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Sizing and economic analysis of stand-alone hybrid photovoltaic-wind system for rural electrification: A case study Lundu, Sarawak

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ABSTRACT

Energy Consumption has been increasing at an alarming rate due to the growing energy need. More and more non-renewable sources are harvested to fulfill the energy demand resulting in and rising environmental health issues. However, harvesting Solar and Wind energy is considered as the best alternative in generating energy as these resources are renewable. Hybrid Renewable Energy System (HRES) has been grabbed the attention recently, as it involves with renewable, environmentally friendly sources to generate energy. The limitation of single Renewable Energy (RE) system is overcome by systems such as HRES. Even though it has been introduced different sizing and optimization techniques, due to the lack of system function, it had posed issues in calculating the optimized cost of a hybrid system considering the solar, wind resources and load demand as the optimization of the system cannot be predicted accurately. The aim of this research was to obtain optimization of a Hybrid PV-wind system in term of sizing and cost over the 20 years of the period of interest. The simulation of the PV-Wind Hybrid system using MATLAB for the verification purpose. This work includes detailed calculation using the Life Cycle Cost method for identifying all possible combinations. The combination of eleven Solar Panels, one Wind Turbine and nine Batteries was identified as the optimal Combination with LCC of RM 221,329.97 and has been verified using simulation results. Lastly, a sensitivity test was carried out using the exiting results of verified by the simulation to identify the most deterministic system in affecting LCC of the Hybrid system. Further, total Cost distribution for the Optimized hybrid PV-Wind system was conducted and identified that 50% of system cost was contributed by the Wind turbine. Determination of LCC, was done as a combination of Component and Operation costs. It was identified that Replacement cost contributed the highest while Wind turbine showed the highest Operation cost from the system cost. Thus, this work was included with the sensitivity test assuming 10% price increment for each component and it was concluded that price changes in Wind turbine results the greatest difference in LCC while further verified with the results of the simulation.

1. Introduction

Consumption on non-renewable sources such as coal and gas to produce energy has an adverse impact to nature (Tambi et al., 2020). Even though these sources are being used as the primary Energy Sources (ES) for energy production globally, it is proved that these non-renewable ES cause harm for the health and lead for the global warming (Al zahrani et al., 2021). However, due to the improvements

Abbreviations: Renewable Energy, RE; Malaysian Ringgit, RM; Energy Sources, ES; Photovoltaic, PV; Hybrid Renewable Energy System, HRES; Life Cycle Cost, LCC; Direct Current, DC; Vertical Axis Wind Turbine, VAWT; Horizontal Axis Wind Turbine, HAWT; Deficiency of Power Supply Probability, DPSP; Lost of Power Supply Probability, LPSP; State of Charge, SOC; Hybrid Optimization Model for Electric Renewable, HOMER; National Renewable Energy Laboratory, NREL; Levelized Cost of Energy, LCE; Artificial Intelligence, AI.

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and efficiency in technologies, the exploitation of renewable energies is increasing exponentially (Al Busaidi et al., 2016).

Solar Energy is preferable with the least impacts on the environment and different types of Photovoltaic (PV) configurations have been tested and concluded with different efficiency. Solar cells are much more expensive compared to traditional ES (Gulaliyev et al., 2020). Thus, countries with strong wind have already started utilizing wind energy and research has been done to increase the effectiveness of solar and wind energy conversions (Ji et al., 2021). Various sizing techniques were considered in this research to achieve the peak energy demand with the limited source available and the probabilistic method was one of them (Sawle et al., 2016). Even though a variety of sizing and optimizing techniques are commonly used in the world that possesses different accuracy, complexity etc., due to lack of real-life implementation, it had caused difficulty in selecting methods to be used. Therefore, different sizing and optimization techniques were studied thoroughly to select the best method to address in this study. Thus, due to the lack of system function, it had posed issues in calculating the optimized cost of the hybrid system considering the solar, wind resources and load demand as the optimization of the system cannot be predicted accurately. With less studies and the presence of Hybrid Renewable Energy System (HRES) in Lundu, it was required the installation of electrification and essential to research how effective and efficient the hybrid system in producing the electricity in an identified area. Therefore, a critical review on hybrid PV-wind system was done and PV configuration was designed with careful consideration on partial shading while the wind turbine selection was done considering the quality of the wind at the project location. Optimization of the hybrid PV- Wind system was done through Life Cycle Cost (LCC) analysis to achieve the load demand with the minimum cost criteria. Then function system was simulated using MATLAB to determine the optimized PV-Wind system.

2. Literature review

2.1. Design of hybrid PV-wind system

Fig. 1 shows the completed and simple schematic diagram of a hybrid PV-wind system. HRES is an electrical system that comprises more than one ESs, while at least one is renewable (Kartite and Cherkaoui, 2019) and boosts up the performance in terms of efficiency, stability and reliability of the system. Wind and PV generate energy to supply the load demand and channel the excess energy to battery chargers. Both battery chargers are connected to a common Direct Current (DC) bus to charge the battery bank using respective solar and wind sources (Faizan et al., 2021). The DC energy goes through DC/AC inverter before the End-user usage. HRES system in general leads to overcome the limitation of single RE system as wind turbine and PV plants are not eligible to produce energy all the time due to the dependency on the weather (Mehrjerdi, 2020). Due to the limitation of renewable resources, the "Stand-alone system", experiences various difficulties including efficiency, reliability etc (Faizan et al., 2021). The Hybrid system is enabled to compensate during the lack of each resource to achieve the demand and contribute to better reliability and more economical operation (Al Badwawi et al., 2015). Uncertain load demand and unpredictable resources are some of the concerns that cause difficulty for the optimization of the hybrid system (Al Busaidi et al., 2016).

2.2. PV system

In term of PV system, PV cell is a device that converts the solar radiation into electrical energy using semiconductors as the medium and the performance can be affected by different factors including partial shading, cell temperature, wind speed and tilt angle etc (Vengatesh and Rajan, 2016). Fig. 2 shows a basic structure of a PV system. PV generation has an uncertainty associated to its energy output as it mainly depends on the weather conditions i.e. solar irradiance and temperature (Quiles et al., 2020). Due to the limitation of solar irradiation, the battery bank is required to ensure a continuous supply of energy in achieving the load demand. Research had been done on the economic viability of hybrid system on rural areas in Peru and the usefulness & effectiveness had been proven (Rinaldi et al., 2020).

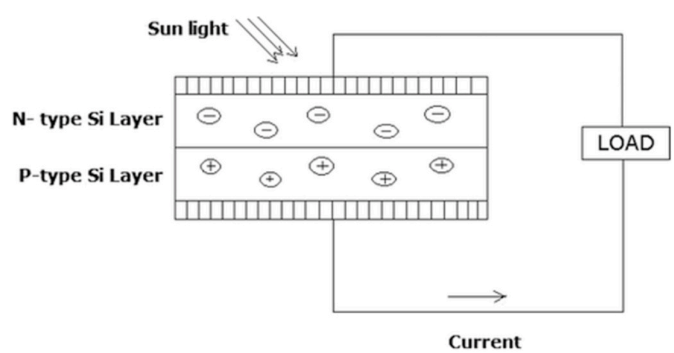

Fig. 2. Simple Structure of PV cell (Vengatesh and Rajan, 2016).

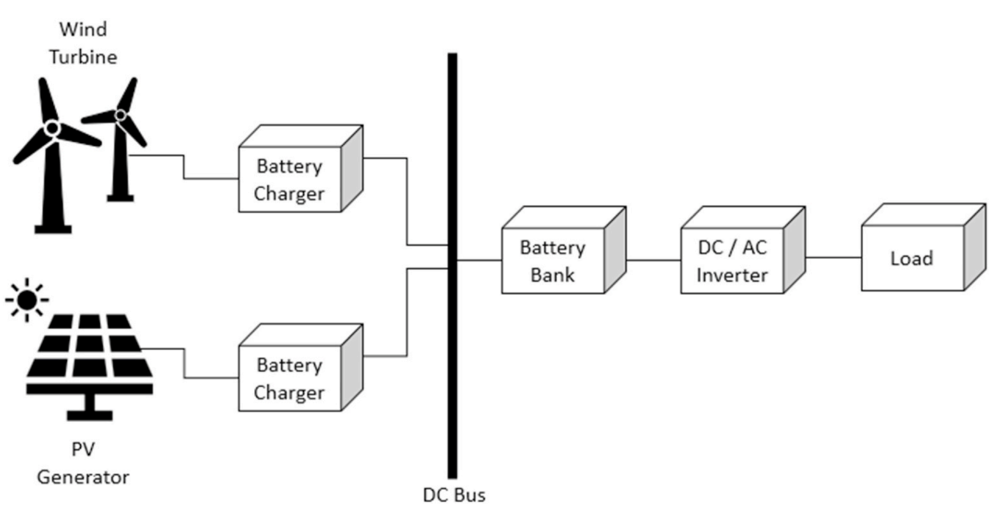

Fig. 1. Overview of hybrid PV-wind system.

