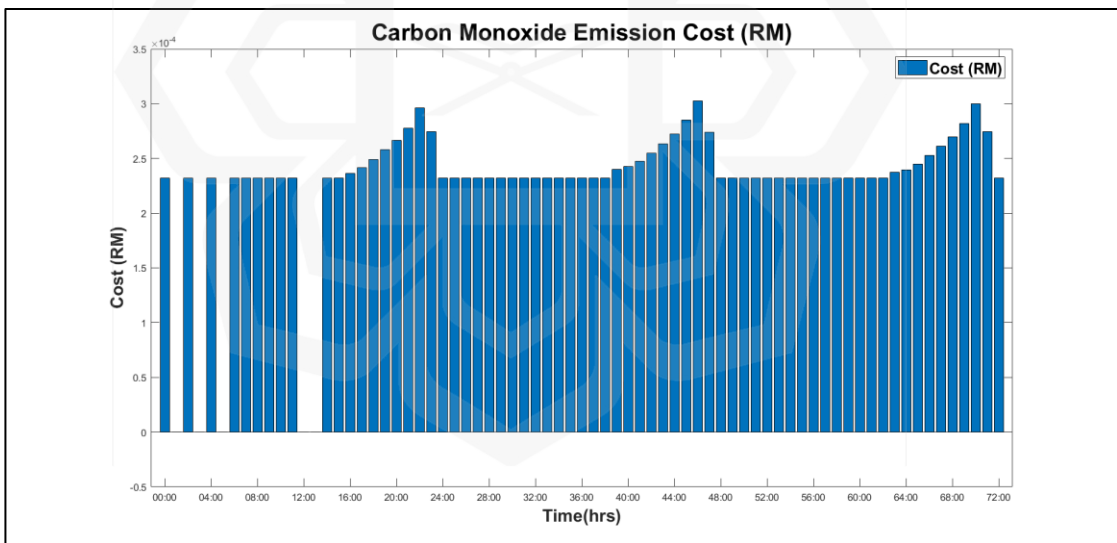


Figure 4.32 Carbon Monoxide Emission Cost Pattern for MPC-Based EMS of

Scenario 2

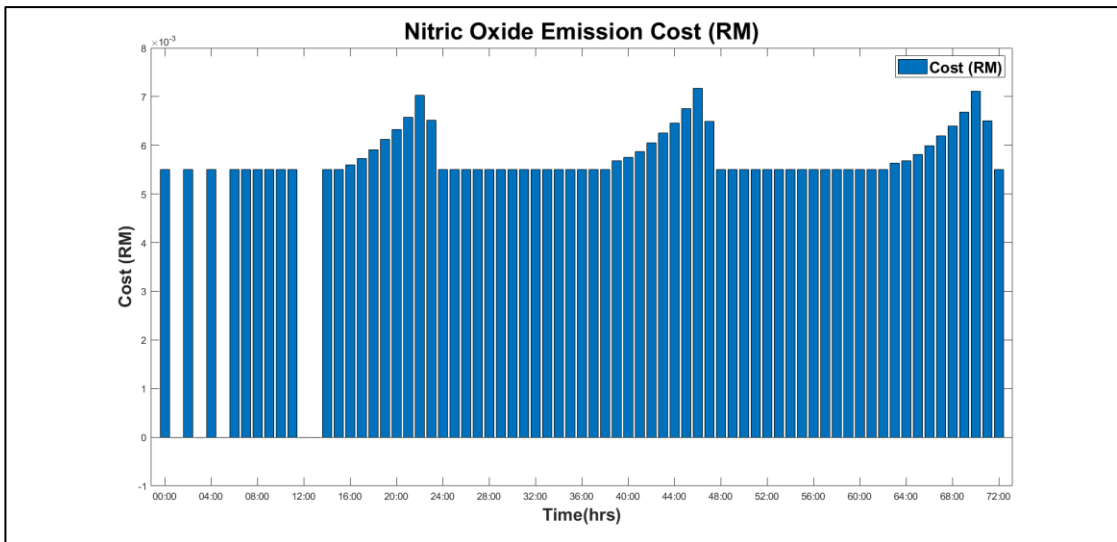


Figure 4.33 Nitric Oxide & Nitrogen Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario 2

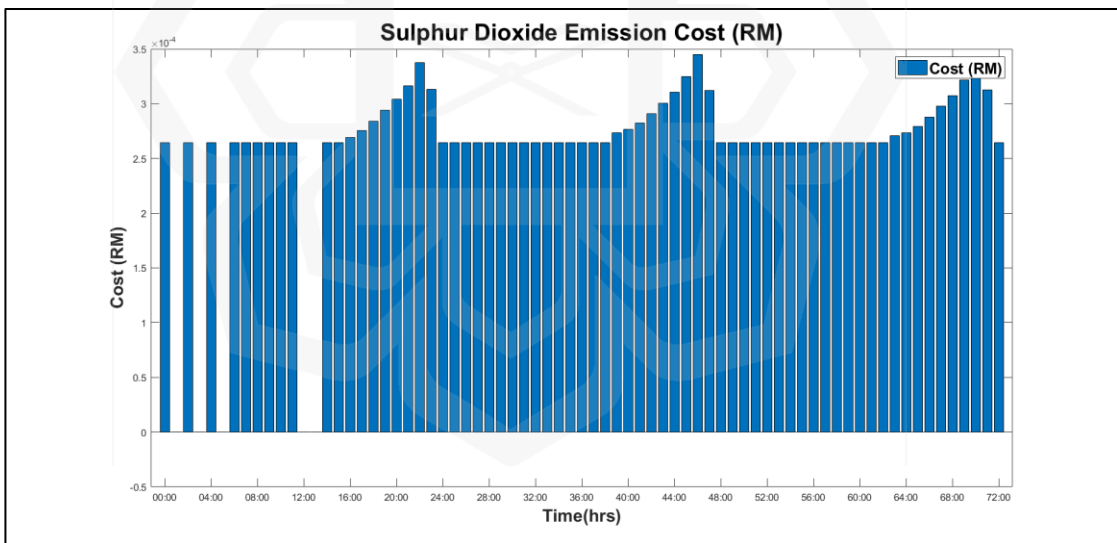


Figure 4.34 Sulphur Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario 2

Table 4.13 Greenhouse Gas Emission Cost for MPC-Based EMS of Scenario 2

<b>Greenhouse Gas</b>	<b>Cost</b>
Carbon Dioxide	RM 0.0946
Carbon Monoxide	RM 0.0166
Nitric Oxide & Nitrogen Dioxide	RM 0.3933
Sulphur Dioxide	RM 0.0189
<b>Total Emission Cost</b>	<b>RM 0.5234</b>

From Table 4.13, the total greenhouse emission cost is RM 0.5234 for 72-hours period. The cost of the carbon dioxide emission, carbon monoxide emission, nitric oxide & nitrogen dioxide emission and sulphur dioxide emission are RM 0.0946, RM 0.0166, RM 0.3933, and RM 0.0189 respectively.

#### 4.4.3 Scenario 3

In the third scenario, the weight is assigned more on the greenhouse gas emission cost function while the diesel generator cost function is set to zero. The cost function of the BESS remains constant. By setting the weight of greenhouse gas emission cost function higher than the diesel generator cost function, it is expected that the diesel generator usage will also become low. Hence, reducing the fuel consumption and consequently, the diesel fuel cost. Figures 4.35 and 4.36 shows the energy profile for all the components and SoC of the BESS for the 72-hours period.

