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DEVELOPMENT OF COST-EFFECTIVE ENERGY MANAGEMENT STRATEGY FOR STAND-ALONE HYBRID SYSTEM

Mohd Zaini Ab Ghani[a], Madihah Md Rasid[a*], Mohd Shafiq Anuar[b]

[a]School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bharu, Johor, Malaysia
[b]PLUS Berhad (S5&S6), KM25 Lebuhraya Perling, 81200, Johor Bahru, Johor, Malaysia

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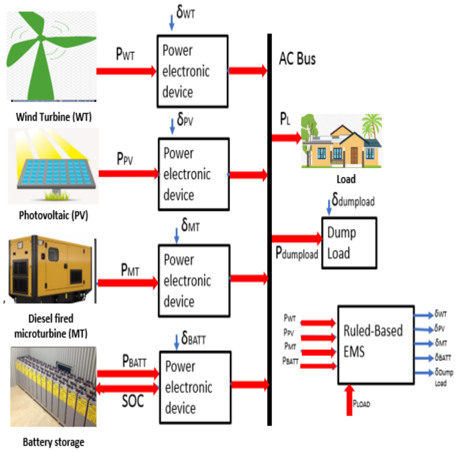
*Corresponding author
madihahmdrasid@utm.my

Graphical abstract



Abstract

Deployment of Photovoltaic (PV) and Wind Turbine (WT) as a stand-alone system are the most affordable solution to the electrification problem in the rural areas. However, the main challenge that hinder the sustainability of PV and WT is the output fluctuation. Thus, the battery and the non- Renewable Energy (RE) sources are required to make sure the continuous supply to the load is met. Therefore, the purpose of this paper is to propose the rule-based Energy Management Strategy (EMS) for the stand-alone hybrid system in order to ensure the continuity of supply and the minimum utilization of non-RE can be achieved. The continuous monitoring is designed to avoid the degradation of battery performance while minimizing the non-RE cost. The efficient Stage of Charge (SoC) limit of battery is investigated and applied in this study to store the excess RES power effectively. In this paper, the diesel fired Microturbine (MT) is selected as a non-RE source to integrate into the stand-alone hybrid system that consists of PV, WT and battery. The result shows that the proposed rule-based EMS for the in the stand-alone hybrid system is able to reduce the cost of MT operation to a minimum. Restricting the SoC limits effects the use of MT.

Keywords: Renewable Energy, photovoltaic, wind turbine, microturbine, energy management system, state of charge

Abstrak

Penggunaan Photovoltaic (PV) dan Turbin angin (WT) sebagai sistem berdiri sendiri adalah cara penyelesaian yang paling efektif dari segi kos dalam menyelesaikan masalah elektrik di kawasan pedalaman. Walaubagaimanapun, cabaran utama yang boleh mengganggu kelestarian PV dan WT adalah keadaan turun naik pengeluaran. Oleh itu, bateri dan sumber tenaga tidak boleh diperbaharui adalah diperlukan untuk memastikan bekalan berterusan seperti yang diperlukan oleh beban. Kajian ini adalah bertujuan untuk mencadangkan sistem pengurusan tenaga (EMS) berperaturan untuk system hibrid berdiri sendiri dalam memastikan bekalan berterusan dan penggunaan minima tenaga tidak boleh diperbaharui dapat dicapai. Pemantauan berterusan direka untuk mengelakkan penurunan prestasi bateri di samping meminimakan kos tenaga yang tidak boleh diperbaharui. Peringkat caj bateri (SoC) yang efisyen telah dikaji dan digunakan dalam kajian ini untuk menyimpan lebihan kuasa RES secara efektif. Kajian ini juga memilih penggunaan turbin mikro (MT) berasaskan disel sebagai sumber tenaga tidak boleh diperbaharui untuk digunakan di dalam system hibrid berdiri sendiri yang terdiri daripada PV, WT dan bateri. Keputusan kajian menunjukkan EMS berperaturan yang dicadangkan untuk sistem hibrid berdiri sendiri dapat mengurangkan kos operasi MT kepada tahap minima. Sekatan terhadap had SoC memberi kesan terhadap penggunaan MT.