2.3. Wind system

People have been harvesting wind for different purposes since the early centuries. Before the introduction of the wind turbine to supply electrical energy, wind energy has been used to propel boats, grinding grain or pumping water. The very first windmill was constructed by Prof James Blyth of Anderson's College, Glasgow and located strategically in Scotland in July 1887 (Bhandari et al., 2015).

The rotation of wind turbines installed produce kinetic energy, then convert into electrical energy by the aid of a generator (Chavan et al., 2021). Thus, the factors like wind speed, density, and tower height etc are some of the factors that affect for the efficiency of the wind turbine (Chen et al., 2017). Type of wind turbines selection is based on the geology as the efficiency of wind turbines installed is affected by the type of wind presence. Vertical-axis (VAWT) and Horizontal-axis (HAWT) wind turbines are two distinguished types while HAWT has higher efficiency compared to VAWT (Pope et al., 2010).

2.4. Battery bank

The size of the battery bank must be able to meet the load demand during the lowest wind speed or solar radiation period, basically referred as days of autonomy. As specified, battery configuration and capacity are two important factors. The configuration differs from a single battery to multiple batteries connecting to form one large battery fulfilling the required voltage and ampere (Al zahrani et al., 2021).

2.5. DC – AC inverter

DC-to-AC Inverter converts the supplied DC power from PV and wind sources into AC power before the End-user usage.

3. Review on different sizing and optimization techniques

3.1. Sizing techniques

The sizing technique is closely related to reliability analysis. Climate and weather conditions are factors that affect the hybrid PV-wind system in terms of performance, production, or reliability (Sawle et al., 2016). There are several sizing techniques namely probabilistic methods, DPSP/LPSP method, analytical method, and simulation method to determine the size of PV panels and wind generators that have been introduced with the intention of minimizing the System Cost while maintaining the system reliability (Al Busaidi et al., 2016). These systems are considered as reliable if they are satisfied by the load demand.

(a) Probabilistic Method

The probabilistic method is the simplest yet direct method that has a less complexity and simple to implement, however, the output generated using such a method may not result in the best solution (Al-Shahri et al., 2021). It can be further categorized as annual monthly average sizing technique and most unfavorable month technique (Dawoud et al., 2018). The annual monthly average sizing technique is implemented to determine the size of PV panels and wind generators by referring to the average monthly solar irradiation and wind speed per year (Al Busaidi et al., 2016). The most unfavorable month technique on the other hand is used to calculate the size of PV panel and wind generators during the month of autonomy (Al Busaidi et al., 2016). The system is bound to function reliably throughout the year if it operates normally by the month with the lowest wind speed and solar irradiation. This method saves cost & time and loads data collection required is minimum (S. Diaf et al., 2008).

(b) DPSP/LPSP

Deficiency of Power Supply Probability (DPSP) or Lost of Power Supply Probability (LPSP) on the other hand is a technique to determine the reliability of the system (Suman et al., 2021). It can be defined as the probability causes by insufficient power supply provided making the hybrid system unable to achieve the load demand (Hatata et al., 2018). The excess energy produced by renewable sources is stored in the battery bank based on the State of Charge (SOC) of specific battery system while the battery bank discharges energy to load, if the RE does not fulfill the load demand (Sinha and Chandel, 2015). The value of LPSP/DPSP will always be ranging from 0 to 1. If the LPSP value obtained from optimization equal or closer to 0, that implies that the load is always or nearly satisfied while value 1 implies the energy supply will never be able to satisfy the load demand (Konneh et al., 2019). End-user will experience electrical shortages if the battery fully discharges while supplied by insufficient energy from PV and wind systems.

(c) Analytical Method

A hybrid system can achieve the required load demand provided that they are of different size, configurations and different models of equipment usage. Thus, a method must be used to access the performance of the system in terms of possible system configurations and the size of components. The selection of an optimized system is determined by analyzing the system in terms of single to multiple performance indexes. Besides, it is used for multiple system comparison through certain simulation programs, and it is required a long time of interest (Luna-Rubio et al., 2012). Certain simulation or Computational tools and programs have been developed to assist the assessment of the performance of the hybrid system.

(d) Simulation Method

Simulation Method is a direct approach and can be used to generate optimal sizing of hybrid system with clear parameters or data. Hybrid Optimization Model for Electric Renewable (HOMER) is an example for commonly used simulation software that was developed by Dr. Lilienthal at National Renewable Energy Laboratory (NREL) (Singh et al., 2016). HOMER is usually applied to identify all possible hybrid system combinations and to satisfy the reliability and load demand, and the optimal sizing configuration is selected from all combinations (Sawle et al., 2016). The optimal configurations of the hybrid system were obtained with the help of HOMER by (Balachander et al., 2021), (Al-Shammari et al., 2021) and (Faizan et al., 2021). Furthermore, Adefarati et al. (2021), published their work on designing and analyzing of a photovoltaic battery methanol diesel power system using HOMER software.

3.2. Optimization techniques

Optimization is a technique that is used to improve the hybrid PV -wind system in terms of sizing with the minimum cost involved (Huda et al., 2019). The purpose of optimization technique or cost analysis is to achieve an optimized hybrid PV-wind system in terms of sizing from the economic point of view. There are different optimization techniques including Iterative, LCC, Graphic Construction, and AI methods (Bhandari et al., 2015).

(a) Iterative Method

The iterative method is an approach to identify the optimum configuration of a hybrid system through the iterative search of all the possible system configurations to achieve the lowest Levelized Cost of Energy (LCE) (Al Busaidi et al., 2016). The deterministic property of his method is that it is a recursive process where it only comes to a halt once the best configuration is achieved and the specifications are clearly provided (Sinha and Chandel, 2015). According to Pasquali et al.

(2020), LCE is defined as the ratio of total annualized cost (TAC) of the system to the total electricity provided by the system annually. TAC is calculated by including the present value of cost (PVC) and capital recovery factor (CRF). PVC consists of initial cost, current maintenance cost and present value of replacement cost while CRF is obtained by considering of discount rate over the effective project lifetime (Luna-Rubio et al., 2012).

(b) LCC Method

Life Cycle Cost (LCC) Analysis is a method of optimization by relying heavily on the initial, present, and future cost where it is the total cost of the hybrid system ranging from initial project commencement until several years later depending on the period of interest (Askarian and Fakher, 2021). The total cost involves all components and operation costs (Anoune et al., 2020). Components costs involved initial capital cost while operational cost consists of the present value of replacement cost and the present value of maintenance cost. The output with the configuration of the lowest LCC generated or calculated will be taken as the optimized system provided that the system fulfills the reliability criteria as well (Agarwala et al., 2012).

(c) Graphic Construction Technique

Graphic Construction Technique is often used to determine only two essential variables as the optimum combination of battery bank and PV array or PV array and wind system. The limitation of this method is that it does not tolerate more than two essential variables. Solar radiation and wind speed over a long time in a 1-h basis are the deterministic requirement for the implementation. The required data on both variables mentioned are of a 1-h basis (Zhang et al., 2018). According to Bhandari et al. (2015), all constraint functions are plotted onto the same chart initially while observing the changes that occurred with respect to each variable will enable the solving of problem referring to two design variables. The number of batteries in the bank and PV modules in linear are some of the assumptions that must be made before implementation. By observing the plotted chart, the optimized point or known as the point of tangency of the curve which represents the relationship of both variables will show the minimum cost (Al Busaidi et al., 2016). Moreover, Ai et al. (2003) observed the performance of hybrid PV-wind systems on an hourly basis while fixing the wind generators capacity. The optimal configuration of hybrid PV-wind system was obtained by drawing a tangent to the trade-off curve provided that annual LOLP of different PV array configurations and battery bank is calculated or obtained.

(d) AI Method

Artificial Intelligence (AI) method is implemented to optimize the hybrid system to maximize the benefits from an economic point of view (Al Busaidi et al., 2016). AI is a branch of programming that mimics the human intelligence through software and machines (Bhandari et al., 2015). An Intelligent agent that is developed by human being will play a vital role in aiding or maximizing the chance of success. According to Al Busaidi et al. (2016), AI can be sub-divided into Genetic Algorithms (GA), Artificial Neural Networks (ANN) and Fuzzy Logic (FL). System improvement can be achieved virtually by the implementation of AI. Such improvement can be identified in terms of performance or other characteristics where traditional method cannot succeed. When optimizing a larger hybrid energy system is the main focus, GA will be considered due to its capability to handle complex problems. This method is less preferable due to its high complexity of the operation but provides legit solution than other techniques (Sawle et al., 2016). According to Bhandari et al. (2015), GA is considered global search heuristics and evolutionary algorithms that use techniques bio-inspired by natural evolution such as inheritance, mutation, selection, and recombination. The definition of GA can be clearly seen with the presence of genetic representation of the solution domain and fitness function to the solution domain.

