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MODEL PREDICTIVE CONTROL-BASED ENERGY MANAGEMENT SYSTEM WITH LOAD CURTAILMENT FOR STANDALONE MICROGRID

MUHAMMAD SHARIR FATHULLAH BIN MOHD YUNUS[1], SITI HAJAR YUSOFF[1], SITI NADIAH MOHD SAPIHIE[2], MOHD SHAHRIN BIN ABU HANIFAH[1], TEDDY SURYA GUNAWAN[1], SURIZA AHMAD ZABIDI[1]

[1]*Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia*
[2]*Petronas Research Sdn Bhd, Bandar Baru Bangi, Malaysia*

**Corresponding author: fathullah.sharir@gmail.com*

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ABSTRACT: The standalone microgrid emerges as an economical solution for providing electricity to remote areas disconnected from the main grid. However, the intermittent nature of renewable energy sources (RES) and unpredictable load demands can disrupt its balance. Diesel generators are commonly used to supply auxiliary power and serve as a backup for the microgrid. Nevertheless, inefficient utilization of diesel generators can lead to high operational costs, shortened lifespan, and environmental pollution. An energy management system (EMS) is implemented to optimize the operational cost and reliability of the microgrid by incorporating model predictive control (MPC), which has grown in popularity in recent years due to its ability to support multiple inputs and multiple outputs. The MPC-based EMS is developed using MATLAB/Simulink software, with the optimization problem formulated using mixed integer quadratic programming (MIQP). A comparative analysis is conducted between the MPC-based EMS with and without load curtailment capability, revealing a significant improvement of 52.21% in diesel fuel cost savings with the inclusion of load curtailment capability.

ABSTRAK: Grid mikro berdiri sendiri muncul sebagai penyelesaian ekonomi untuk menyediakan perkhidmatan elektrik kepada kawasan terpencil yang jauh daripada grid utama. Walau bagaimanapun, ciri-ciri ketidaktentuan sumber tenaga boleh diperbaharui (RES) dan permintaan beban yang tidak dapat diramalkan boleh mengganggu keseimbangan dalam grid mikro. Jentera diesel selalunya digunakan untuk menyediakan kuasa tambahan dan berfungsi sebagai sandaran untuk grid mikro. Namun begitu, penggunaan jentera diesel yang tidak cekap boleh menyebabkan kos operasi yang berlebihan, pengurangan jangka hayat dan pencemaran alam sekitar. Pengurusan tenaga (EMS) dilaksanakan untuk mengoptimumkan kos operasi grid mikro dan kebolehpercayaan dengan menggunakan kawal perkiraan model (MPC) yang semakin popular kerana keupayaannya dalam menyokong input dan output yang pelbagai. EMS berasaskan MPC dibangunkan menggunakan perisian MATLAB/Simulink, dengan masalah pengoptimuman diformulasikan menggunakan pengaturcaraan kuadratik berbilangan campuran (MIQP). Analisis perbandingan dijalankan antara EMS berasaskan MPC dengan dan tanpa keupayaan pemangkasan beban, yang mendedahkan pengurangan yang signifikan sebanyak 52.21% dalam penjimatan kos bahan api diesel dengan penambahan keupayaan pemangkasan beban.

KEYWORDS: *Model Predictive Control (MPC), Energy Management System (EMS), Microgrid, Mixed Integer Quadratic Programming (MIQP), Load Curtailment*

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1. INTRODUCTION

Increased energy demand, environmental pollution, and high costs are some reasons why renewable energy sources (RES), such as solar photovoltaics (PV), wind energy, and others, have emerged in popularity to replace the traditional energy generation sources [1]. RES has become the first choice to replace the infeasible traditional energy sources due to their clean nature, abundance availability, and low cost. However, RES is heavily dependent on environmental conditions. Hence, RES poses some uncertainties in the energy generation. Microgrid is introduced to properly manage the RES to overcome the impact of these uncertainties [2-4].

A microgrid is a structure that incorporates distributed energy resources (DER), either renewable or non-renewable energy sources, with other components such as energy storage systems (ESS) to meet the load demand [2]. The Department of Energy of the United States of America defines a microgrid as " a group interconnected loads and distributed energy resources (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" [5]. Microgrids can be categorized into grid-connected and islanded modes. The difference between these two modes is the connection or disconnection of the microgrid from the grid through the point of common coupling [1, 2]. The islanded microgrid can also be considered a standalone or isolated microgrid due to the unavailability of the main grid.

The intermittent nature of RES and the unpredictable nature of load can cause instability in the microgrid. In addition, the inefficient usage of non-renewable energy sources such as diesel generators can cause immediate wear and tear, shorten the life span, and pollute the environment [6]. Hence, an energy management system (EMS) is introduced for efficient DER management in the microgrid. According to [7], EMS can help maintain the supply and demand in the microgrid, improve reliability, and reduce energy production costs, especially for non-renewable energy sources such as diesel generators. While researchers have developed various EMS techniques for microgrids, model predictive control (MPC) has emerged as a particularly popular approach within the research community [8]. This is due to its capability to forecast the dynamic of the system, thus reducing the uncertainty in managing the microgrid [1, 9]. This will improve the overall operation of the microgrid in terms of operational cost and efficiency.

MPC does not relate to a specific control strategy but rather a group of control approaches that take full use of the system model under certain constraints to generate control signals or directives by minimizing predetermined cost functions [10]. Some advantages of MPC are the ability to handle multiple inputs and multiple outputs (MIMO) and allow the plant constraints to be defined explicitly, unlike other control approaches. However, MPC needs the control system designer to understand the system to create an accurate model thoroughly. In addition, MPC requires powerful processing since it is computationally expensive [8].

Demand Side Management (DSM) is a part of the branches under the EMS. DSM is important for EMS in microgrids since it helps relax the tightness of an optimization problem, improving the load patterns and reducing the peak load demand in the microgrid [11]. DSM is important, especially in standalone microgrids, since it relies only on the energy sources available in the microgrid. Figure 1 shows some of the side management techniques [12]. Load shedding or curtailment is one of the famous techniques under DSM, and it can help in reducing the operational cost in the microgrid [13]. Many papers have been observed focusing on developing MPC-based EMS for standalone microgrids.

