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Sizing and Analysis of Grid-Connected Photovoltaic System with Battery Storage

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Abstract: Due to the COVID-19 pandemic, the rise in electrical demand has affected the stability of the power system. Malaysia is a developing country with a huge energy demand and has undergone a lot of efforts to implement renewable energy, especially for power generation. To provide useful grid services and allow high penetration of photovoltaic (PV) systems, battery energy storage systems (BESS) are considered a promising option. This study aims to size and analyze a grid-connected photovoltaic system with battery storage for a residential house, develop a Graphical User Interface (GUI) that can perform sizing of a grid-connected photovoltaic system with battery storage and compare the generated GUI result with the manual sizing result. To test out the hypothesis that a grid-connected photovoltaic system with battery storage leads to a more stable power system, the house's load data and size are collected, and the GUI is developed using MATLAB software to size the grid-connected photovoltaic system with battery storage. The GUI can size the load consumption and determine of every component, costing and return on investment (ROI) for the grid-connected photovoltaic system with savings battery storage. The result is observed and the generated GUI result must correspond to the manual calculation. These results suggest that the correct sizing is crucial as the total payback period depends on total monthly saving and the total cost of the PV system installation. On this basis, the grid-connected photovoltaic system with battery storage should be considered to achieve more stable power system.

Keywords: Photovoltaic System, Graphical User Interface (GUI), Battery Storage

1. Introduction

Malaysia is a developing country with huge energy demand and has undergone a great deal of effort to implement renewable energy, especially for power generation [1]–[4]. Renewable energy is defined as the electrical energy that is being generated from the natural sources such as wind, solar photovoltaic (PV), flywheel, biomass, battery, fuel cells and distributed generation (DG) with a strong

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emphasis on environmental friendliness [5]. Renewable energy sources (RES) are known to be cleaner with low environmental Supreme relative to the traditional energy sources [6], [7].

Photovoltaic PV cell is an electronic system that effectively transforms solar energy from sunlight to electrical energy and is best suited to adapt in Malaysia as the weather in Malaysia is quite hot and receives abundant amount of sunlight what do you throughout the year. One of the benefits of photovoltaics is the lack of moving components that reduce tears and wear and their related repair costs [8]. The two main types of PV system are Grid-connected PV system and stand-alone PV system. The photovoltaic system usually consists of several panels and arrays. However, when a large-scale PV systems are used, the system normally consists of one or more DC or AC converter or inverter PV plates for the generation of electricity that is fed into the load [6]. Additionally, large-scale PV system may also require storage modules to mitigate the intine intermittency of the generation caused by various environmental factors and control the flow of energy through the grid [9]. PV systems are now the most promising field for solar energy harvesting in limited or larger capacities [10]. Therefore, in order to provide useful grid services and allow high penetration of PV systems, battery energy storage systems (BESS) are considered as a promising option due to their simplest scalability and versatility in any kind of project [11].

In addition, the sizing of Grid-Connected PV system with battery storage includes numerous steps and calculations. The Graphical User Interface (GUI) system is a system that is an interactive visual component that can collect the data required and display the parameters and equations involved to provide the desired sizing needed. The GUI plays a vital role in programming, as the GUI has its benefits. In addition, it would help non-technical people or beginners [12]. The GUI will conduct the sizing from the load usage analysis to the return on investment required for the user to install the grid-connected PV system with battery for their home.

2. Materials and Methods

2.1 Materials

The experimental measurement of the electrical load demand was measured for a typical household in Jalan Universiti 15, Taman Universiti, Batu Pahat, Johor. The typical considered household is a reception, living room, kitchen, and four bedrooms with two occupied by family consist, two adults and three children. The cooking, hot water and heating system were powered by natural gas. A few devices with high nominal electrical power are used: refrigerator 228 W, washing machine 460 W, Light Emitting Diode (LED) lamps 8 W, 6 ceiling fan 60 W, 10 fluorescent lamps.

2.2 Methods

This project starts with finding information related to the grid-connected PV system with battery storage. Hence, the load data from the selected household is collected. The calculations are mostly dependent on other parts of the calculation. When the manual calculation is completed, the GUI is developed, and the result is compared between the manual calculation and the GUI application. The GUI is be developed using MATLAB software which is app designer tools.