3. Methodology

3.1. Design of a hybrid PV-Wind system for a case study in lundu

3.1.1. Load forecasting for the case study in Lundu

The design of hybrid PV and wind system of this project was to supply electricity to a rural area in Sarawak whereas the longhouse was selected as the most popular residence type in the respective rural area. The designated point of location was based on an unnamed road in Lundu at the coordination of 1°33′51.2″N and 109°51′27.4″E. The designated point was surrounded by forest and it was considered that electrification had not been available then. The longhouse selected in this research was a house built with long and narrow concepts and was constructed from timber by tiding together with creeper fiber while roofed with leaf thatch. This house was located near to a riverbank to ensure the supply of water in daily necessity. Longhouse can be built in different sizes and with a different number of rooms based on accommodated number of family members and typically, it can be even large to accommodate members in the range of 15–30. According to BERNAMA: Malaysian National News Agency, the CRT television set, Fluorescent lamps, Refrigerator are some of the basic appliances in longhouses nowadays (Sovacool and Valentine, 2011). Table 1 shows the basic appliance in longhouses along with the total capacity (W) and capacity per unit (kW) (Sarawak Energy, 2015; Moh, 2015).

With all the basic appliances obtained, the total load capacity in terms of kW can be calculated. A rough estimation of 5 fluorescent lamps, one CRT television set and a refrigerator are predicted to be the essential household appliances for a longhouse in Lundu. The load profile for these typical longhouses is illustrated in Fig. 3. It was concluded that the highest load demand of 490 W is required at 8.00 p.m. due to the reason that children have their TV on, refrigerator going into power-saving mode while all lamps are on in the night. Thus, Load demand is higher during the night compared to the morning due to the power consumption of fluorescent lamps during the night.

The detail of the load demand is tabulated in Table 2 shows the detailed descriptions on load demand over every hour in a longhouse. Load demand will be higher during the night compared to the morning due to the power consumption of fluorescent lamps. It is estimated that the fridge will be opened and close for gathering ingredients for lunch from 11:00 to 12:00 while 18:00 to 19:00 for dinner. The residence is predicted to be sleeping by 23:00 thus all lamps are off.

3.1.2. Solar and wind data

As the literature states, 25% of energy demand in Lundu is covered by solar energy and meanwhile the research has concluded that Lundu has an average sunshine of 4 h per day (Huda et al., 2019). Thus, it was concluded that solar energy has a high potential to be utilized in Lundu due to its unique climate. Fig. 4 shows the average sun hour in Lundu is concluded Lundu experience the lowest solar radiation in January, February, and December.

Wind energy is not that popular in Lundu due to its poor wind

Table 1
Basic appliances in longhouse.

Appliances	No. of units	Capacity per unit (kW)	Total Capacity (W)
Fluorescent lamps.	5	36	180
CRT television set	1	110 to 130	110 to 130
Refrigerator	1	100 to 200	100 to 200
Total			**510 (using max capacity)**

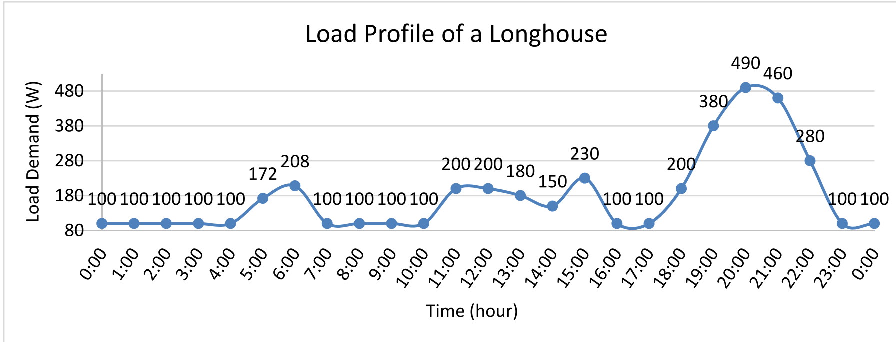

Fig. 3. Load profile of the longhouse.

Table 2
Detail description of load demand over time.

Time (h)	Load demand (W)	Descriptions
0:00	100	Fridge in power-conservation mode
1:00	100	Fridge in power-conservation mode
2:00	100	Fridge in power-conservation mode
3:00	100	Fridge in power-conservation mode
4:00	100	Fridge in power-conservation mode
5:00	172	Fridge in power-conservation mode + 2 lamps on
6:00	208	Fridge in power-conservation mode + 3 lamps on
7:00	100	Fridge in power-conservation mode
8:00	100	Fridge in power-conservation mode
9:00	100	Fridge in power-conservation mode
10:00	100	Fridge in power-conservation mode
11:00	200	Fridge in full power mode
12:00	200	Fridge in full power mode
13:00	180	Fridge starting to go into power-conservation mode
14:00	150	Fridge starting to go into power-conservation mode
15:00	230	TV on for kids' free time.
16:00	100	Fridge in power-conservation mode
17:00	100	Fridge in power-conservation mode
18:00	200	Fridge in full power mode
19:00	380	Fridge starting to go into power-conservation mode + all lamps on
20:00	490	Fridge starting to go into power-conservation mode + all lamps on + TV on
21:00	460	Fridge starting to go into power-conservation mode + all lamps on + TV on
22:00	280	Fridge in power-conservation mode + all lamps on
23:00	100	Fridge in power-conservation mode
Total	**4350 W per day.**	

resources (Anyi et al., 2010) and the wind turbines implemented in a rural area are usually smaller in size and do not generate lots of energy. Fig. 5 depicts the average wind speed in Lundu over the year and it can conclude that Lundu experiences slightly higher wind speed in January and December while the wind speed is quite average for the rest of the months. As mentioned earlier, wind energy is possible to be harnessed most and acts as compensation by January and December whereby Lundu experiences the least solar radiation.

3.1.3. Optimization and sizing of PV system according to our case study data

Chosen PV module was configured in series-parallel connection and SP connected PV module generates high output power (Balato et al., 2015). A commercial type of SP-PV module named, 'Kaneka Hybrid U-SA110' was selected as the PV system for this case study. Following Table 3 shows the operation detail of Kaneka Hybrid U-SA110 such as the material of the product, Maximum power, Max voltage & current, short-circuit current and open-circuit voltage etc.

In terms of sizing, PV module efficiency and temperature coefficient are some of the factors that affect the real output power of PV array while the number of arrays is dependent on the load demand. Equation (1) is used to determine the output power.

$$P_{out} = I_{out} \times V_{out} \tag{1}$$

Output current of PV module was obtained by considering the solar irradiance or average sun hour, temperature coefficient and temperature of operation. Equation (2) is used to determine the output current.

$$I_{out} = \frac{G}{G_{nm}} I_{sc}[1 + C_{Isc}(T - T_{nm})] \tag{2}$$

Output Voltage was obtained by considering the solar irradiance or average sun hour, temperature coefficient of nominal PV array and temperature of operation and equation (3) is used to determine the output voltage.

$$V_{out} = \frac{G}{G_{nm}} \times [V_{oc} + C_{Voc}(T - T_{nm})] \tag{3}$$

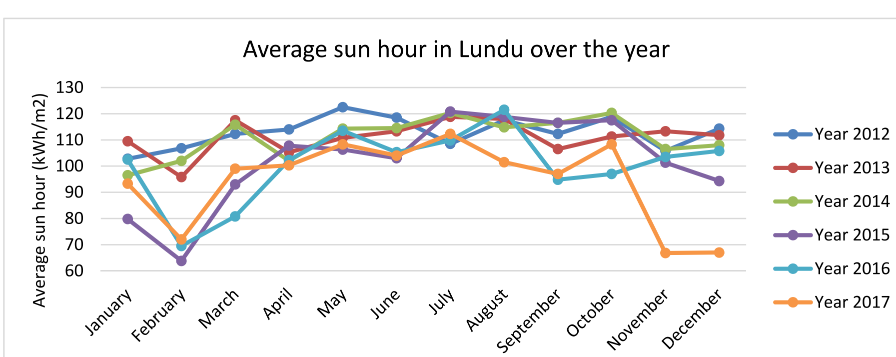

Fig. 4. Average Sun hour in Lundu Over the Year.

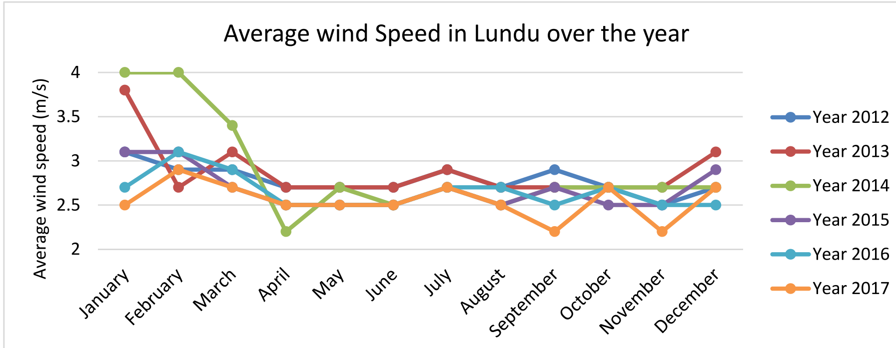

Fig. 5. Average Wind Speed in Lundu Over the year.

