Journal of Engineering Science and Technology
Vol. 10, No. 7 (2015) 943 - 957
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STANDALONE PHOTOVOLTAIC SYSTEMS SIZING OPTIMIZATION USING DESIGN SPACE APPROACH: CASE STUDY FOR RESIDENTIAL LIGHTING LOAD

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Abstract

This paper presents a sizing optimization methodology of panel and battery capacity in a standalone photovoltaic system with lighting load. Performance of the system is identified by performing Loss of Power Supply Probability (LPSP) calculation. Input data used for the calculation is the daily weather data and system components parameters. Capital Cost and Life Cycle Cost (LCC) is calculated as optimization parameters. Design space for optimum system configuration is identified based on a given LPSP value, Capital Cost and Life Cycle Cost. Excess energy value is used as an over-design indicator in the design space. An economic analysis, including cost of the energy and payback period, for selected configurations are also studied.

Keywords: Sizing, Standalone PV system, LPSP, Design space, Economic analysis.

1. Introduction

In the near future, Malaysia is expected to be a net importer of oil, and the nation will have to live up to issues related to the security of supply and the economic consequences of a commodity which is highly volatile [1]. Realizing the situation, it is important that further emphasis is given into diversifying of the energy resources with a special consideration into renewable energy systems such as photovoltaic systems.

Photovoltaic (PV) systems, especially the standalone configuration, have been widely used for renewable energy applications in Malaysia. More than 90% of

Nomenclature

C_{bat}	Battery capacity, Ah
DoD	Depth of discharge, %
$E_{B(n)}$	Energy stored in the battery on the day *n*, Wh
$E_{Bhalf(n)}$	Battery energy condition during sunset on the day *n*, Wh
$E_{B\min}$	Minimum energy stored in the battery, Wh
$E_{B\max}$	Maximum energy stored in the battery, Wh
$E_{load(n)}$	Nominal load energy of the day, Wh
$E_{PV(n)}$	PV panels power output, Watt
G_{Tt}	Global total solar irradiation, Watt/m^2
H	Daily average of irradiation, Watt/m^2
$LPSP$	Loss of Power Supply Probability
LPS	Loss of Power Supply, Wh
n	Number of days
P_{PV}	Nominal peak power of solar panel, Watt peak
PSH_t	Peak Sun Hour, hour
$PSH_{t(n)}$	Peak sun hour on the tilted surface, hour
SOC	State of charge, %
$\overline{T_{panel}}$	PV panel temperature, ^{o}C
$\overline{T_{amb}}$	Daily average of ambient temperature, ^{o}C
V_{rated}	Rated voltage/voltage of the system, Volt

Greek Symbols

ρ	Negative temperature coefficient of power
η_{system}	Total system efficiency, %
η_{self}	Daily self-discharge factor, %
η_{inv}	Inverter efficiency, %

installed PV systems in Malaysia are standalone applications and installed mainly for rural electrification schemes and non-building structures [2]. However, advances in PV and storage systems technology have improved the commercial viability and point towards a larger market share in residential applications. To convince potential investors into financing PV system installation, an appropriate supply and demand matching exercise is required. Here, a sizing and analysis tools are important features, which can strengthen the reliability of a PV system. Sizing is an essential part of PV system design to ensure reliability of the system by ensuring the number of solar panels used to capture solar energy and the capacity of the batteries for energy storage is sufficient [3].

Among the current approaches used for modelling, and sizing PV system includes the use of a deterministic, stochastic, empirical and statistical model. Deterministic methods are sometimes chosen because of its simplicity, but it will be only suitable for an initial design or quick estimate. Due to the stochastic nature of solar radiation as the resource of the system, more sophisticated results will be obtained by using a statistical method. Through the deterministic method, the storage system capacity is determined by the "autonomy-day" to ensure reliability of the system. This concept, however, does not ensure a direct relationship between reliability and PV systems component capacity [4].