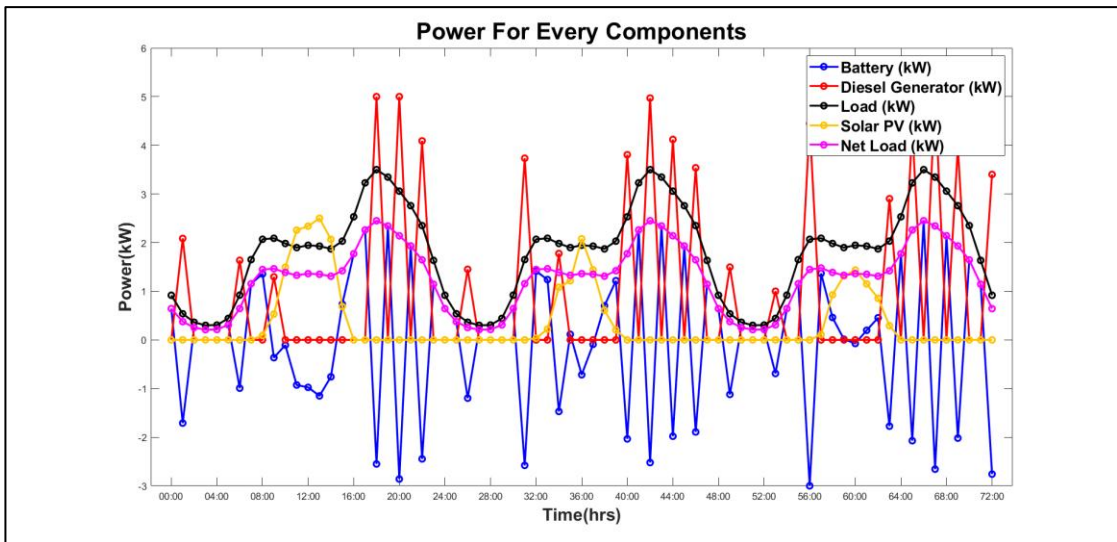


Figure 4.35 Energy Profile for All Components for MPC-Based EMS of Scenario 3

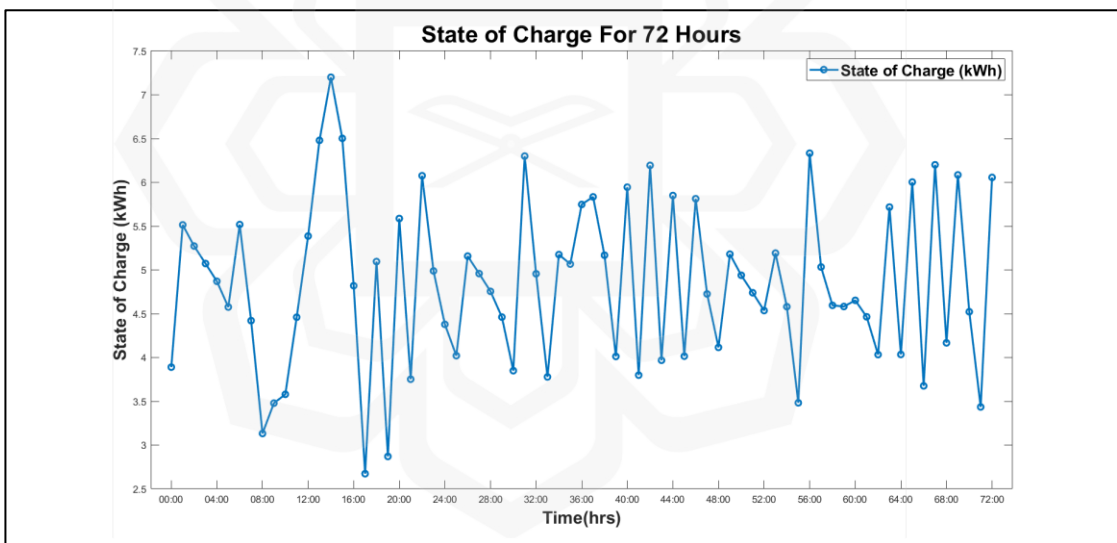


Figure 4.36 SoC of the BESS for MPC-Based EMS of Scenario 3

Figure 4.35 shows the energy profile of each components by setting the weight more on the greenhouse gas emission cost and less focus on the BESS. The weight of the diesel generator cost function is set to zero to remove the influence of it in determining the optimal power set-point of each components in the islanded microgrid.

It is observed that the diesel generator is used less frequently, however, whenever it is utilised, the output power is almost at the maximum, which is 5 kW. This can be seen, especially during the evening until the night when the load demand is high.

The diesel generator is once again used, mainly to charge the BESS. This can be observed from Figure 4.35, where the BESS power pattern is almost the same; however, the opposite of the diesel generator output indicates the BESS is charged when the diesel generator is generating power. Figures 4.37 and 4.38 shows the diesel fuel consumption and diesel fuel cost under scenario 3. Table 4.14 shows the diesel fuel consumption and cost for scenario 3.

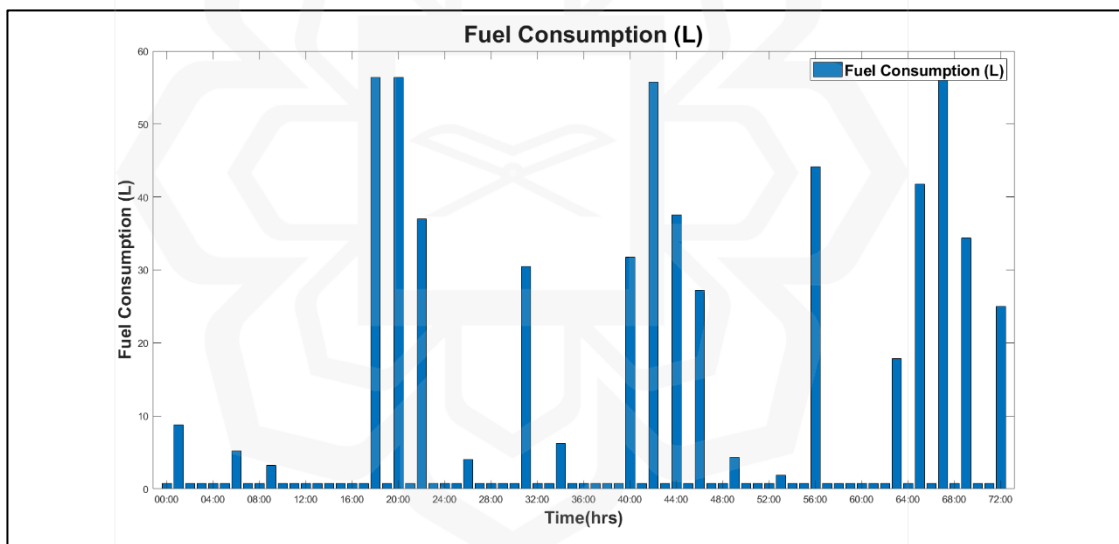


Figure 4.37 Diesel Fuel Consumption Pattern for MPC-Based EMS of Scenario 3

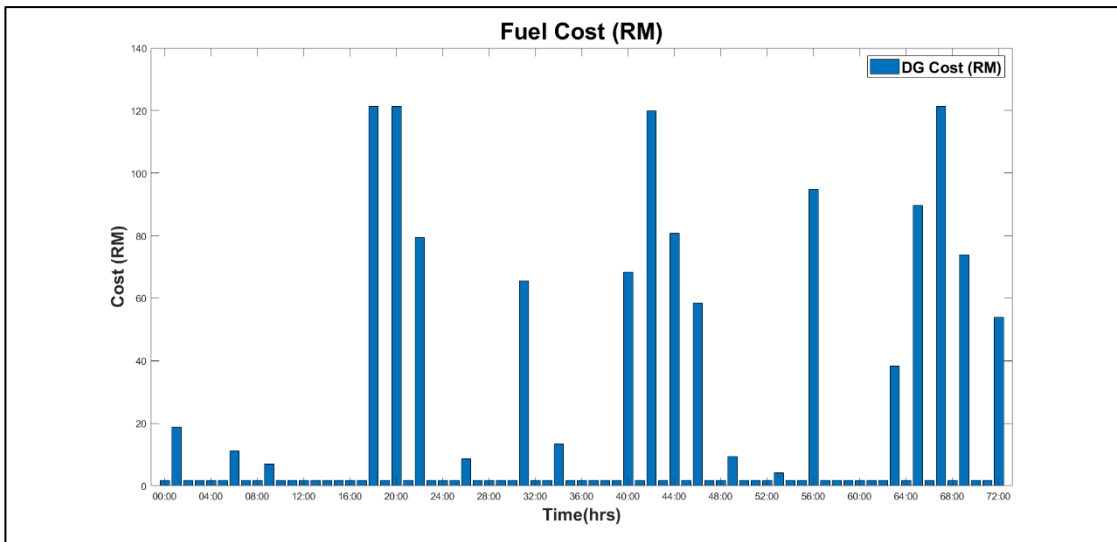


Figure 4.38 Diesel Fuel Cost Pattern for MPC-Based EMS of Scenario 3

Table 4.14 Diesel Fuel Consumption and Diesel Fuel Cost for MPC-Based EMS of Scenario 3

<b>Diesel Fuel Consumption</b>	626.43 Litres
<b>Diesel Fuel Cost</b>	RM 1346.80

From Table 4.14, the diesel consumption for 72-hours period in scenario 3 is 626.43 litres which costed RM 1346.80. Figures 4.39 until 4.42, shows the carbon dioxide emission cost, carbon monoxide emission cost, nitric oxide & nitrogen dioxide emission cost and sulphur dioxide emission cost respectively. Table 4.15 summarised each greenhouse gas emission cost and total emission cost.