Table 3
Operation detail of kaneka hybrid U-SA110.

Parameters	Description
Material	Microcrystalline and amorphous silicon
Warranty	25 y
Maximum power, P_{max}	110 W
Maximum Voltage, V_{max}	53.5 V
Maximum Current, I_{max}	2.04 A
Guaranteed minimum P_{max}	104.5 W
Short-circuit Current, I_{sc}	2.5 A
Open-circuit Voltage, V_{oc}	71 V
Temperature coefficient of open-circuit voltage	−0.39 V/°K
Temperature coefficient of short-circuit current	0.056%/°K
Temperature coefficient of power	−0.35%/°K
NOCT[2]	45 °C

Table 4
Operation detail of Pitchwind wind turbine.

Power		
Rated power	30	kW
Rated wind speed	15	m/s
Cut-in wind speed	2	m/s
Cut-out wind speed	None	m/s
Maximum withstand wind speed	250	km/h
Dimension		
Rotor weight	550	kg
Rotor diameter	14	M
Swept area	154	m2
Height of the mast	20/62	M
Extra Information		
Maximum rpm	81 at rated wind speed	Rpm
Brake system	Pitch by electrical actuator at service parking brake	
Number of blades	2	
Blades material	Steel Polyester	
Output voltage	380–500	V
Minimum operation temperature	−40	°C
Lifetime	20	y
Self-starting	Yes	
Asynchronous generator	Absent	
Yaw control system	Wind Wheels	
Wind type	Upwind	

3.1.4. Optimization and sizing of wind turbine according to our case study data

Chosen wind turbine for the designated location was HAWT considering the high quality of Pitchwind that the location experiences. This type of wind turbine has a cur-in wind speed of 2 m/s and is the perfect solution for compensation of energy in Lundu as the designated area chosen experiences wind speed ranging from 2.2 to 3.5 m/s in average. Table 4 represents the details of the operation principle of Pitchwind. The wind turbine starts operating when the wind speed of 2 m/s is present while achieving maximum power when the wind speed is 15 m/s or above.

In terms of sizing, the output power of wind turbines is Kinetic energy over time. Thus, other factors such as rotor blades and overall efficiency affect the performance of wind turbines. The total output power of HAWT was calculated using equation (4) (Goodier, 2017).

$$P_{out} = \frac{1}{2}\rho \times A \times v^3 \times C_0 \quad (4)$$

The overall efficiency was derived as the multiplication of power coefficient, mechanical transmission efficiency and generator efficiency and equation (5) is used to calculate it (Goodier, 2017).

$$C_0 = C_p \times n \times C_g \quad (5)$$

3.2. Optimization and sizing of battery bank according to our case study data

Battery banks played an essential role in the hybrid system in this research and were required to compensate the load demand during the days of autonomy due to the limitation of solar and wind sources in Lundu. The modelling of the battery bank in our research was based on LPSP sizing methodology as explained earlier. There are two essential stages regarding the battery bank as charging and discharging, thus, the charging period occurs only when the energy produced by PV and wind system exceeds the load demand while discharging is when the load demand is greater than energy produced (S. Diaf et al., 2008). The charging period was determined by equation (6) given below (Kartite and Cherkaoui, 2019).

$$C_{batt}(t) = C_{batt}(t-1)(1-\sigma) + \left[E_{PV+wind}(t) - \frac{E_{load}(t)}{n_{inv}}\right] \times n_{batt} \quad (6)$$

After determining the capacity of the battery, LPSP was applied to calculate if the system can fulfill the required load demand within the period of interest. LPSP value '0' is the desired value that indicates that load demand is achieved while '1' indicates the opposite (Kartite and Cherkaoui, 2019). Equation (7) is used to calculate the LPSP (Dawoud et al., 2018).

$$LPSP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} E_{load(max)}(t)} \quad (7)$$

If Battery capacity is greater than Maximum battery capacity; Maximum battery capacity at the specific time is taken as the $C_{batt}(t)$ while no changes to the energy deficit. If Battery capacity is lower than the Minimum battery capacity; Minimum battery capacity at the specific time is taken as the $C_{batt}(t)$ while the next energy deficit is affected. The energy deficit at such condition can be calculated using equations (8) and (9) given below.

$$DE(t) = E_{load}(t) - [E_{PV+wind}(t) + C_{batt}(t-1) - C_{batt(min)}] + d \quad (8)$$

$$d = C_{batt(\min)} - C_{batt}(t-1) \quad (9)$$

Where $C_{batt}(t-1)$ in equation (8) is updated to minimum battery capacity while $C_{batt}(t-1)$in equation (9) is for original battery capacity calculated.

3.2.1. Inverter selection

The inverter selected for the research was called as 'Solar Combi' with model no: SC1000M-LV. This is a small independent inverter specially designed for rural areas with high efficiency of 92%. Considering the small input voltage supplied by the overall system, this model inverter was selected with DC input of 24 V and has a high efficiency. This Inverter has certain important features including 2 years of warranty, 1 kW of output power at 40 °C, 24 V DC of DC input voltage, 50 Hz or 60 Hz ± 0.5% of output frequency, 92% of Max efficiency, 18 W of zero load power etc.

3.2.2. Flowchart of proposed sizing and optimization technique

PV and Wind system harness energy through RE sources and produce DC voltage. Afterwards, it is channelled through an inverter to change the initial DC to AC voltage before End-user. Excess energy produced by primary sources is used to charge the battery bank and then the battery bank compensates for the lack of energy when load demand is higher than energy produced. Fig. 6 represents the detail of the simulation program, and each essential step is considered starting from inputting the most important data then by inserting the specifications of all components. The sizing method was considered to ensure that the load demand was achieved while the optimized cost of the system was calculated from LCC. The proposed function displayed the total LCC over 20 years and the number of PV modules needed to ensure the system works optimally. Fig. 7 shows the sizing method flow chart detailing the simulation function.

3.3. Cost analysis for the case study

Life Cycle Cost analysis (LCC) was chosen as the optimization technique in the Methodology part. LCC determines the total cost incurred over the project lifetime based on the period of interest of 20 years for the future cost calculation or predictions. LCC can be sub-divided into 'Components and Operation cost (Dawoud et al., 2018). Component cost consists of the price of components (PV modules, wind turbines, battery bank, inverter per kW) Civil work cost, Installation and Connection costs. Also, known as the cost required during the initial period of the project (initial capital cost) (S. Diaf et al., 2008) and it is obtained based on present real-life prices. Civil works and Installation costs are 40% of the power generated by PV and 20% for wind systems respectively (S. Diaf et al., 2008). Calculation of connection cost was neglected as it had a minimal effect on the total component cost. Operation cost is a combination of present and future Replacement and Maintenance Cost (Anoune et al., 2020). Replacement cost is based on several affecting factors such as discount rate, a number of replacements, NOR of components over the period etc (Zhang et al., 2018) and equation (10) is used to calculate the replacement cost.

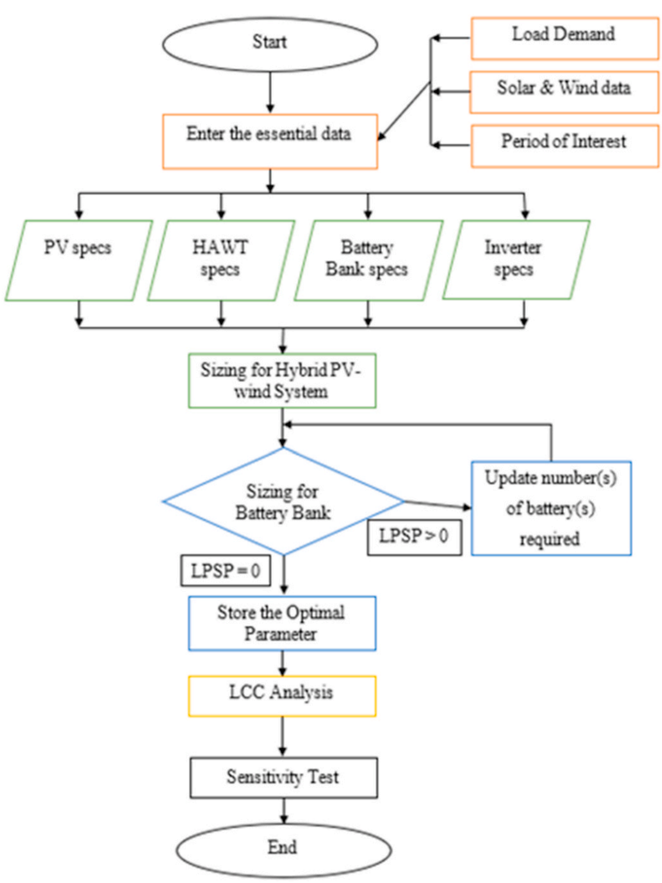

Fig. 6. Detail flowchart of the proposed simulation function.