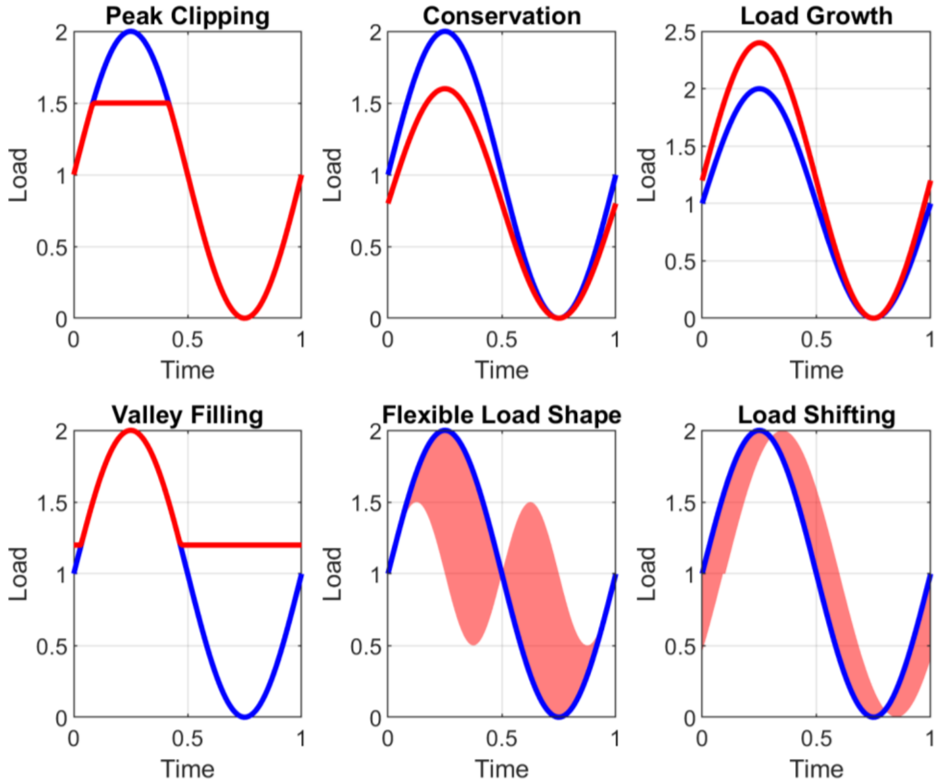

Figure 1. Demand Side Management Techniques

Several research, such as [14] and [15] has been observed implementing load curtailment in the standalone microgrid. [14] utilized MPC in their EMS to implement load curtailment to minimize the operation cost of the diesel generator. On the other hand, load curtailment is utilized in [15] to manage power balance by decreasing the reliance on diesel generators. However, these two papers focus on industrial microgrid and electric vehicle applications. In contrast, studies [6], [16], [17], [18] and [19] stated that a standalone residential microgrid indicates no load curtailment is implemented. Authors in [20] while not implementing load curtailment, the authors penalized the unmet demand and curtailed the PV power output. According to [6], this move defeats the microgrid's purpose, where the RES's power consumption should be maximized. Properly sizing the microgrid at the design stage helps prevent unmet demand and RES curtailment. Correctly sizing the microgrid components ensures that energy can be delivered to meet demand effectively in all situations [21].

This paper simulates MPC-based EMS with load curtailment for a standalone microgrid using MATLAB/Simulink. The standalone microgrid comprises solar PV, battery ESS, diesel generators, and loads for residential applications. The MPC-based EMS is intended to reduce the fuel cost of the diesel generator through load curtailment and ensure the power balance in the standalone residential microgrid. A comparison is made between MPC-based EMS without load curtailment and load curtailment under residential usage.

2. METHODOLOGY

2.1. Microgrid Design

In this paper, a standalone AC/DC microgrid is considered. Figure 2 shows the standalone microgrid. Solar PV is the primary energy generation source and is set in maximum power point tracking (MPPT) mode. This ensures that the maximum power is extracted from the solar

PV. A diesel generator will be acting as a backup energy generation source. Its usage should be minimized to reduce operational costs and protect the environment. The BESS is used to store the excess energy produced by solar PV and release the energy when the solar PV is unable to meet the demand. When solar PV and BESS are unable to meet the demand, diesel generators will be turned on to aid in ensuring the power balance is met.

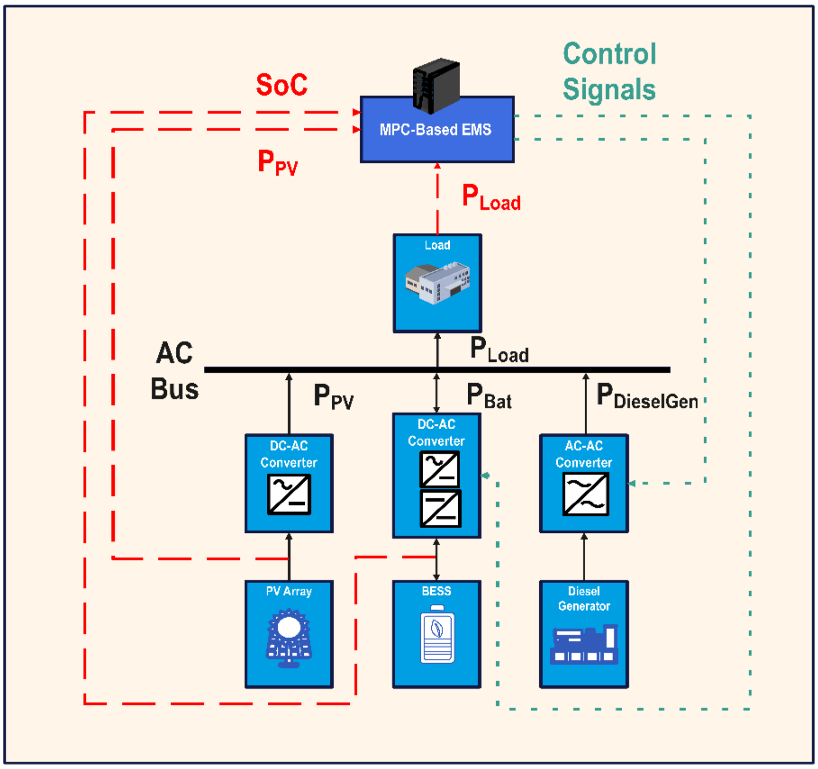

Figure 2. Proposed Standalone Microgrid

From Figure 2, MPC-based EMS collects information such as the current power output of solar PV, P_{PV}, current BESS power, P_{Bat}, current load, P_{Load} and the BESS's current state of charge (SoC). This information will be processed to generate the optimal control signals for the BESS, diesel generator, and load.

2.2. System Modelling

The BESS considered in this paper is a Lithium-ion (Li-Ion) battery. The dynamic model of the BESS can be represented as the SoC of the BESS. There are many ways to model the SoC of the BESS. One of the methods is the Coulomb Counting method. The dynamic model of BESS is shown in Eq. (1) [22, 23].

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

where $SoC(k+1)$ is the SoC of the BESS at the next time step, $SoC(k)$ is the current SoC of the BESS, $P_{Bat}^{discharging}(k)$ and $P_{Bat}^{charging}(k)$ are the current discharging and charging battery power in watts, respectively, T_s is the sampling time in hours and C_{Bat}^{max} is the maximum capacity of the battery in watt-hours. The efficiency of the power converter, as well as the charging and discharging efficiency, need to be considered in the model. Furthermore, the dynamic model can be divided to show the SoC of the BESS when charging and discharging mode. This is shown in Eq. (2).

$$SoC(k+1) = \begin{cases} SoC(k) - \frac{P_{Bat}(k).T_S.\eta_{charging}}{C_{Bat}^{max}} & if\ P_{Bat}(k) < 0 \\ SoC(k) - \frac{P_{bat}(k).T_S}{C_{Bat}^{max}.\eta_{discharging}} & if\ P_{Bat}(k) \geq 0 \end{cases} \quad (2)$$

where $\eta_{charging}$ and $\eta_{discharging}$ represents the product of BESS charging and discharging efficiency and power converter efficiency, respectively. Eq. (2) is a hybrid dynamical model where the system's dynamic changes according to the power flow from and to the BESS and cannot be used directly in the optimization problems [6]. It needs to be converted into a mixed logical dynamic (MLD) where a particular model form can be represented using the Boolean variable. The MLD model of the BESS Is shown in Eq. (3) [6].

$$oC(k+1) = SoC(k) + \frac{T_s}{C_{Bat}^{max}}.Z_{Bat}(k).\left(\eta_{charging} - \frac{1}{\eta_{discharging}}\right) - \frac{T_S.\eta_{charging}}{C_{Bat}^{max}} P_{Bat}(k) \quad (3)$$

where $Z_{Bat}(k)$ is an auxiliary variable, which $Z_{Bat}(k) = \delta_{Bat}(k).P_{Bat}(k)$. $\delta_{bat}(k)$ is the Boolean variable, and $\delta_{Bat}(k) \in \{0,1\}$. When $[\delta_{Bat}(k) = 1] \leftrightarrow [P_{Bat}(k) < 1]$. The BESS will be set to charging mode when $\delta_{Bat}(k)$ is equal to 1 and vice versa. The auxiliary variable is introduced to ensure the formulation is linear. The constraints for BESS model are listed in equation (4) – (9) [6].