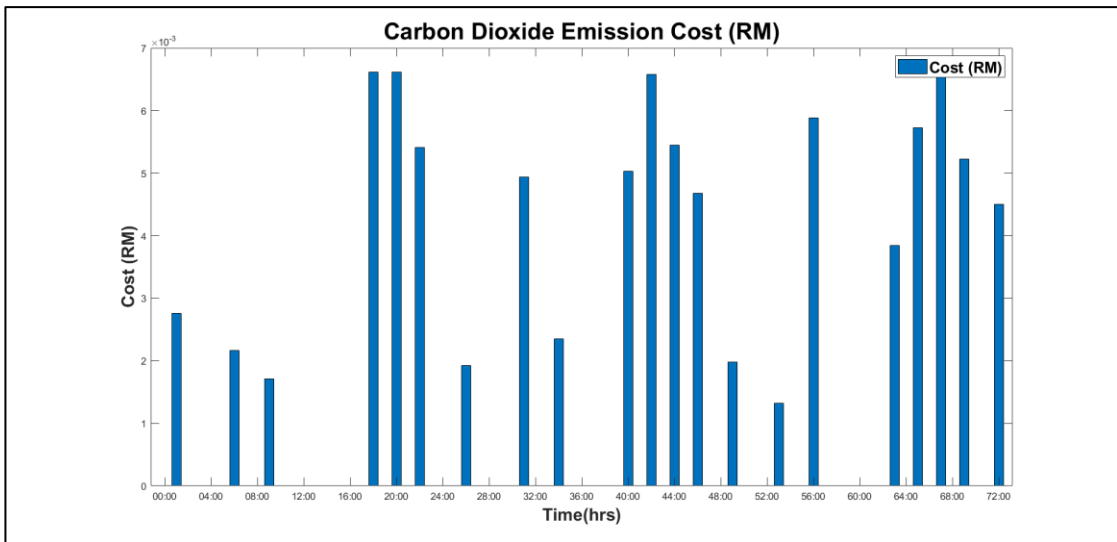


Figure 4.39 Carbon Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario

3

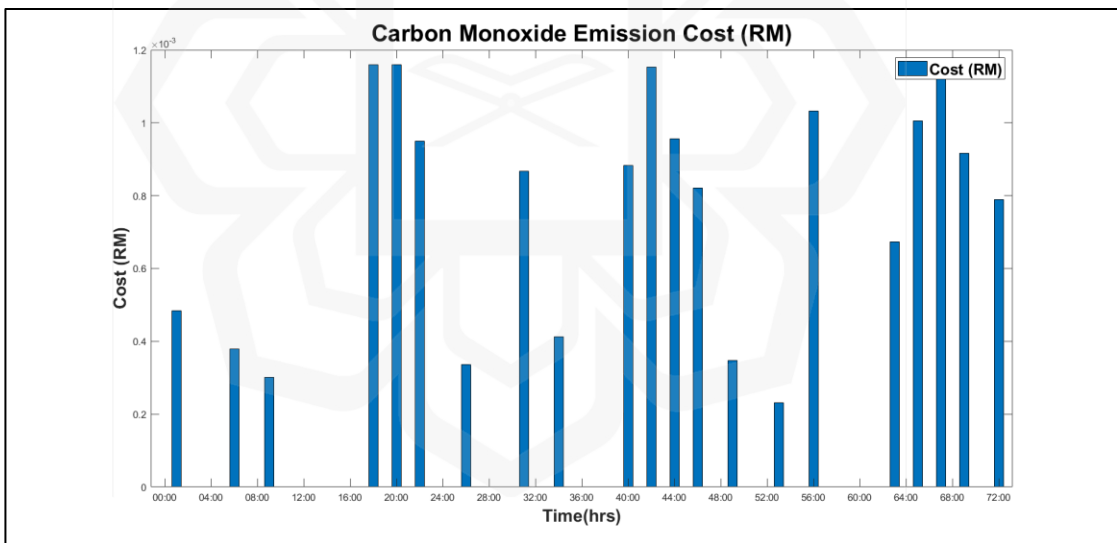


Figure 4.40 Carbon Monoxide Emission Cost Pattern for MPC-Based EMS of Scenario 3

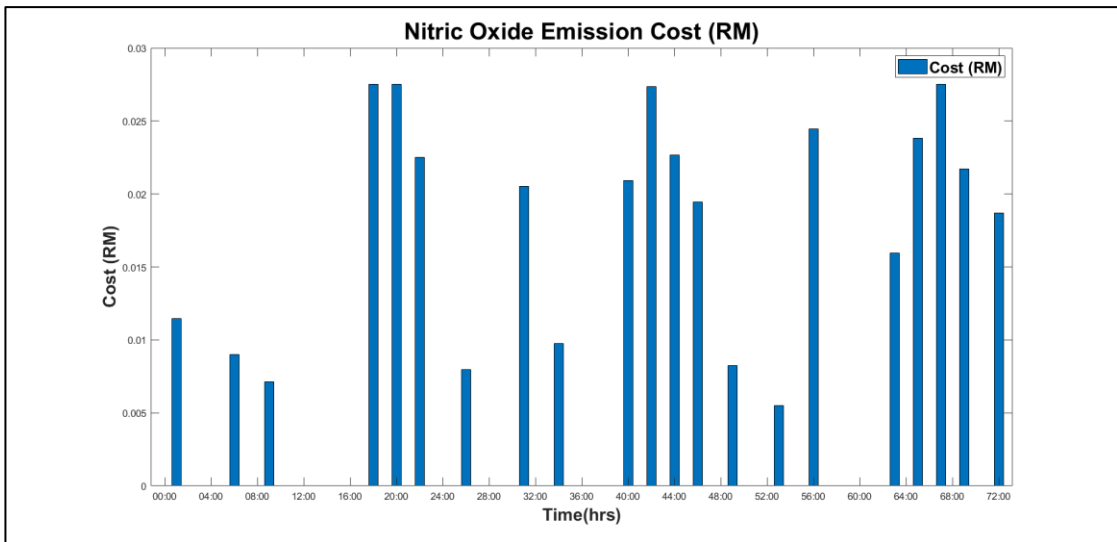


Figure 4.41 Nitric Oxide & Nitrogen Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario 3

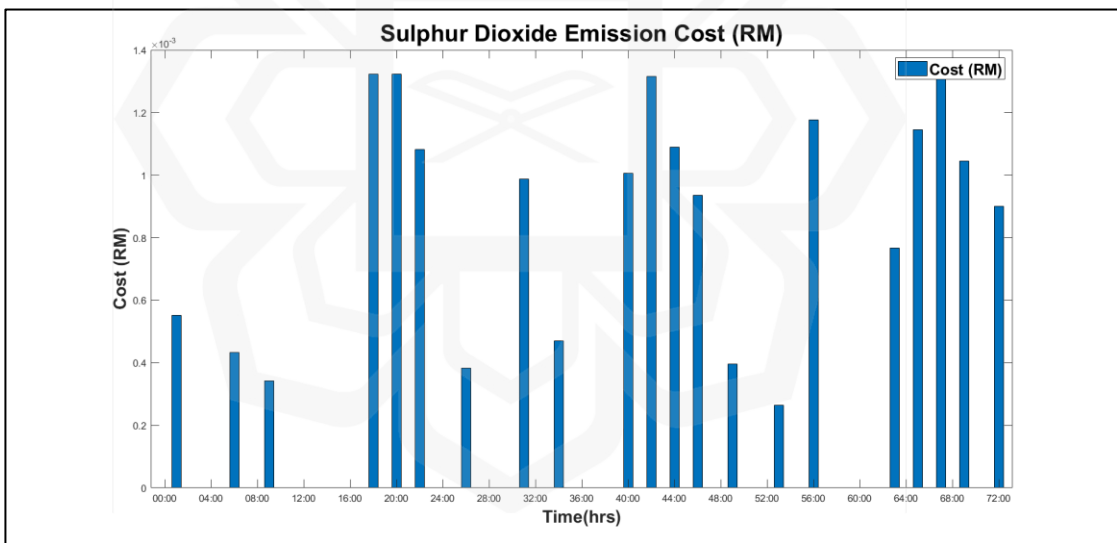


Figure 4.42 Sulphur Dioxide Emission Cost Pattern for MPC-Based EMS of Scenario 3

Table 4.15 Greenhouse Gas Emission Cost for MPC-Based EMS of Scenario 3

<b>Greenhouse Gas</b>	<b>Cost</b>
Carbon Dioxide	RM 0.0913
Carbon Monoxide	RM 0.0160
Nitric Oxide & Nitrogen Dioxide	RM 0.3797
Sulphur Dioxide	RM 0.0183
<b>Total Emission Cost</b>	<b>RM 0.5053</b>

From Table 4.15, the total cost of greenhouse emissions over a 72-hours period is RM 0.5053. The costs of carbon monoxide emission, nitric oxide and nitrogen dioxide emission, and sulphur dioxide emission are RM 0.0913, RM 0.0160, RM 0.3797, and RM 0.0183, respectively.