Keywords: Tenaga yang boleh diperbaharui, fotovoltaik, turbin angin, turbin mikro, sistem pengurusan tenaga, peringkat caj bateri

1.0 INTRODUCTION

Serving the rural electrification is challenging yet the lack of electricity supply is the issue to deal with. The majority of the rural areas in the developing countries are located far away from the electricity grid. Extending the grid across the immerse distance and the difficult terrains is not an effective decision because it involves a complex technical framework and an unreasonable infrastructure cost. Therefore, the diesel generator is preferred to be used among the rural communities although the environmental and the maintenance issues becomes the main concerns [1].

To address aforementioned issues, the deployment of stand-alone Renewable Energy (RE) system is the promising solution and able to reduce the energy poverty in rural areas. The RE sources particularly solar and wind are the most abundant resources in the rural area [2]. The solar and wind energy are relatively clean, cheap, versatile, economical, and environmentally sustainable compared to other energy sources like fossil fuels and gas. The combustion of coal and gas can cause environmental pollution and natural instability to occurs [3], [4]. However, one of the challenges and disadvantages of RE is the reliability of supply. The solar and wind energy are highly influenced by the weather variation thus, the energy produced has always been intermittent and unpredictable. Therefore, the authors in [5] integrated the battery into the PV stand-alone system. The battery is useful mainly for stand-alone system to store the surplus energy created by the RE sources and will be activated when needed. Since the RE is the most economical sources, authors in [6], [7] combined a multiple RE sources like PV, fuel cell and Wind Turbine (WT) as well as the storage energy in their stand-alone system, so that more economical benefits can be achieved. However, the RE is less reliable than non-RE and it is crucial to ensure the load is constantly supplied. In addition, the battery bank is a short-term storage device and requires additional long-term fuels although it is beneficial in RE sustainability. Thus, the system needs a support from Non-RE sources. Authors in [8]-[9] focused on the stand-alone hybrid system that consist of PV, WT, battery and diesel generator. The system is becoming complicated when multi-sources are integrated. Therefore, an effective and efficient Energy Management System (EMS) plan is essential to manage the energy flow while providing uninterruptible power to the load. Several articles have been published regarding EMS, which may control supply-demand balance and optimize environmental or economic advantages [8]-[10]. In these studies, the EMS is implemented on the hybrid stand-alone system cooperating battery. However, aiming at the maximum utilization of RE is not adequately discussed. The system can supply the power continuously but the maximum use of RE is not guaranteed. The batteries in respect of the EMS, the monitoring regulation must be emphasized so that it can operate efficiently. The battery must be protected from the overcharging and over discharging because it will decrease the battery's performance hence lowering its efficiency in terms of ability to store charge [11], [12]. The problem can be avoided by monitoring the State of Charge (SoC) in real time. The SoC is the rate of a battery's available capacity to its full capacity when fully charged, and it shows the remaining percentage of storage capacity [13]. In addition, the SoC limit must be properly decided [14]. By doing so, the battery lifetime can be extended as well as the battery safety [15], [16]. Though, the accurate SoC level has not yet been finalized and still being investigated.

Therefore, the well-planned EMS strategy for stand-alone hybrid system consisting of WT, PV, battery energy storage and Microturbine (MT) is proposed in this paper. The cost effectiveness of continuous monitoring is designed to manage the power flow between the generation and load at minimum utilization of MT. The battery is applied to store the excess RES power while the MT is used to support an insufficient energy supplied to the load. In addition, the efficient SoC limit is studied and applied. The proposed EMS strategy is able to reduce the cost of MT operation to a minimum, hence the optimal wind and PV utilization is guaranteed.

2.0 METHODOLOGY

This section discusses the proposed rule-based EMS for hybrid RE and Non-RE system. The aim of this strategy is to determine the output power generated by PV, WT and MT on hourly basis at minimum cost of MT operation. Figure 1 shows the stand-alone hybrid system with AC bus cooperating main controller implementing EMS. This type of topology is used due to the low construction cost and simple installation [17]. The WT and PV energy generations are treated as the primary component of the supply system. The battery is used to store the excess power from PV and WT, while MT is operated as a backup system when supply could not meet the demand. This study focuses on the development of rule-based EMS, therefore the optimal size of the RE, non-RE generations as well as the battery capacity are randomly selected. The ratings of component used in this paper are 50 kW for WT, 40 kW PV, 55 kW for MT and 78 kWh for capacity of battery[18].