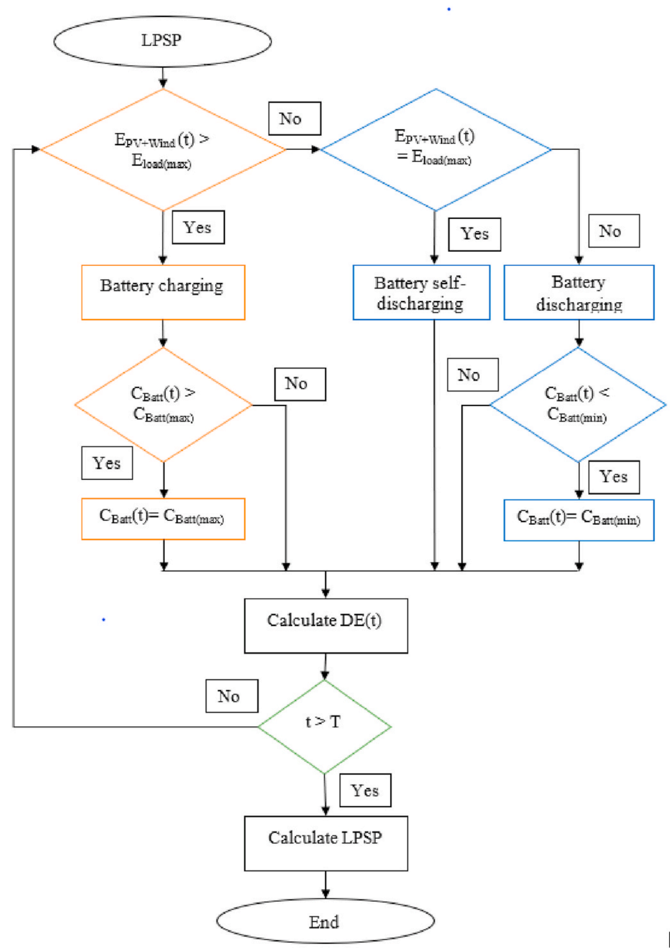

Fig. 7. Detail flowchart showing LPSP technique.

$$Cost_{Replacement} = IC_{component} \times \sum_{i=1}^{NOR} \left(\frac{1+g}{1+d}\right)^{\frac{T_i}{NOR}} \quad (10)$$

Maintenance cost is the calculation of the cost required for the maintenance of the system by the period of interest (S. Diaf et al., 2008) and can be calculated using equation (11).

$$Cost_{Maintenance} = IC_{component} \times p \times T \quad (11)$$

The calculation of operational cost required certain important parameters such as discount rate (d, %), inflation rate (%), percentage of maintenance cost (p, %) and component lifetime (L, year). Therefore, equation (12) can be written for the LCC system for Hybrid PV-Wind.

$$LCC_{system} = Cost_{Components} + Cost_{Operation} - S \quad (12)$$

4. Results and discussion

4.1. Calculation, simulation and discussion on sizing of PV system

Considering the limitation of time, the 'Probabilistic Method' was chosen for sizing of PV system regardless of fact that it produces results of lower accuracy compared to other possible methods. As discussed in the Methodology part, the most unfavorable month with the lowest average sun hour was observed to be 63.8 kWh/m^2 in February by the year 2015. Lundu city which experiences an average sun hour of 8 h per day, solar irradiance experience throughout the month was calculated as $7,975\ W/m^2$. 'Average Temperature' is another essential parameter required for the sizing of PV system. Accordingly, the average temperature experience in Lundu is 32 °C when the sun is up (Daniel Tang, 2019). By using the data and formula in the methodology part, the sizing of PV was calculated. To obtain the output power that a single Kaneka Hybrid U-SA110 produces in a month, certain parameters were obtained that are included in Table 5 below.

Even for the code used in simulation, the Probabilistic Method was used in where the least favorable monthly average solar energy was calculated automatically using the data of solar irradiance, "G (m, y)" from the year 2012–2017. Table 6 below shows the desired results that were generated by the simulation software used.

4.2. Calculation, simulation and discussion on sizing of wind turbine

The option for wind turbine for Lundu was limited as Lundu experience less favorable wind speed comparatively. Pitchwind wind turbine was chosen for this study that has a cut-in wind speed of 2 m/s. The least favorable month and the minimum wind speed experienced in Lundu wherein was 2.2 m/s as observed in April by the year 2014. $A = 154m^2$, $C_g = 0.9$, were certain parameters required and the air density was estimated to be 1.1644 as the surrounding temperature was above 30 °C. The Output power of Pitchwind wind turbine per day and per month was calculated as $773.296 \frac{W}{day}$, $23,198.892 \frac{W}{month}$ respectively.

The simulation code in determining the monthly average wind energy, practiced Probabilistic Method where the least favorable month wind energy was automatically calculated using the wind speed data "v (m, y)" from the year 2012–2017. When "WT" was input as 2, parameters such as area of a rotor blade, and efficiency of a wind turbine were put manually. As the result 'the minimum output power from each wind turbine throughout the years was generated as 23,198.891728 W.

Table 5
Essential parameters of kaneka hybrid U-SA110.

Essential Parameter from datasheet to calculate Output Current for U-SA110	Essential Parameter from datasheet to calculate Output Voltage for U-SA110
$I_{sc(U-SA110)} = 2.5\ A$	$V_{oc(U-SA110)} = 71\ V$
$C_{Isc(U-SA110)} = 0.0002058\ A/°C$	$C_{Voc(U-SA110)} = -0.001433\ V/°C$

Output Current, Output Voltage and Output Power were calculated as $I_{out} = 19.966 \frac{A}{month}$, Vout $= 566.145 \frac{V}{month}$, *and* Pout $= 11,320.635 \frac{W}{month}$ respectively.

Table 6
Sizing of PV system generated using simulation software.

Type of Solar Panel	Simulation Results (Minimum Output Power over the year)
MSX-64	8258.820999 W
Kaneka Hybrid U-SA110	11,303.774292 W
VLX-53	4479.954819 W

4.3. Calculation, simulation and discussion on sizing of hybrid PV-Wind system

It was essential to determine the load to obtain all the possible combinations of PV and wind systems. The load forecast was done under Methodology. The combination of both systems must achieve the load forecast but not by a large margin. In this case study, all possible combinations of the system were obtained for the range of (load forecast * 1.10) to (load forecast *1.20). This range implied that the hybrid system must achieve the minimum load forecast with a 10% tolerance (safety margin) while saving cost without exceeding an increment of 20% (Excessive). The load forecast was calculated as $130,500\ W$.The range of interest was calculated as $143,550\ W(100\%)$, $156,600\ W(120\%)$. Table 7 shows the optimized possible combination of wind and Solar according to the required load.

Fig. 8 shows the sequence of code used in simulation to obtain all possible combinations of PV and wind that achieve the range of predetermined load demand for a month. The variables 'a' and 'b' represent the number of solar panels and wind turbines, respectively. All the possible combinations were automatically generated together with the total generated power over the month.

4.4. Calculation, simulation and discussion on sizing of battery bank

Before sizing the battery bank, a load forecast was made in terms of power consumption per hour using the data mentioned under the Methodology section. With the assumption of that, Lundu experiences peak sun hour of 8 h per day while experiencing 24 h of wind, the power generated by both systems can be calculated using equations (13) and (14) given below.

$$P_{out(solar)per\ hour} = \frac{No.of solarpanel(s) \times P_{out(solar)per\ month}}{8\ hours \times 30\ days} \quad (13)$$

$$P_{out(wind)per\ hour} = \frac{No.of wind\ turbine(s) \times P_{out(wind)per\ month}}{24\ hours \times 30\ days} \quad (14)$$

The following Table 8 shows all the possible combinations of Hybrid U-SA110 and Pitchwind wind turbine with LPSP of every number of batteries tested. The minimum number of batteries required for each

Table 7
Optimized possible combination of wind and solar according to the required load.