#### 4.4.4 Results Discussion

The simulation and the result for the three cases are presented in the previous sections. In the first scenario, the weight for each cost functions are equalised. The first scenario is intended for control purposes. In the second and third scenarios, the weight for the diesel generator cost function and greenhouse gas cost function are modified. In the second scenario, the diesel generator cost function had the greatest influence, while the greenhouse gas emission cost function was set to zero. Meanwhile in the third scenario, the greenhouse gas emission cost function has the greatest influence, and the diesel generator cost function was set to zero.

In the first scenario, the MPC-based EMS equally prioritizes the cost functions. The diesel generator occasionally remains off but is observed to turn on, particularly during periods of low or unavailable solar PV generation. Diesel generator usage is highest from evening until midnight, with its maximum output reaching up to 2 kW. Due to the equal prioritization by the MPC-based EMS, tracking the State of Charge (SoC) of the BESS becomes crucial. It can be observed that the SoC of the BESS fluctuates consistently around the reference value of 4.5 kWh.

In the second scenario, the MPC-based EMS prioritizes the diesel generator cost function, giving less attention to SoC tracking and none to greenhouse gas emissions. The diesel generator operates relatively consistently, maintaining a minimum power output of 1 kW over the 72-hour period, with only small fluctuations observed during the evening to night. This contrasts with scenario 1, where the diesel generator is occasionally turned off and produces high power output when active. On other hand, the SoC of the BESS is less frequently maintained at 50% of its maximum capacity, unlike in scenario 1. This is expected as the focus is given more on the reduction of the diesel generator cost function.

In the third scenario, the MPC-based EMS prioritizes the greenhouse gas emission cost function while still giving less attention to the SoC tracking and none to diesel generator cost function. The diesel generator is observed to have a fluctuating usage pattern. Generally, the diesel generator is used to charge the BEES and supply the loads. When operational, its output power can reach up to 5 kW, significantly higher than the maximum 2 kW observed in scenarios 1 and 2. It can be observed that the diesel generator is rarely used, and the microgrid relies on the BESS during this period, similar to scenario 1. Table 4.16 and Figure 4.43 shows the comparison of the diesel fuel consumption and diesel fuel cost for all three scenarios.

Table 4.16 Comparison of the Diesel Fuel Consumption and Diesel Fuel Cost for Three Scenarios

	<b>Scenario 1</b>	<b>Scenario 2</b>	<b>Scenario 3</b>
<b>Diesel Fuel Consumption</b>	225.34 Litres	147.88 Litres	626.43 Litres
<b>Diesel Fuel Cost</b>	RM 484.75	RM 317.95	RM 1346.80

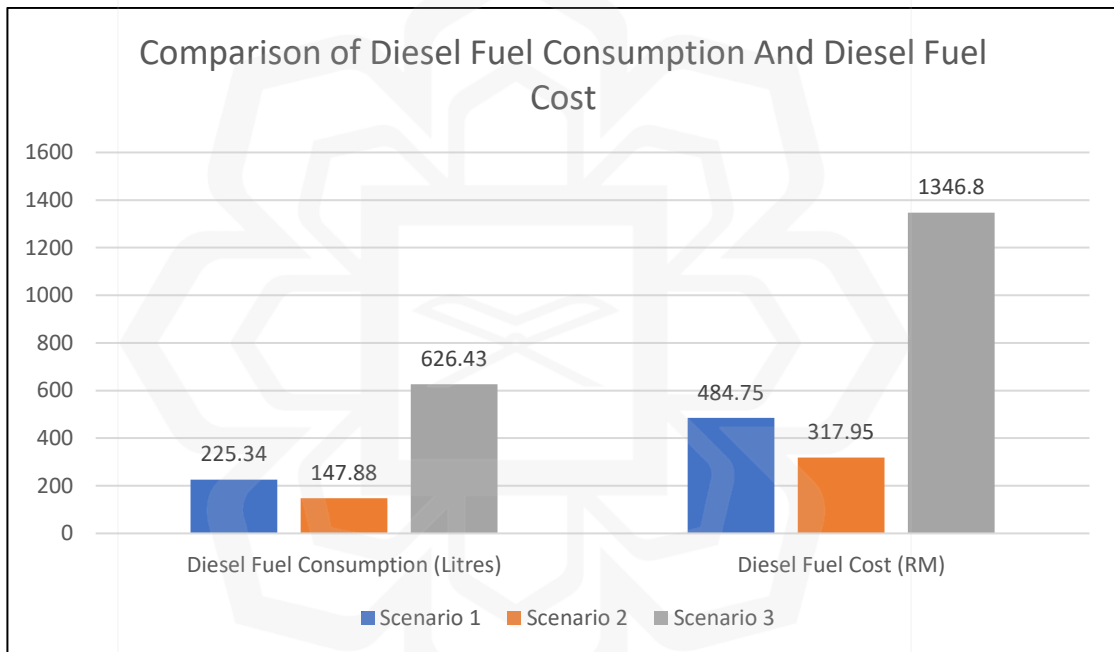


Figure 4.43 Comparison of Diesel Fuel Consumption and Diesel Fuel Cost

In Figure 4.43, it can be observed that the diesel fuel consumption is reduced when the cost reduction is focussed on the diesel generator cost function with the reduction of the diesel fuel consumption and diesel fuel cost of around 34% compared to scenario 1. In scenario 3, the diesel generator consumed ironically huge amount of diesel which results in higher cost. The diesel fuel consumption and cost increased 178% and 323.6% compared to scenario 1 and scenario 2 respectively. This might be

due to the complexity of the cost functions. The diesel generator cost function is quadratic, whereas the greenhouse gas emission cost function is linear. Table 4.17 and Figure 4.44 shows the comparison of greenhouse gas emission cost between the three cases.

Table 4.17 Comparison of Greenhouse Gas Emission Cost Between Three Scenarios

Scenario	1	2	3
<b>Carbon Dioxide</b>	RM 0.0969	RM 0.0946	RM 0.0913
<b>Carbon Monoxide</b>	RM 0.0170	RM 0.0166	RM 0.0160
<b>Nitric Oxide &amp; Nitrogen Dioxide</b>	RM 0.4031	RM 0.3933	RM 0.3797
<b>Sulphur Dioxide</b>	RM 0.0194	RM 0.0189	RM 0.0183
<b>Total Emission Cost</b>	RM 0.5364	RM 0.5234	RM 0.5053

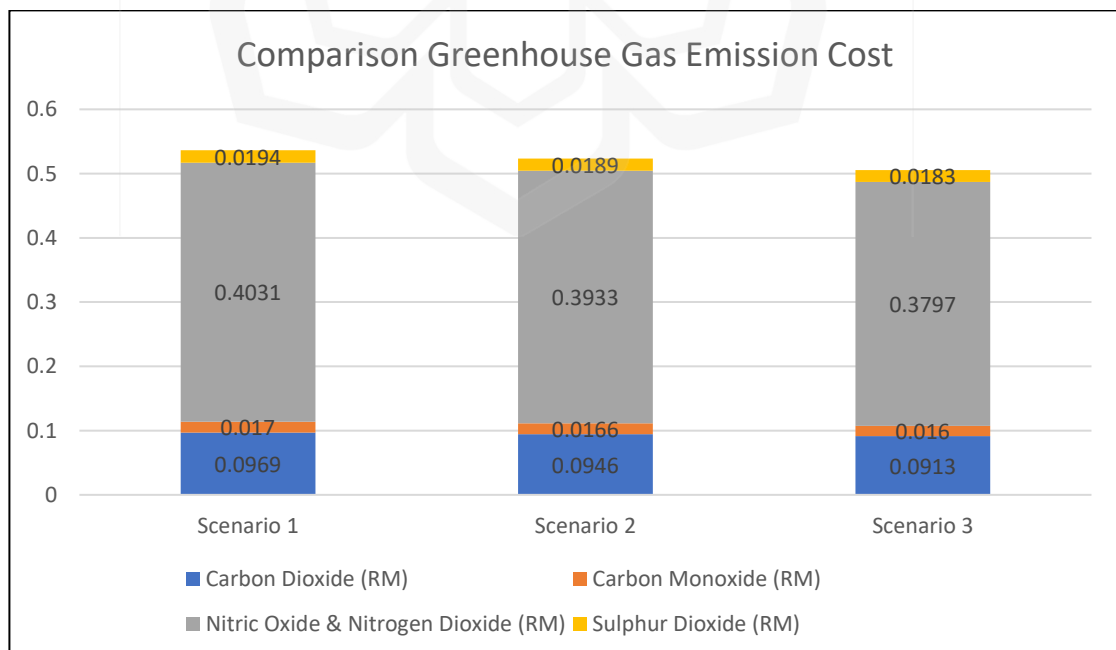


Figure 4.44 Comparison of Greenhouse Gas Emission Cost Between Three Scenarios

Figure 4.44 shows that greenhouse emission costs were lowered by 2.42 percent and 5.8 percent for scenario 2 and 3, respectively, compared to scenario 1. There are no significant changes in greenhouse cost reduction across all scenarios, even though the greenhouse gas emission cost function has a bigger influence than the other cost functions in scenario 3. However, in scenario 3, the diesel generator burned a significant amount of diesel fuel compared to scenario 1 and 2, resulting in a high cost.