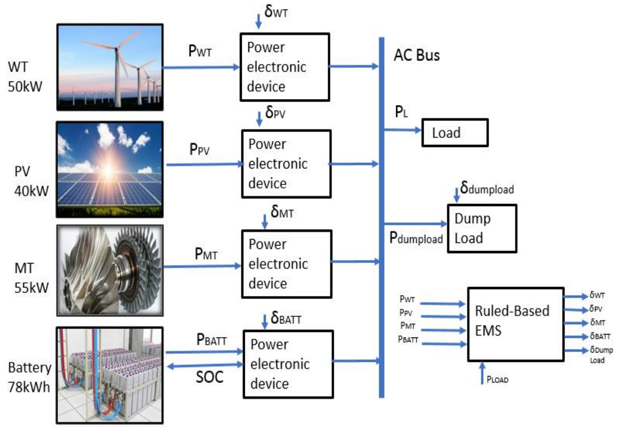


Figure 1 Configuration of proposed system

2.1 Cost-Effectiveness of Continuous Monitoring EMS Strategy

Figure 2 shows the proposed EMS strategy for the stand-alone hybrid system. The main purpose is to utilize the PV and WT power outputs to the maximum, and emphasize the effective battery management simultaneously. In the strategy, the available PV and WT power outputs and the load consumption for each hour are monitored in order to control the energy flow and the charging and discharging process of battery. Two possible battery conditions are accessed and it depends on the SoC level. In this paper, the maximum and the minimum SoC limit are set to 90% and 30%, respectively. This is due to the medium range of SoC limit provides superior cycling stability[19].

For condition 1, if the maximum available power generates from RE sources is greater than the load demand as shown in Equation 1, the excess power is used to charge the battery until it reaches the maximum SoC level, 90%, and the spare power is then channeled to the dump load.

On the other hand, condition 2 is triggered if the PV and WT power outputs are insufficient to supply the load demand. In this stage, the battery is activated and discharged to support part of the load. The discharging process will be stopped when the SoC reaches the minimum level and the MT will be activated to provide the not enough energy. To avoid the degradation of battery performance, the discharging process is only occurred if the SoC above the minimum level, and the MT will take place to provide the inadequate energy. Additionally, The MT is also operated to satisfy Equation 2 when the RE sources and the battery are still not enough to supply power to the load.

$$Pt, supply = P^{avail}_{t,PV} + P^{avail}_{t,WT} \tag{1}$$

$P^{avail}_{t,PV}$ = Available PV power at hour *t*
$P^{avail}_{t,WT}$ = Available WT power at hour *t*
$Pt, supply$ = Total power supply at hour *t*

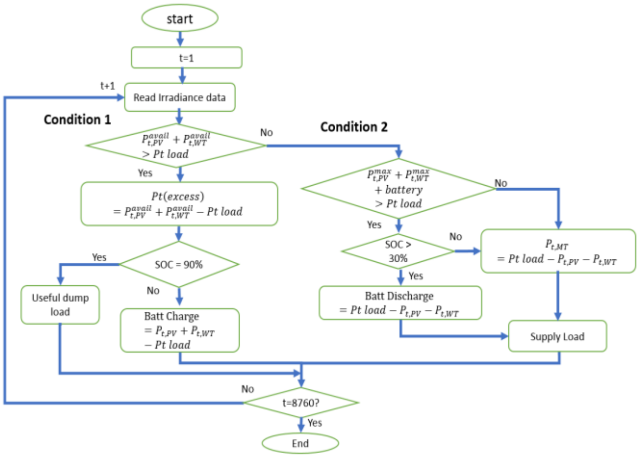


Figure 2 Proposed energy management strategy for PV, WT and MT

$$Pt, supply = P^{max}_{t,PV} + P^{max}_{t,WT} + P^{avai}_{t,MT} \tag{2}$$

$P^{max}_{t,PV}$ = Maximum limit of PV power at hour *t*
$Pt,^{max}_{WT}$ = Maximum limit of WT power at hour *t*
$P^{avail}_{t,MT}$ = Available MT power at hour *t*
$Pt, supply$ = Total power supply at hour *t*

