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Optimal Techno-Economic Design of Standalone Hybrid Renewable Energy System Using Genetic Algorithm

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Abstract. This paper presents a methodology to size Standalone Hybrid Renewable Energy System (SHRES) which combines solar PV, wind turbine (WT) and battery energy storage (BES) for application in rural areas. These sources are integrated via an AC bus to support the load demand. SHRES is simulated under varying load demand, solar radiation, temperature and wind speed obtained from the Malaysian Meteorological Department. A Multi-objective Optimization using Non-dominate Sorting Genetic Algorithm (NSGA-II) was utilized to determine the best sizing of PV/ wind turbine/ battery, and minimize Cost of Energy (COE) and Loss of Power Supply Probability (LPSP). The results show that the NSGAII optimization of the model is able to determine the best techno-economic sizing for the suggested location. For the case study, the optimum COE was 0.1099 (USD/kWh) and LPSP was 0.0865. The proposed tool can be used to size the SHRES for rural electrification and enhance energy access within remote locations.

1. Introduction

Nowadays, SHRES has become an alternative solution to meet environmental concerns and electricity demand. With the complementary characteristics of solar PV and WT, hybrid PV-WT system with batteries provide an option to supply power to rural loads where distribution lines from the utility grid do not exist. Since these hybrid systems produce reliably and cheaper energy source, their application and related research are gaining more traction [1]. However, due to the random behaviour for both PV and wind sources, the main consideration in the system design of the SHRES is the reliability of power supplied to the user under unpredictable climatic conditions and COE [2]. Optimization tools can play a vital role in determining the sizing and utilization of a SHRES, for a given load demand. Artificial Intelligent (AI) techniques are significantly employed to optimize a stand-alone hybrid system to achieve its maximize of economic benefits. Genetic Algorithm (GA) is one of the AI techniques which provides a practical approach to optimize the sizing of hybrid systems, notably in complicated networks where a significant number of criterions such as the specification of solar PV, WT, BES, wind turbine height, project lifetime, meteorological data, as well as reliability and cost have to be considered. This method provides the flexibility for different sizes of components in SHRES to satisfy the load demand in a given location and to evaluate them based on the defined fitness function [3].

A Multi-objective Optimization using GA method was promoted in the hybrid system developed by K. Deb in 2002 [4]. Investigation of the hybrid renewable system to obtain the maximum generation, high reliability and low economic solutions with various objectives were reported using multi-objective optimization. The multi-objective optimization is generally employed to realize a trade-off solution once there are different objectives notably when they are contradictory to one other. Some articles have used Pareto optimization established for a problem with multiple objectives, using NSGA-II method [5-7]. In ref [8], a new approach for optimal sizing of stand-alone Solar PV with battery energy storage system is presented using a numerical method to consider the accuracy of energy flow calculation model. In ref [9], the optimization of an off-grid hybrid micro-grid system to determine the optimal sizing in twelve Swedish regions is proposed. PSO method is used to determine the optimal design of three objectives: COE, LPSP, and impact of environmental pollution (CO2).

Some researchers have introduced the optimization procedure for the hybrid PV/wind energy system. However, some of the models are not accurate and failed to consider the heights of wind turbine towers. Some of the intelligent optimization algorithms are fast but cannot meet the optimum global point. Additionally, some methods are only applicable to the constant load demand problem, which makes the application of formula very limited. Hence, the need for the robust optimization algorithm.

The primary objective of this research is to utilize NSGA-II method to determine the optimal sizing of SHRES using Pareto optimization to have a cost and reliable, effective system for electrification of some houses in the rural area. The contribution of this paper is summarized as follows. Two objective functions using NSGAII is proposed to determine the optimized system sizing, with minimum COE and LPSP. The considerations in the optimization manner are the number of PV modules, WT, and BES. Also, the batteries charging /discharging state can be achieved in the suggested method, because the BES is becoming a crucial component in the hybrid energy system, especially in isolated areas, to enhance the reliability and sustainability. The paper is organized into six sections. Section 2 presents the architecture of hybrid PV- Wind and battery system. Optimal design criteria for SHRES are demonstrated in Section 3. The hybrid system optimization technique using NSGAII is described in Section 4. Section 5 summarizes the optimization results and conclusion is presented in Section 6.