As a result, the greenhouse gas emission cost function alone cannot significantly reduce the cost of diesel generator operating. A more complex greenhouse gas emission cost function needs to be proposed in which more resemble to the actual greenhouse gas emission due to the usage of diesel generator instead of through governmental policy or penalty. As of now, it is sufficient to include the diesel generator cost function or fuel consumption cost function in the EMS formulation. This is due to the nearly identical greenhouse gas emission cost when the greenhouse gas emission cost function is used or not as seen in the results.

## **4.5 SUMMARY**

In this chapter, the results of the simulation are presented and discussed. The simulation is conducted based on two cases: impact of load curtailment and weight of cost functions. In the first case, load curtailment can improve the cost saving of the diesel generator in terms of diesel fuel consumption cost. In the second case, it is discovered that the diesel generator cost function or fuel consumption cost function is sufficient to reduce the diesel fuel consumption cost with an insignificant cost increase on the greenhouse emission cost. Later, Chapter 5 will conclude this research. Future improvements will also be highlighted in the next following.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 CONCLUSION

This thesis focusses on the implementation of MPC-based EMS for a PV-BESS islanded microgrid. The primary goal of this thesis is to develop cost-efficient control of islanded microgrid through EMS using MPC approach by reducing the usage of diesel generator. This project successfully integrates PV systems, diesel generator, and BESS and managed by the proposed MPC-based EMS. The use of MPC as the core strategy enhances the predictability and stability of microgrid, ensuring optimal energy utilization and reduced dependency on non-renewable energy sources.

The objective of this research has been successfully achieved which is to develop the MPC-based EMS for islanded microgrid. The islanded microgrid consists of PV system, BESS, diesel generator, and loads. The islanded microgrid also have the load curtailment capability. BESS model is used to predict the future dynamic of the microgrid. The objective functions are defined to minimise the fuel cost of the diesel generator, greenhouse gas emission cost and SoC tracking. The objective functions are formulated using MIQP. The constraints are also defined based on the physical limitation of the components in the microgrid. The objective functions are solved by using the CPLEX toolbox.

The proposed systems successfully integrate and manage photovoltaic (PV) systems, battery energy storage system (BESS), diesel generator, and AC load which represents a significant leap in sustainable energy management. The seamless integration of renewable energy sources, diesel generator and load curtailment offer a steady, dependable power that can ensure power stability in the microgrid while

reducing environmental effect. The strategic use of BESS not only bridges the gap during periods of poor solar generation, but also optimises the operation of the diesel generator, lowering fuel consumption and operational expenses. This approach illustrates a sustainable, efficient, and economically feasible energy management paradigm that can be copied and scaled in a variety of scenarios. This system establishes an opportunity for future energy systems attempting to achieve a balance between environmental sustainability and energy reliability by prioritising renewable sources and integrating them with existing power solutions.

From the results, it is observed that the proposed MPC-EMS can reduce the environmental effect through the low use of diesel generator which support Sustainable Development Goals (SDG) 7. The suggested MPC-based EMS can be enhanced in a few ways. To attain better results, other suggestions can be considered. These are the recommendations required to improve future work for this projected while still providing cost-saving benefits in the islanded microgrid.

## **5.2 RECOMMENDATIONS**

The suggested MPC-based EMS can be enhanced in a few ways. To attain better results, other suggestions can be considered. These are the recommendations required to improve future work for this project:

1. Consideration of renewables DGs power forecasting and load forecasting.

This project does not consider renewable DGs power forecasting and load forecasting. The data used for this project is deterministic where no uncertainty is presence. By introducing uncertainty, we are able to observe and assess the robustness of the proposed MPC-based EMS in handling uncertainty inside the microgrid.

2. BESS degradation effect.

The current model of the BESS does not consider the degradation effect. It is known that the BESS degrades over time. It is proposed that the degradation effect is included in the EMS formulation. The implementation of AI-based modelling of the BESS may improve the effectiveness of the proposed EMS.

3. Demand side management strategy for islanded microgrid.

Load curtailment strategies generally require the load to be classified as critical or non-critical. This is not the situation in the common grid, where the load is treated as a single component. In addition, the monetary scheme is commonly utilised for grid-connected microgrids. This does not apply to islanded or freestanding microgrids that are not connected to a major grid. As a result, a new method is required to address demand side management for the islanded/standalone microgrid.

In conclusion, this study represents an important step toward sustainable and effective energy management in microgrids. Its forward-thinking approach to integrating sophisticated technologies offers a better, greener future in energy management. More research and development in this subject can pave the road for global adoption and optimization of renewable energy systems.

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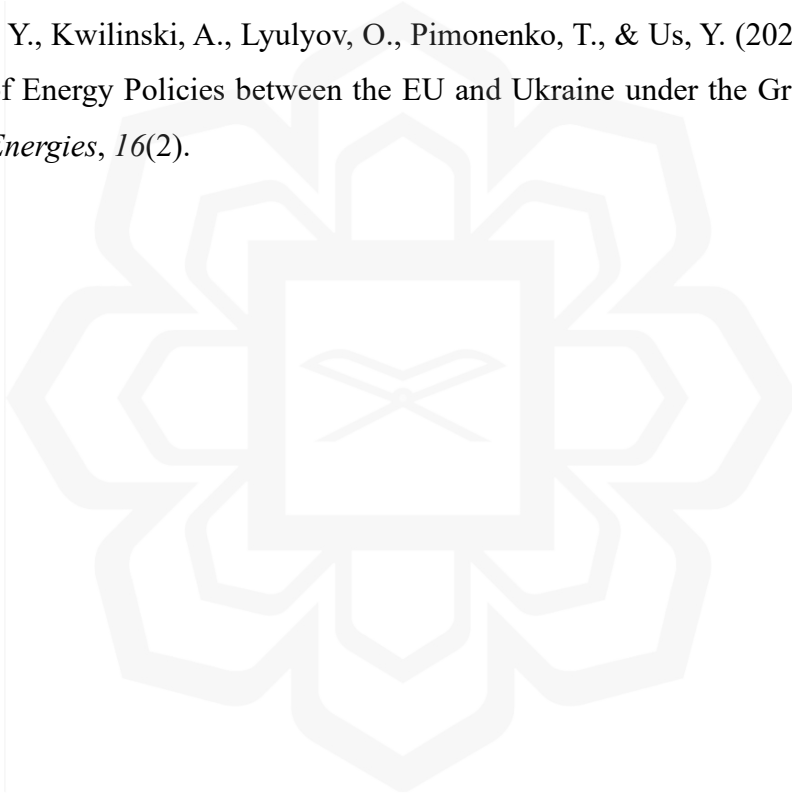
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## LIST OF PUBLICATIONS

### Scopus Indexed Journal

1. Syazana Izzati Razali, N., Hajar Yusoff, S., Liza Tumeran, N., & Sharir Fathullah Mohd Yunus, M. (2023). Indoor light energy harvesting technique to energize a heat sensor using polycrystalline solar panel. *Bulletin of Electrical Engineering and Informatics*.
2. Tumeran, N. L., Yusoff, S. H., Gunawan, T. S., Hanifah, M. S., Zabidi, S. A., Pranggono, B., Yunus, M. S., Sapihie, S. N., & Halbouni, A. H. (2023). Model Predictive Control Based Energy Management System Literature Assessment for RES Integration. *Energies*, 16(8).
3. Mohd Yunus, M. S. F., Yusoff, S. H., Mohd Sapihie, S. N., Abu Hanifah, M. S., Gunawan, T. S., & Suriza Ahmad Zabidi. (2025). Model Predictive Control-Based Energy Management System with Load Curtailment for Standalone Microgrid. *IIUM Engineering Journal*, 26(1), 169–186

### Conference Paper

1. Yunus, M. S. F. M., Yusoff, S. H., Sapihie, S. N. M., & Razali, N. S. I. (2023, 15-16 Aug. 2023). Smart Meter Based on IoT Platform. 2023 9th International Conference on Computer and Communication Engineering (ICCCE).