2.2 Problem Formulation

The aim of this strategy is to minimize the MT cost as defined in Equation 3 [18],

$$F_{t,MT} = (C_{MT}.F_{MT}.P_{tMT}\Delta T) + (OM_{tMT}) + (SC_{tMT}) \tag{3}$$

Where

$F_{t,MT}$ = total operating cost of the MT at hour *t* ($)
C_{MT} = fuel cost of the MT ($/m^3)
F_{MT} = fuel consumption rate (m^3/kWh)
P_{tMT} = decision variable represents the real power output from MT at hour *t* (kW)
OM_{tMT} = operational and maintenance cost of the MT at hour *t* ($)
ΔT = energy management time step
SC_{tMT} = start-up cost of the MT unit at hour *t* ($)

The MT used in this study is based on diesel generation sources. The total cost of electricity for MT is the cost of producing one kWh of electricity, represented in dollars per kWh. The MT cost is the combination of capital cost, fuel cost, and maintenance cost. All parameter values applied in calculating MT cost are taken from reference [20].

To minimize the MT cost, the power output of PV, WT battery and MT are measured and satisfies the constraints in Equation (4) and Equation (5) [20].

$$P_{t,supply} = P_{t,Load} \tag{4}$$

$$P_{t,supply} = P_{t,PV} + P_{t,WT} + P_{t,MT} \pm Pt,batt \tag{5}$$

Where

$P_{t,supply}$ = Total power supply at hour *t*
$P_{t,Load}$ Total power load at hour *t*
$P_{t,PV}$ = PV power at hour *t*
$P_{t,WT}$ = WT power at hour *t*
$P_{t,MT}$ = MT power at hour *t*
$P_{t,batt}$ = Power from battery at hour *t*

2.3 PV Data

Daily irradiation data for a year is collected for 1 year at KKTM Sri Gading and to be analysed to identify the weather patterns which are sunny day and cloudy day. The amount of solar irradiance is different for each weather patterns. The solar irradiance received during sunny day in tropical region is much higher compared to the day with the presence of cloud. The amount of irradiance during cloudy day is only 7.18% of the sunny day[21]. Therefore, in this paper, each month is represented by a sunny day and a cloudy day which are based on a highest and lowest irradiance in a month. The instantaneous PV power output (kWh) is calculated as per Equation 6 [20].

$$P_{t,PV} = \frac{Irradiation(t)\ (Wh/m^2)}{1000\ (W/m^2)}\ x\ Pmax\ (kWp) \tag{6}$$

Where

$Pmax$ = Peak power of solar panel
$P_{t,PV}$ = PV power at hour *t*
$Irradiation(t)$ = Irradiation on sunny and cloudy day at hour *t*

The peak power of solar panel applied in this study is 40 kWp.

2.4 Wind Data

The wind speed data and all parameter values applied in calculating WT power output are taken from reference [18]. The power output of WT is calculated using Equation 7 [22].

$$P_{tWT} = \frac{1}{2}\ x\ \rho\ x\ Cp\ x\ A\ x\ V^3\ x\ Ng\ x\ Nb \tag{7}$$

Where

P_{tWT} = WT power at hour *t*
Cp = Coefficient of performance
V = Wind velocity (m/s)
A = Rotor swept area (m^2)
ρ = Air density (kg/m^3)
Ng = Generator efficiency
Nb = Gear box bearing efficiency

The output of WT is proportional to the area swept by the rotor blade and power generated from WT is comparable to the wind speed cube.

2.5 Load Data

An hourly average load demand for a residential as utilized in reference [23] is used in this paper. Figure 3 shows the variation of load demand for a house. The total hourly average load demand profile of residential is presented over 24 hours period. The maximum load is 35 kWh and it occurred at 7:00 am.

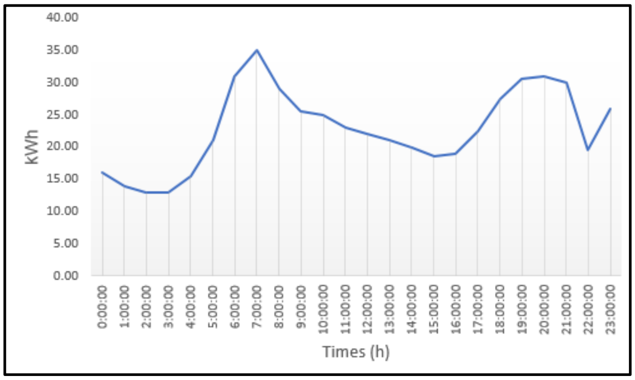


Figure 3 Hourly average load demand for simulation study

3.0 RESULT AND DISCUSSION

In this section, the pattern of the output of PV, wind and the load are firstly observed. Then, the effectiveness of the proposed EMS is evaluated by applying the strategy for two different weather conditions, which are sunny and cloudy. For simplicity, the same load variation is applied in both situations. The battery capacity of 78kWh is selected in this paper. The impact of the weather on the MT cost is observed. Additionally, 2 different sets of SoC level are applied to investigate the impact of the SoC on the MT cost.

