Journal of Physics: Conference Series

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To cite this article: J. Nazar *et al* 2023 *J. Phys.: Conf. Ser.* **2523** 012027

18th International Engineering Research Conference 2022 (Eureca 2022)
IOP Publishing
Journal of Physics: Conference Series **2523** (2023) 012027 doi:10.1088/1742-6596/2523/1/012027

New Dynamic Time-of-Use Tariff For Islanded Microgrid System With High Penetration of Renewable Energy

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Abstract. This paper proposes a dynamic time-of-use (d-TOU) tariff scheme for microgrid (MG) systems in islanded mode. The main problem for the islanded MG is the high cost of electricity, and the output from renewable energy is uncontrollable compared to the traditional grid. Therefore, this paper focuses on developing a suitable tariff scheme that provides reliability and financial benefits for both utility and customer. The time zone energy prices based on the Levelized Cost of Energy (LCOE) are introduced for islanded MG. The results show a contradiction between islanded MG with the standard traditional power generation TOU. Even though the LCOE obtained for MG is higher than conventional electricity rates, the greenhouse gas (GHG) emissions rate is reduced by 85%. In conclusion, the proposed d-TOU tariff scheme is suitable for the islanded MG system and it is beneficial for both the utility and the customer by not causing a financial burden to the utility and encouraging the customer to make a demand response in the future.

1. Introduction

Over recent years, the issue of global warming and climate change has become more popular among researchers. The ever-increasing demand for electrical energy has caused the consumption rate of fossil fuels to increase drastically. This issue poses two negative impacts: the rapid depletion of fossil fuels and the increased greenhouse gas (GHG) emissions in the atmosphere. Presently, fossil fuels contribute to 85% of the world's primary energy demand while being responsible for 56.6% of the total GHG emissions [1]. This alarming situation has motivated environmentalists, researchers, and policymakers to explore renewable energy sources (RES), such as solar, wind and biomass, to substitute conventional energy resources to deal with the growing energy demand and GHG emissions.

Extensive research has been carried out to explore the potential of renewable energies worldwide. The amount of solar energy reaching the Earth's surface is approximately four million Exajoules (4x1024 Joules) annually, which is enough to meet the world's energy demands [2]. However, this is not realizable due to technological limitations and economic factors. Similarly, the global potential of wind energy for electricity generation is 580PWh annually [3]. The potential, essence and impact of utilizing renewable energy in curbing carbon emissions in Malaysia and other southeast Asian countries are highlighted in [4, 5].

Even though the world has sizeable potential energy from renewable energy sources, the main challenges associated with these sources are their intermittency and uncertainty, which necessitates the provision of the energy storage system in the microgrid (MG) systems. Many researchers have analyzed the impact of this renewable energy sizing on socioeconomic benefits and system performance. Authors in [6], for example, have outlined the maximization of socio-economic benefits for the solar-wind hybrid MG system in the grid-connected configuration. The results show that many parameters need to be considered when considering renewables in the planning stage. Authors in [7] proposed a framework for optimal sizing of hybrid MG with solar PV, wind turbine and battery storage in grid-tied mode to improve economic viability and system reliability. Besides, authors in [8] have tried to implement a meta-heuristic technique, which is a particle swarm optimization (PSO) algorithm for a techno-economical sizing of the battery energy storage system (BESS) that improves the stability and reliability of the MG. An improved Model Predictive Control (MPC) strategy to attain a dynamic and optimized energy flow between BESS and a standalone photovoltaic (PV) system is proposed in [9], thereby improving the efficiency of energy flow in the MG.

Furthermore, to encourage the consumer to invest in renewable energy, the government has proposed many incentives, such as feed-in tariffs, net energy metering, and self-consumption. In [10], for example, the authors investigated the benefits of the feed-in tariff (FiT) on government policies for RES in the Korean market, considering net present value (NPV) and benefit-cost ratio. On the other hand, authors in [11] highlight the economic advantages of net-metering pricing over FiT by investigating a PV case study in Slovenia. The results show that net metering is more sustainable for utility and government than the feed-in tariff. Also, for a MG system, [12] highlights the necessity and significance of time-variant tariff structures. The authors proposed a three-leveled tariff structure: time-of-use (TOU) tariff, critical peak pricing (CPP), and real-time pricing (RTP) with their advantages over the conventional tariff schemes. The environmental impact of solar PV and wind energy systems concerning the GHG emissions rate throughout their life cycles is discussed in [13-15].