## APPENDIX A: MATLAB CODE

This appendix contains the MATLAB scripts developed for MPC-based EMS with and without load curtailment.

### A.1 MPC-BASED EMS WITHOUT LOAD CURTAILMENT

```
clc
clear

options = cplexoptimset('cplex');
options.output.clone_log = -1;

%%Simulation Parameter(s)%%
Sampling_min = 60;           %In minutes
Sim_duration_hrs = 73;      %In hours
Prediction_hrs = 24;%       %In hours 2/6/12/24
Ts = Sampling_min/60;       %Sampling time in hours
Sim_Duration = Sim_duration_hrs*Ts; % 1 day, 12 samples in
hour, in one day 288 samples
Np = Ts*Prediction_hrs;     %Prediction horizon: 5 steps ahead
(i.e: k+1...K+5) 72
MV =5;                       %Manipulated variable removed

%%Objective functions weight%%
weight1 = 1;
weight2 = 10;
weight3 = 10;

%%Battery Parameter(s)%%
Eff_ch_bat = 0.95;           %Battery charging efficiency:0.95
Eff_dis_bat = 0.95;         %Battery discharging
efficiency:0.95
C_max = 9;                   %Max battery capacity:9kWh
SoC_nom = 0.5;               %Nominal SoC: 50% or 4.5kWh
SoC_min = 0.1;               %Minimum SoC (allowed): 10% or
0.9kWh
SoC_max = 0.8;               %Maximum SoC (allowed): 80% or
8.1kWh
SoC_min_kWh = SoC_min*C_max;
SoC_max_kWh = SoC_max*C_max;
```

```

Pbat_min = -3; %Maximum charge: 3kW
Pbat_max = 3; %Maximum discharge: 3kW
currentSoC = 0.5; %Initial SoC of the battery
y_ref = SoC_nom;

%%Generator Parameter(s)%%
Pgen_max = 5; %Maximum power of DG (allowed): 5kW
Pgen_min = 1; %Minimum power of DG (allowd): 1kW

%%Fuel Price Cost%%
FuelPrice = 2.15; %%in RM/L

%%Fuel consumption coefficient%%
ai = 2.5; %L/kWh^2
bi = -1.375; %L/kWh
ci = 0.7813; %L/hr

%%Emission parameters (price and emission factor)%%
PF_CO2 = 0.0057; %RM/Kg
E_CO2 = 232.037e-3; %Kg/KWh
PF_NOX = 1.27; %RM/Kg
E_NOX = 4.331e-3; %Kg/KWh
PF_CO = 0.10; %RM/Kg
E_CO = 2.32e-3; %Kg/KWh
PF_SO2 = 0.57; %RM/Kg
E_SO2 = 0.464e-3; %Kg/KWh

%%Emission formula%%
EmissionCost = (PF_CO2*E_CO2) + (PF_NOX*E_NOX) + (PF_CO*E_CO) +
(PF_SO2*E_SO2);

%%Load and PV Power Forecasted Data%%
LoadPowerData = Power_Consumption_Data();
PVPowerData = PV_Generation_Data();

%%Preallocation%%
Pbat = zeros(Sim_Duration, 1);
Pgen = zeros(Sim_Duration, 1);
Pcur = zeros(Sim_Duration, 1);
LoadNet = zeros(Sim_Duration, 1);
delBat = zeros(Sim_Duration, 1);
delGen = zeros(Sim_Duration, 1);
SoC = zeros(Sim_Duration, 1);
Ppv = zeros(Sim_Duration, 1);
Pload = zeros(Sim_Duration, 1);
FuelCost = zeros(Sim_Duration, 1);
FuelConsumption = zeros(Sim_Duration, 1);
powerBalance = zeros(Sim_Duration, 1);
CarbonDioxideCost = zeros(Sim_Duration, 1);

```

```

NitricOxideCost = zeros(Sim_Duration, 1);
CarbonMonoxideCost = zeros(Sim_Duration, 1);
SulphurDioxideCost = zeros(Sim_Duration, 1);

%%Model%%
%%State:x(k+1)=A*x(k)+B*u(k) u(k)=(Pbat, Pgen, Pcur, del_bat,
del_gen, z_bat)%%
A = [1];
B = [((-Ts*Eff_ch_bat)/C_max) 0 0 0 -(((Ts*Eff_ch_bat)/C_max)-
(Ts/(Eff_dis_bat*C_max)))];%#ok<*NBRAK>

%Output:y(k)=C*x(k)+D*u(k)
C = [1];
D = [0];

for i = 1:Sim_Duration

    %%Deterministic moving horizon%%
    PVPower = PVPowerData(i:Np-1+i);
    LoadPower = LoadPowerData(i:Np-1+i);

    %%System definition using recursion%%
    %%Refer Rossiter pg40%%
    [Px, Hx, P, H] = Predmat(A,B,C,Np);

    %%Square part and single part
    %%U^T*X*U+U^T*Z
    [X,Z]=QP_prep(P,H,weight1, weight2,
weight3,currentSoC,y_ref,Np, MV, ai, bi, EmissionCost);

    %%Constraints%%
    %%equality%
    [Aeq,beq] = Equality(Np, PVPower, LoadPower);

    %%inequality%
    [Aineq, bineq] = Inequality(currentSoC, SoC_min, SoC_max,
Pbat_min, Pbat_max, Pgen_min, Pgen_max, Px, Hx, Np, LoadPower);

    X = (X' + X)/2;

    %%Change the ctype according to duration time
    [U,fval,exitflag,output] =
cplexmiqp(X,Z,Aineq,bineq,Aeq,beq,[],[],[],[],[], 'CCBCCCBBCCCB
BCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCC
CBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCCCBCC',[],options);
    %output %#ok<NOPTS>
    disp(i);
    if exitflag <= 0
        disp('Error');
    end
end

```

```

        return;
    end

    currentSoC = A*currentSoC + B(1)*U(1) + B(2)*U(2) +
B(3)*U(3) +B(4)*U(4) + B(5)*U(5);
    fuelConsumption = (ai*U(2)^2 + bi*U(2) + ci);
    fuelCostCalc = FuelPrice*fuelConsumption ;
    CarbonDioxideCalc = PF_CO2*E_CO2*U(2);
    NitrousOxideCalc = PF_NOX*E_NOX*U(2);
    CarbonOxideCalc = PF_CO*E_CO*U(2);
    SulphurDioxideCalc = PF_SO2*E_SO2*U(2);
    %LoadNetCalc = LoadPower(1) - U(3);

    SoC(i,1) = currentSoC*C_max;
    FuelConsumption(i,1) = fuelConsumption;
    FuelCost(i,1) = fuelCostCalc;
    CarbonDioxideCost(i,1) = CarbonDioxideCalc;
    NitricOxideCost(i,1) = NitrousOxideCalc;
    CarbonMonoxideCost(i,1) = CarbonOxideCalc;
    SulphurDioxideCost(i,1) = SulphurDioxideCalc;
    %LoadNet(i,1) = LoadNetCalc;

    Pbat(i,1) = U(1);
    Pgen(i,1) = U(2);
    %Pcur(i,1) = U(3);
    delBat(i,1) = U(3);
    delGen(i,1) = U(4);
    Pload(i, 1) = LoadPower(1);
    Ppv(i,1) = PVPower(1);
    powerBalance(i,1) = PVPower(1) + U(1) + U(2) -
LoadPower(1);
end

%%Plot%%
t = hours(0):hours(1):hours(Sim_duration_hrs-1); %%Change the
second and the third
PVPowerData = PVPowerData(1:Sim_Duration);
LoadPowerData = LoadPowerData(1:Sim_Duration);

%PV Generation Graph
%subplot(2,3,1);
f1 = figure;
plot(t, Ppv, 'y--+');
xtickformat('hh:mm');
title('Solar Power Generation For 72 Hours');
xlabel('Time(hrs)');