$$-P_{Bat}^{min}.\delta_{Bat} \leq P_{Bat} - P_{Bat}^{min} \quad (4)$$

$$-P_{Bat}^{max}.\delta_{Bat} \leq -P_{Bat} \quad (5)$$

$$Z_{Bat} \leq P_{Bat}^{max}.\delta_{Bat} \quad (6)$$

$$Z_{Bat} \geq P_{Bat}^{min}.\delta_{Bat} \quad (7)$$

$$Z_{Bat} \leq P_{Bat} + P_{Bat}^{max}.(1-\delta_{Bat}) \quad (8)$$

$$Z_{Bat} \geq P_{Bat} + P_{Bat}^{min}.(1-\delta_{Bat}) \quad (9)$$

This paper does not consider the detailed model of the diesel generator. The diesel generator is assumed to be fast-acting and has low start-up time. The constraint of the diesel generator is defined as the minimum and maximum power output that can be generated by the diesel generator. The constraints are shown in Eq. (10) and Eq. (11) [6].

$$P_{DiseselGen}^{min}\delta_{DieselGen} \leq P_{DieselGen} \quad (10)$$

$$P_{DieselGen} \leq P_{DieselGen}^{max}\delta_{DieselGen} \quad (11)$$

where $\delta_{DieselGen}(k)$ is the Boolean variable, and $\delta_{DieselGen}(k) \in \{0,1\}$. The diesel generator is ON and OFF when $\delta_{DieselGen}(k) = 1$ and when $\delta_{DieselGen}(k) = 0$ respectively. The diesel generator can operate by generating output power ranging from $P_{DieselGen}^{min}$ until $P_{DieselGen}^{max}$ when in ON mode while output none when in OFF mode.

The constraint for the load curtailment is shown in Eq. (12) [15]. The load curtailment cannot exceed a specified value.

$$P_{Curtail}^{min} \leq P_{Curtail}(k) \leq P_{Curtail}^{max} \quad (12)$$

where $P_{Curtail}^{min}$ and $P_{Curtail}^{max}$ are the minimum and maximum power that can be curtailed by the EMS, respectively.

The power balance in the microgrid should always be met and cannot be violated. The equality equation in Eq. (13) shows the power balance equation for the microgrid.

$$P_{PV}(k) + P_{Bat}(k) + P_{Dieselgen}(k) = P_{Load}(k) - P_{Curtail}(k) \tag{13}$$

$P_{PV}(k)$ is the PV output power, $P_{Bat}(k)$ is the BESS output power, $P_{DieselGen}(k)$ is the diesel generator output power, $P_{Load}(k)$ is the load consumption power and $P_{Curtail}(k)$ is the load curtailment power. The power flow considered is that power is positive when flowing into the grid while negative when flowing out from the grid.

2.3. Objective Functions

The first objective function is to minimize the fuel cost of the diesel generator. For this, the fuel consumption of the diesel generator needs to be reduced by efficiently using the diesel generator. The fuel cost function of the diesel generator can be represented by the quadratic cost curve (QCC) [24]. Equation (14) shows the fuel cost function equation of the diesel generator.

$$J_{DG} = C_{DieselGen}.[a.P_{DieselGen}(k)^2 + b.P_{DieselGen}(k) + c] \tag{14}$$

where $P_{DieselGen}(k)$ is diesel generator power output. a, b and c are the fuel cost coefficients. $C_{DieselGen}$ is the cost of the diesel. The QCC is illustrated in Figure 3.

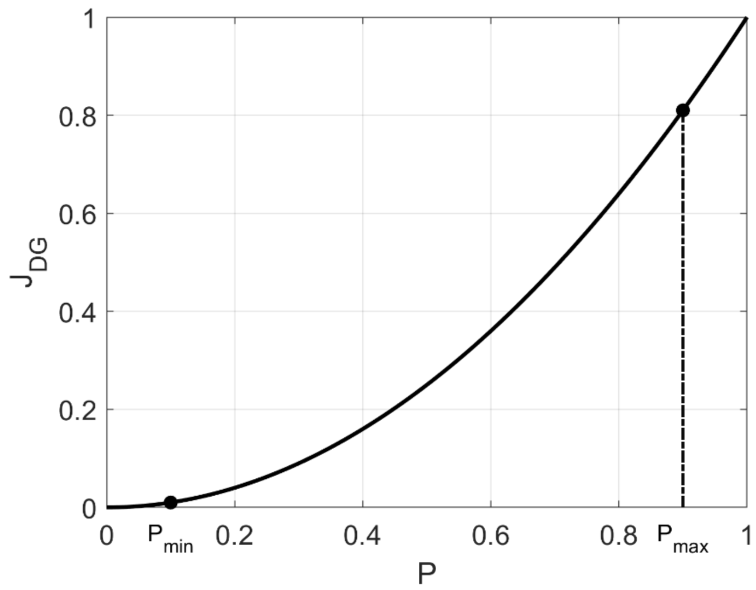

Figure 3. Quadratic Cost Curve

Figure 3 illustrates that when the diesel generator power delivered to the grid decreases, the fuel cost required while the generator runs also decreases. If the diesel generator is not supplying power to the grid, the fuel cost is zero. It is advisable to either switch off the diesel generator most of the time or to provide the grid with less electricity.

Next, the second objective is to guarantee that the BESS's SoC always follows the reference SoC value. This ensures that there will always be reserved energy in the BESS. The

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SoC reference value is recommended to be between the minimum and maximum SoC. The objective function is shown in Eq. (15).

$$J_{Bat} = \left[SoC\ (k+1) - SoC_{ref}\right]^2 \tag{15}$$

where $SoC\ (k+1)$ is the future or predicted SoC value and SoC_{ref} is the reference SoC value. Lastly, the third objective is to reduce greenhouse gas emissions due to the burning of diesel fuel [25]This is represented in Eq. (16). Burning diesel fuel from the diesel generator releases greenhouse gases into the atmosphere. Reducing the microgrid's diesel generator usage can reduce this.

$$J_{GHG} = \left[\alpha_{NO_x}\mu_{NO_x} + \alpha_{CO_2}\mu_{CO_2} + \alpha_{CO}\mu_{CO} + \alpha_{SO_2}\mu_{SO_2}\right].P_{DieselGen}(k) \tag{16}$$

where α is the emission factor of a greenhouse gas expressed in kg/kWh. μ is the environmental damage cost due to the gas emission expressed in RM/kg. $P_{DieselGen}(k)$ is DG power output. NO_x, CO_2, CO and SO_2 are nitric oxide, nitrogen dioxide, carbon dioxide, carbon monoxide, and sulfur dioxide.

The overall objective functions can be formulated as in Eq. (17). It can be observed that the cost function of the BESS, J_{Bat}, is the only cost function defined with error square optimization, while other cost functions, $J_{DieselGen}$ and J_{GHG} are not. The J_{Bat} is intended to ensure that the EMS always maintains the SoC of the BESS according to the reference. In contrast, the other cost functions can vary if their constraints are not violated. However, depending on the weights assigned to each cost function, the optimization might focus on a specific cost function instead of balancing all of them [26].

$$J_{Global} = J_{DieselGen} + J_{Bat} + J_{GHG} \tag{17}$$

2.4. Optimization Using Mixed Integer Quadratic Programming (MIQP) under MPC Framework

The overall optimization problem can be formulated by combining the system model, constraints, and objective functions discussed in previous sections.