However, the abovementioned studies are focused on grid-connected systems, where the traditional electrical supply is continuously available. Conversely, authors in [16] and [17] have analyzed the performance of islanded MG systems that integrated with high renewable energy. In [16], energy management strategies are used to manage the demand. By controlling the power source scheduling in the rescheduling step, the cost of electricity for the islanded MG can be reduced significantly. The demand response also is implemented to have a balance supply-demand scheme. In line with that, authors in [17] have also evaluated the demand response performances for a standalone MG using techno-economic analysis. The authors have used a dynamic tariff scheme to influence the customer side in adjusting their demand. The PV-WT-PTES is found to be the most techno-economical configuration for the islanded MG system.

On the other hand, this paper presents a new tariff scheme, known as dynamic time-of-use (d-TOU) tariff, defined from three time zones and the LCOE value, especially for islanded MG systems with 100% renewable energy. d-TOU tariff scheme is proposed based on a limited generation profile, dividing a day into three time zones: Peak hours (highest electricity rate), Mid-peak hours (mid-range rate), and Off-peak hours (lowest rates). The results from the analysis can give an indicator of the possibility of having an islanded MG system with 3 different tariffs per day. As Malaysia starts to implement the islanded microgrid system, such as in Banggi Island and Tanjung Labian, this new d-TOU can guide the power utility on the electricity charges that will give economic viability and environment-friendly impact for both utility and customer.

2. System Design Parameters

In order to introduce the new tariff scheme for an islanded MG system, the analysis of generation and consumption profiles is required to optimize the integration of DEGs. The optimization of islanded MG system to determine the best PV, WT, and BESS size is based on HOMER software. At the same time, the categorization of time zones and development of the d-TOU tariff is mainly done using the generation curve.

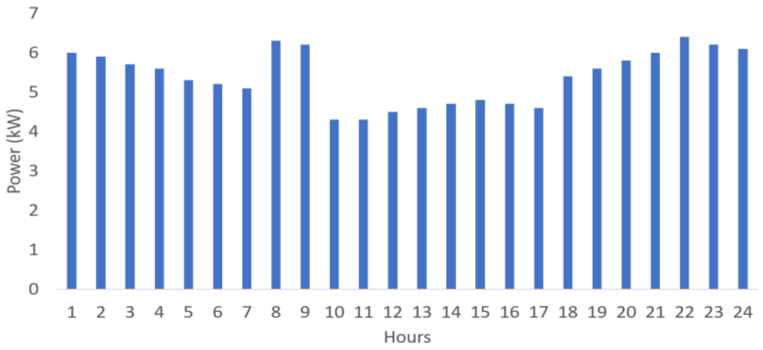

Fig. 1. Daily load curve of residential load in Malaysia [18].

2.1. *Residential Load Curve*

The sweeping curve of 24-hr residential load in Malaysia was obtained from ref [18], as shown in Figure 1. The load profile shows that electricity consumption increases in the evening until midnight, i.e., 2000hrs to 0300hrs. The baseline average daily energy demand is 116.81 kWh/day. The features of percent day-to-day and percent timestep random variability are utilized to calculate the maximum and minimum energy demand based on the set variability limits. These limits are set to 10% and 5%, respectively. As a result, the scaled average daily energy demand is 170 kWh/day.

2.2. *Solar Irradiance*

The geographical coordinates of Malaysia are 1.4927° N, 103.7414° E. National Aeronautics and Space Administration (NASA) provides real-time solar irradiance data based on the monthly average radiation data of 22 years (July 1982 to June 2005) shown in Figure 2 [19]. The annual average solar irradiance is 4.56 kWh/m2/day.