3.1 WT Output Power

Figure 4 shows the output power produced from WT for 24 hours when considering the 50 kW of WT rated power and the 3 m radius rotor blade. The fluctuation of WT output power is strongly influenced by uncertain wind speed that is affected by the number of factors including geography and weather. Even though the WT has the capability of producing more electricity, the output power remains constant when the wind speed exceeds the rated wind velocity. When the wind speed exceeds 25 m/s (cut out speed) and 3 m/s (cut in speed) the system is taken out of operation. When the wind speed exceeds 14 m/s at 00:00 a.m. to 01:00 a.m. and 03:00 a.m. to 04:00 a.m., the pitch angle controller limits the output power to 50 kW. At 21:00 p.m. to 23:00 p.m. there is no wind power created when the wind speed is less than the WT cutting speed (3 m/s).

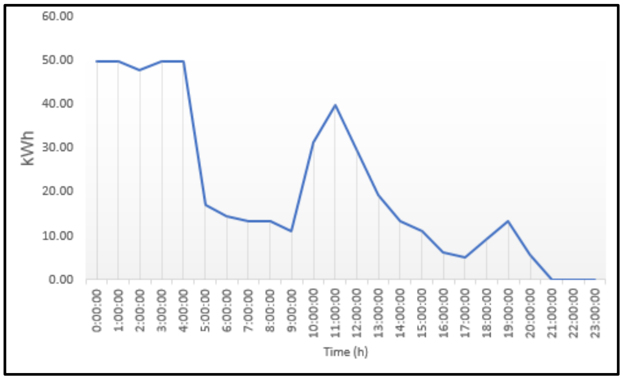


Figure 4 Wind power data for simulation study

3.2 PV Output Power

The 24 hours PV power output at KKTM Sri Gading is collected using HD32MT Logger tool. The daily PV power output during sunny day and cloudy day in January is illustrated in Figure 5. It shows a significant difference when the output during a sunny day is compared to cloudy day. At 13.00 p.m. to 14:00 p.m., the maximum irradiance is obtained at 935 Wh/m^2 which can generate a power of 37.4 kWh. While in cloudy day, it shows that the maximum irradiance is 431Wh/m^2 and power generated by PV is 17.24 kWh at 14:00 p.m. until 15:00 p.m. It can be concluded that the higher the irradiance at one time the more energy is produced by the PV.

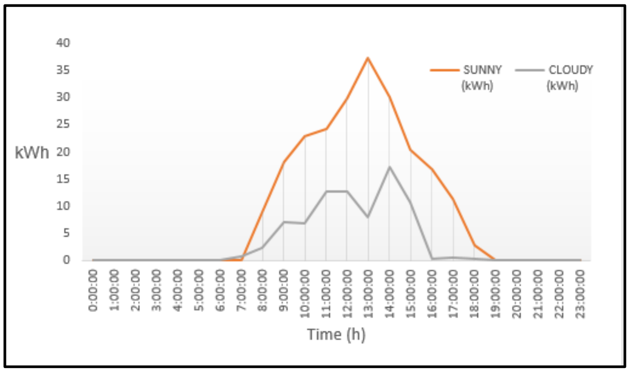


Figure 5 PV power data for simulation study

3.3 The Analysis on the Implementation of EMS Strategy for Standalone Hybrid System

Figure 6 shows the result after EMS strategy is applied on sunny day in January. At 0:00 a.m. to 4:00 a.m., the load is supplied by WT, while PV cannot supply to the load because there is no irradiation during that time. The energy generated by the WT exceeds the required load. Therefore, the excessive power will be channelled to the dump load. When WT is not generating due to the absence of wind starting at 4:00 a.m. until 7:00 a.m., the battery was discharged and supplied to the load until the SoC decrease to 30% (28.26 kWh). When the SoC is 30% and RE (WT and PV) still cannot supply to the load, MT will take over to supply power to the load.