2.3 Equations

2.3.1 Load Consumption

A single storey house was selected for the estimated load consumption. The data for the load consumption was assume as basic appliance needed in a household such as light, fan, refrigerator, washing machine, laptop, and mobile charger. The load consumption is determined and calculated to total daily energy consumption, total monthly energy consumption, total AC power demand, and weighted average operating time using the Equation 1 [13], Equation 2 [13], Equation 3 [13] and Equation 4 respectively.

$$\sum E_{AC} = \frac{\sum(Q \times PR \times t)}{\eta_{inv}} \qquad Eq. 1$$

$$\text{MEC} = \sum E_{AC} \times 30\ days \qquad Eq. 2$$

$$P_{AC} = \sum(Q \times PR) \qquad Eq. 3$$

$$t_{op} = \frac{(\mathrm{E_1} \times \mathrm{t_1}) + (\mathrm{E_2} \times \mathrm{t_2}) + \cdots + (\mathrm{E_n} \times \mathrm{t_n})}{\mathrm{E_1} + \mathrm{E_2} + \cdots + \mathrm{E_n}} \qquad Eq. 4$$

2.3.2 Inverter Sizing

Selecting the suitable size of inverter is the second step of sizing a grid-connected photovoltaic system with battery storage. There are a few factors that need to be considered in the inverter selection. The first factor is the inverter must be able to supply at least the same amount of power as the total AC power demand obtained in the load analysis. However, it is really recommended that the size of the inverter should be slightly higher than the total AC power demand by 10 to 40%. The second factor is that the output voltage of the inverter must be the equal to the AC system voltage. The third factor is the DC input voltage of the inverter must be equal with the battery system voltage. The power rating of the inverter can be calculated using Equation 5 [13].

$$P_{inv} = P_{AC} \times 1.25^{*} \qquad Eq. 5$$

2.3.3 Solar Array Sizing

The required current and voltage produced by the solar array are determined in this step by using Equation 6 and Equation 7 [13] respectively. The position of the solar arrays are then determined using Equation 8 for the number of solar string in parallel and Equation 9 for the number of solar string in series.

$$I_{array} = \frac{\sum \mathrm{E}_{AC}}{\eta_{batt} \times \mathrm{V}_{SDC} \times PSH \times C_s} \qquad Eq. 6$$

$$V_{array} = \frac{1.2 \times \{\mathrm{V_{SDC}} + [\mathrm{V_{SDC}} \times \mathrm{C_{\%V}} \times (\mathrm{T_{max}} - \mathrm{T_{ref}})]\}}{\eta_{\mathrm{batt}} \times \mathrm{C_s}} \qquad Eq. 7$$

$$Number\ of\ solar\ string\ in\ parallel = \frac{\mathrm{I}_{array}}{\mathrm{I}_{mp}} \qquad Eq. 8$$

$$Number\ of\ solar\ string\ in\ series = \frac{V_{array}}{\mathrm{V}_{mp}} \qquad Eq. 9$$

2.3.4 Solar Charge Controller Sizing

Like inverter, there are few factors that needs to be considered before selecting the suitable solar charge controller. The important factor is that the charge controller should be rated at least 125% of the maximum current from the solar array. The next factor is the charge controller voltage rating is able to operate with the battery system voltage. The current readings of the charge controller can be calculated using Equation 10 [13].

$$I_{cc} = I_{mp} \times no\ of\ solar\ array\ in\ parallel \times 1.25 \qquad Eq. 10$$

2.3.5 Battery Bank Sizing

This step determines the required ampere hour and system voltage of the battery according to the size of the system's power. Determining the required capacity of the battery bank is the first step in sizing the battery bank. Equation 11 [13] can be used to determine the required capacity of the battery bank while Equation 12 [13] shows the second step in battery bank sizing which is determining the average discharge rate of the battery bank.

$$B_{out} = \frac{\sum E_{AC} \times t_a}{V_{SDC}} \qquad Eq. 11$$

$$r_d = \frac{t_{op} \times t_a}{DOD_a} \qquad Eq. 12$$

The value of the discharge rate of the battery bank, r_d is used to determine the temperature and the discharge rate derating factor, $C_{T,rd}$. $C_{T,rd}$ is the percentage of usable capacity of the battery bank and is determined from a graph of discharge rates versus operating temperatures that can be obtained from the battery's datasheet. Finally, the rated capacity of the battery bank is calculated using Equation 13 [13].

$$B_{rated} = \frac{B_{out}}{DOD_a \times C_{T,rd}} \quad Eq. 13$$

Similar to solar array sizing, the number of batteries connected in parallel is determined using Equation 14 [13] by dividing the rated battery bank capacity, B_{rated} with the capacity of the selected battery. On the other hand, the number of batteries connected in series is determined using Equation 15 [13] by dividing the system voltage of the battery bank, V_{SDC} with the nominal voltage of the selected battery.

$$No\ of\ string\ of\ batteries\ in\ parallel = \frac{B_{rated}}{\text{capacity of the selected battery}} \quad Eq. 14$$

$$No\ of\ string\ of\ batteries\ in\ series = \frac{V_{SDC}}{\text{capacity of the selected battery}} \quad Eq. 15$$

2.3.6 Costing

Costing is needed for the user to calculate the total cost for the PV system installation. Total costing can prepare user with their own budget to install the system at their house. The calculation is divided by seven sections which are PV panel, Inverter, Solar Charge Controller, Battery, Installation and Maintenance. The calculation can be calculated by using Equation 16 - 23 [13]