```

```

ylabel('Solar Power Generation (kW)');
legend('Solar Power Generation (kW)');

%Load Graph
%subplot(2,3,2);
f2 =figure;
plot(t, Pload, 'b--+');
xtickformat('hh:mm');
title('Load Demand For 72 Hours');
xlabel('Time(hrs)');
ylabel('Power Consumption (kW)');
legend('Power Consumption (kW)');

%SoC
%subplot(2,3,3);
f3 = figure;
plot(t,SoC,'-o','LineWidth', 2);
xtickformat('hh:mm');
title('State of Charge For 72 Hours', 'FontSize', 24,
'FontWeight','bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('State of Charge (kWh)', 'FontSize', 18,
'FontWeight','bold');
legend('State of Charge (kWh)', 'FontSize', 16,
'FontWeight','bold');

%subplot(2,3,4);
f4 = figure;
plot(t, Pbat, 'b--o', t, Pgen, 'r--*', t, Pload, 'k--x', t,
Ppv, 'y--+');
xtickformat('hh:mm');
title('Power For Every Components');
xlabel('Time(hrs)');
ylabel('Power(kW)');
legend({'Battery (kW)','Diesel Generator (kW)','Load
(kW)','Solar PV (kW)'});

plot(t, Pbat, '-ob', 'LineWidth', 2); % Pbat with blue color
and line width of 2
hold on;
plot(t, Pgen, '-or', 'LineWidth', 2); % Pgen with red color and
line width of 2
plot(t, Pload, '-ok', 'LineWidth', 2); % Pload with black color
and line width of 2
plot(t, Ppv, '-o', 'Color', [1, 0.7647058823529411, 0],
'LineWidth', 2); % Ppv with specified color and line width of 2
hold off;
xtickformat('hh:mm');

```

```

title('Power For Every Components', 'FontSize', 24,
'FontWeight','bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('Power(kW)', 'FontSize', 18, 'FontWeight','bold');
legend({'Battery (kW)', 'Diesel Generator (kW)', 'Load
(kW)', 'Solar PV (kW)'}, 'FontSize', 16, 'FontWeight','bold');

%subplot(2,3,5);
f5 = figure;
plot(t, Pbat, 'b--o');
xtickformat('hh:mm');
title('Battery Charging and Discharging');
xlabel('Time(hrs)');
ylabel('Power(kW)');
legend('Battery (kW)');

%subplot(2,3,6);
f6 = figure;
bar(t, Pgen);
xtickformat('hh:mm');
title('Diesel Generator Power (kWh)');
xlabel('Time(hrs)');
ylabel('Power(kW)');
legend('DG Power (kW)');

f7 = figure;
bar(t, FuelCost);
xtickformat('hh:mm');
title('Fuel Cost (RM)', 'FontSize', 24, 'FontWeight','bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('Cost (RM)', 'FontSize', 18, 'FontWeight','bold');
legend('DG Cost (RM)', 'FontSize', 16, 'FontWeight','bold');

f8 = figure;
bar(t, FuelConsumption);
xtickformat('hh:mm');
title('Fuel Consumption (L)', 'FontSize', 24,
'FontWeight','bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('Fuel Consumption (L)', 'FontSize', 18,
'FontWeight','bold');
legend('Fuel Consumption (L)', 'FontSize', 16,
'FontWeight','bold');

f9 = figure;
bar(t, CarbonDioxideCost);
xtickformat('hh:mm');
title('Carbon Dioxide Emission Cost (RM)', 'FontSize', 24,
'FontWeight','bold');

```

```

xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Cost (RM)', 'FontSize', 18, 'FontWeight', 'bold');
legend('Cost (RM)', 'FontSize', 16, 'FontWeight', 'bold');

f10 = figure;
bar(t, NitricOxideCost);
xtickformat('hh:mm');
title('Nitric Oxide Emission Cost (RM)', 'FontSize', 24,
'FontWeight', 'bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Cost (RM)', 'FontSize', 18, 'FontWeight', 'bold');
legend('Cost (RM)', 'FontSize', 16, 'FontWeight', 'bold');

f11 = figure;
bar(t, CarbonMonoxideCost);
xtickformat('hh:mm');
title('Carbon Monoxide Emission Cost (RM)', 'FontSize', 24,
'FontWeight', 'bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Cost (RM)', 'FontSize', 18, 'FontWeight', 'bold');
legend('Cost (RM)', 'FontSize', 16, 'FontWeight', 'bold');

f12 = figure;
bar(t, SulphurDioxideCost);
xtickformat('hh:mm');
title('Sulphur Dioxide Emission Cost (RM)', 'FontSize', 24,
'FontWeight', 'bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Cost (RM)', 'FontSize', 18, 'FontWeight', 'bold');
legend('Cost (RM)', 'FontSize', 16, 'FontWeight', 'bold');
%
f13 = figure;
plot(t, Pcur);
xtickformat('hh:mm');
title('Curtailed Power For 24 Hours' 'FontSize', 24,
'FontWeight', 'bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Power (kW)', 'FontSize', 18, 'FontWeight', 'bold');
legend('Power (kW)', 'FontSize', 16, 'FontWeight', 'bold');

f14 = figure;
plot(t, LoadNet);
xtickformat('hh:mm');
title('Net Load Demand For 24 Hours' 'FontSize', 24,
'FontWeight', 'bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Power (kW)', 'FontSize', 18, 'FontWeight', 'bold');
legend('Power (kW)', 'FontSize', 16, 'FontWeight', 'bold');

```

## A.2 MPC-BASED EMS WITH LOAD CURTAILMENT

```
clc
clear

options = cplexoptimset('cplex');
options.output.cloneolog = -1;

%%Simulation Parameter(s)%%
Sampling_min = 60;           %In minutes
Sim_duration_hrs = 73;      %In hours
Prediction_hrs = 24;%       %In hours 2/6/12/24
Ts = Sampling_min/60;       %Sampling time in hours
Sim_Duration = Sim_duration_hrs*Ts; % 1 day, 12 samples in
hour, in one day 288 samples
Np = Ts*Prediction_hrs;     %Prediction horizon: 5 steps ahead
(i.e: k+1...K+5) 72
MV = 6;                     %Manipulated variable

%%Objective functions weight%%
weight1 = 1;
weight2 = 70;
weight3 = 475.17;

%%Battery Parameter(s)%%
Eff_ch_bat = 0.95;          %Battery charging efficiency:0.95
Eff_dis_bat = 0.95;        %Battery discharging
efficiency:0.95
C_max = 9;                 %Max battery capacity:9kWh
SoC_nom = 0.5;             %Nominal SoC: 50% or 4.5kWh
SoC_min = 0.1;            %Minimum SoC (allowed): 10% or
0.9kWh
SoC_max = 0.8;            %Maximum SoC (allowed): 80% or
8.1kWh
SoC_min_kWh = SoC_min*C_max;
SoC_max_kWh = SoC_max*C_max;
Pbat_min = -3;            %Maximum charge: 3kW
Pbat_max = 3;            %Maximum discharge: 3kW
currentSoC = 0.5;        %Initial SoC of the battery
y_ref = SoC_nom;

%%Generator Parameter(s)%%
Pgen_max = 5; %Maximum power of DG (allowed): 5kW
Pgen_min = 1; %Minimum power of DG (allowd): 1kW

%%Fuel Price Cost%%
FuelPrice = 2.15;%%in RM/L
```

```

%%Fuel consumption coefficient%%
ai = 2.5;          %L/kWh^2
bi = -1.375;     %L/kWh
ci = 0.7813;    %L/hr

%%Emission parameters (price and emission factor)%
PF_CO2 = 0.0057;    %RM/Kg
E_CO2 = 232.037e-3; %Kg/KWh
PF_NOX = 1.27;     %RM/Kg
E_NOX = 4.331e-3;  %Kg/KWh
PF_CO = 0.10;     %RM/Kg
E_CO = 2.32e-3;   %Kg/KWh
PF_SO2 = 0.57;    %RM/Kg
E_SO2 = 0.464e-3; %Kg/KWh

%%Emission formula%%
EmissionCost = (PF_CO2*E_CO2) + (PF_NOX*E_NOX) + (PF_CO*E_CO) +
(PF_SO2*E_SO2);

%%Load and PV Power Forecasted Data%%
LoadPowerData = Power_Consumption_Data();
PVPowerData = PV_Generation_Data();

%%Preallocation%%
Pbat = zeros(Sim_Duration, 1);
Pgen = zeros(Sim_Duration, 1);
Pcur = zeros(Sim_Duration, 1);
LoadNet = zeros(Sim_Duration, 1);
delBat = zeros(Sim_Duration, 1);
delGen = zeros(Sim_Duration, 1);
SoC = zeros(Sim_Duration, 1);
Ppv = zeros(Sim_Duration, 1);
Pload = zeros(Sim_Duration, 1);
FuelCost = zeros(Sim_Duration, 1);
FuelConsumption = zeros(Sim_Duration, 1);
powerBalance = zeros(Sim_Duration, 1);
CarbonDioxideCost = zeros(Sim_Duration, 1);
NitricOxideCost = zeros(Sim_Duration, 1);
CarbonMonoxideCost = zeros(Sim_Duration, 1);
SulphurDioxideCost = zeros(Sim_Duration, 1);

%%Model%%
%%State:x(k+1)=A*x(k)+B*u(k) u(k)=(Pbat, Pgen, Pcur, del_bat,
del_gen, z_bat)%
A = [1];
B = [((-Ts*Eff_ch_bat)/C_max) 0 0 0 0 -
(((Ts*Eff_ch_bat)/C_max)-
(Ts/(Eff_dis_bat*C_max)))];%#ok<*NBRAK>