During 9:00 a.m. until 16:00 p.m., the RE (WT and PV) return to supply to the load demand and have the access power to charging the battery. Battery was charge until SoC is achieved at 90%. Once the charging process reaches the 90% level, the excessive energy generated by WT and PV will be channelled to the dump load. Again, at 17:00 p.m. until 19:00 p.m. the RE (WT and PV) cannot supply to the load demand and battery will take over to discharge and supply until SoC is reduced to 30%. MT will again take over to supply to the load at 19:00 p.m. until 23:00 p.m.

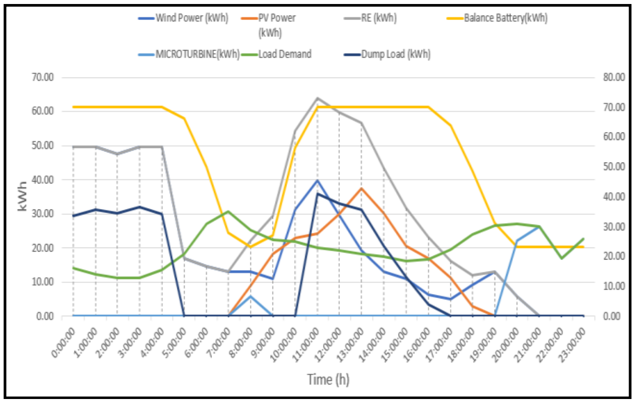


Figure 6 Energy Flow During Sunny Day in January

Figure 7 shows the result after EMS strategy is applied on cloudy day in January. At 0:00 a.m. to 4:00 a.m., the load is supplied only by the WT since there is no solar irradiation at that time. The energy generated by the WT exceeds the required load. Therefore, the excessive power will be channelled to the dump load. When WT is not generating due to the absence of wind starting at 4:00 a.m. until 7:00 a.m., the battery was discharged and supplied to the load. The battery is continuously decreased until the SoC reaches the 30% (28.26 kWh) until 8:00 a.m. due to insufficient supply from the RE. The MT is then activated from 8:00 a.m. until 10.00 a.m. since the RE output (PV and WT) is still not enough to supply power to the load.

From 10:00 a.m. until 16:00 p.m. the RE (PV and WT) is sufficient to supply to the load. During this time, the battery is charging because the power generated from RE is greater than the load and have an excess power. Battery is charged until SoC achieve 90%. After reaching 90% the battery will be in inactive condition. The excessive energy generated by WT and PV will be channelled to the dump load. At 15:00 p.m. until 23:00 p.m., again the RE (WT and PV) cannot supply to the load, and battery will take over to supply. When SoC reduce to 30%, MT will again take over to supply to the load.

There is a significant difference when EMS is applied on a sunny day and a cloudy day. The total MT use on a sunny day differs by one hour from that on a cloudy day. There is also difference in the battery where the usage of batteries in supporting supply to the load is more because the charging process occurs quickly due to excess power from WT and PV. However, in the context of excessive power, both conditions supplied power to the dump load where the excessive power during sunny day is 50% greater than excessive power during cloudy day. This result shows that the selected system capacity is not optimum for the load demand considered in this study. This is due to the oversized RE system hence producing more power during off-peak hour. To avoid large excessive power, PV and WT capacities need to be determined effectively. The suitable battery capacity also can be improved so that more energy can be stored, indirectly reduce more power utilized from the MT.

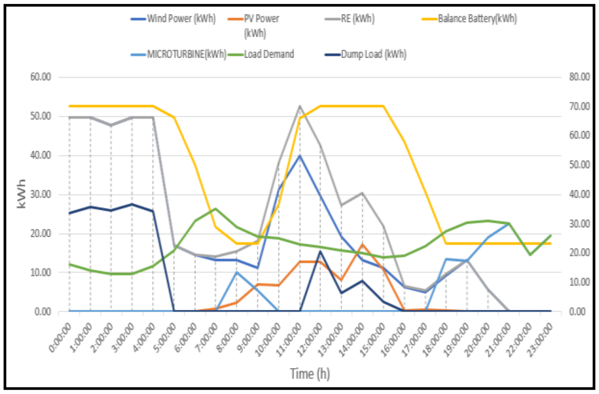


Figure 7 Energy Flow During Cloudy Day in January

3.4 Impact of Weather on MT Cost

Table 1 and Figure 8 shows the operating cost of a MT on a sunny and cloudy day in January. The operation of MT are 5 hours on sunny day and 8 hours on cloudy day. The operating costs only occur at 8:00 a.m. and again occur at 20:00 p.m. to 23:00 p.m. The total cost of MT on that day is $17.86. Compared with sunny day, the operating costs occur at 8:00 a.m. until 09:00 a.m. and again start at 18:00 p.m. to 23:00 p.m. It also shows that during cloudy times, MT operation is often used to supply power to the load demand and operating costs will also increase slightly to $26.03. The MT cost difference between these two weather conditions is $ 8.17.