PV Panel

Total PV Panel Price (RM) = Cost Per Panel X Total Panel $\quad Eq. 16$

Inverter

Total Inverter Price (RM) = $Inv. Pout_{DC}$ $\quad Eq. 17$

Where,

$Inv. Pout_{DC}$ = Inverter Maximum DC Power

Solar Charge Controller

Total Solar CC Price (RM) = Cost Per Unit $\quad Eq. 18$

Battery

Total Battery Price (RM) = Cost Per Battery X Total Battery $\quad Eq. 19$

Installation

Labour Price (RM) = Labour Rate $\quad Eq. 20$

$$\text{Wiring Price (RM)} = (\%/100) \times \sum(\text{PV panel} + \text{inverter} + \text{solar cc} + \text{battery} + \text{labour}) \text{ price} \qquad Eq. 21$$

Where,

The percentage is set by 30% from the total price of panel, inverter, solar charge controller, battery and labour.

Maintenance

$$\text{Total Maintenance Price (RM)} = \text{Annual Cleaning} + \text{Annual Inspection} \qquad Eq. 22$$

Total Costing Price

$$\text{Total Cost (RM)} = \sum(\text{PV panel} + \text{Inverter} + \text{Solar CC} + \text{Installation} + \text{Maintenance}) \text{ price} \qquad Eq. 23$$

2.3.7 Tariff

The tariff is determined by multiplying the total load consumption and average daily energy production with 30 days respectively. Hence, the value of kWh will be calculated by referring to the TNB tariff rates in Table 1 [13].

2.3.8 Return on Investment

With the energy production from the PV panel, the user are able to know their entire payback period after the consideration of the total cost of the overall installation. The calculation can be calculated using Equation 24 [13].

$$\text{Total Payback Period (years)} = \frac{\dfrac{Total\ Costing\ Price\ (RM)}{Total\ Monthly\ Saving\ (RM)}}{12\ months} \qquad Eq. 24$$

3. Results and Discussion

In this part, the findings of the sizing of a grid-connected photovoltaic system with battery storage at Jalan Universiti 15, Taman Universiti, Batu Pahat, Johor is analyzed and discussed.

3.1 Results

The load data collected in Jalan Universiti 15, Taman Universiti, Batu Pahat, Johor is tabulated in Table 1. The result obtained from manual calculation and GUI is tabulated in Table 2. Table 4 shows the comparisons of four different rating of PV panels.

Table 1: Typical load data in a household

ELECTRICAL LOADS	QUANTITY, Q	POWER RATING, PR (WATT)	OPERATING HOUR, t (HOUR/DAY)	ENERGY CONSUMPTION, E (WATT HOUR/DAY)
Fluorescent light (Porch)	2	40	4	320
uorescent light (Living Roo	2	40	5	400
Ceiling Fans (Living Room)	2	60	14	1680
luorescent light (Bedroom	4	40	2	320
Ceiling Fans (Bedrooms)	3	60	8	1440
Mobile Phone Charger	5	5	2	50
Laptop Charger	3	45	1	135
Table Fan	3	50	8	1200
LED light (Toilet)	1	8	5	40
orescent light (Dining Roo	1	40	1	40
Ceiling Fans (Dining Room	1	60	1	60
Refrigerator	1	228	24	5472
Fluorescent light (Kitchen)	1	40	5	200
Washing Machine	1	460	1	460

Table 2: Comparisons of computational and GUI results

Parameter	Computational Result	GUI Result
Total daily energy consumption (WH/Day)	12271.03	12271
Total monthly energy consumption (kWH)	368	368
Total AC power demand (W)	1766	1766
Weighted average operating time (Hr/Day)	15.39	15.3916
Power rating of the inverter (W)	2207.5	2207
Required solar array current (A)	45.30	45.30
Required solar array voltage (V)	52.06	52.06
No of solar string in parallel	4	3.92
No of solar string in series	2	1.20
Current rating of the charge controller (A)	57.80	56.63
Required battery bank capacity (Ah)	255.65	255.6
Average discharge rate of the battery bank (hr)	20	19.24
Rated battery bank capacity (Ah)	323.23	322.8
No of battery string in parallel	2	1.614
No of battery string in series	1	1
Total PV panel price (RM)	3680	3680
Total inverter price (RM)	500	500
Total solar charge controller price (RM)	400	400
Total battery price (RM)	800	800
Labour price (RM)	1500	1500
Wiring price (RM)	2064	2064
Total maintenance price (RM)	350	350
Total cost (RM)	9294	9294
Actual monthly bill (RM)	112.09	112.1
Total bill after PV installation (RM)	49.65	49.54
Total monthly saving (RM)	62.44	62.56
Total payback period (RM)	12.40	12.38