Minimize	Eq. (17)
Subject to	BESS Model: Eq. (3)
	BESS Constraints: Eq. (4) – Eq. (9)
	Diesel Generator Constraints: Eq. (10) – Eq. (11)
	Load Curtailment Constraint: Eq. (12)
	Power Balance: Eq. (13)

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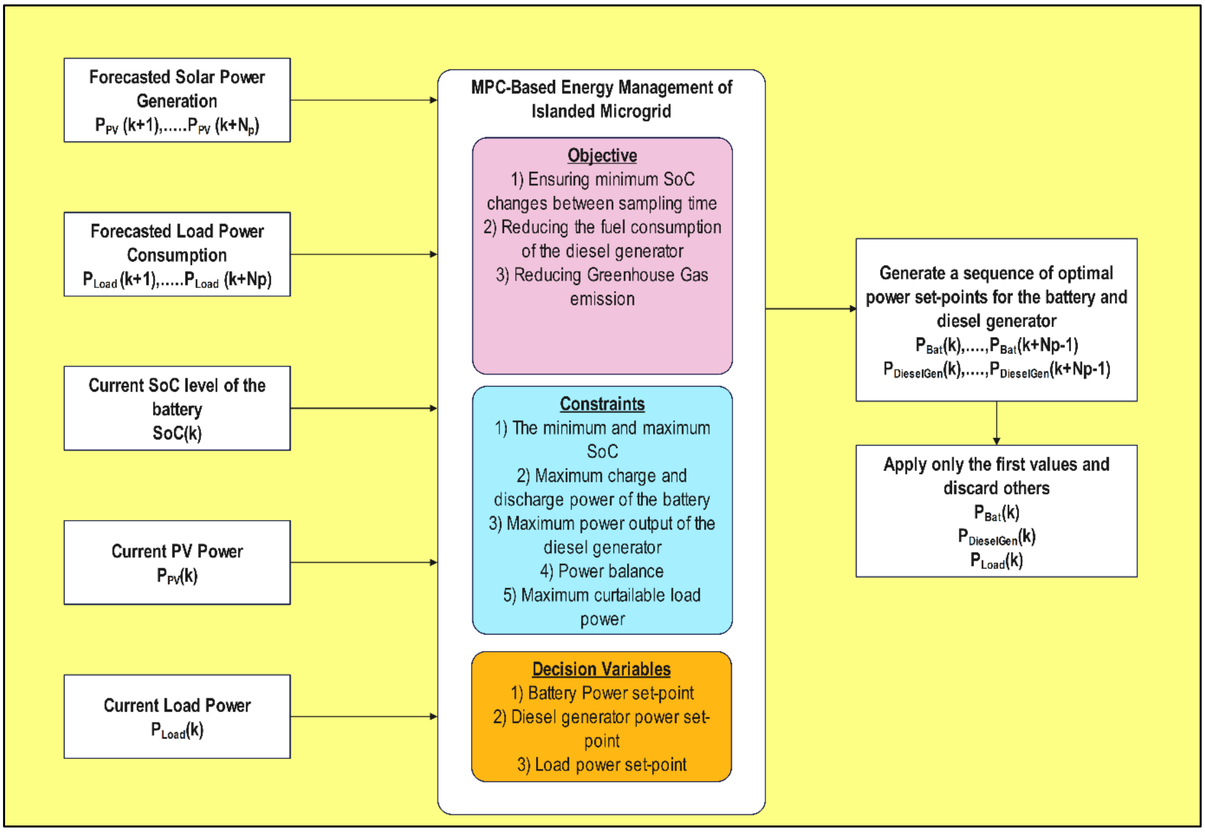

Figure 4. MPC-Based EMS of Islanded Microgrid

From Figure 4, the optimization problem is solved, and the optimal input sequence for the prediction horizon N_p is obtained. Although a complete sequence of N_p is computed, only the first element is sent to the system, and the remaining optimal values are discarded. The prediction horizon is shifted at the following sample time, and the optimization problem is solved again with EMS collecting a new information value from the microgrid.

In this paper, MPC-based EMS is developed by using MATLAB software. CPLEX is utilized to solve the energy management optimization problem. CPLEX is a mathematical optimization software package developed by IBM, and CPLEX version 12.10 is employed, which is the most recent version to support MATLAB integration. CPLEX is used to solve the MIQP optimization problem due to the unavailability of the MIQP solver in MATLAB. Multiple commercial solvers, such as CPLEX, Gurobi, etc., are available. CPLEX is chosen due to its extensive documentation and easy integration [6].

2.5. Solar PV Generation Forecasting and Load Forecasting

In this paper, future solar PV generation and the load demand are certainly known. With this, solar PV generation forecasting and load demand forecasting are perfect with no uncertainty. The MPC-based EMS may not be able to be tested for its robustness due to the absence of uncertainty, especially in real-time systems. However, according to [27], the MPC-based EMS can perform excellently with or without uncertainty factors in forecasting generation and load demand.

3. RESULT AND DISCUSSION

The microgrid, cost, and simulation parameters are listed in Tables 1, 2, and 3. The solar PV generation and load demand data are obtained from [28]. The dataset consists of residential load and PV systems with a 1-minute resolution. This paper resamples the dataset into a 1-hour interval for 72 hours. Figures 5 and 6 show the profile of solar PV generation and load demand.

Table 1. Microgrid Parameters

Microgrid Parameters	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%
η_{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)

Table 2. Cost Functions Parameters

Cost Parameters	Value
Weight of BESS Cost Function, λ_1	1
Weight of Fuel Consumption Cost Function, λ_2	70
Weight of Greenhouse Emission Cost Function, λ_3	475.17
a	2.5 $\frac{L}{kWh^2}$
b	-1.375 $\frac{L}{kWh}$
c	0.7813 $\frac{L}{h}$
C_{DG}	2.05 $\frac{RM}{L}$
α_{CO_2}	0.232037 $\frac{kg}{kWh}$
α_{NO_x}	0.00431 $\frac{kg}{kWh}$
α_{CO}	0.00233 $\frac{kg}{kWh}$
α_{SO_2}	0.00464 $\frac{kg}{kWh}$
μ_{NO_x}	1.27 $\frac{RM}{kg}$
μ_{CO_2}	0.0057 $\frac{RM}{kg}$
μ_{CO}	0.10 $\frac{RM}{kg}$
μ_{SO_2}	0.57 $\frac{RM}{kg}$

Table 3. Simulation Parameters

Simulation Parameters	Value
Sampling Time, T_s	1 Hour
Simulation Duration	72 Hours
Prediction Horizon, N_P	24 Hours

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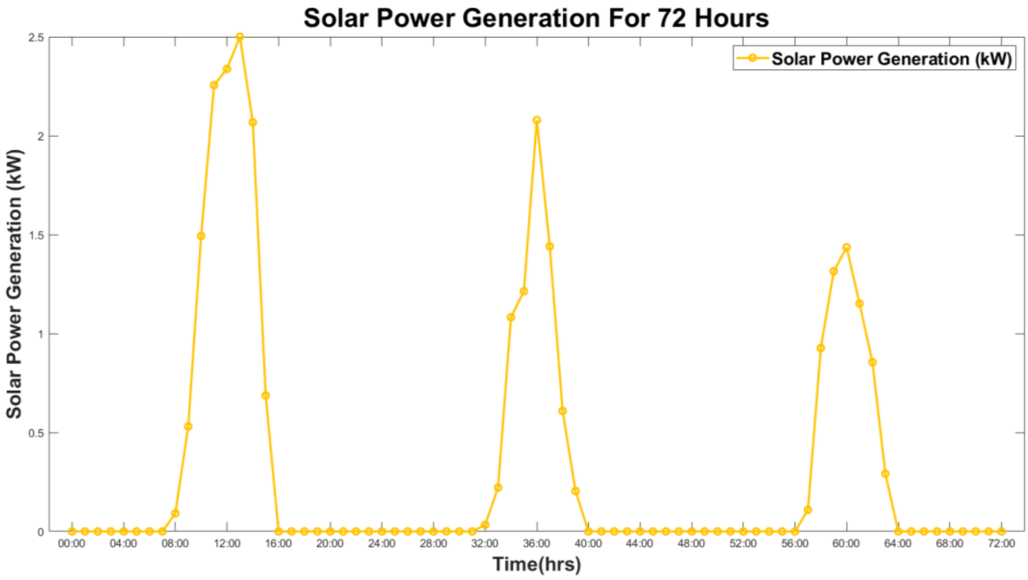