Number of U-SA110	Number of Pitchwind wind turbine	Total power generated by U-SA110 in a month (kW)	Total power generated by Pitchwind in a month (kW)	Total power generated by the combination in a month (kW)
1	6	11.304	139.193	150.497
3	5	33.911	115.994	149.906
5	4	56.519	92.796	149.314
7	3	79.126	69.597	148.723
9	2	101.734	46.398	148.132
11	1	124.342	23.199	147.540

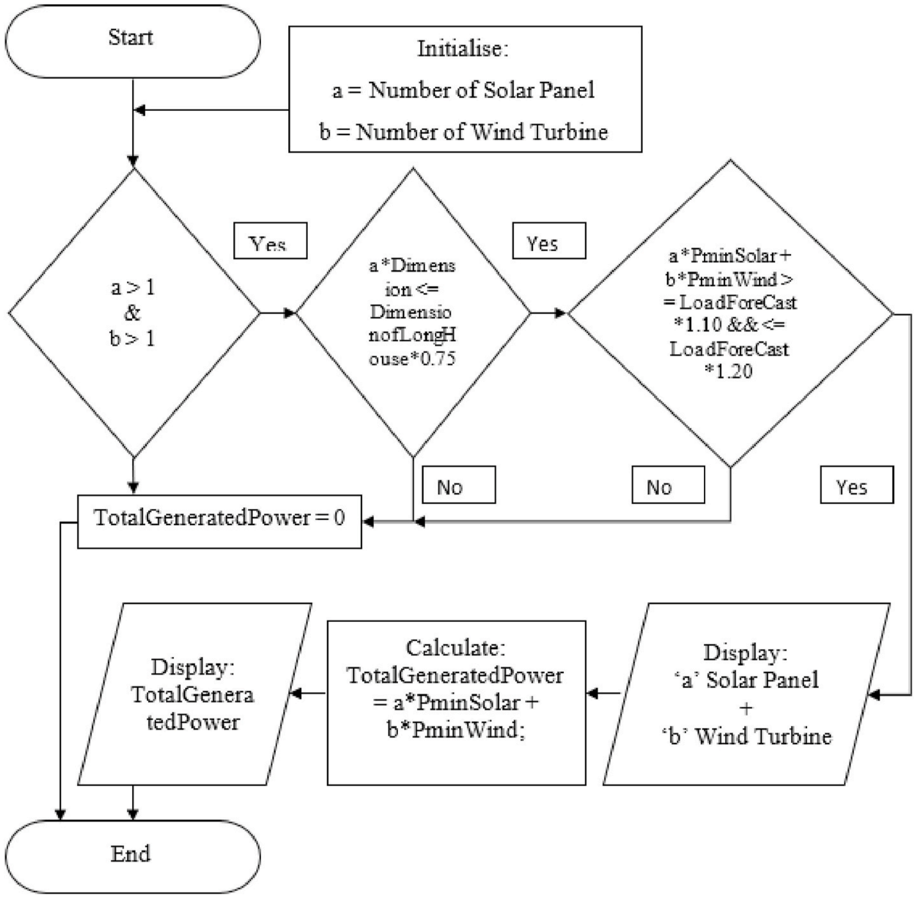

Fig. 8. Flow chart for Sizing.m.

Table 8
Sizing of Battery Bank using LPSP Method.

LPSP	No of Battery Bank								
	1	2	3	4	5	6	7	8	9
1 SP 6 WT	0	0	0	0	0	0	0	0	0
3 SP 5 WT	0.0187	0.0002	0	0	0	0	0	0	0
5 SP 4 WT	0.1149	0.0367	0.0036	0	0	0	0	0	0
7 SP 3 WT	0.3124	0.1642	0.0647	0.0133	0.0001	0	0	0	0
9 SP 2 WT	0.5523	0.3773	0.2290	0.1058	0.0319	0.0028	0	0	0
11 SP 1 WT	0.7944	0.6086	0.4523	0.3006	0.1628	0.0625	0.0127	0.0002	0

combination were decided when the LPSP was equal to 0.

These results verified that LPSP can be used to determine the battery bank capacity required as the capacity of battery bank has never dropped below the 50% threshold while has never exceeded the maximum available capacity.

Fig. 9 shows the sequence of code used in simulation to obtain the power generated by solar and wind per hour. The function of simulation software is continued by DPSP/LPSP Test. A minimum number of battery(s) for each combination was obtained from the simulation. The capacity of battery, "CapBatt (t, day)" per hour was updated depending on the time, day, load at the specific hour. Similarly, in the manual calculation, the capacity of the battery has never exceeded the maximum capacity "CapBattMax" while if the capacity has dropped minimum, "CapBattMin" gave value to "d" and updated the capacity of battery to CapBattMin at given time. By using all the parameters generated by simulation software, Energy deficit, "DE" was calculated. 'LPSP' was calculated for all values of DE. If it is greater than '0' that triggers a loopback towards the initial step with an increment in number of batteries, "N (a,b)". This code only stopped when LPSP is equal to '0' and number of batteries was taken at the time.

Two days of autonomy was assumed into the simulation code by estimating that Lundu experiences two days of autonomy in every month. The generated results are shown in Table 9.

4.5. Optimization of hybrid PV-Wind system using life-cycle cost system

The Table 10, summarizes the certain essential parameters that required for LCC analysis for the investigation period of 20 years and all costs has been converted from USD to MYR.

Using a MARLAB code, the LCC of the system was calculated where the component and operation cost were calculated separately. LCC for each combination was calculated and the optimal combination that can be achieved by the load demand in terms of lowest cost was automatically displayed. Table 11 below summarizes the results generated. When it was compared all three PV system with the same Pitchwind wind turbine, it was noted that the calculated results and the optimized

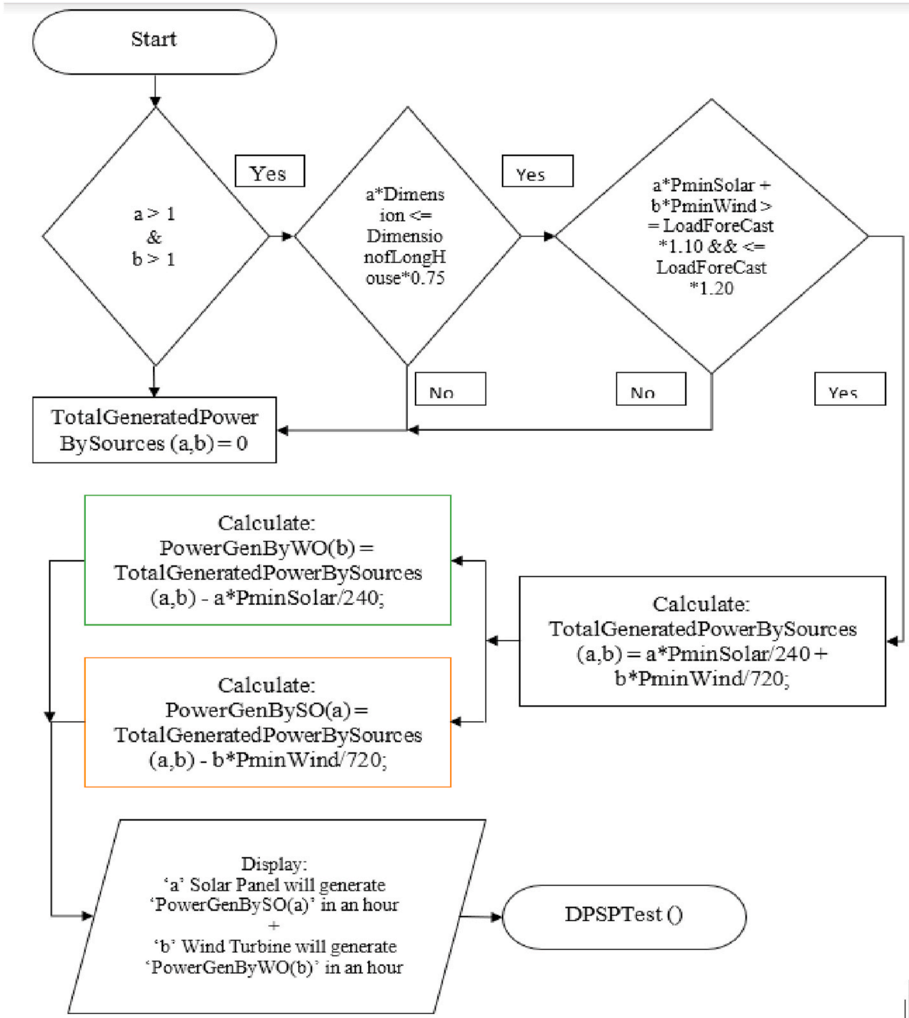

Fig. 9. Flow chart for power generation per Hour.m.

Table 9
Sizing of battery bank generated by simulation software.

No of solar Panels	Amount of Energy generated in an hour (W)	No of Wind Turbines	Amount of Energy generated in an hour (W)	No of Batteries
1	47.09906	6	193.324098	1
3	141.297179	5	161.103415	3
5	235.495298	4	128.882732	4
7	329.693417	3	96.662049	6
9	423.891536	2	64.441366	7
11	518.089655	1	32.220683	9

system generated through the function of simulation software did tally with each.

Fig. 10 depicts the percentage contribution of each component on the total cost of the optimized hybrid system and was concluded as cost induced for Wind system contributed to the largest portion that almost 50% of the total cost while only 8% of the total cost was associated with the inverter regardless of the least lifetime compared to other components.

The optimized system consisted of 11 Kaneka Hybrid PV-wind solar panels, 1 Picthwind wind turbine, 9 batteries and 1 inverter. According to the pie chart, 1 wind turbine contributed 50% while 11 solar panels only contributed to 14%. It was concluded that more wind turbines induce more cost even though battery banks can be reduced.