2. Architecture of hybrid PV-wind system

2.1. Prediction of the Wind Turbine Performance

Before estimating the power output of a wind turbine, the average hourly wind speed measured data is converted to the corresponding hub height values. The wind speed measurement at a reference height (H_{ref}), is extrapolated to a particular hub height (*H*) speed for that location on an hourly basis through the subsequent expression.

$$V_W \, / \, V_{ref} = \left(\frac{H}{H_{ref}}\right)^{\alpha} \qquad (1)$$

where V_W is the wind speed at the hub height *H* (m/s) and equals 70m and V_{ref} is the wind speed at reference height, H_{ref} (m/s) and equals 10m. α is the power-law exponent ratio of 0.1428 for open land as suggested in reference.

2.2. Formatting Prediction of Solar Module Performance

The output of PV module will depend on the solar radiation, PV module temperature and soiling effect at the desired location. Therefore, knowing the PV module output at different operating conditions is imperative for appropriate module selection and correct determination of their power output. The solar panel can be defined as a group of modules electrically connected in series and parallel combination to generate the desired voltage and power. The most common model used to predict the output power of a PV cell can be represented by Equations (3) and (4).

$$P_{PV} = PV_{STC} \left(\frac{G}{G_{ref}}\right)(1 + KT(T_C - T_{ref})) \qquad (2)$$

$$T_C = Ta + (0.0256 * G) \qquad (3)$$

where PV_{STC} is nominal power in (kW), G is global solar radiation (kW/m^2), G_{ref} is solar radiation under STC (1000/m^2), T_C is temperature of PV Cell, T_{ref} is $25\,C^{\circ}$, K_T is the PV temperature coefficient and equals to $3.7*10^{-3}$ (1/Ċ) and Ta is the ambient temperature.

2.3. Prediction of Battery Energy Storage (BES) Performance

Due to the intermittent output power of PV and WT, battery bank is necessary to sustain the balance of the SHRES. Battery bank can supply the load when there is a shortage of electricity, and store excess power when the generated power surpasses the load demand. The main type of storage system often used in the hybrid power system is the lead acid or lithium based battery. The operating modes of batteries used in this research can be expressed using the following equations:

$$\Delta E_{net} = E_{RE}(t) - E_L(t) \tag{4}$$

$$E_{RE}(t) = N_{WT} * E_{WT}(t) + N_{PV} * E_{PV}(t) \tag{5}$$

Where, ΔE_{net} is the net energy of SHRES, N_{WT} is the number of WTs, N_{PV} is the number of PV panels, E_{WT} is the energy generated by the wind turbines, E_{PV} is the energy generated from the PV panels, E_L (t) is the load demand at hour (t); where (t) equals one hour. The operating model of the battery bank can be summarized as follows:

- When the energy generated from the PV only or from the PV and WT together are greater than the load demand, $E_{RE}(t) > E_L(t)$, the surplus energy employed to charge the battery bank at the hour (t) is expressed by:

$$E_{BAT}(t) = E_{BAT}(t-1) * (1 - \sigma) + \left[\left(E_{RE}(t) - \left(\frac{E_L(t)}{\mu_{inv}}\right)\right)\right] * \mu_{bat} \tag{6}$$

- When $E_{RE}(t)$ is lower than load demand, $E_{RE}(t) < E_L(t)$, the battery bank is discharged to sufficiently supply the load demand. Thus, the charge quantity of battery bank at the hour (t) is expressed by:

$$E_{BAT}(t) = E_{BAT}(t-1) * (1-\sigma) - [(E_L(t)/\mu_{inv}) - E_{RE}(t)] \tag{7}$$

Where, $E_{BAT}(t)$ and $E_{BAT}(t-1)$ are the battery charge quantities at the hour t and t-1, respectively and σ is the battery hourly self- discharge rate. At any given duration, the charge quantity of the battery is subjected to the next constraint:

$$E_{B.MIN} \leq E_{BAT}(t) \leq E_{B.MAX}$$

where the maximum charge quantity of the battery, $E_{BAT.MAX}$ takes the amount of available battery capacity, C_B (Ah) and $E_{B.MIN}$ is the minimum charge quantity of battery that is limited by the depth of discharge (DOD) [10].

$$E_{B.MIN} = (1 - DOD) * C_B \tag{8}$$

The battery capacity for the hybrid system is designed to satisfy the load profile (kW) and the days of autonomy, according to the following equation.

$$C_B = \frac{E_L * AD}{DOD * \mu_{inv} * \mu_{bat}} \tag{9}$$

where, days of storage required (AD) is taken to be one day, DOD is the maximum depth of discharge (70%), μ_{inv} is inverter efficiency and μ_{bat} is battery efficiency.