Table 3: Comparisons of four different rating of PV panels

Parameter	600W	505W	420W	280W
Required solar array current (A)	45.30	45.30	45.30	45.30
Required solar array voltage (V)	52.06	52.06	52.31	49.96
No of solar string in parallel	3	4	5	6
No of solar string in series	2	2	2	2
Current rating of the charge controller (A)	65.03	57.80	58.31	66.15
Required battery bank capacity (Ah)	255.65	255.65	255.65	255.65
Average discharge rate of the battery bank (hr)	20	20	20	20
Rated battery bank capacity (Ah)	323.23	323.23	323.23	323.23
No of battery string in parallel	2	2	2	2
No of battery string in series	1	1	1	1
Total PV panel price (RM)	3000	3680	4500	4200
Total inverter price (RM)	500	500	500	500
Total solar charge controller price (RM)	500	400	400	500
Total battery price (RM)	800	800	800	800
Labour price (RM)	1500	1500	1500	1500
Wiring price (RM)	1890	2064	2310	2250
Total maintenance price (RM)	350	350	350	350
Total cost (RM)	8540	9294	10360	10100
Actual monthly bill (RM)	112.09	112.09	112.09	112.09

Total bill after PV installation (RM)	56.36	49.65	47.07	59.97
Total monthly saving (RM)	55.73	62.44	65.02	52.12
Total payback period (Year)	12.77	12.40	13.28	16.15

3.2 Discussions

The comparison between the computational result and GUI application is shown in Table 2. The computational result and the GUI generates the nearly same. The GUI can only generate the exact number of solar strings in parallel and series and the number of battery string in series and parallel, hence the difference in results. However, the GUI will help user to size the system faster than manual sizing. Therefore, user can also modify the PV sizing and cost depending on their budget. The total payback period of computational result is longer than the GUI by RM0.02 because the total monthly saving generated by the GUI is greater than the computational result. The price of total cost estimation may vary due to current price of the equipment used.

Table 3 shows the result of the total payback period due to different solar panel rating. For this comparison, PV panel with rating of 600 W, 505 W, 420 W and 280 W were chosen and the size of inverter is set to 2300 W to ensure the price of inverter is the same. Therefore, PV panel with rating 505 W was chosen as it shows the shortest payback period which is 12.40 years. The total payback period for 600 W panel is longer than the chosen PV panel of 505 W. This is due to the price of each panel is expensive and it uses higher rating of solar charge controller that effect the total cost and total monthly saving even if it only uses six modules of PV panels.

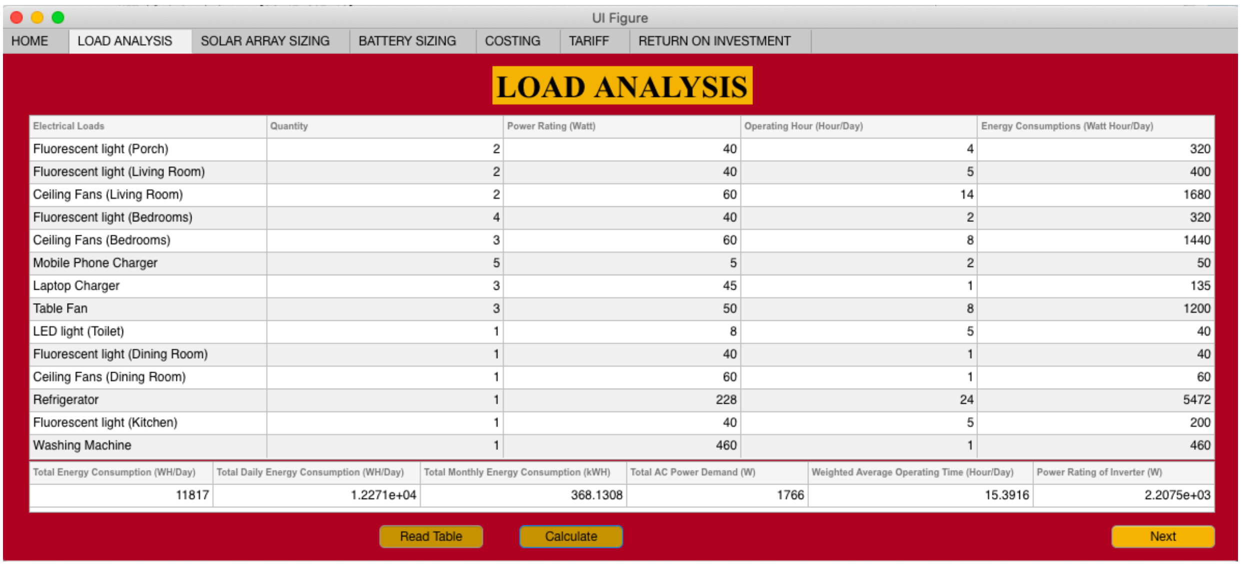
Furthermore, PV panel with the rating of 420 W shows the highest monthly saving which is RM65.02 but also has the highest total cost of system installation compared to other rating of PV panel. Lastly, the total payback period is higher compared to the PV panel with rating of 600 W and 505 W, it is still a shorter payback period compared to PV panel with the rating of 280W. Due to the amount of PV panels required in an array, the total payback period with longest payback period is the PV panel with rating of 280 W. Even though it has the cheapest value per PV panel, due to the amount of PV Panel required, the total cost of system is affected. Hence, having the longest payback period. Table 1 shows TNB tariff rates for domestic category.