Figure 5. Solar PV Generation Profile

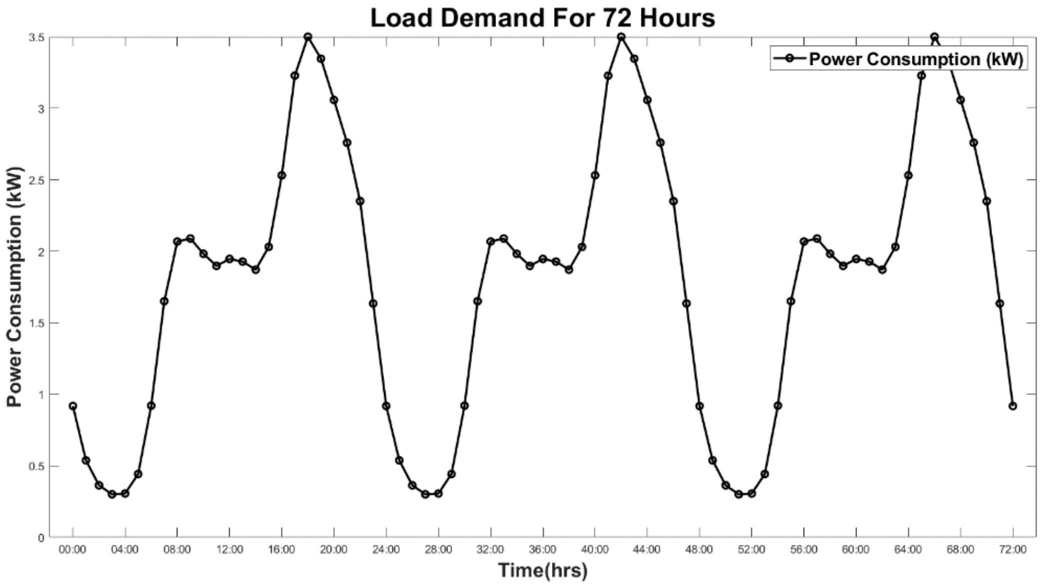

Figure 6. Load Demand Profile

The BESS cost function is assigned a weight of 1, while the fuel consumption cost function and greenhouse gas emission cost function are given weights of 70 and 475.17, respectively. This allocation of weights aims to balance the final cost value, accounting for the difference between the fuel cost and greenhouse gas emission cost, which are 2.05 $\frac{RM}{L}$ and 0.302 $\frac{RM}{kWh}$ respectively.

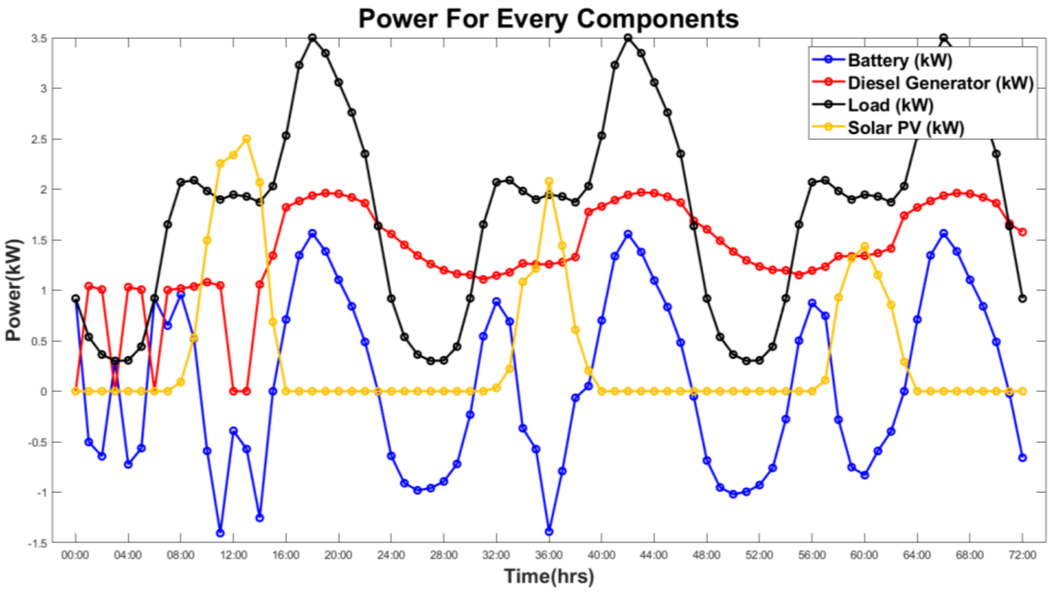

Figure 7. Energy Profile for All Components for MPC-Based EMS Without Load Curtailment

Table 2. Power Set-Point for Every Component for MPC-Based EMS Without Load Curtailment for the first 24 hours

Time (h)	P_{PV} (kW)	P_{DG} (kW)	P_{BESS} (kW)	P_{Loads} (kW)
00:00	0	0	0.9176	0.9176
01:00	0	1.0403	-0.5027	0.5375
02:00	0	1.0069	-0.6438	0.3631
03:00	0	0	0.3	0.3
04:00	0	1.0306	-0.7249	0.3057
05:00	0	1.0057	-0.5636	0.4422
06:00	0	0	0.9202	0.9202
07:00	0	1.0012	0.6492	1.6505
08:00	0.0916	1.0179	0.9587	2.0681
09:00	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	3.2281
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	3.0575
21:00	0	1.9188	0.8402	2.7590
22:00	0	1.8619	0.4880	2.35
23:00	0	1.6387	-0.0040	1.6347
00:00	0	1.5574	-0.6398	0.9176

Figure 7 shows the energy profile for all components in MPC-based EMS without load curtailment, while Table 2 shows the power set-point for every component in MPC-based EMS without load curtailment for the first 24 hours. It shows that the MPC-based EMS effectively manages energy within the islanded microgrid. The constraints for all components, particularly the BES and diesel generator, are adhered to. The BESS maintains its charging and discharging power within the limits of 3 kW and -3 kW, respectively. Similarly, the diesel generator's output does not exceed the 5 kW threshold. The power balance is consistently maintained, as demonstrated in Table 2. Figure 8 illustrates the SoC of the BESS over 72 hours, showing that the SoC remains within the prescribed limits to prevent deep charging and discharging, as indicated in Table 4.5