Table 10
Essential parameters required for operation and calculation of deterministic components.

	Component	Initial cost for each component, IC (RM)	Discount rate of component, d (%)	Inflation rate, g (%)	Percentage of maintenance cost, p (%)	Component Lifetime, L (y)
PV system	Kaneka Hybrid U-SA110	995.00	5%	6%	1%	20
Wind System	Pitchwind wind turbine	37,440.00	5%	6%	3%	20
Battery Bank	Fullriver 415 Ah Battery Bank	2205.00	5%	6%	0%	7
Inverter	Solar Combi	1500.00	5%	6%	1%	2

Table 11
Life cycle cost analysis generated by simulation software.

Hybrid PV-Wind System	Result Generated by Simulation Software
MSX-64 + Pitchwind + Battery bank	Optimal Combination – 15 Solar Panels,1 Wind Turbine, 9 Batteries with LCC of RM 250,507.798,604.
Kaneka Hybrid U-SA110 + Pitchwind + Battery bank	Optimal Combination – 11 Solar Panels,1 Wind Turbine, 9 Batteries with LCC of RM 221,329.966,502.
VLX-53 + Pitchwind + Battery bank	Optimal Combination – 27 Solar Panels,1 Wind Turbine, 9 Batteries with LCC of RM 320,267.996,166.

4.6. *Calculation, simulation and discussion on component and operation cost*

Using the formulae mentioned in the Methodology, 'Component cost' was calculated and tabulated below in Table 12. Civil and Installation (C&I) cost of the solar system was taken as 40% of the Initial cost (IC) of the solar system and 20% of wind system.

As discussed under the Methodology section, Operation cost is a combination of Replacement & Maintenance cost, and the calculation was done for a period of 20 years as shown in Table 13.

Operation cost was divided as replacement and maintenance cost and can be seen as three individual sections in the following Fig. 11. Further, it can clearly see that replacement cost contributes the highest towards the total system cost and is followed by component cost. Maintenance cost seems slightly insignificant for all systems except for wind systems. Battery Bank shows larger Replacement cost, may be due to their lower lifetime as shown in the following graph.

4.7. *Summary of LCC*

Salvage Cost was estimated as 5% of the total component cost after 20 years. By including all the cost required, LCC of the corresponding combination was obtained. The combination included 11 Kaneka Hybrid U-SA110 Solar Panels, 1 Pitchwind Wind Turbine, 9 Fullriver 415 A h, 6 V Battery Bank and 1 Solar Combi. Inverter was the cheapest yet feasible solution to achieve the required load demand in comparison to other combinations.

Fig. 12 shows the plotted graph, using the total cost for each system. The salvage value was down below the origin as the salvage value was negative. The total of all five elements contributed towards the 'LCC' value and it was already verified as it tallied with the calculated results.

4.8. *Sensitivity test*

It was determined the most deterministic factors that affect the cost of the system by applying the sensitivity test for the optimized hybrid combination. Fig. 13 was plotted showing the sensitivity of the system price for each increasing factor by assuming an approximately 10% of increment of the price of each component. As the graph indicates, the system was most sensitive to the price increments of wind turbines even though by a small margin while the system was least sensitive to the price increment of Inverters.

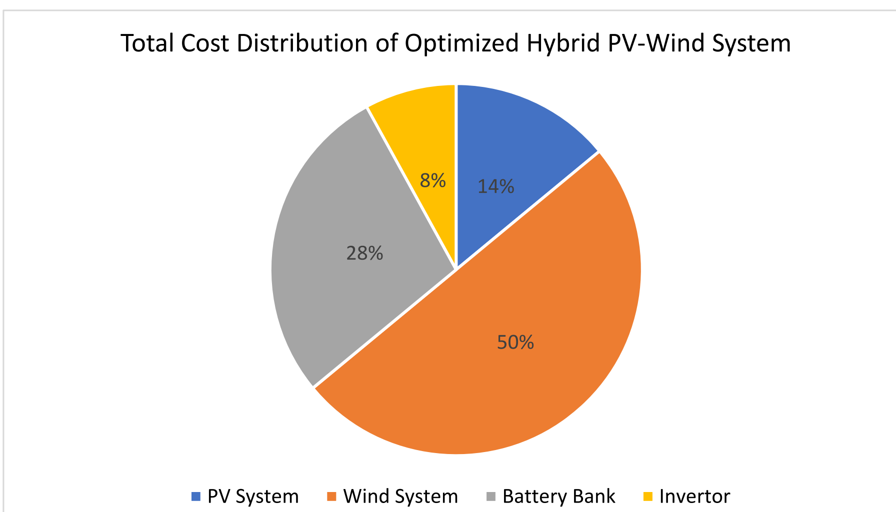

Fig. 10. Average contribution towards the optimized hybrid PV-Wind PV systems total cost.

Table 12
Component cost of all possible combination.

Possible Combination	IC of Solar System, (RM)	IC of Wind System, (RM)	C&I Cost of Solar System, (RM)	C&I Cost of Wind System, (RM)	Battery Bank Cost, (RM)	Inverter Cost, (RM)	Total Component Cost, (RM)
1 SP 6 WT 1 Battery 1 Inverter	995	224,640	398	44,928	2205	1500	274,666
3 SP 5 WT 3 Battery 1 Inverter	2985	187,200	1194	37,440	6615	1500	236,934
5 SP 4 WT 4 Batteries 1 Inverter	4975	149,760	1990	29,952	8820	1500	196,997
7 SP 3 WT 6 Batteries 1 Inverter	6965	112,320	2786	22,464	13,230	1500	159,265
9 SP 2 WT 7 Batteries 1 Inverter	8955	74,880	3582	14,976	15,435	1500	119,328
11 SP 1 WT 9 Batteries 1 Inverter	10,945	37,440	4378	7488	19,845	1500	81,596

Table 13
Operation cost of all possible combinations.

Possible Combination	Replacement Cost			Maintenance Cost		Total Operation Cost, (RM)
	NOR for each system	Replacement Cost for each system, (RM)	Total Replacement Cost, (RM)	Maintenance Cost for each system, (RM)	Total Maintenance Cost, (RM)	
1 SP 6 WT 1 Battery 1 Inverter	1 1 2 10	1202 271,530 4874 16,550	294,156	199 134,784 0 300	135,283	429,439
3 SP 5 WT 3 Battery 1 Inverter	1 1 2 10	3606 226,275 14,622 16,550	261,053	597 112,320 0 300	113,217	374,270
5 SP 4 WT 4 Batteries 1 Inverter	1 1 2 10	6010 181,020 19,496 16,550	223,076	995 89,856 0 300	91,151	314,227
7 SP 3 WT 6 Batteries 1 Inverter	1 1 2 10	8414 135,765 29,244 16,550	189,973	1393 67,392 0 300	69,085	259,058
9 SP 2 WT 7 Batteries 1 Inverter	1 1 2 10	10,818 90,510 34,118 16,550	151,996	1791 44,928 0 300	47,019	199,015
11 SP 1 WT 9 Batteries 1 Inverter	1 1 2 10	13,222 45,255 43,866 16,550	118,893	2189 22,464 0 300	24,953	143,846

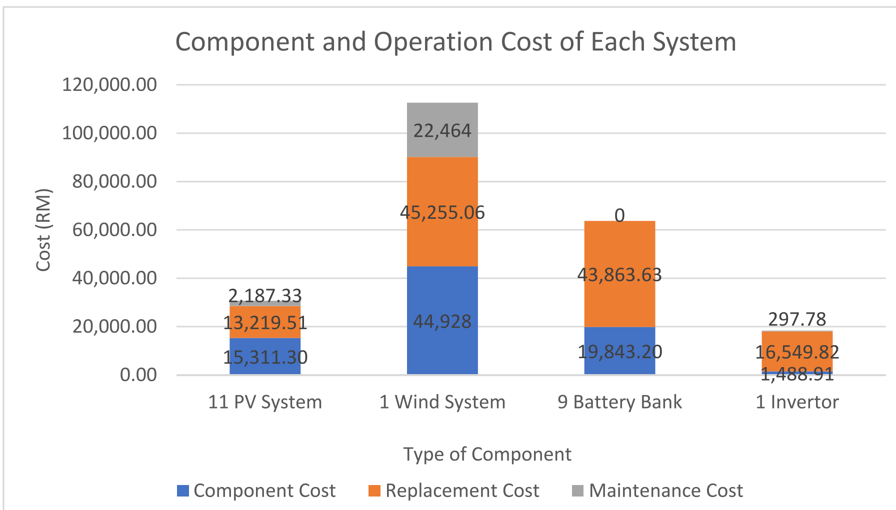

Fig. 11. Breakdown of each system cost.