Stochastic method considers the random nature of solar radiation as the most important data input for PV system sizing. Usually this method is carried out by calculating Loss of Power Supply Probability (LPSP) as the design parameter representing the reliability of the system [5]. Some author uses a different term such as Loss of Power Probability (LPP) [6], Loss of Load Probability (LOLP/LLP) [7] and Loss of Energy Probability (LOLE) [8]. Loss of Power Supply Probability (LPSP) is the total time when the power supply is not able to supply the load [4]. Another definition of LPSP is given by T. Markvart [9] as the ratio between the estimated energy deficit and the energy demand over the total operation time of the installation.

The stochastic method is frequently used and studied by many researchers. Shen [10] carried out solar array and battery sizing for stand-alone PV system in Malaysia using daily PSH data and an energy balance concept to calculate LPSP. Posadillo and Luque [11, 12] developed sizing method for stand-alone PV system using the LLP concept and proposed the annual number of system failures and standard deviation of the annual number of failures as new sizing parameters. T. Markvart et al. [13] proposed a sizing method based on LLP concept using a graphical method of solution and the sizing curve was obtained in combination with a climatic cycle line.

Fragaki and Markvart [14] presented the results of a new sizing approach and recommend a combination of a large array and smaller storage size to reduce the loss of load. Some authors also implemented simulation methods using hourly data to calculate LLP [15, 16]. Balouktsis et al. [17] used stochastic time series model as the data input for PV system sizing for locations where no actual data exist. Based on the above mentioned researches, stochastic method can use hourly or daily data, actual data or even artificial data. In this study, we are interested to develop LPSP calculation procedure using daily data and incorporate parameters that were not considered in the previous research [10] such as tilted angle and LCC.

The optimum size of a PV array and battery system can be obtained based on a minimum cost of the system [8]. A.N. Celik et al. [18] used a Life Cycle Cost (LCC) concept to find the optimal size of a PV system configuration. J.K. Kaldellis et al. [19] carried out optimization based on energy pay back analysis and P. Arun et al. [20] used Cost of Energy (COE) and Annualized Life Cycle Cost (ALCC) in their study. P. Arun et al. [20] proposed design space approach for choosing optimum PV-battery system configuration. A. Roy et al. [21] also proposed design space methodology for a wind-battery system. In this study, a sizing calculation algorithm for the daily data based LPSP calculation procedure was developed. Optimum size is identified by design space approach using LPSP, Capital Cost, Life Cycle Cost (LCC) and Excess energy value as design criteria.

2. Methods

2.1. Data set

In LPSP calculations, daily weather data is required (at least hourly or daily solar irradiation data must be available for one year). This kind of data is not always available for most locations, and not always accessible, even if there is a weather station nearby. Furthermore, the available data may contain missing data for several days in the absence of measurement. In this study weather data from Ipoh city meteorological station for 2003 was used to calculate LPSP. The data contain 5 (five) parameters that were recorded hourly throughout 2003. The parameters are solar irradiation, ambient temperature, relative humidity (RH), speed and direction of the wind. In this gathered data, there were 23 days with missing solar radiation data. Data filling procedure for those missing data has been discussed in another paper [22].

Figure 1 shows a complete hourly solar radiation data set on the horizontal surface. To obtain solar radiation on a tilted surface, the data is processed with TRNSYS 16 weather data component using Reindl model [23]. The optimum tilt angle for the area in Ipoh is 5°. Then Peak Sun Hour on the tilted surface can be calculated using following equation:

$$PSH_t = G_{Tt(daily)}/1000 \tag{1}$$

$$G_{Tt(daily)} = \int_{sunrise}^{sunset} G_{Tt}(t)dt \tag{2}$$

where PSH_t is Peak Sun Hour on the tilted surface and $G_{Tt(daily)}$ is integral of hourly global solar radiation on the tilted surface ($G_{Tt(t)}$) from sunrise to sunset.