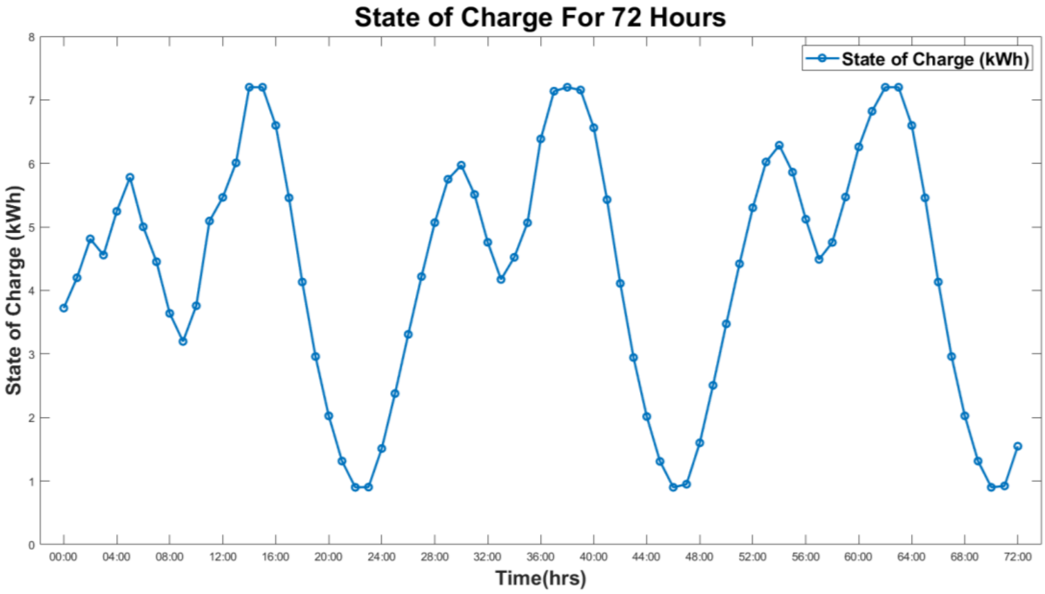

Figure 8. SoC of the BESS for MPC-Based EMS Without Load Curtailment

Figure 8 shows that the BESS charges whenever the solar PV generates power, typically between 8:00 AM and 3:00 PM. During this period, the EMS directs the BESS to store the excess energy, and the diesel generator either remains inactive or outputs minimal power, especially on subsequent days. The stored energy is utilized from 3:00 PM onwards, when the solar PV ceases power generation, causing the BESS to discharge alongside the diesel generator to meet the energy demand.

Additionally, the BESS charges after midnight when the load demand decreases, utilizing power from the diesel generator. The diesel generator's output during this time also supplies the loads. However, this extensive use of the diesel generator results in high fuel consumption, leading to increased operational costs. Figure 9 shows the energy profile for all components for MPC-based EMS with load curtailment, while Table 3 shows the power set-point for every component for MPC-based EMS with load curtailment for the first 24 hours.

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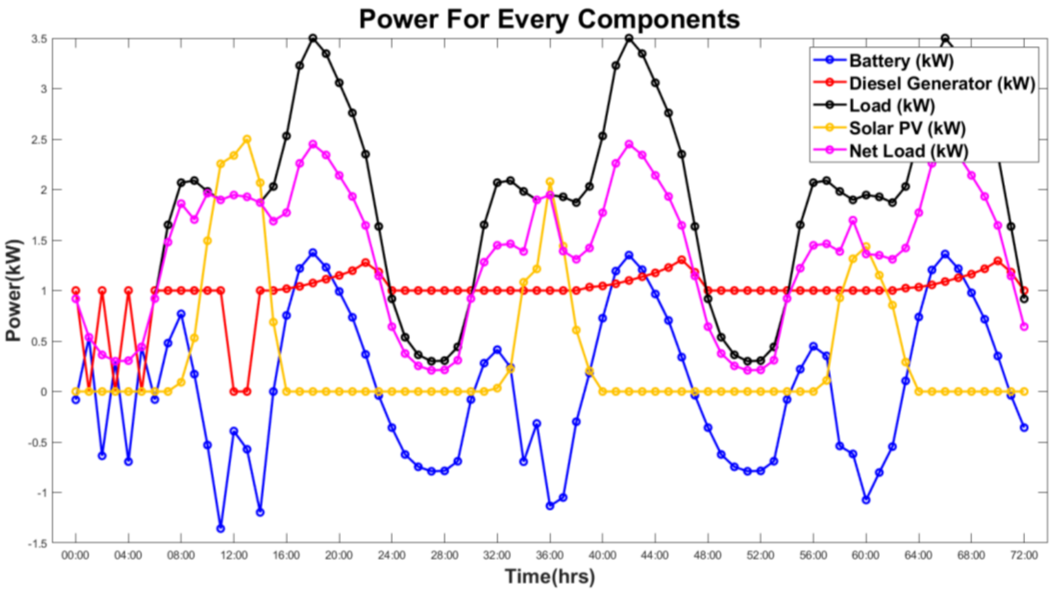

Figure 9. Energy Profile for All Components for MPC-Based EMS With Load Curtailment

Table 3. Power Set-Point for Every Component for MPC-Based EMS With Load Curtailment for the First 24 hours

Time (h)	P_{PV} (kW)	P_{DG} (kW)	P_{BESS} (kW)	P_{Loads} (kW)	$P_{CURTAIL}$ (kW)
00:00	0	1	-0.0824	0.9176	0
01:00	0	0	0.5375	0.5375	0
02:00	0	1	-0.6369	0.3631	0
03:00	0	0	0.3	0.3	0
04:00	0	1	-0.6943	0.3057	0
05:00	0	0	0.4422	0.4422	0
06:00	0	1	-0.0798	0.9202	0
07:00	0	1	0.4793	1.6505	0.1712
08:00	0.0916	1	0.7689	2.0681	0.2076
09:00	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	1.8709	0
15:00	0.6872	1	0	2.0305	0.3433
16:00	0	1.0180	0.7535	2.5306	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	3.3465	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	1.6347	0.4904
00:00	0	1	-0.3577	0.9176	0.2753

Figure 9 demonstrates that the proposed MPC-based EMS effectively manages energy within the islanded microgrid while adhering to the constraints of all components, particularly the BES and diesel generator. The BESS operates within its charging and discharging limits of

3 kW and -3 kW, respectively, while the diesel generator's output remains below the 5-kW threshold. The power balance is consistently maintained, as outlined in Table 3. Additionally, Figure 9 illustrates the SoC of the BESS over a 72-hour period, showing that it stays within the prescribed boundaries, thereby protecting the BESS from deep charging and discharging.

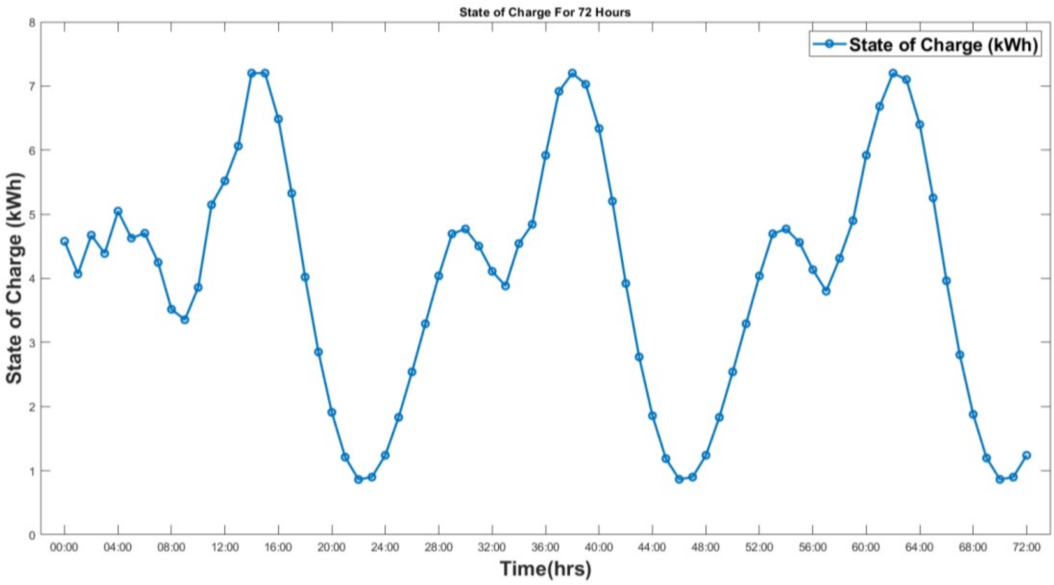

Figure 10. SoC of the BESS for MPC-Based EMS With Load Curtailment

It is observed that the MPC-based EMS applied load curtailment, as shown in Figure 9. Load curtailment occurred from morning until noon and from evening until night, consistently staying within 30% of the original loads. While the EMS aimed to curtail all loads by 30%, it did not always achieve this level. For example, during 6:00 AM, 7:00 AM, and 8:00 AM, the curtailment ranged from 10% to 20% of the original loads, likely due to the availability of solar PV power, which provided additional energy to meet demand. In contrast, during the evening and night, when there was little to no sunlight and solar PV could not generate power, load curtailment increased. Table 3 indicates that from 3:00 PM until midnight, load curtailment was generally around 30% of the original loads. During this period, the BESS discharged to help supply the load alongside the diesel generator. Figure 9 shows that the diesel generator's output remained constant throughout the 72-hour period, suggesting that load curtailment effectively reduced the supply and demand gap between the solar PV, diesel generator, BESS, and loads.