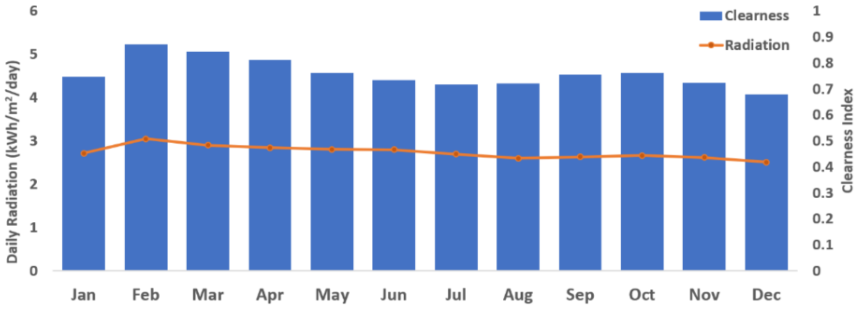

Fig. 2. Monthly Solar Irradiance of Malaysia from NASA database [19].

The annual solar energy generation is calculated using Eq. (1). H represents annual average irradiance (W/m2), A is total solar panels area (m2), η denotes the solar panel yield or efficiency (%), and loss factor represents the coefficient of losses, i.e. temperature, dirt and module mismatch.

$$\boldsymbol{Annual\ Solar\ Energy\ Output}\left(\frac{\boldsymbol{kWh}}{\boldsymbol{year}}\right) = \boldsymbol{H} \times \boldsymbol{A} \times \boldsymbol{\eta} \times \boldsymbol{Loss\ Factor} \tag{1}$$

2.3. *Wind Profile*

The NASA database contains the historical real-time annual wind speed profile for Malaysia, calculated from the scaled measured data of 10 years (July 1983 to June 1993) as shown in Figure 3 [19]. A wind turbine's (WT) annual operation and maintenance cost is kept at 5% of the initial capital cost [20]. The annual wind energy generation is calculated by Eq. (2).

$$\boldsymbol{Annual\ Wind\ Energy\ Output}\ \left(\frac{\boldsymbol{kWh}}{\boldsymbol{year}}\right) = \frac{\mathbf{1}}{\mathbf{2}} \times \boldsymbol{A} \times \boldsymbol{C_p} \times \boldsymbol{\eta} \times \boldsymbol{\rho} \times \boldsymbol{v^3} \times \boldsymbol{t} \tag{2}$$

In Equation (2), A represents the swept area of WT blades (m2), Cp represents technical efficiency (%), η denotes the generator efficiency (%), ρ is air density (kg/m3), t is the annual windy hours, and v denotes the wind speed (m/s).

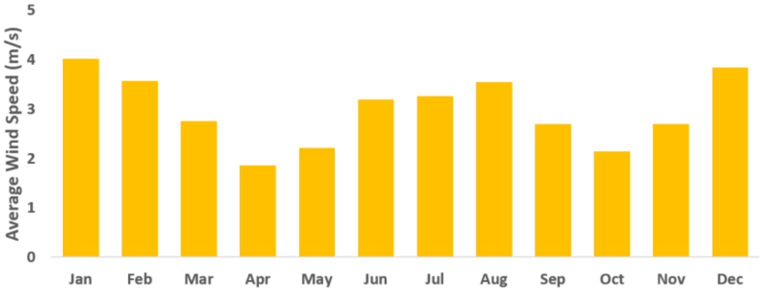

Fig. 3. Monthly Average Wind Speed of Malaysia from NASA database [19].

2.4. Battery Energy Storage System (BESS)

The battery storage is kept sufficient to fulfil the daily energy demand while keeping the minimum depth of discharge (DoD) at 25%. Deep-cycle dry cell lead-acid (LA) batteries are chosen because of the enhanced efficiency and performance at an economical cost [21]. The system voltage is set to 480 V using 12V battery units, each having the designed capacity of 2.52 kWh. The capacity of BESS is calculated by using Equation (3).

$$Battery\ Capacity\ (Wh) = \frac{P \times h}{DoD \times \eta} \tag{3}$$

In Equation 3, P represents electrical load to be supported by batteries (kW), h represents the backup time (hrs.), η denotes the battery conversion efficiency (%), DoD represents the battery's depth of discharge (%).