Table 1: TNB tariff rates for domestic category

	TARIFF CATEGORY	UNIT	CURRENT
1	**Domestic Category**		
	Tariff A - Domestic Tariff		
	For the first 200 kWh (1 - 200 kWh) per month	sen/kWh	**21.8**
	For the next 100 kWh (201 - 300 kWh) per month	sen/kWh	**33.4**
	For the next 300 kWh (301 - 600 kWh) per month	sen/kWh	**51.6**
	For the next 300 kWh (601 - 900 kWh) per month	sen/kWh	**54.6**
	For the next kWh (901 kWh onwards) per month	sen/kWh	**57.1**
	The minimum monthly charge is RM3.00		

Figure 1 -7 show the developed GUI.

Figure 1: Home tab of GUI



Electrical Loads	Quantity	Power Rating (Watt)	Operating Hour (Hour/Day)	Energy Consumptions (Watt Hour/Day)
Fluorescent light (Porch)	2	40	4	320
Fluorescent light (Living Room)	2	40	5	400
Ceiling Fans (Living Room)	2	60	14	1680
Fluorescent light (Bedrooms)	4	40	2	320
Ceiling Fans (Bedrooms)	3	60	8	1440
Mobile Phone Charger	5	5	2	50
Laptop Charger	3	45	1	135
Table Fan	3	50	8	1200
LED light (Toilet)	1	8	5	40
Fluorescent light (Dining Room)	1	40	1	40
Ceiling Fans (Dining Room)	1	60	1	60
Refrigerator	1	228	24	5472
Fluorescent light (Kitchen)	1	40	5	200
Washing Machine	1	460	1	460

Total Energy Consumption (WH/Day)	Total Daily Energy Consumption (WH/Day)	Total Monthly Energy Consumption (kWH)	Total AC Power Demand (W)	Weighted Average Operating Time (Hour/Day)	Power Rating of Inverter (W)
11817	1.2271e+04	368.1308	1766	15.3916	2.2075e+03