From these results, it can be concluded that the MPC-based EMS effectively and efficiently manages the microgrid's components in both scenarios. The power balance is maintained, and the power output constraints are respected, as shown in Table 2 and Table 3. Additionally, in both cases, the SoC of the BESS is kept within the specified range, as depicted in Figure 8 and Figure 10. The fluctuating SoC of the BESS is attributed to the weight assignments in the optimization process, which prioritize reducing fuel consumption and greenhouse gas emissions.

In the scenario without load curtailment, the diesel generator is used excessively to meet the high demand, especially during the evening and night. Conversely, with load curtailment, the diesel generator exhibits an almost constant low power output. This reduction is attributed to load curtailment, which helps minimize the gap between generation and demand. Table 4 compares diesel fuel consumption and fuel costs between the MPC-based EMS with and without load curtailment, further highlighting the benefits of incorporating load curtailment into the energy management strategy.

Table 4. Fuel Consumption and Fuel Cost Comparison

	Case 1: MPC-based EMS Without Load Curtailment	**Case 2: MPC-based EMS With Load Curtailment**
Diesel Fuel Consumption	309.50 Litres	147.88 Litres
Diesel Fuel Cost	RM 665.43	RM 317.95

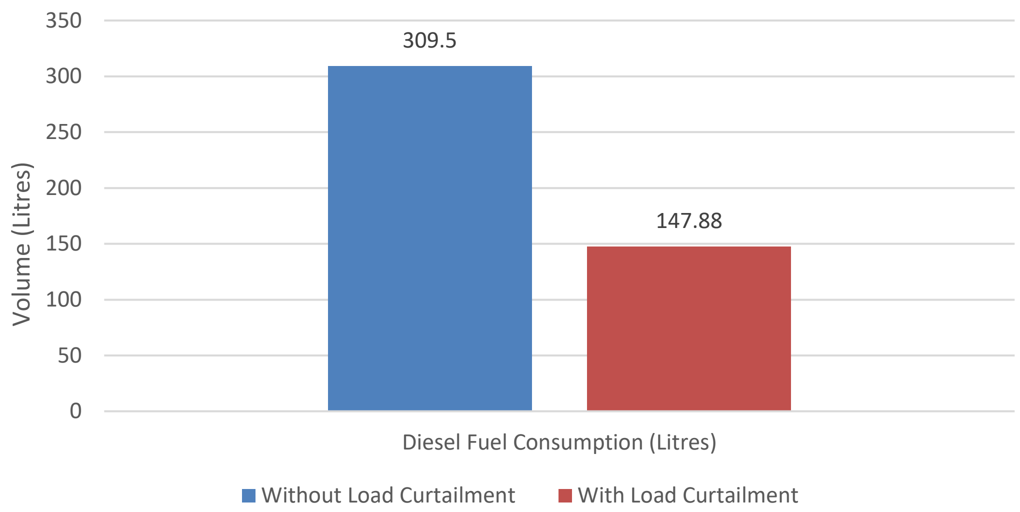

Figure 11. Diesel Fuel Consumption Comparison

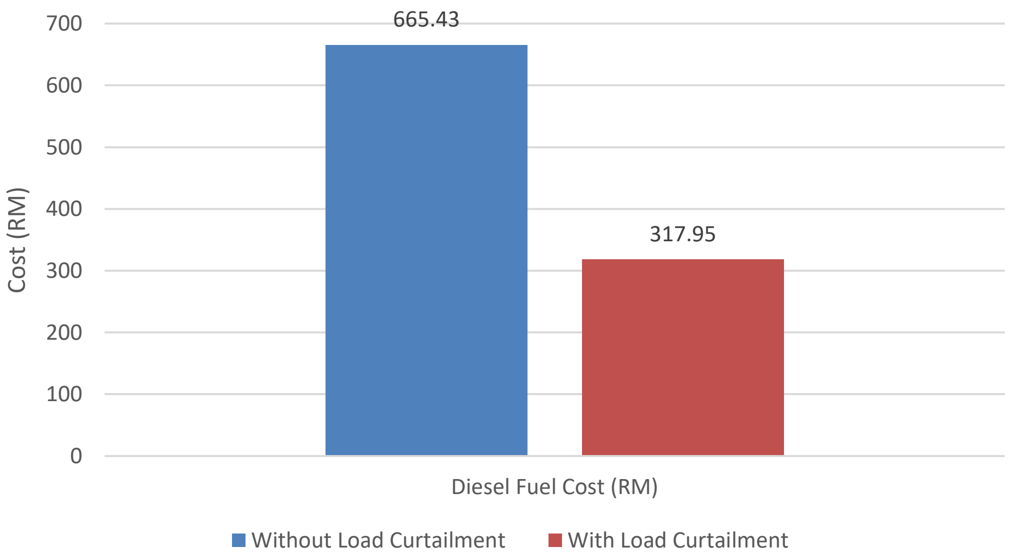

Figure 12. Diesel Fuel Cost Comparison

Figures 11 and 12 illustrate a significant reduction in diesel fuel consumption and expenses achieved by implementing load curtailment in an islanded microgrid. Diesel fuel consumption decreased drastically from 309.50 liters to 147.88 liters, representing a remarkable reduction of 52.21%. Correspondingly, diesel fuel expenses dropped from RM 665.43 to RM 317.95, highlighting the economic benefits of integrating load curtailment within the MPC-based EMS. This substantial improvement underscores the effectiveness of load curtailment in optimizing resource utilization and reducing operational costs.

The results strongly demonstrate that the proposed MPC-based EMS, equipped with load curtailment capabilities, minimizes diesel generator operation costs within an islanded microgrid. The 52.21% reduction in fuel consumption and expenses underscores the system's efficiency and indicates its potential for further cost savings. Beyond cost reductions, the MPC-based EMS ensures efficient microgrid component management by maintaining power balance and adhering to predefined constraints. This capability highlights the robustness and practicality of the system for real-world applications, making it a highly viable solution for enhancing the performance and sustainability of islanded microgrids.

4. CONCLUSION

This paper presents the implementation of an MPC-based EMS for a standalone microgrid, focusing on integrating load curtailment to optimize diesel generator fuel consumption. The results demonstrate the system's ability to manage microgrid components while adhering to predefined constraints effectively. With load curtailment, the MPC-based EMS achieved a remarkable 52.21% reduction in diesel fuel consumption, saving 161.52 liters of diesel, valued at RM347.80, compared to operations without load curtailment. These findings highlight the dual benefits of enhanced economic efficiency and environmental sustainability, as the significant reduction in diesel usage minimizes greenhouse gas emissions, paving the way for more eco-friendly microgrid operations. The integration of load curtailment within the MPC framework enhances resource efficiency and ensures a more sustainable and cost-effective energy management strategy for standalone microgrids. However, recognizing the potential discomfort to users caused by curtailed loads, future work should explore penalizing load curtailment to balance operational efficiency with user satisfaction. Future developments can further refine the MPC-based EMS to deliver even more robust, user-friendly, and sustainable energy management solutions by addressing this trade-off.