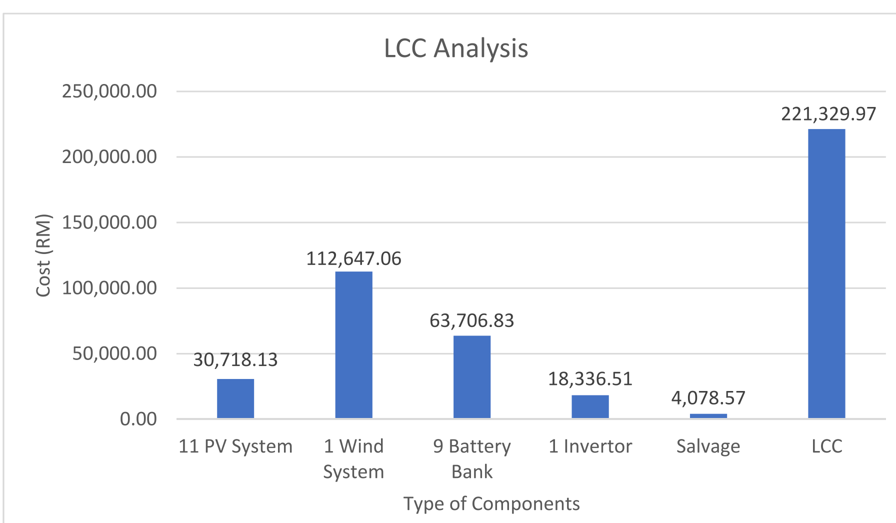

Fig. 12. Lcc analysis for optimized hybrid PV-Wind system.

The sensitivity of the system was obtained from a code of simulation software and the sensitivity test range was set to be from −10% to 10%. The shown detail graph of Hybrid U-SA110, Pitchwind, battery bank and inverter (Fig. 14) show the relationship of each system towards the optimal configuration of the Hybrid system. From the results obtained from the graph, it was concluded that wind system undergoing the sensitivity test provided the steepest gradient while the inverter showed least steep. Ultimately, a simple conclusion was made as the optimal

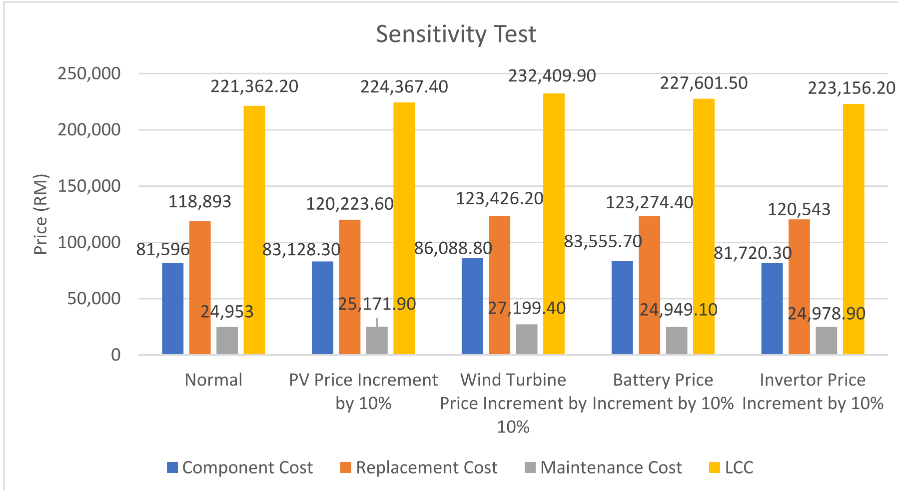

Fig. 13. Sensitivity test of 10% for optimized hybrid PV-Wind system.

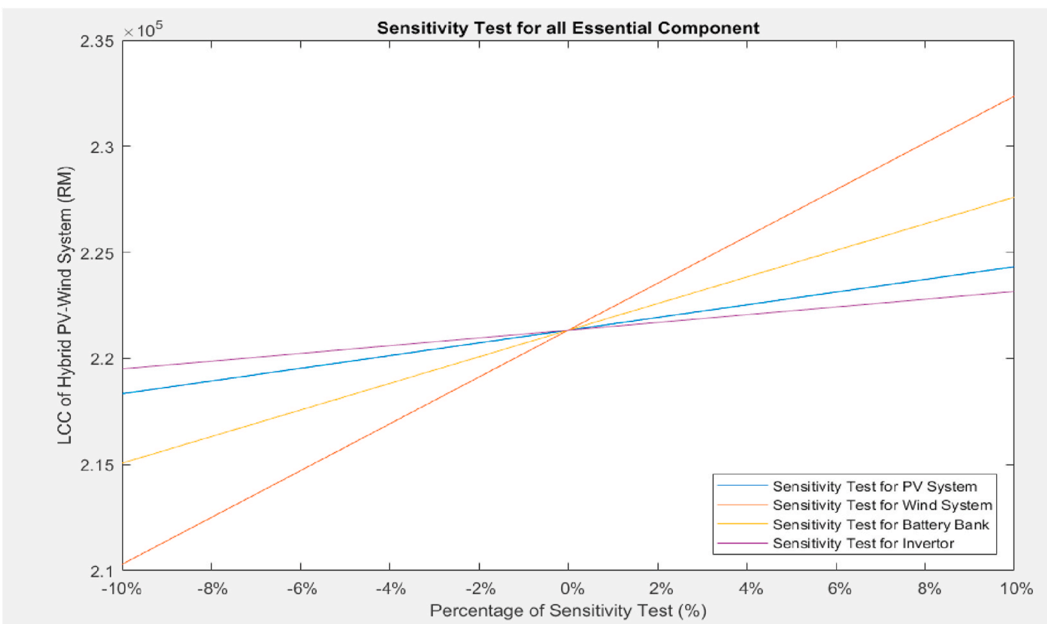

Fig. 14. Sensitivity test for all essential equipment.

system was most sensitive on the price changes of wind turbine while the least towards the inverter. Table 14 contains the simple calculation considering an 10% of sensitivity and had been verified the results shown above and is tabulated below.

5. Conclusion

Various sizing and optimization techniques were reviewed in this case study to achieve the peak energy demand with the limited sources available and the probabilistic method was chosen as the best method for this study for the sizing of both PV and Wind turbine. For the design of the Hybrid system, initially the coordination of the designated point was identified within Lundu city and then the targeted load was determined. Later, the load profile of the longhouse in Lundu was plotted and the Solar & Wind weather data were gathered. Based on the data obtained, the Sizing of the PV system was calculated. Thus, the output power a single Kaneka Hybrid U-SA110 production in a month was calculated as $11,303.774292$ W and was verified with the results of the simulation. In similar, the sizing of the Pitchwind wind turbine was done and the minimum output power from each wind turbine throughout the years was calculated as 23,198.891728 W per month and was verified with the simulation results. Optimization of the Hybrid PV-Wind system was done through LCC analysis to determine the total cost incurred over the project lifetime. The findings of this study are that 11 Solar Panels,1 Wind Turbine, 9 Batteries with LCC of RM 221,329.966,502 are the optimal combination to provide the electrification to longhouses in Lundu over the period of 20 years. Secondly, LCC was determined as a

Table 14
Percentage difference for LCC at sensitivity test of 10%.

Type of system used for Sensitivity Test	LCC when Sensitivity Test is 0%	LCC when Sensitivity Test is 10%	Percentage Difference (%)
Hybrid U-SA110	RM 221,329.97	RM 224,325.22	1.35%
Pitchwind	RM 221,329.97	RM 232,370.03	4.99%
Battery bank	RM 221,329.97	RM 227,601.43	2.83%
Inverter	RM 221,329.97	RM 223,156.17	0.83%

combination of component and operation costs. It was identified that the Replacement cost contributes the highest towards the total system cost requiring and followed by the component cost. Lastly, according to the total cost distribution of the optimized hybrid PV-Wind system, cost induced for one wind turbine contributed the largest portion about 50% while the inverter was only 8% of the total cost by being the least.

Further, a sensitivity test for the Optimized combination was conducted assuming 10% of increment from the price to determine the most deterministic factors that affect the total cost. It was concluded that the system was most sensitive to the price increment of Wind turbines having the highest LCC of 232,409.9. After the comparison, it was noticed that 10% increment of Wind turbine contributed for 4.99% difference in LCC while the Inverter contributed the least of 0.83%. Alternatively, it was concluded that the optimized system was most sensitive to the price changes of Wind turbines and proved with results of the simulation.

If you require any additional materials or information, I am happy to supply it. Thank you so much for your consideration; I look forward to hearing from you.

Conflicts of interest

The authors declare that there is no conflict of interest.

Credit author statement

Hadi Nabipour Afrouzi: Supervision, preparing the first draft., **Ateeb Hassan:** Revising the draft, Editing,**., Yuhani Pamodha Wimalaratna**: Revising the first draft, Editing., **Kamyar Mehranzamir**: Validation, Reviewing and Editing, **Zulkurnain Abdul Malek:** Supervision, Validation, and Reviewing., **San Chuin Liew:** Validation, Reviewing and Editing., **Jubaer Ahmed:** Reviewing and Editing.

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