3. Financial Analysis for islanded Microgrid System

In this study, the nominal interest rate (%) and the annual inflation rate (%) are set to be 8% and 1.5%, respectively [22]. Equations (4) – (7) are used to determine the levelized cost of energy (LCOE) for the islanded MG system. Thus, by using the technical costing to set up an islanded MG system, as shown in Table 1, the estimated energy cost in the system can be obtained. Hence the design for the tariff to the consumer can be evaluated.

$$Annual\ Real\ Interest\ Rate, i = \frac{i' - f}{1 + f} \tag{4}$$

$$Capital\ recovery\ factor, CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5}$$

$$Total\ annualized\ cost, C_{ann,tot} = CRF(i, N).NPC_{tot} \tag{6}$$

$$Levelized\ cost\ of\ energy, LCOE = \frac{C_{ann,tot}}{E_{AC}} \tag{7}$$

i' = percentage nominal interest rate
f = the percentage annual inflation rate
N = project lifetime in yeaers
NPC_{tot} = total net present cost
E_{AC} = Energy in AC

The technical specifications and costing of the designed MG system components are detailed in Table 1.

Table 1. Technical Parameters and Costing of MG System Components.

Component Description	Specification
PV Array	
PV Module	Canadian Solar CS6U-330P
Unit Rated Power (P)	330 W
Unit Rated Power (P)	330 W
HOMER optimized size	66 kW
Capital Cost [23]	25,466 $
O&M Cost	10 $/year
Replacement Cost	21,120 $
Lifetime	25 Years
Solar Inverter	
Brand and Model	SNADI TP-100kW
Power Rated	100 kW
Capital Cost [23]	10,500 $
O&M Cost	10 $/year
Replacement Cost	10,500 $
Lifetime	15 Years
Wind Turbine	
Brand and Model	BOYANG FD5-5000
Unit Rated Power (P)	5 kW
HOMER optimized size	5 kW
Capital Cost [23]	8000 $
O&M Cost [20]	400 $/year
Replacement Cost	7000 $
Lifetime	20 Years
Battery Storage	
Brand and Model	EverExceed AGM
Rated Specifications	12V, 210Ah
HOMER optimized size	240 pcs (604.80 kWh)
Capital Cost [23]	52,500 $
O&M Cost	10 $/year
Replacement Cost	52,500 $/year

From Table 1, the cost considered in this research includes the capital cost, operation and maintenance (O&M) cost, and replacement cost. Next, the individual component costs have been normalized with the accessories and retrofitting associated with the respective component. The installation cost of each component is set to 2% of the purchase price. The non-technical and different cost factors incorporated in the annual cash flows for the total NPC of the system are presented in Table 2.

Table 2. This figure shows the non-technical and miscellaneous cost factors of the project.

Description	Cost [$]
Cabling, Meters and Accessories	1200.00
Employees' Annual Wages and Salaries	6,331.00
Annual Travelling Expenses	200.00
Annual O&M (General & Admin)	300.00

Figure 4 shows the overall process to obtain a d-TOU scheme for the islanded MG system with high penetration of renewable energy. The flow chart shows that the comparison between renewable energy output and load profile will be the main indicator for the time zone scheme before obtaining the d-TOU. The impact of the d-TOU versus the traditional system will be discussed in the next section.