Table 1 MT cost on sunny day and cloudy day

Time (h)	Irradiance Sunny (Wh/m²)	Irradiance Cloudy (Wh/m²)	MT Sunny ($)	MT Cloudy ($)
08:00	225	57	1.13	2.24
09:00	455	176	0.00	1.22
18:00	72	8	0.00	2.97
19:00	0	0	0.00	2.87
20:00	0	0	4.20	4.20
21:00	0	0	4.98	4.98

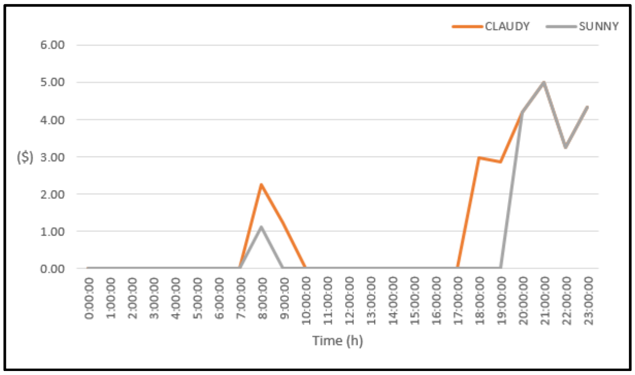


Figure 8 MT cost on sunny day and cloudy day

3.5 Impact of Weather on MT Cost for 1 Year

Figure 9 shows the difference in MT per year for two different weather conditions. Significant cost differences were found in January. It can be observed that on a cloudy day the cost of a MT is quite high in January at $26.39. However, the total MT cost was the highest for sunny days and cloudy days in May which was $44.12. The lowest MT cost for sunny and cloudy days was in September at $37.42. The total MT cost a year is $483.88. The total MT cost difference between sunny day and cloudy day is $ 216.71 and $ 266.94, respectively.