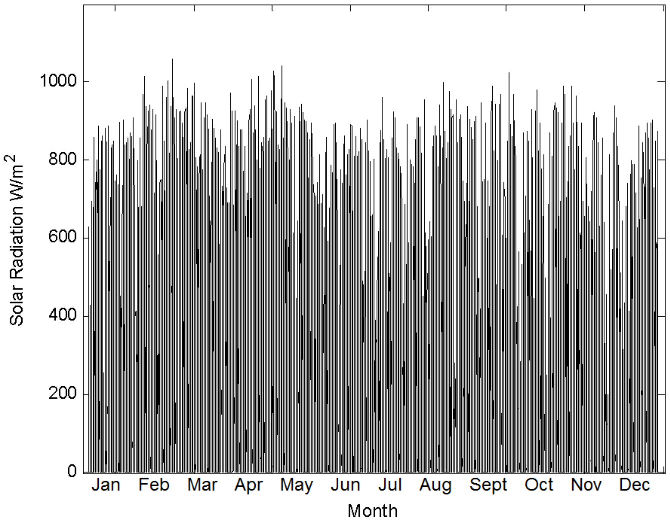

Fig. 1. Complete One Year Hourly Solar Radiation Data Set.

2.2. PV panel power output calculation procedure

Previous studies have shown that PV panel temperature affects the efficiency of the panel [10]. Since PV panel temperature is not always measured in a PV system, the PV panel temperature prediction is necessary. PV panel temperature ($\overline{T}_{panel}$) can be approximately estimated by using ambient temperature and solar radiation as described by [10] as follows:

$$\overline{T_{panel}} = \overline{T_{amb}}(1 + 1.25H) \tag{3}$$

where $\overline{T_{amb}}$ and H are daily average of ambient temperature and irradiation. $\overline{T_{panel}}$ and $\overline{T_{amb}}$ is in °C. Then PV panel output is calculated using the equation below:

$$E_{PV(n)} = P_{PV(n)}(1 + \rho(\overline{T_{panel(n)}} - 25H)) \times PSH_{t(n)} \times \eta_{system} \tag{4}$$

P_{PV} is nominal peak power of solar panel, ρ is the negative temperature coefficient of power with respect to solar cell temperature. $PSH_{t(n)}$ is Peak sun hour on the tilted surface and η_{system} is total system efficiency.

2.3. Daily battery condition calculation

The operating condition of PV system depends on the weather condition on the site. This makes the PV system performance prediction rather complicated. The output power of PV panels, which is used to charge the battery, varies with solar radiation and temperature. The estimation of the battery state of charge (SOC) is complicated under such uncontrolled charge/discharge cycles. In tropical countries like Malaysia, duration of daytime and nighttime is almost the same throughout the year. Therefore, the term “half day” was used in this study to describe this condition. Condition in half day is a condition at sunset, and full day is at sunrise. The energy stored in the battery on the day *n* ($E_{B(n)}$) is calculated by:

$$E_{Bhalf(n)} = E_{B(n-1)} + E_{PV(n)} \tag{5}$$

$$E_{B(n)} = E_{Bhalf(n)}(1 - \eta_{self}) - E_{load(n)} / \eta_{inv} \tag{6}$$

$E_{Bhalf(n)}$ is battery energy condition during sunset on the day n. η_{self} is a daily self-discharge factor, which is occurred during discharge period. $E_{load(n)}$ is nominal load energy of the day and η_{inv} is inverter efficiency. The self-discharge’s rate is a measure of how quickly a cell will lose its energy while sitting on the shelf due to unwanted chemical actions within the cell. The rate depends on the cell chemistry and the temperature of the battery bank. Typical self-discharges rates for common rechargeable cells are as follows [24]:

- Lead Acid 4% to 6% per month
- Nickel Cadmium 15% to 20% per month
- Nickel Metal Hydride 30% per month
- Lithium 2% to 3% per month

In this study, the daily self-discharge factor (η_{self}) value is assumed to be 1% per day; this value was obtained by assuming battery bank temperature about 30°C and weekly self-discharge rate about 7%.

On any day *(n)*, the energy stored in the battery is subject to the following constraints:

$$E_{B\min} \le E_{B(n)} \le E_{B\max} \tag{7}$$

$$E_{B\min} = (1 - DoD) \times E_{B\max} \tag{8}$$

$E_{B\min}$ is minimum energy stored in the battery and $E_{B\max}$ maximum energy stored in the battery. The selection of the maximum allowable *DoD* is actually a compromise between system life and cost. Thus, the calculation of the battery state of charge (*SOC)* is,

$$SOC_{(n)} = E_{B(n)} /(C_{bat} \times V_{rated}) \tag{9}$$

C_{bat} is battery capacity and V_{rated} is system's rated voltage.