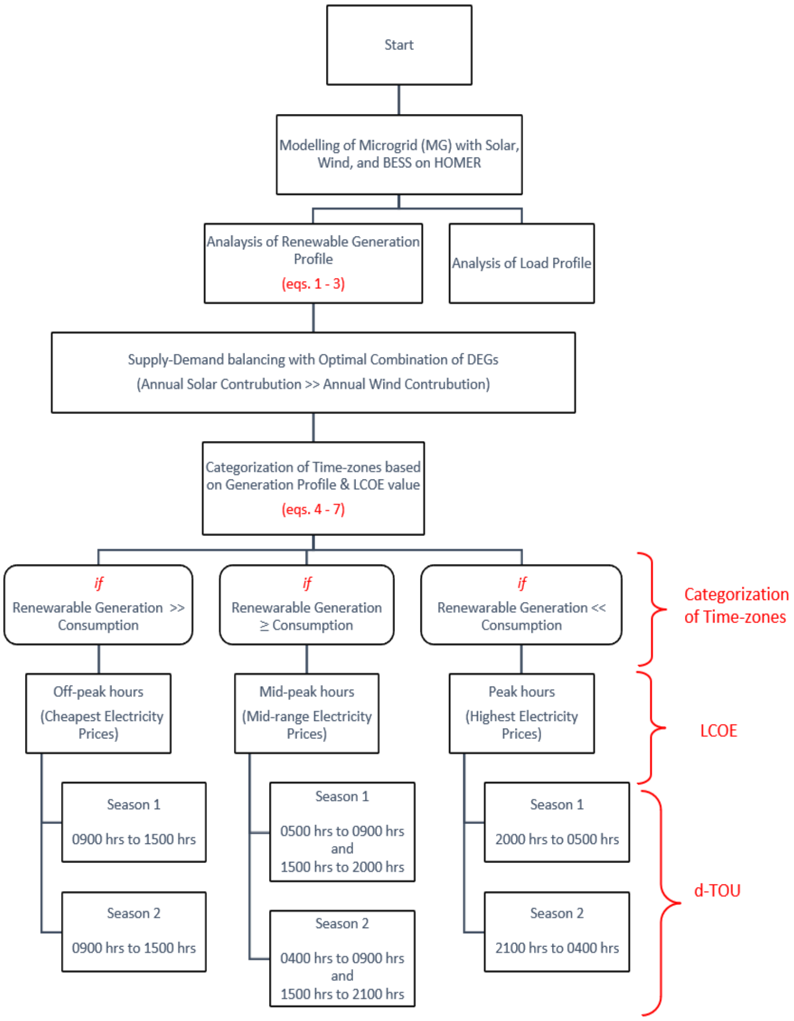

Fig. 4. The process to obtain d-TOU scheme for islanded microgrid system.

4. Results and Discussion

The result and analysis will be separated into four parts; First part focuses on determining the lowest NPC value for the islanded MG system that can give zero loss of load probability. The second part is categorizing the 3-time zone tariff based on the generation-load profile. The third part will discuss the d-TOU at each zone, and the last part discusses the impact on GHG.

4.1. Cost Analysis

Based on all the parameters in Section 2, the lowest NPC value is obtained when the islanded MG system consists of 66 kW solar PV capacity, 5 kW wind turbine, and 604.80 kWh BESS capacity. Since the case study in this research considers the initial capital cost, operation, and maintenance (O&M) cost and the replacement cost of each system component as in Table 1, the summary for the lifetime cost for the lowest NPC is calculated and shown in Table 3 and Figure 5.

Table 3. Cost Summary of MG system components.

MG Components	Capital Cost [$]	Replacement Cost [$]	O&M Cost [$]	Salvage [$]	Total Cost [$]
Solar PV system	25,466.00	0.00	135.91	0.00	25,601.91
System Converter	10,500.00	4,793.92	135.91	-947.48	14,482.35
Wind Turbine	8,000.00	2,460.94	5,436.35	-1,421.22	14,476.25
BESS	52,500.00	113,981.20	135.91	0.00	16,6617.11
Total System Cost	96,466.00	121,236.06	5,844.27	-2,368.70	221,177.62