3. Optimal design criteria for SHRES

3.1. Technical analysis

Due to the intermittency of renewable energy supply, energy system reliability is regarded as essential criteria in the design of SHRES. In simple terms, the system reliability is expressed as an LPSP. The probability of insufficient power takes place when the hybrid energy system cannot satisfy the load demand. The LPSP function is performed by equation (10).

$$LPSP = \frac{\sum_{t=1}^{T} E_L(t) - E_{RE}(t) + (Eb(t) - Ebmin(t)) * \mu_{inv}}{\sum_{t=1}^{T} E_L(t)} \tag{10}$$

In this case, the operating time of the hybrid system is chosen as one year and, the daily operating time is 24 hours. Hence, LPSP of 0 means that the supply of energy can meet the load demand, whereas LPSP of 1 means the supply of power cannot meet the load profile.

3.2 Economic analysis

Many researchers have given prominence to the cost analysis in SHRES to optimize the system sizing. In this study, the economic approach according to the COE is presented as the standard cost per kilowatt-hour ($/kWh) of beneficial electrical power generated via the hybrid system [11, 12]. The above approach can be achieved using the following equations.

$$COE = \frac{(CRF * TAC)}{E_L} \tag{11}$$

$$CRF = \frac{d(1+i)^T}{(1+i)^T - 1} \tag{12}$$

where, CRF is the Capital Recovery Factor, which is a ratio utilized to compute the present value of an annuity [13]. In this paper, i = 3.2 % [14], T is 20 years and TAC is the Total Annualized Cost ($). TAC is the sum of annualized Capital Cost (C_C), Operation and Maintenance Cost ($C_{O\&M}$) and the Replacement Cost (C_R).

$$TAC = C_C + C_{O\$M} + C_R \tag{13}$$

The total annualized cost (CC) is the sum of annualized capital cost defined using the following equation:

$$C_C = (N_{PV} * P_{PV} * C_{PV}) + \left((N_{WT} * P_{WT} * C_{WT}) + \left(C_{WT} * N_{WT} * \frac{20}{100}\right)\right) + (N_B * C_b * C_B) +$$
$$(N_{INV} * C_{INV}) + (C_{REG-PV} + C_{REG-WT}) \tag{14}$$

Where, C_{PV}, C_{WT}, and C_b, C_{INV}, C_{REG-PV} and C_{REG-WT} are PV panel unit-price, wind turbine unit-price, battery unit-price, inverter unit price, regulator of wind turbine price and regulator of PV price respectively. N_{INV} is the number of inverters, as well as the cost of the wind tower taken as 20% of the capital cost. The $C_{O\&M}$ is taken as 1% of the total cost [13]. For the Replacement Cost, only the battery, regulators and inverters need to be replaced during the project duration.

$$C_R = C_{REP} * SFF(i, P_{R-LF}) \tag{15}$$

$$C_{REP} = ir * ((N_B * CR_B) + (N_{INV} * CR_{INV}) + (N_{REG-PV} * CR_{REG-PV}) + (N_{REG-WT} * CR_{REG-WT})) \tag{16}$$

Where, SFF is the sinking fund factor, P_{R_LF} is the lifespan of components (battery, inverter and regulators), ir is the number of times of replacement of batteries, inverters, and regulators during the lifespan of the system. CR_B, CR_{INV}, CR_{REG_PV} and CR_{REG_WT} are the replacement cost of the battery, inverter, PV regulator and wind turbine regulator respectively. Therefore, the sinking fund factor is clarified by the following equation:

$$SFF(i, P_{R-LF}) = \frac{i}{(1+i)^{P_{R-LF}} - 1} \tag{17}$$

4. Hybrid system optimization using NSGA_II

This study employs the NSGAII technique to determine the techno-economic sizing of the SHRES to satisfy the load demand. Therefore, the primary aim of the proposed method is to optimally size the PV-WT and battery by minimizing the two objectives: LPSP and COE that guarantees the energy autonomy of a rural area consumer Furthermore, the battery's charging/ discharging on an hourly basis was considered to mitigate thef intermittency of PV/WT output by minimizing energy losses. The Pareto surface of the multi-objective optimization is produced where the global optimum point can be found. For more clarification on how the NSGAII method works in SHRES, the following references can be referred [5, 6]. Figure displayed the NSGA-II implementation flow diagram for further illustrations. The hourly meteorological data applied in the model includes the solar radiation, temperature, wind speed, load demand, and the specifications of the hybrid system components. The output power from the solar PV is determined by the PV model by employing the technical requirements of the PV system module and environmental data. The installation height of WT needs to consider the wind turbine performance calculations. The battery capacity, C_B (kWh) is allowed to discharge up to a limit which is given by the system designer. There are a collection of constraints which have to be followed during the system operation for any possible solution, as follows:

$$N_{PV}^{MIN} < N_{PV,} < N_{PV}^{MAX}$$
$$N_{WT}^{MIN} < N_{WT} < N_{WT}^{MAX}$$
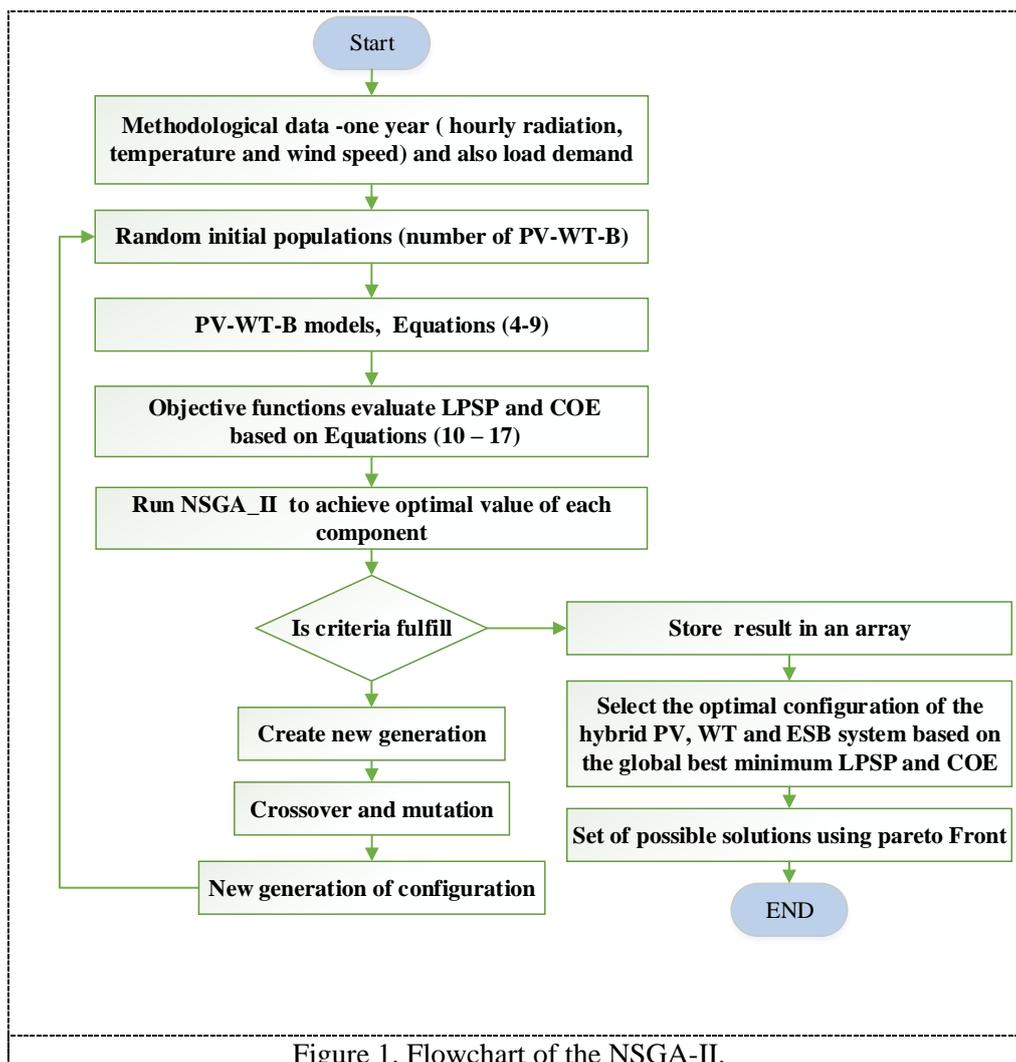$$N_{B}^{MIN} < N_{B} < N_{B}^{MAX}$$

Figure 1. Flowchart of the NSGA-II.