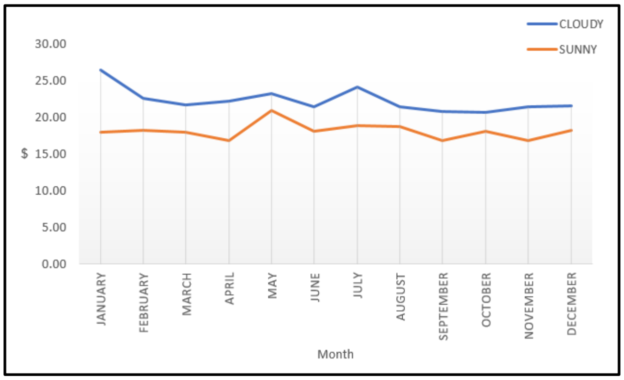


Figure 9 MT cost for 1 year

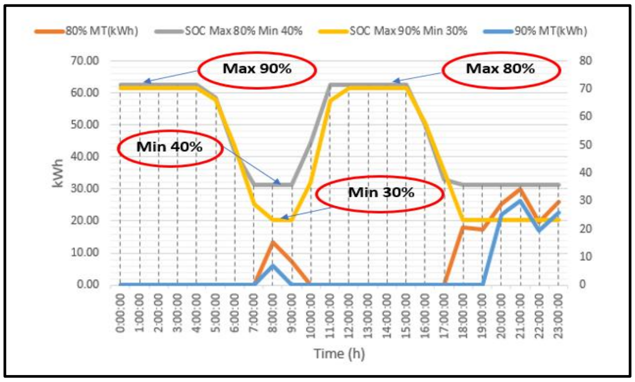


Figure 10 Battery SoC and MT cost

3.6 Impact of SoC Level on the System Performance

The analysis is done with a focus on MT cost when the battery SoC level is changed from Max 90% Min 30% to Max 80% Min 40%. Table 2 and Figure 10 show the charging and discharging process of battery for SoC set to max 90% and min 30%. During 12:00 a.m. to 4:00 a.m., the battery was at inactive condition, where the generation of WT and PV is greater than load required. At 4:00 a.m. to 8:00 a.m., the battery is discharging when the PV and WT is less than load demand, with the SoC battery declining until the SoC achieved the min 30% at 8:00 a.m. During that time, the system generation are less than load demand; Thus, MT produce the supply to meet the load demand. At 9:00 a.m. to 11:00 a.m., the battery is at charging condition in which the system generation is greater than load demand, with the SoC rising. The battery is charging until the SoC battery achieving the max 90%. at 11.00 a.m. and it remain constant until 16.00 p.m. At 16:00 p.m. to 20:00 p.m., again the battery was in discharge condition when the system generation is less than load required, with the SoC declining until achieving the 30%. The battery was in inactive condition at 20:00 p.m. to 23:00 p.m. Thus, MT produce the supply to meet the load demand.

When the SoC level is limited to 40% of min and 80% of max, the MT is operated more longer than when SoC is set to max 90% and min 30%. The MT is activated twice which is from 8 a.m. until 10 a.m. and 17.00 p.m. until 23.00 p.m. Indirectly, it causes the high cost of MT. This analysis shows that the selection of SoC level for battery will affect the cost on the MT. The cost of the MT can be saved depending on the SoC was set as shown in Table 2. When the SoC is set to max 90% and min 30%, the total generation power from MT is 107.59 kWh and cost of using a MT is $17.86.

Meanwhile, when the SoC was set to max 80% and min 40%, the total generation power from MT is 156.82 kWh and total cost of using a MT is $24.35. This provides total difference between these conditions by 36%. This comparison shows that the higher SoC level, the higher battery capacity, thus less power from MT is required.

Table 2 MT cost on sunny day and cloudy day

SoC Level	Total Power MT (kWh/day)	Total Cost MT ($/Day)
Max 90% Min 30%	107.59	17.86
Max 80% Min 40%	156.82	24.35

Table 3 and Figure 11 show the difference in MT cost for each SoC level for 1 year. The lower the SoC level is set, the higher the cost of the MT. Results show that by using SoC level Max 90% Min 30% on a sunny day can reduce the cost of MT to $216.71, compared to SoC level at Max 80% Min 40% the cost is $294.10 where the total difference is 36%. The same goes for the result on cloudy days, for SoC battery level set to Max 90% Min 30%, the total cost per year for MT is $266.94 while for SoC level at Max 80% Min 40%, the total cost increased to $330.64. MT cost is increased by 24%.

Table 3 MT cost on sunny day and cloudy day with difference SoC level for 1 year

SoC Max 90% Min 30%		SoC Max 80% Min 40%	
Sunny	Cloudy	Sunny	Cloudy
$216.71	$266.94	$294.10	$330.64

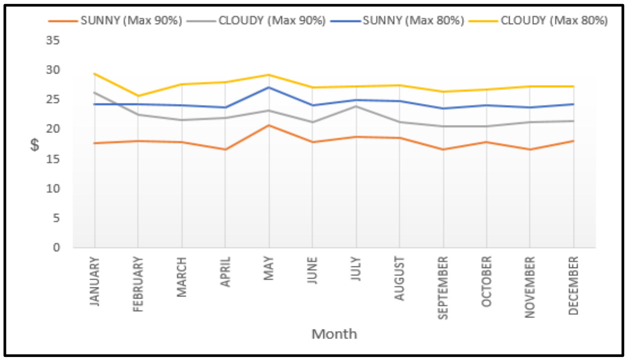


Figure 11 Battery SoC and MT cost for 1 year

4.0 CONCLUSION

In conclusion, the continuous monitoring on power generation, load and the battery management is able to achieve the minimum utilization of MT. The effective SoC level plays an important role in achieving this objective. Using SoC level of Max 90% and Min 30% can reduce 26% of the cost of MT compared to SoC level at Max 80% Min 40%. Besides, the amount of power generated from the RE that solely depends on the weather conditions gives impact on the cost of MT. High MT cost is generated during cloudy day compared to during sunny day. As for future work, the optimization of stand-alone hybrid system consisting of PV, WT and battery can be included in the EMS so that the minimum used MT and excessive power can be produced.

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