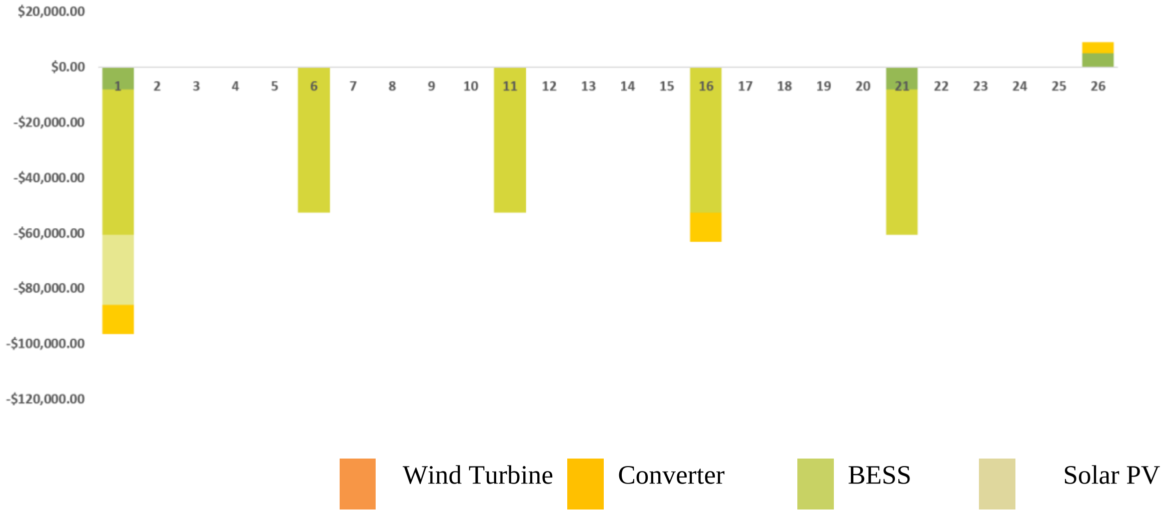

Fig. 5 25-year nominal cash flow summary of the MG system.

The total replacement cost has the highest value from the results due to the multiple replacements of components that need to be done for 25 years. Furthermore, battery or BESS contributes the highest cost in the MG system due to the requirement to have higher reliability or zero loss of load probability. Therefore, the batteries or BESS give the highest NPC, followed by wind turbines, while solar PV energy inflicts the lowest NPC. Table 4 shows the energy generation price ($/kWh) for each system component.

Table 4. Electricity Generation Cost from each DG.

Generation Source	Generation Cost [$/kWh]
Solar PV	0.013
Wind Turbine	0.755
Lead-acid Batteries	0.271

In terms of energy, the total contribution of each renewable is illustrated in Table 5. The results show that solar PV generates 98.43% of total annual electricity, while wind turbines contribute only 1.56%. The excess energy 56,074 kWh/year generated by renewables is stored in BESS to meet load demand during peak or non-generation hours.

Table 5. Energy Supply-Demand analysis.

Economic Parameters	Annual energy [kWh/year)]
AC Primary Energy Demand	62,039
Solar Energy Generation	125,871
Wind Energy Generation	1,997
Excess Energy	56,074

From all these results, the total NPC (NPCtot), total annualized cost (Cann, tot) and levelized cost of energy (LCOE) of the designed system, based on the results, is obtained and presented in Table 6.

Table 6. Cost analysis of MG system (Annual Energy Demand 62,039 kWh/year)

Economic Parameters	Values
Total Net Present Cost	294,563.60 $
Total Annualized Cost ($C_{ann,tot\ (gen)}$)	11,782.55 $/year
Levelized Cost of Energy (LCOE $_{(gen)}$)	0.190 $/kWh
Profit of Utility per kWh	10%
Total Annualized Cost ($C_{ann,\ tot\ (sale)}$)	12,960 $/year
Levelized Cost of Energy (LCOE $_{(sale)}$)	0.209 $/kWh
Utility's Annual Profit	1178.74 /year

4.2. Categorization of Time-zones

In this research, the structure of time zones depends on analyzing the generation profile by renewable energy and the BESS status. A higher percentage of renewable penetration per day results in more significant hours for accumulative off-peak and mid-peak hours and fewer peak hours. Thus, based on historical data in Section 2 and the combination sizing in Section 4.1, each year is divided into two tariff seasons (six months). Season 1 includes months from April to September, while season 2 consists of months from October to March following the equinoxes. Thus, the time zones are identified based on the difference between energy generation and consumption profiles in each season. Figure 6 shows one day profile of renewable generation and battery's SOC. Each day is categorized into three time zones; peak hours (expensive time block), mid-peak hours (mid-range priced time block), and off-peak hours (cheapest time block).

The categorization of time zones is shown in Figure 7. From the figure, the total energy produced by renewable generation is approximately five times higher than the consumption for the off-peak hours. In the mid-peak hours, the difference between renewable generation and consumption is relatively smaller than off-peak hours. During this time, solar energy is the primary source, followed by BESS, and the wind contributes a small portion of the energy. In peak hours, either there is no generation at all or insignificant compared to energy consumption. Thus, load demand is fulfilled through BESS, which is the most expensive component of the MG. So, the electricity price comes out to be maximum during this time.