2.4. LPSP calculation procedure

When the SOC of the battery is fully charged, the system controller will stop charging and prevent the battery from overcharging. On the other hand, the controller will cut off the load if the SOC of battery reaches the minimum allowed value. In terms of the allowable minimum battery SOC, the LPSP can be mathematically defined as:

$$LPSP = \sum_{n=1}^{N} LPS_{(n)} \Big/ \sum_{n=1}^{N} E_{load(n)} \tag{10}$$

where N is number of days, $LPS_{(n)}$ is Loss of Power Supply for day n and $E_{load(n)}$ is load energy for day n.

In a daily cycle PV-system, time of the day can be differentiated into two conditions. First, time with the presence of solar radiation, during this period battery charging is possible as long as load energy during the daytime less than input energy. Second is night time (no solar radiation), which only battery discharges condition is possible. Figure 2 shows LPSP calculation procedure.

2.5. Optimization procedure

Optimum configuration was obtained using the following constraints:

- Minimum LPSP
- Minimum Excess Energy
- Minimum Cost (Capital Cost and Life Cycle Cost)

Cost analysis was carried out using Life Cycle Cost analysis adopted from [18, 25-27] as follows:

$$LCC=CC+M+R+S \tag{11}$$

CC is the capital cost. M is operation and maintenance cost. R is repair and replacement cost. S is the salvage value (the estimated value of an asset at the end of its useful life). All costs are converted to present worth value for the single present value (P_s) and for the uniform present value (P_u) respectively:

$$P_s = F/(1 + I_d)^N \tag{12}$$

$$P_u = A\left[1-(1+I_d)^{-N}\right]/I_d \tag{13}$$

F is sum of money for single present value and *A* are a sum of money of uniform present value. *N* is a given year for Eq. 12 and is the period of time in question for Eq. 13. I_d is the net discount rate (i.e. nominal discount rate minus the rate of inflation). The present worth factor for a single payment is P_s/F, and, for an annual payment, P_u/A. Further economic analysis can also be carried out. Annual energy service (AES), Annual Life Cycle Cost (ALCC), Cost of Energy (COE) and Payback Period are calculated using the following formula:

$$AES = \sum(E_{load}/\eta_{inv}) - \sum LPS \tag{14}$$

$$ALCC=ACC+AM \tag{15}$$

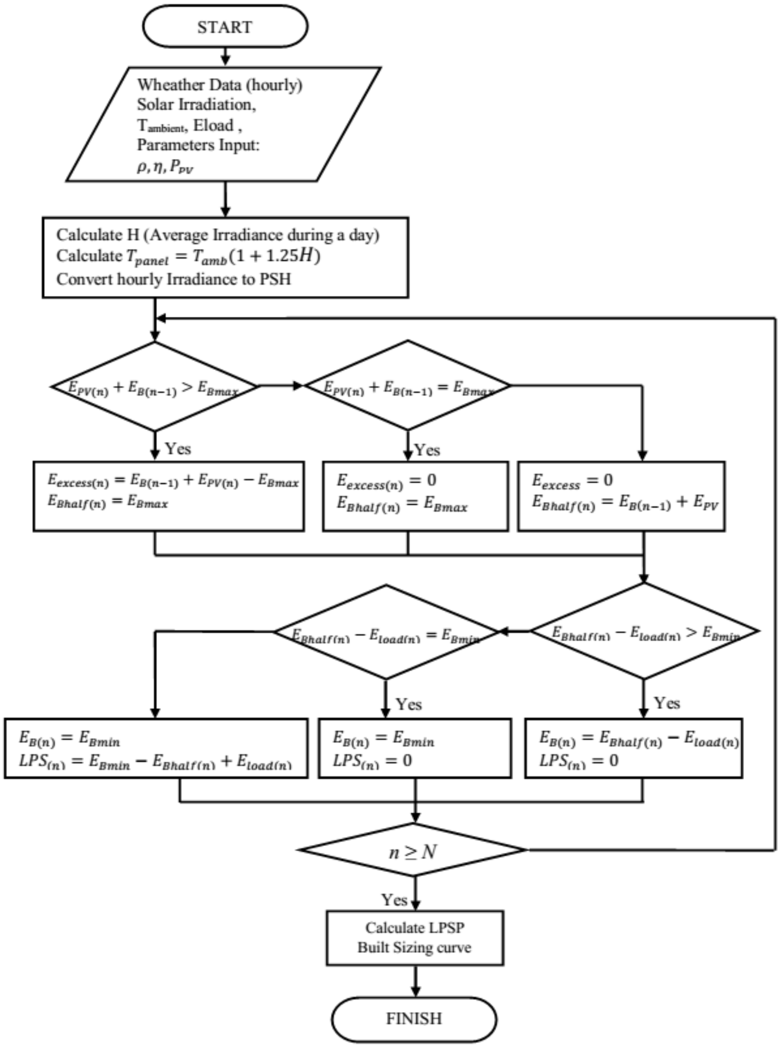

Fig. 2. Simplified Flow Chart to Calculate LPSP.

where AM is annual maintenance and operation cost, assumed to be 1% of capital cost. ACC is Annualized capital cost as follows:

$$ACC = CC \times CRF \tag{16}$$

The capital recovery factor (CRF) is a function of discount rate and life time as described by the following equation:

$$CRF = I_d (1 + I_d)^N / (1 + I_d)^N - 1 \tag{17}$$

Then the cost of energy can be calculated using following equation:

$$COE = ALCC / AES \tag{18}$$

Cost of energy then can be compared with grid electricity tariff, Table 1 shows electricity tariff from Tenaga Nasional Berhad for domestic consumer [28].

Table 1. Electricity Tariff for Domestic Consumer (TNB) [28].

Tariff A - Domestic Tariff	UNIT	RATES
For Monthly Consumption Between 0-400 kWh/month		
For the first 200 kWh (1 - 200 kWh) per month	sen/kWh	21.8
For the next 200 kWh (201 -400 kWh) per month	sen/kWh	33.4
For Monthly Consumption More Than 400 kWh/month		
For the first 500kWh (401-600kWh) per month	sen/kWh	51.6
For the next 100 kWh (601-900kWh) per month	sen/kWh	54.6
For the next kWh (901 kWh onwards) per month	sen/kWh	57.10

The component cost used for cost analysis in this study was adapted from [29-31]. Table 2 shows cost of component and parameter that used in the cost analysis. Total cost is calculated based on project life time of 20 years. This value is taken from the longest life time of component in PV-system, in this case PV panels, which have life time about 20-30 years.

Table 2. Component Costs and Parameters used in LCC Analysis [30-34].

Component/Parameter	**Price**[a)]
PV panel cost	6.5 RM/Wp
Battery cost	0.8 RM/Wh
Controller cost	22 RM/Amp
Inverter cost	2.2 RM/Wp of load
Installation cost	2 RM/Wp
PV Array life	20 years[b)]
Battery life	5 years[c)]
Controller life	10 years
Inverter life	10 years
Annual operation and maintenance cost	1% of initial capital cost
Net discount rate	5%
Retail markup	30%

a) 1 USD = 3.2 RM, b) Worst case, average lifetime of PV panel is about 20-30 years [18], [34], c) Calculated using method from reference [34]

Table 3 shows calculation example of CC and LCC for 450 Wp PV panel and 850 Ah battery capacities. The calculation is based on project lifetime of 20 years.

This value is taken from the longest lifetime of component in PV-system, in this case PV panels that have a lifetime about 20-30 years. The cost presented in the Table 3 include GST/VAT rate (Goods and Services Tax/Value added Tax) 15% [32, 33]. Retail mark-up factor of 30% was used to calculate CC. Maintenance Cost was assumed to be 1% of capital cost per year. For Repair and Replacement, it was assumed that only batteries need to be replaced every 5 years. Salvage cost is assumed to be 10% of CC.

Table 3. LCC Calculation Example for 400Wp PV Panel and 864 Ah Battery Capacity.