5. Result and discussion

In order to determine the optimal size for the SHRES, the load profile is of importance. The operation of various electrical devices and also the behavior of the customers are the parameters that determine the load curve. For the purpose of finding the optimal sizing of the SHRES, the load profile for rural households in Malaysia are commonly classified as low energy and ranged from 1 to 5 kW per household [15]. Load variations could emerge because of the use of different electrical equipment in every home. However, the load might not differ much from the types of electrical appliances used in the rural houses, as shown in Table 1. The load profile for a typical rural area in Malaysia consists of 20 households and the total energy consumption per day is assumed as 134.4 kWh [16].The specification of the wind turbines, PV modules, battery and inverters are shown in Table 2.

In this research paper, the proposed method was examined using the NSGAII Optimization toolbox in MATLAB, based on 200 population size, 0.80 crossover, and 500 generations. Meanwhile, the optimization procedure was aimed to find the numbers of variables which depend on the state of NPV, NWT, and NBES to meet the minimized LPSP and COE. Figure 2 shows the response of PV-WT-with BES and load demand. The BES output is positive when the battery was discharging. In this figure, the State of Charge (SOC) and State of Discharge (SOD) are illustrated. From this figure, it can be seen that the total power generated is sufficient to fulfill the load demand during the day, while the extra energy is used to charge the battery bank. Meanwhile, the wind power was deficient due to low wind speed in Malaysia. Also, the output of the NSGA-II indicates that this location is poor for wind energy. The performance of the proposed system was based on the load demand at its peak in the evening starting from 18:00 until 7:00 and the available power from solar PV and WT were not sufficient to feed the load at the time. Hence, the energy required was supplied by the battery bank.
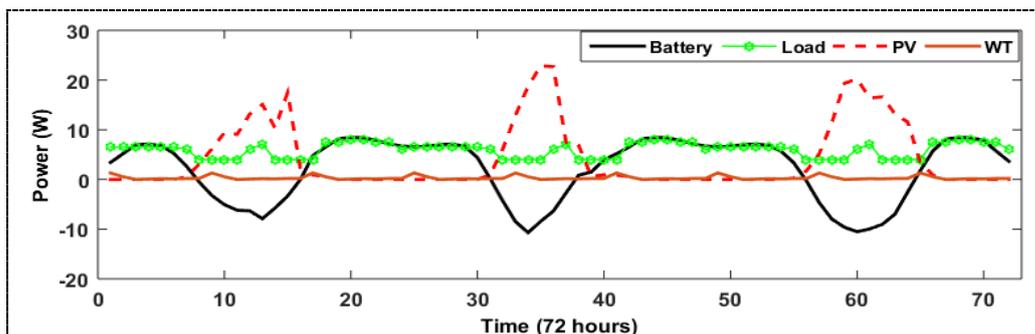

Figure 2. Output of PV-WT-battery and load demand.
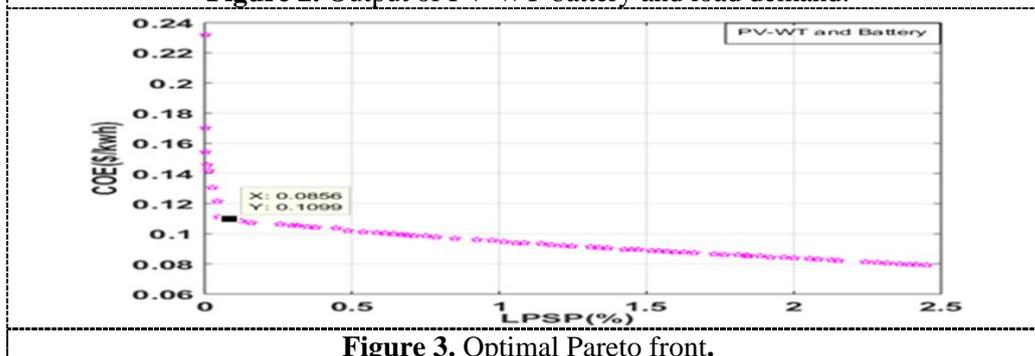

Figure 3. Optimal Pareto front.