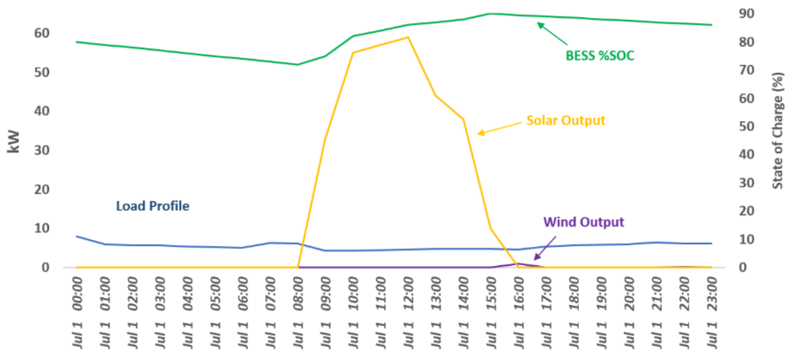

Fig. 6 Renewable generation, load consumption and battery % state of charge (SOC) profile in the microgrid system.

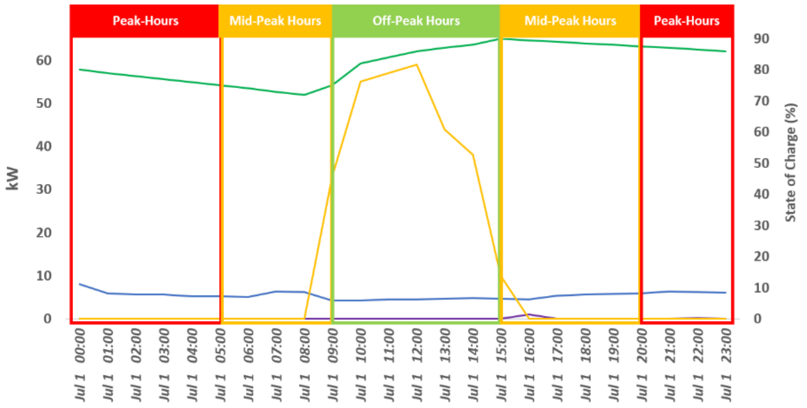

Fig. 7 Categorization of time zones.

4.3. Development of d-TOU Tariff Structure

Table 7 shows the detailed tariff structure for the independent MG system proposed in this study. The tariff is based on the hourly categorization of time blocks in each season. The results (tariff) are obtained based on individual time zone analysis using equations (4) – (7), the available total renewable energy, as well as the amount of energy supported by the battery. Since the battery energy cost is high, the zone that uses the battery the most will be the most expensive.

Figure 8 (a) & (b) shows that the renewable penetration is more in season 2 compared to that of season 1. Therefore, Table 7 shows that 52% of the total annualized cost is recovered in season 1, while 48% will be recovered in season 2. Throughout the year, energy prices in off-peak and mid-peak hours remain the same. However, peak-hour energy price in season 1 is more than that of season 2 since the energy from renewable is more due to the penetration factor. Consequently, the price for electricity will be lower since there is less dependency on expensive system components such as the batteries

Table 7. Seasonal time zones, energy consumption and d-TOU tariff structure.

Description	**SEASON 1 (April to September)**				**SEASON 2 (October to March)**			
	Off-peak	**Mid-peak hours**		**Peak hours**	**Off-peak**	**Mid-peak hours**		**Peak hours**
Hours	6	9		9	6	11		7
Duration	0900hrs to 1500 hrs	0500hrs to 0900hrs	1500hrs to 2000hrs	2000hrs to 0500 hrs	0900hrs to 1500 hrs	0400hrs to 0900hrs	1500hrs to 2100hrs	2100hrs to 0400 hrs
% of Daily Total Energy Consumption	21.07	35.44		43.49	21.07	44.17		34.76
Generation Source Proportion	Solar	Solar > BESS >> Wind		BESS >> Wind	Solar	Solar > BESS >> Wind		BESS >> Wind
Energy Price ($/kWh)	**0.41**	**0.82**		**1.22**	**0.41**	**0.82**		**1.13**