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REFERENCES

[1] J. M. Raya-Armenta, N. Bazmohammadi, J. G. Avina-Cervantes, D. Sáez, J. C. Vasquez, and J. M. Guerrero (2021). Energy management system optimization in islanded microgrids: An overview and future trends. Renewable and Sustainable Energy Reviews, 149: 111327. https://doi.org/10.1016/j.rser.2021.111327

[2] Y. Zahraoui, I. Alhamrouni, S. Mekhilef, M. R. Basir Khan, M. Seyedmahmoudian, A. Stojcevski, and B. Horan, (2021). Energy Management System in Microgrids: A Comprehensive Review. Sustainability, 13(19). https://doi.org/10.3390/su131910492

[3] A. Badawi, N. Hasbullah, S. Yusoff, and A. Hashim (2019). Energy and power estimation for three different locations in Palestine. Indonesian Journal of Electrical Engineering and Computer Science, 14: 1049-1056. https://doi.org/10.11591/ijeecs.v14.i3.pp1049-1056

[4] A. Badawi, A. Zyoud, S. Khan, A. Hashim, and N. Hasbullah (2019). Evaluation of Wind Power for Electrical Energy Generation in the Mediterranean Coast of Palestine for 14 Years.

International Journal of Electrical and Computer Engineering, 9: 2212-2219. https://doi.org/10.11591/ijece.v9i4.pp2212-2219

[5] M. F. Zia, E. Elbouchikhi, and M. Benbouzid (2018). Microgrids energy management systems: A critical review on methods, solutions, and prospects. Applied Energy, 222: 1033-1055. https://doi.org/10.1016/j.apenergy.2018.04.103

[6] U. R. Nair and R. Costa-Castelló (2020). A Model Predictive Control-Based Energy Management Scheme for Hybrid Storage System in Islanded Microgrids. IEEE Access, 8: 97809-97822. https://doi.org/10.1109/ACCESS.2020.2996434

[7] S. Rathor and D. Saxena (2020). Energy management system for smart grid: An overview and key issues. International Journal of Energy Research, 44. https://doi.org/10.1002/er.4883

[8] K. S. Joshal and N. Gupta, (2023). Microgrids with Model Predictive Control: A Critical Review. Energies, 16(13). https://doi.org/10.3390/en16134851

[9] S. K. Rathor and D. Saxena (2020). Energy management system for smart grid: An overview and key issues. International Journal of Energy Research, 44(6): 4067-4109.

[10] J. Hu, Y. Shan, J. M. Guerrero, A. Ioinovici, K. W. Chan, and J. Rodriguez (2021). Model predictive control of microgrids – An overview. Renewable and Sustainable Energy Reviews, 136: 110422. https://doi.org/10.1016/j.rser.2020.110422

[11] C. Essayeh, M. Raiss El-Fenni, H. Dahmouni, and M. A. Ahajjam (2021). Energy Management Strategies for Smart Green MicroGrid Systems: A Systematic Literature Review. Journal of Electrical and Computer Engineering, 2021: 6675975. https://doi.org/10.1155/2021/6675975

[12] A. M. Jasim, B. H. Jasim, B.-C. Neagu, and B. N. Alhasnawi, (2023). Efficient Optimization Algorithm-Based Demand-Side Management Program for Smart Grid Residential Load. Axioms, 12(1). https://doi.org/10.3390/axioms12010033

[13] S. Ahmad, M. Shafiullah, C. B. Ahmed, and M. Alowaifeer (2023). A Review of Microgrid Energy Management and Control Strategies. IEEE Access, 11: 21729-21757. https://doi.org/10.1109/ACCESS.2023.3248511

[14] H. He, S. Huang, Y. Liu, and T. Zhang (2021). Robust Model Predictive Control for Energy Management of Isolated Microgrids Based on Interval Prediction. Discrete Dynamics in Nature and Society, 2021: 2198846. https://doi.org/10.1155/2021/2198846

[15] K.-S. Ryu, D.-J. Kim, H. Ko, C.-J. Boo, J. Kim, Y.-G. Jin, and H.-C. Kim (2021). MPC Based Energy Management System for Hosting Capacity of PVs and Customer Load with EV in Stand-Alone Microgrids. Energies, 14(13). https://doi.org/10.3390/en14134041

[16] T. Pippia, J. Sijs, and B. D. Schutter (2020). A Single-Level Rule-Based Model Predictive Control Approach for Energy Management of Grid-Connected Microgrids. IEEE Transactions on Control Systems Technology, 28(6): 2364-2376. https://doi.org/10.1109/TCST.2019.2945023

[17] I. Novickij and G. Joós, (2019). Model Predictive Control Based Approach for Microgrid Energy Management. IEEE: 1-4. https://doi.org/10.1109/CCECE.2019.8861781

[18] P. K. Ndwali, J. G. Njiri, and E. M. Wanjiru (2021). Economic Model Predictive Control of Microgrid Connected Photovoltaic-Diesel Generator backup Energy System Considering Demand side Management. Journal of Electrical Engineering & Technology, 16(5): 2297-2312. https://doi.org/10.1007/s42835-021-00801-w

[19] A. Salazar, D. Arcos-Aviles, J. Llanos, D. Ortiz, M. Rodríguez, E. Motoasca, and W. Martinez, (2021). Model predictive control-based energy management system for isolated electro-thermal microgrids in rural areas of Ecuador. IEEE: 1-10. https://doi.org/10.23919/EPE21ECCEEurope50061.2021.9570196

[20] S. Polimeni, L. Meraldi, L. Moretti, S. Leva, and G. Manzolini (2021). Development and experimental validation of hierarchical energy management system based on stochastic model predictive control for Off-grid Microgrids. Advances in Applied Energy, 2: 100028. https://doi.org/10.1016/j.adapen.2021.100028

[21] M. Abbasi, E. Abbasi, L. Li, R. P. Aguilera, D. Lu, and F. Wang, (2023). Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods. Energies, 16(1). https://doi.org/10.3390/en16010484

[22] M. A. Alarcón, R. G. Alarcón, A. H. González, and A. Ferramosca, (2021). Economic model predictive control for energy management in a hybrid storage microgrid. IEEE: 1-6. https://doi.org/10.1109/RPIC53795.2021.9648465

[23] S. U. Ali, A. Waqar, M. Aamir, S. M. Qaisar, and J. Iqbal (2023). Model predictive control of consensus-based energy management system for DC microgrid. PLoS One, 18(1): e0278110. https://doi.org/10.1371/journal.pone.0278110

[24] M. Ajani (2020). Model Predictive Control Approach to Microgrid Operation. Master Thesis. McGill University (Canada).

[25] M. S. Taha, H. H. Abdeltawab, and Y. A. R. I. Mohamed (2018). An Online Energy Management System for a Grid-Connected Hybrid Energy Source. IEEE Journal of Emerging and Selected Topics in Power Electronics, 6(4): 2015-2030. http://doi.org/10.1109/JESTPE.2018.2828803

[26] G. S. Thirunavukkarasu, M. Seyedmahmoudian, E. Jamei, B. Horan, S. Mekhilef, and A. Stojcevski (2022). Role of optimization techniques in microgrid energy management systems—A review. Energy Strategy Reviews, 43: 100899. https://doi.org/10.1016/j.esr.2022.100899

[27] A. Elmouatamid, R. Ouladsine, M. Bakhouya, N. E. Kamoun, K. Zine-Dine, and M. Khaidar, (2019). A Model Predictive Control Approach for Energy Management in Micro-Grid Systems. IEEE: 1-6. https://doi.org/10.1109/SEST.2019.8848995

[28] J. L.-L. X. A. L. R. B. G. M. D. J. Morrow (2021). Annual timeseries (1-minute resolution) of per-unit profiles of residential electric load and 8 PV systems: a case study in Northern Ireland, UK.). https://doi.org/10.21227/edzt-vh05