```

```

%Output:y(k)=C*x(k)+D*u(k)
C = [1];
D = [0];

for i = 1:Sim_Duration

    %%Deterministic moving horizon%%
    PVPower = PVPowerData(i:Np-1+i);
    LoadPower = LoadPowerData(i:Np-1+i);

    %%System definition using recursion%%
    %%Refer Rossiter pg40%%
    [Px, Hx, P, H] = Predmat(A,B,C,Np);

    %%Square part and single part
    %%U^T*X*U+U^T*Z
    [X,Z]=QP_prep(P,H,weight1, weight2,
weight3,currentSoC,y_ref,Np, MV, ai, bi, EmissionCost);

    %%Constraints%%
    %%equality%
    [Aeq,beq] = Equality(Np, PVPower, LoadPower);

    %%inequality%
    [Aineq, bineq] = Inequality(currentSoC, SoC_min, SoC_max,
Pbat_min, Pbat_max, Pgen_min, Pgen_max, Px, Hx, Np, LoadPower);

    X = (X' + X)/2;

    %%Change the ctype according to duration time
    [U,fval,exitflag,output] =
cplexmiqp(X,Z,Aineq,bineq,Aeq,beq,[],[],[],[],[], 'CCCBCCCCBBCC
CCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCB
BCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCCCCBBCC
CCBBC',[],options);
    %output %#ok<NOPTS>
    disp(i);
    if exitflag <= 0
        disp('Error');
        return;
    end

    currentSoC = A*currentSoC + B(1)*U(1) + B(2)*U(2) +
B(3)*U(3) +B(4)*U(4) + B(5)*U(5);
    fuelConsumption = (ai*U(2)^2 + bi*U(2) + ci);
    fuelCostCalc = FuelPrice*fuelConsumption ;
    CarbonDioxideCalc = PF_CO2*E_CO2*U(2);
    NitrousOxideCalc = PF_NOX*E_NOX*U(2);

```

```

CarbonOxideCalc = PF_CO*E_CO*U(2);
SulphurDioxideCalc = PF_SO2*E_SO2*U(2);
LoadNetCalc = LoadPower(1) - U(3);

SoC(i,1) = currentSoC*C_max;
FuelConsumption(i,1) = fuelConsumption;
FuelCost(i,1) = fuelCostCalc;
CarbonDioxideCost(i,1) = CarbonDioxideCalc;
NitricOxideCost(i,1) = NitrousOxideCalc;
CarbonMonoxideCost(i,1) = CarbonOxideCalc;
SulphurDioxideCost(i,1) = SulphurDioxideCalc;
LoadNet(i,1) = LoadNetCalc;

Pbat(i,1) = U(1);
Pgen(i,1) = U(2);
Pcur(i,1) = U(3);
delBat(i,1) = U(4);
delGen(i,1) = U(5);
Pload(i, 1) = LoadPower(1);
Ppv(i,1) = PVPower(1);
powerBalance(i,1) = PVPower(1) + U(1) + U(2) +U(3) -
LoadPower(1);

end

%%Plot%%
t = hours(0):hours(1):hours(Sim_duration_hrs-1); %%Change the
second and the third
PVPowerData = PVPowerData(1:Sim_Duration);
LoadPowerData = LoadPowerData(1:Sim_Duration);

%PV Generation Graph
%subplot(2,3,1);
f1 = figure;
plot(t, Ppv, '-o', 'color', "[1, 0.7647058823529411,
0]", "LineWidth", 2);
xtickformat('hh:mm');
title('Solar Power Generation For 72 Hours', 'FontSize', 24,
'FontWeight', 'bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight', 'bold');
ylabel('Solar Power Generation (kW)', 'FontSize', 18,
'FontWeight', 'bold');
legend('Solar Power Generation (kW)', 'FontSize', 16,
'FontWeight', 'bold');

%Load Graph
%subplot(2,3,2);

```

```

f2 =figure;
plot(t, Pload, '-ok', "LineWidth",2);
xtickformat('hh:mm');
title('Load Demand For 72 Hours', 'FontSize', 24,
'FontWeight','bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('Power Consumption (kW)', 'FontSize', 18,
'FontWeight','bold');
legend('Power Consumption (kW)', 'FontSize', 16,
'FontWeight','bold');

%SoC
%subplot(2,3,3);
f3 = figure;
plot(t,SoC,'-o', "LineWidth",2);
xtickformat('hh:mm');
title('State of Charge For 72 Hours');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('State of Charge (kWh)', 'FontSize', 18,
'FontWeight','bold');
legend('State of Charge (kWh)', 'FontSize', 16,
'FontWeight','bold');

%subplot(2,3,4);
f4 = figure;
plot(t, Pbat, '-ob', 'LineWidth', 2); % Pbat with blue color
and line width of 2
hold on;
plot(t, Pgen, '-or', 'LineWidth', 2); % Pgen with red color and
line width of 2
plot(t, Pload, '-ok', 'LineWidth', 2); % Pload with black color
and line width of 2
plot(t, Ppv, '-o', 'Color', [1, 0.7647058823529411, 0],
'LineWidth', 2); % Ppv with specified color and line width of 2
plot(t, LoadNet, '-om', 'LineWidth', 2); % LoadNet with magenta
color and line width of 2
hold off;
xtickformat('hh:mm');
title('Power For Every Components', 'FontSize', 24,
'FontWeight','bold');
xlabel('Time(hrs)', 'FontSize', 18, 'FontWeight','bold');
ylabel('Power(kW)', 'FontSize', 18, 'FontWeight','bold');
legend({'Battery (kW)', 'Diesel Generator (kW)', 'Load
(kW)', 'Solar PV (kW)', 'Net Load (kW)'}, 'FontSize', 16,
'FontWeight','bold');

%subplot(2,3,5);
f5 = figure;
plot(t, Pbat, 'b--o');

```

```

xtickformat('hh:mm');
title('Battery Charging and Discharging');
xlabel('Time(hrs)');
ylabel('Power(kW)');
legend('Battery (kW)');

%subplot(2,3,6);
f6 = figure;
bar(t, Pgen);
xtickformat('hh:mm');
title('Diesel Generator Power (kWh)');
xlabel('Time(hrs)');
ylabel('Power(kW)');
legend('DG Power (kW)');

f7 = figure;
bar(t, FuelCost);
xtickformat('hh:mm');
title('Fuel Cost (RM)');
xlabel('Time(hrs)');
ylabel('Cost (RM)');
legend('DG Cost (RM)');

f8 = figure;
bar(t, FuelConsumption);
xtickformat('hh:mm');
title('Fuel Consumption (L)');
xlabel('Time(hrs)');
ylabel('Fuel Consumption (L)');
legend('Fuel Consumption (L)');

f9 = figure;
bar(t, CarbonDioxideCost);
xtickformat('hh:mm');
title('Carbon Dioxide Emission Cost (RM)');
xlabel('Time(hrs)');
ylabel('Cost (RM)');
legend('Cost (RM)');

f10 = figure;
bar(t, NitricOxideCost);
xtickformat('hh:mm');
title('Nitric Oxide Emission Cost (RM)');
xlabel('Time(hrs)');
ylabel('Cost (RM)');
legend('Cost (RM)');

f11 = figure;
bar(t, CarbonMonoxideCost);

```

```

xtickformat('hh:mm');
title('Carbon Monoxide Emission Cost (RM)');
xlabel('Time(hrs)');
ylabel('Cost (RM)');
legend('Cost (RM)');

f12 = figure;
bar(t, SulphurDioxideCost);
xtickformat('hh:mm');
title('Sulphur Dioxide Emission Cost (RM)');
xlabel('Time(hrs)');
ylabel('Cost (RM)');
legend('Cost (RM)');

f13 = figure;
plot(t, Pcur, 'b--+');
xtickformat('hh:mm');
title('Curtailed Power For 72 Hours');
xlabel('Time(hrs)');
ylabel('Power (kW)');
legend('Power (kW)');

f14 = figure;
plot(t, LoadNet, 'm--.');
xtickformat('hh:mm');
title('Net Load Demand For 72 Hours');
xlabel('Time(hrs)');
ylabel('Power (kW)');
legend('Power (kW)');

```