Component/Parameter	Single present worth year	Uniform present worth year	Cost (RM)	Present worth factor	Present worth (RM)
Capital Equipment (CC)					
PV panel	-	-	3380.00	1.00	3380.00
Battery	-	-	10782.72	1.00	10782.72
Inverter	-	-	858.00	1.00	858.00
Controller	-	-	858.00	1.00	858.00
Other component (10% of PV)	-	-	338.00	1.00	338.00
Installation cost	-	-	1040.00	1.00	1040.00
Sub total					17256.72
Operation and Maintenance (M)					
Labor: yearly inspection	-	20.00	172.57	12.46	2150.57
Repair and Replacement (R)					
Battery	5.00	-	10782.72	0.78	8448.54
Battery	10.00	-	10782.72	0.61	6619.65
Battery	15.00	-	10782.72	0.48	5186.67
Salvage (S)					
10% of equipment original cost	20.00	-	1725.67	0.38	650.39
Total					39011.77

3. Results and Discussions

The calculation algorithm has been carried out to obtain LPSP values for a 0-990 Wp PV panel capacity and a 0-990 Ah battery capacity. From the calculation algorithm, four graphs have been plotted. Figure 3 shows LPSP surface graphic, Fig. 4 shows Excess Energy surface graphic, Fig. 5 shows Capital Cost surface graphic and Fig. 6 shows LCC surface graphic. The surface graphic then can be used to perform analysis of LPSP, Excess energy, capital cost and LCC value within the graphic range (0-990 Wp of PV panel and 0-990 Ah of battery capacity). In this study design space is identified using a surface graph's combination.

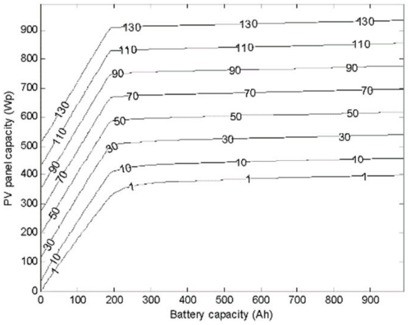

Fig. 3. LPSP Surface Graphic.

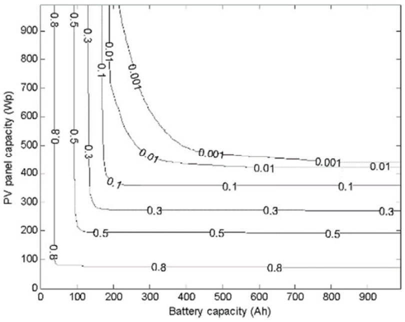

Fig. 4. Excess Energy Surface Graphic (%).

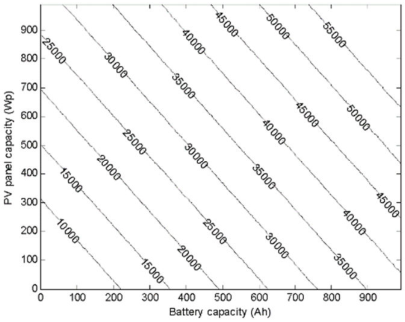

Fig. 5. Capital Cost Surface Graphic (RM).

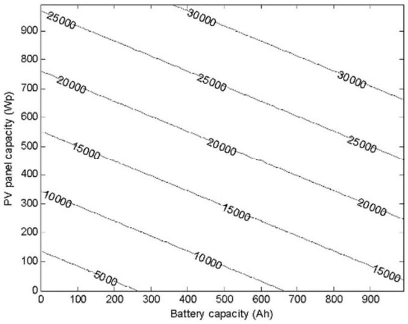

Fig. 6. LCC Surface Graphic (RM).

3.1. Optimization results

Sizing optimization was carried out by (i) minimum capital cost, (ii) minimum LCC and (iii) by using a design space approach. Figure 7 shows the comparison between the deterministic method (initial design) results and size optimization results by minimum capital cost and minimum LCC. It can be seen from Fig. 7 that the deterministic method result is undersized PV panel capacity and oversized battery capacity.