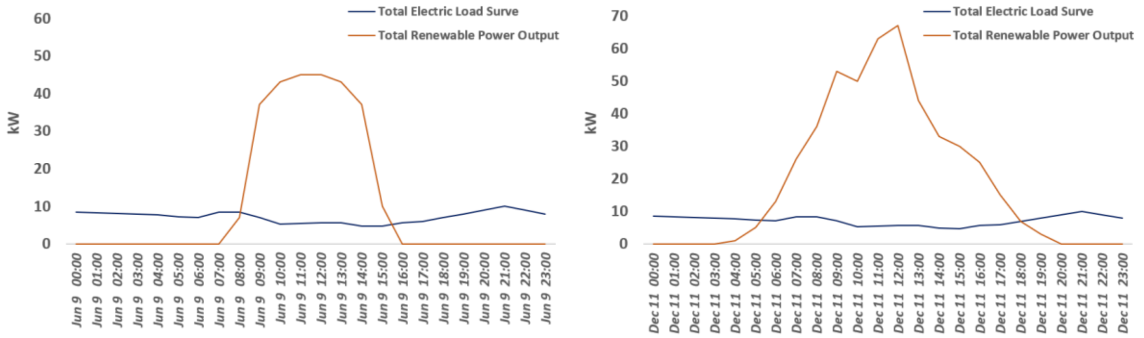

Fig. 8 (a) Renewable penetration per day in season 1, (b) Renewable penetration per day in season 2.

4.4. GH Emissions

The designed MG system solely depends upon the RES and gives zero carbon emissions during their operation. Although their operation is emission-free, a considerable amount of GHGs are emitted during material fabrication, assembly manufacturing, transportation, the balance of system (BOS), and solar and wind systems disposal. For example, in ref [13], GHG emissions from small-scale on-shore horizontal axis wind turbines (HAWT) were found to be approximately 42.7 gCO2e/kWh. According to Malaysia's solar irradiance and ambient conditions, the type and efficiency of chosen PV modules, the lifecycle GHG emissions from solar PV components is approximately 36.75 gCO2e/kWh [14]. Table 8 shows the total GHG (gCO2e/kWh) emissions in the lifespan of the designed MG system.

According to the Sustainability Report 2017 published by Tenaga Nasional Berhad (TNB), the prime electric utility company in Malaysia, the GHG emission from conventional electricity generation, transmission and distribution in 2016 was 29,061,190 tCO2 [24]. The total electricity consumption of Malaysia in 2016 was 145.19 TWh [25], which gives 181.83 gCO2e/kWh. The results in Table 8 show that GHG emissions of electricity generation from designed MG are 85% lesser than that emitted by conventional electricity generation in Malaysia.

Table 8. GHG emissions from the designed MG.

RES	GHG Emission [gCO$_2$e/kWh]	Annual Energy Generation [kWh/year]	Total GHG Emissions [kgCO$_2$e/year]	MG's GHG Emission [gCO$_2$e /kWh]
Solar	36.75	125871	4625.76	-
Wind	42.70	1997	85.27	-
Total	-	127868	4711.03	27.14

5. Conclusion

In this paper, a standalone microgrid (MG) system with solar, wind energy sources and battery storage systems to fulfil a residential load requirement in Malaysia is proposed. A new scheme of dynamic time-of-use (d-TOU) tariff for an islanded MG system with 100% renewable energy resources is introduced based on the generation profile majorly. Three time zones are developed for each day. (i.e., peak, mid-peak and off-peak, with different electricity rates (expensive, mid-range, and cheapest)). Moreover, based on renewable energy penetration, a year is divided into two seasons. Due to the higher lifecycle cost of batteries, the expensive rate is approximately three times more than the cheapest rate and at least 1.6 times more than mid-peak hours of energy price. Although the tariff rates in the proposed MG system are found to be more than the standard electricity tariff due to higher capital and replacement costs, at the same time, the GHG emission rate from the proposed system is 85% lower than that of conventional electricity generation in Malaysia. The results showed that the efficient implementation of the d-TOU scheme could produce a reasonable electricity tariff to consumers and a significant decrement in GHG emissions.

Acknowledgments

This work is supported by Universiti Teknologi Malaysia (UTM) under UTMShine Grant (Q.J130000.2451.09G43) and Industry/International Incentive Grant (IIIG) (Q.J130000.3651.03M40).

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