Figure 2: GUI load analysis results

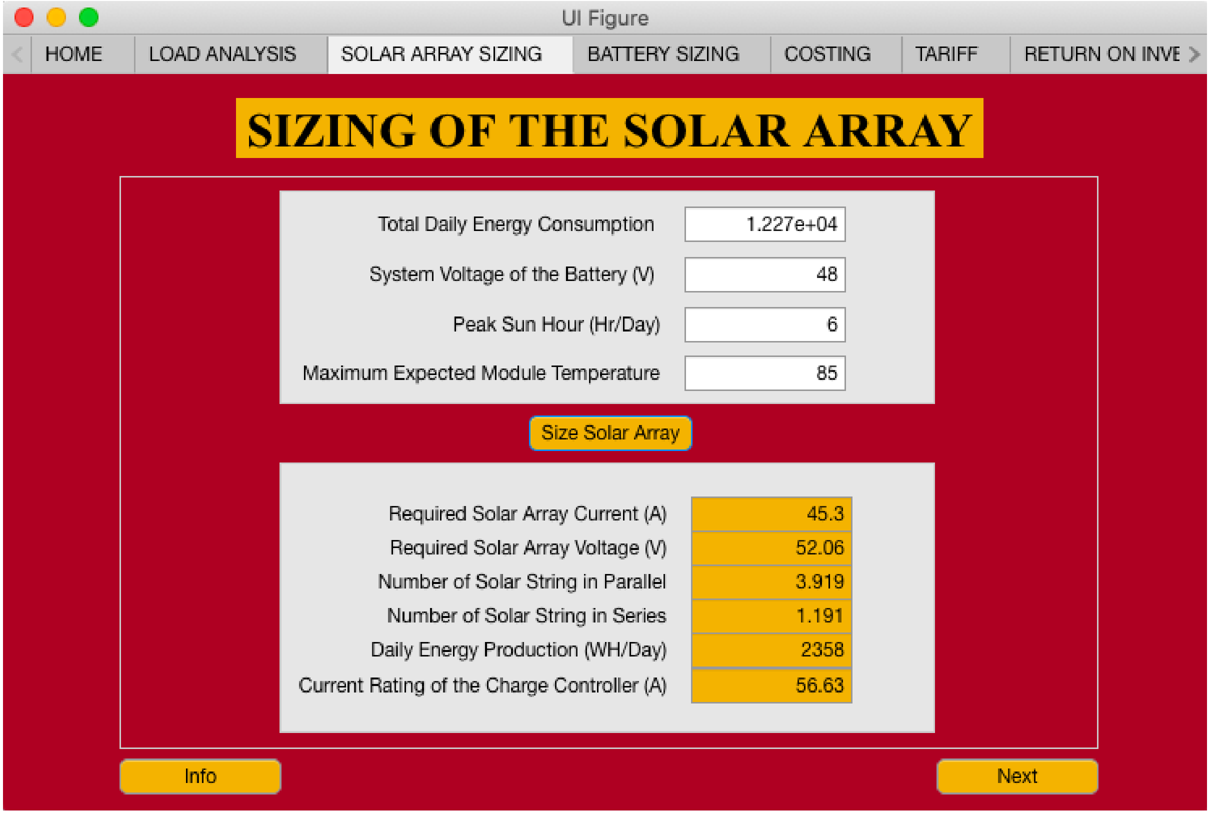


Figure 3: GUI results of Solar array sizing

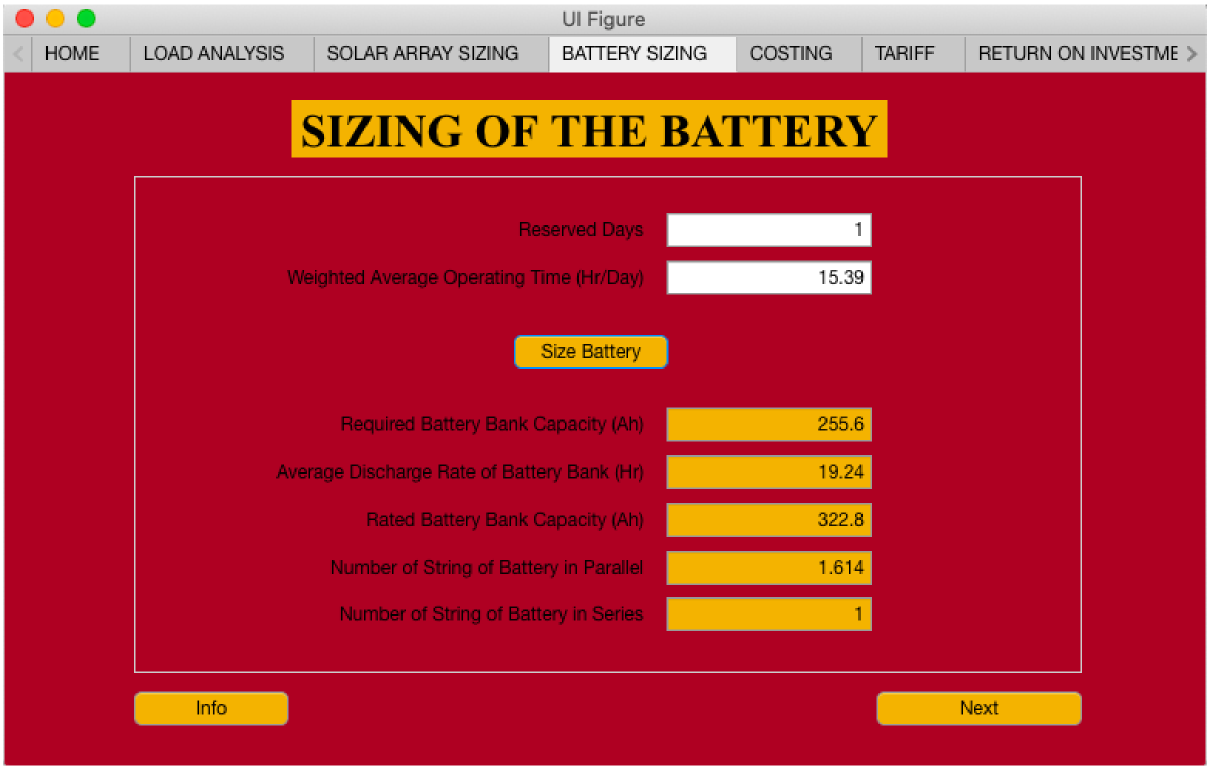


Figure 4: GUI results of battery sizing

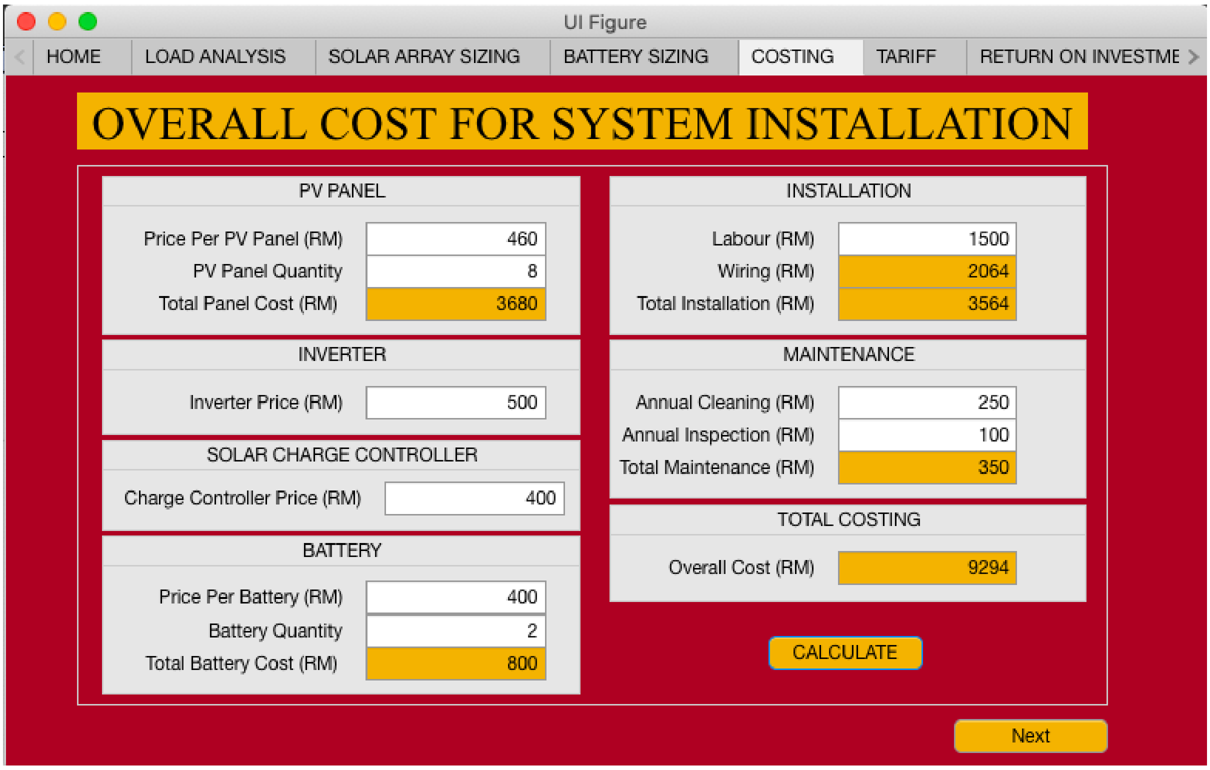


Figure 5: GUI result of overall cost for system installation

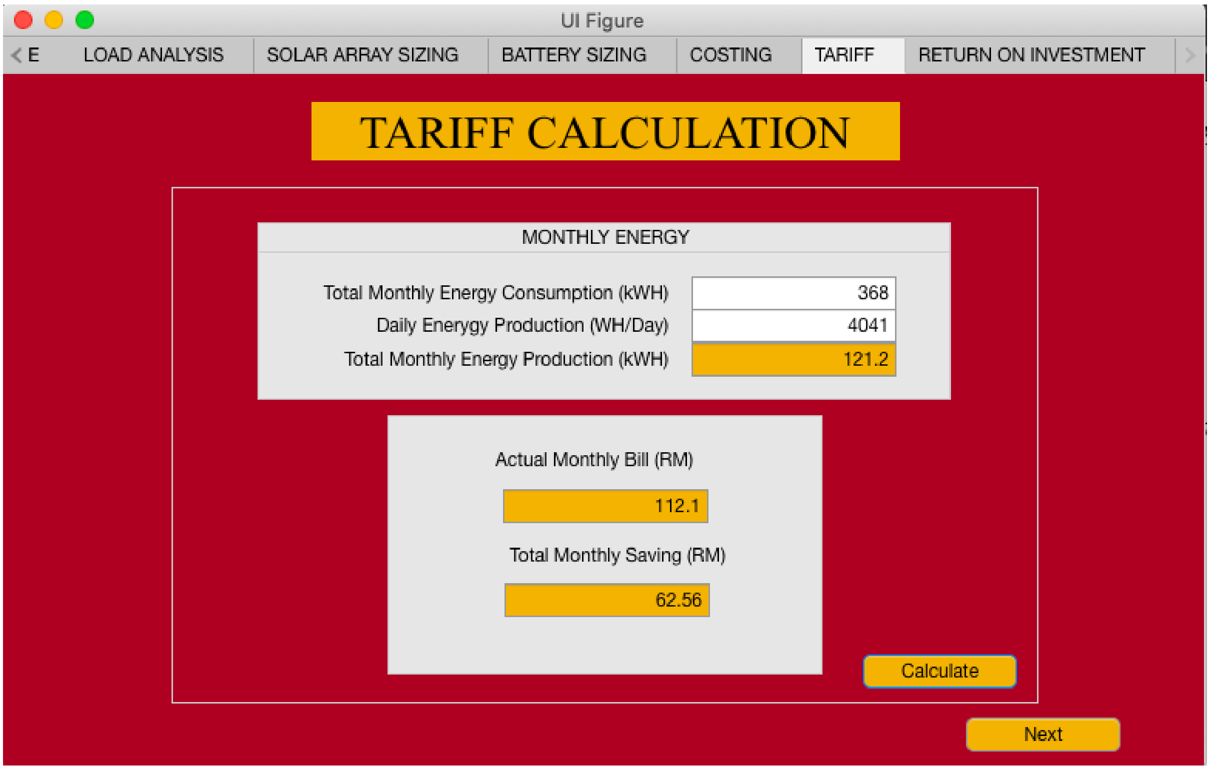


Figure 6: GUI tariff calculation results

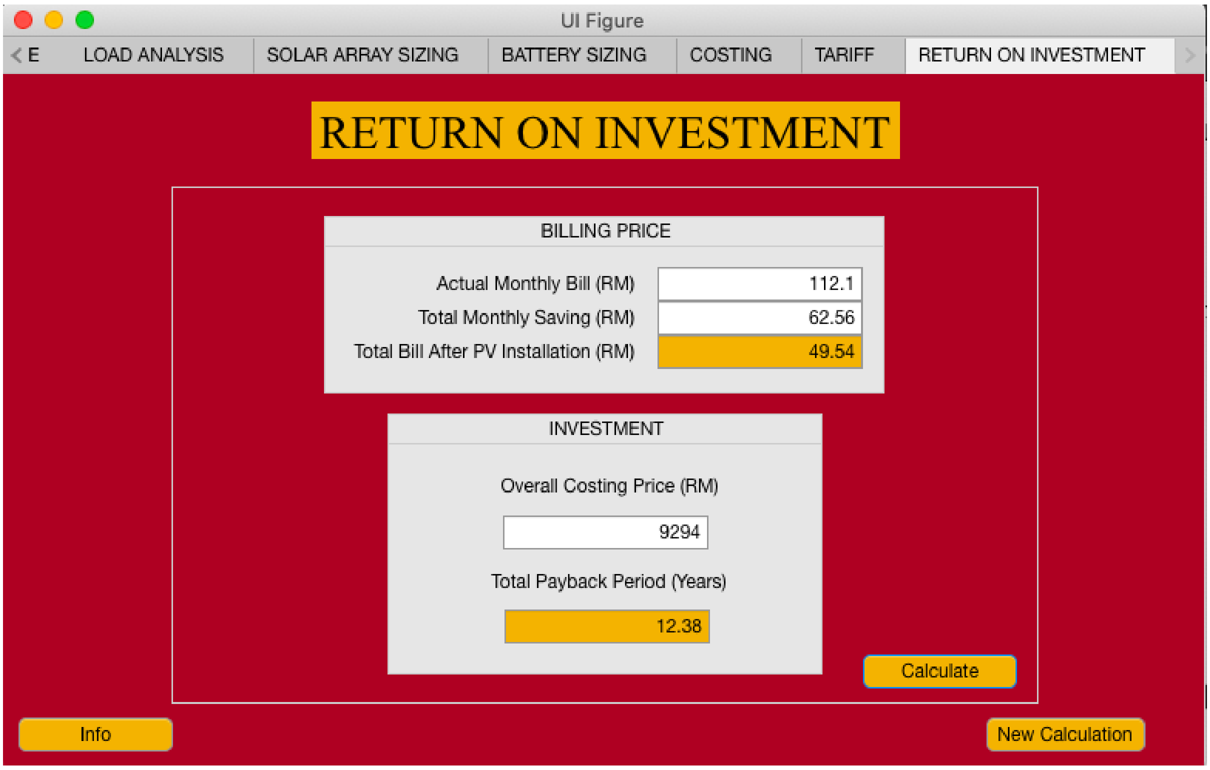


Figure 7: GUI return on investment results

4. Conclusion

In conclusion, this project has successfully size and analyze of grid-connected photovoltaic system with battery storage at Jalan Universiti 15, Taman Universiti, Batu Pahat, Johor. The results were clearly analyzed in section 3. The first objective of this project which is to size a grid-connected photovoltaic system with battery storage for a residential house in Jalan Universiti 15, Taman Universiti, Batu Pahat, Johor has been achieved. Furthermore, the second objective of this project which is to develop a graphical user interface (GUI) that can perform sizing for a grid-connected PV system with battery. In addition, the developed GUI can perform the sizing process and return on investment for the PV system accordingly to the manual calculation. This has been shown the results generated from the GUI is the same to the manual calculated results. With that, the third objective of this project which is to compare the graphical user interface (GUI) results with the computational results has been achieved. Other than that, the GUI also can be used as tools for teaching and learning and it can be use by fresh graduate, junior engineer, and lecturer for sizing purpose. In future it is recommended that the GUI would include additional aspect such better stability performance.

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