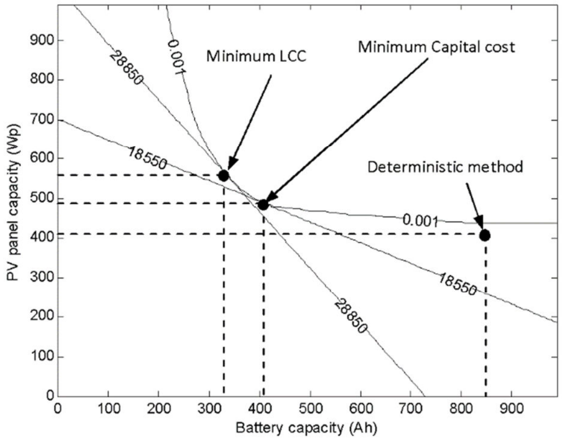

Fig. 7. Sizing Curve Based on Minimum Capital Cost and LCC on Desired LPSP.

For design space approach, sizing optimization was performed by determining the sizing curve of minimum LPSP value, maximum excess energy, maximum capital cost and maximum LCC as can be seen in Figs. 8 and 9. In this study, the design area for LPSP is chosen between 0-0.001, whereby the lower LPSP choice is better. Design area for excess energy is between 0-30% and the design area for LCC is below RM 32000 with a capital cost below RM 20000. PV panel and battery capacity for design space approach are selected based on values that are multiples of the available commercial capacity in the market, in this study it is assumed that commercial capacity of PV panel available in the market is 100 Wp, and commercial capacity of 12V battery are 50 and 100 Ah.

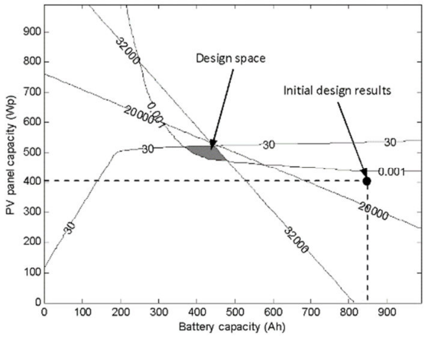

Fig. 8. Design Space Approach Results.

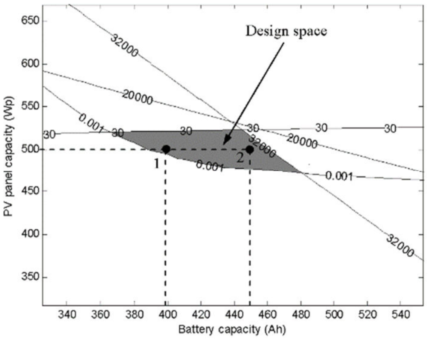

Fig. 9. Design Space (Zoom) Option 1 and 2.

Table 4 shows the comparison of sizing optimization results. It can be seen from the results that the deterministic method shows higher LPSP value, underestimate the PV panel capacity and overestimate the battery capacity. This method also results in higher capital cost and LCC than the proposed daily based LPSP calculation method. Size optimization using minimum capital cost and minimum LCC on 0.001 LPSP shows a more reasonable results eventhough the size of the PV array and battery need to be rounded. More rational PV panel and battery size capacity value for application can be obtained using design space approach by considering market available PV panel and battery capacity. Option 1 shows lower capital cost and LCC than option 2, while option 2 shows lower LPSP value.

Table 4. Comparison of Optimization Results.

No.	Method	System Configuration		Sizing parameters			
		PV panel (Wp)	Battery (Ah)	LPSP	Excess Energy (%)	Capital Cost (RM)	LCC (RM)
1	Initial design (Deterministic method)	400	864	0.031	1.5	17256	39011
2	Minimum capital cost on 0.001 LPSP	495	405	0.001	23	12658	23253
3	Minimum LCC on 0.001 LPSP	560	340	0.001	40	12620	21688
4	Design space approach option 1	500	400	0.001	24	12655	23132
5	Design space approach option 2	500	450	0.0002	24	13279	24983

It is up to the investor's priority to select the appropriate PV panel and battery configuration. Option 1 is preferable for lower system cost while option 2 is preferable for better system performance by lower LPSP value. Further analysis also carried out for the selected configuration by using calculation results from proposed daily based LPSP calculation algorithm. Energy balance by mean of energy excess and losses can be observed. Daily battery status can also be observed. Figure 10 shows daily excess energy and losses energy throughout the year for deterministic method results and Fig. 11 for design space approach (option 1) size configuration. It can be seen that the deterministic method configuration results in small excess energy and large losses otherwise the design space approach (option 1) configuration results in large excess energy but with losses.