The configurations of the batteries with an AD is one-day cannot satisfy the reliability requirement to achieve LPSP is 0% due to the high cost of cells with a short lifetime. Also, increase the number of wind turbine makes the system relatively costly because of low wind speed. Therefore, for a high-reliability system, the best choice would be an increase in the number of PV panels instead of increasing the number of wind turbines or increasing the number of batteries. The solution obtained from the NSGAII method for one year is shown in Figure 3. The figure has also illustrated the trade-off between LPSP and COE that involving the optimal point of the system requirements. Thereby, each solution represents

LPSP and COE that demonstrate the minimum value of the multi-objective optimization set of solutions known as a Pareto optimal set or Pareto front. Any one of these solutions can be optimal, meaning that no improvement may be made on one of the two objectives without worsening at least one of them. This technique permits the user to select between different solutions and gives conception concerning LPSP according to COE. The Pareto set consisted of 70 solutions. At the end, the solution that satisfied the minimum LPSP and COE criterion is chosen as the optimum value. The contribution of PV, wind turbine and battery bank within one year were 70%, 1% and 29% respectively. Table 3 gives the size of devices and optimum result of the multi-objectives for the SHRES. The system was compared in terms of reliability and cost of energy in addition to the minimum total cost system. As a result, the system has good reliability with the lowest cost. Based on the simulation result, it could be concluded that the suggested optimization approach can fulfil a low energy cost and high energy reliability. In case (a), replace wind turbines with diesel generators and in case (b), optimize battery depth of discharge besides consideration of charge-discharge cycles that would prolong battery lifespan.

Table 1. Parameter specification for WT, PV module, BES, and inverter.

Electrical appliance	K1	K2	K3=K1*K2	K4	K5=K3*K4	Usage duration / day (hours)
	Rated Power (watt)	Quantity per house	Power (watt)	House per day used (hours)	Energy per day (Wh /day)	
Tube lighting of the living room	20	1	20	6	120	6pm-12am
Outdoor tube lighting	20	1	20	12	240	6pm-12am
Tube light (bedroom)	10	2	20	2	40	
Ceiling fan in living room	55	1	55	6	330	12pm-2pm and 6pm-12am
Color TV	80	1	80	7	560	12pm-1pm and 6pm-12am
Refrigerator one door	200	1	200	24	4800	All the day
Table fan	50	1	50	6	300	12am-6am
Ceiling fan in bed room	55	1	55	6	330	12am-6am
Total	490	9	500	69	6720	All the day

Table 2. Typical electrical appliances in rural houses in Malaysia.

Wind turbine specifications	PV modules specification	Battery specification	Inverter specifications
Output power = 3 kW. Generator voltage = 230 Vac. Cut.in wind speed = 2m/sec. Wind speed = 12m/sec. Initial cost = $2800 Regulator cost = $750 Lifetime = 20 years.	Power max = 320W Voltage = Vmpp 54.7V Current = Impp 5.49A PV regulator cost = $750 Initial cost = $290 Life time = 25 years	Capacity = 1000 Ah Voltage = 2V Efficiency = 85% DOD = 70% Initial cost = $230	Rated power = 6500 W Input Voltage =12V/24V Frequency = 50 Hz Efficiency = 90% Initial cost = $2528 Life time = 10 years

Table 3. Configuration result of the optimization NSGA_II method in SHRES / year.

Method	N_{PV}	NWT	NB	LPSP (%)	COE ($/kWh)	C_{TOTAL} ($)
NSGAII	178	1	1	0.086	0.1099	66590

6. Conclusion

This paper applied the multi-objective optimization technique based on NSGAII method in order to obtain the best sizing of the hybrid PV-wind turbine and battery. Meanwhile, NSGAII was employed to plot the Pareto front to present the trade-off between the reliability and cost. The control strategy for a SHRES was presented to meet the load demand and to ensure the utilization of renewable energy in the rural area in Malaysia. The optimization was conducted to facilitate the selection of the best configuration across numbers of PV modules, wind turbines and batteries to minimize LPSP and COE. Charging/ discharging of BES on an hourly basis was investigated to mitigate the intermittency of solar PV/WT output for minimizing energy losses. The proposed method was able to optimize any given wind model and solar model for different locations. The results showed that the LPSP and COE of the SHRES can be reduced with proper optimization, and it illustrates the optimum value for LPSP is 0.0865 and COE is 0.1019, thus ensuring a cost-optimized solution.

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