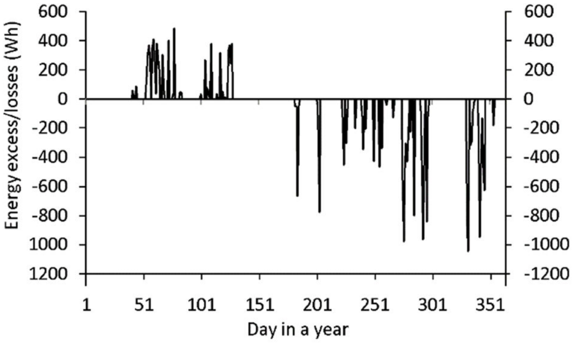

Fig. 10. Daily Excess and Losses Energy for Configuration Obtained using Deterministic Method.

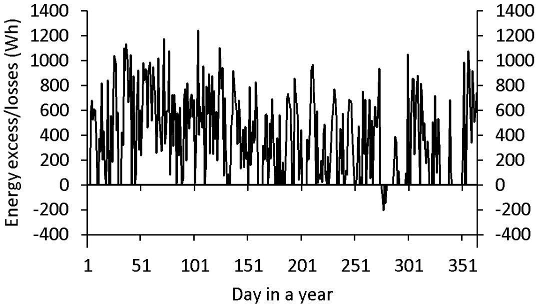

Fig. 11. Daily Excess and Losses Energy for Design Space Option 1 Configuration.

3.2. Economic analysis

Annual Cash Flow (ACF) for conventional grid electricity can be calculated by multiplying it with respective Electricity Tariff (ET) as follows:

$$ACF = AES \times ET \tag{20}$$

Then pay-back period (PBP) can be calculated as follow:

$$PBP = ALCC / ACF \tag{21}$$

AES is Annual energy service, and ALCC is Annual Life Cycle Cost. Table 5 shows calculation results of AES, ALCC, COE (Cost of Energy) and PBP for each configuration. From the results, it can be seen that solar energy now still expensive compared to grid electricity.

Cost of electricity energy generated from PV system during this study is still more than ten times of conventional grid electricity (about 0.22 RM/kWh). This is because grid electricity has got subsidies from the government and PV system technology still considered as expensive technology. However, PV technology has been developing and the PV cost decreasing every year, otherwise cost of grid electricity, which generated from fossil fuel is increasing, it is believed that renewable energy systems are very promising in the future.

Table 5. Economic Analysis Comparison of Sizing Optimization Results.

No.	Method	AES (kWh/year)	ALCC (RM)	COE (RM)	PBP (year)
1	Initial design (Deterministic method) (400 Wp, 864 Ah)	550.274	1557	2.74	12.9
2	Minimum capital cost on 0.001 LPSP (495 Wp, 405 Ah)	567.301	1142	2.01	9.1
3	Minimum LCC on 0.001 LPSP (560 Wp, 340 Ah)	567.287	1138	2.01	9.1
4	Design space approach option 1 (500 Wp, 400 Ah)	567.322	1142	2.01	9.1
5	Design space approach option 2 (500 Wp, 450 Ah)	567.635	1198	2.11	9.6

4. Conclusion

Daily data based LPSP calculation has been developed and carried out. Sizing curve of PV panel and battery configuration were built based on LPSP, Excess Energy, Capital Cost and LCC value. Sizing optimization has been carried out using design space approach and compared with results using deterministic method, minimum Capital Cost and minimum LCC optimization. The results show that design space approach offers several advantages than using other methods. One of the advantages using design space approach is the user can choose the realistic available PV panel and battery size configuration.

Acknowledgements

The authors would like to thank Universiti Teknologi PETRONAS for providing facilities and grant under STIRF schemes code No: 63/08.09.

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