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A SIZING TOOL FOR PV STANDALONE SYSTEM

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ABSTRACT
This project aims to develop a software for sizing a standalone photovoltaic (PV) systems. The proposed tool has the capability to allow the user to employ meteorological data such as ambient temperature, irradiation data, and peak sun hour (PSH) in designing the PV system. Usually, a micropower system is designed to serve a specific load demand, in this work, the stand-alone PV is modelled with a particular load profile to ensure that the system meets required energy demand. The developed tool is used to determine the feasibility of the stand-alone system in terms of PV size and the estimated total power production. The tool developed with a built in database which stores different types of PV panels, batteries, charge controllers and inverters. The proposed sizing tool was validated based on the real data implemented on the case study for a residential buildings.

Keywords: photovoltaic, standalone system, solar radiation, sizing tool.

INTRODUCTION
Carbon dioxide emissions are harmful and dangerous to living things. Based on Carbon Dioxide Information Analysis Centre (CDIAC), fossil fuels produced high emissions of carbon dioxide which is 18.5% or 1551 million metric tons of carbon released from fossil fuels in 2007 [1]. The energy produced by PV system is one of the clean energy sources that does not emit carbon dioxide. Currently, many research works have been carried out to reduce the emissions of carbon dioxide generated from fossil fuel power plants.

Photovoltaic (PV) is a technology that converts solar energy into direct current electricity without undergo any combustion process that may produce environmentally harmful byproducts [2]. In general, the PV system can be classified into stand-alone and grid connected system. The stand-alone system is independent of the power grid hence it is supported by storage batteries or other auxiliary supplies. Conversely, the grid connected system implies a direct connection to the electrical grid; therefore excess energy produced by the PV source can be supplied to the grid or otherwise [3].

Simplicity of the standalone PV design is an advantage of the system to meet the electricity demand. However, to design such simple system will definitely take a lot of time to complete the huge task of calculations. Other than that, manual calculations may easily incur large percentage of errors. Therefore, the use of sizing tool can assist user although have a minimal knowledge about PV system in which they are able to design and predict the output gained from the PV installation. In this work, a residential premise is used as a case study to validate the proposed system configuration.

RELATED WORK
There are several works been done on PV sizing tool. Sulaiman *et al.* [4] proposed an intelligent method for optimizing PV size in grid connected system. Evolutionary programming (EP) was used to determine the optimal set of photovoltaic (PV) module and inverter. Ammar *et al.* [5] proposed an open source tool for characterization of photovoltaic power sources with respect to the state of the battery, load change and climatic parameters variation. The software was developed based on standard algorithms and models.

The solar PV system performance depends upon site parameters, system configuration and load parameters. Therefore, Kushika and Rai [6] presented a solar PV design expert system which determines a composite parameter as a function of latitude and longitude. The parameter combines both site and array characteristics to avoid the problem due to variability of several climatological parameters. Recently a MATLAB based software tool called PV.MY was developed by Khatib *et al.* [7] to find the optimal size of PV systems. The software features the capabilities of predicting meteorological variables using artificial neural network (ANN) function.

PV SIZING TOOL FRAMEWORK
In this work, the sizing tool is developed using GUI platform based on MATLAB software to provide a user friendly interface. The tool can be used to find suitable type of panel, inverter, battery and the configuration of PV array. The overall steps in this work are summarized in the flowchart shown in Figure-1 begins with collecting data and ends with some analysis results on PV sizing performance.

INVERTER SIZING
Using this software, user may easily find the suitable size of inverter that matches with the value of maximum AC load demand and AC surge load demand. The total number of inverter required is calculated using the following formula:
Load assesment:

$$S_{inv\_30min} = S_{max\_AC\_demand} \times sf_{inv} \tag{1}$$

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The apparent power of inverter during surge demand:

$$S_{inv\_surge} = S_{max\_AC\_surge} \times sf_{inv} \quad (2)$$

Number of inverter:

$$N_{inverter} = \frac{S_{inv\_surge\_calculated}}{S_{inv\_surge\_datasheet}} \quad (3)$$

where,

S_{inv_30min} = inverter max. power
$S_{max\_AC\_demand}$ = max. ac load demand
sf_{inv} = inverter safety factor (typically 10%)
S_{inv_surge} = surge rating of the inverter
$S_{max\_AC\_surge}$ = ac surge load demand
$N_{inverter}$ = number of inverter needed
$S_{inv\_surge\_calculated}$ = calculated value of inverter surge rating
$S_{inv\_surge\_datasheet}$ = datasheet value of inverter surge rating

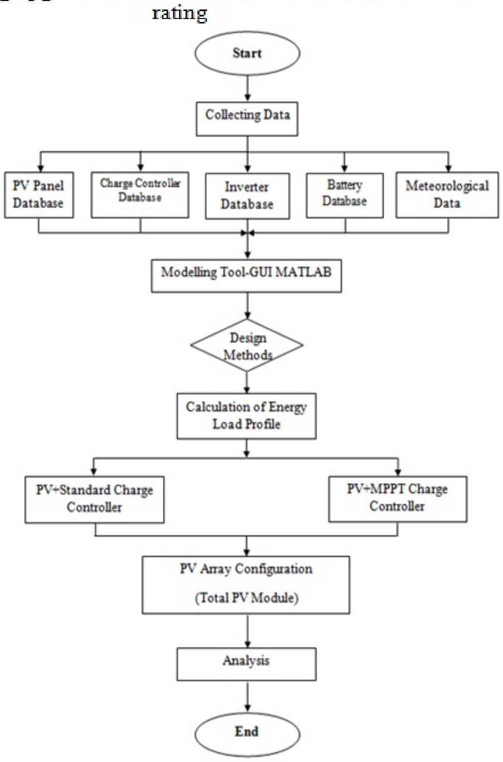

Figure-1. The overall steps in PV sizing tool.

BATTERY SIZING

The sizing of battery is based on the energy requirement and capacity required daily. Currently, there are 52 types of commercial batteries listed in the database. User can select any types of battery available to get the prediction value of batteries needed. The tool will display the possible maximum number of batteries that can fit the required capacity. The total number of battery required is calculated by using.

$$C_{required\_daily} = \frac{E_{required\_daily}}{SV} \quad (4)$$

where,

$C_{required\_daily}$ = Total capacity required daily
$E_{required\_daily}$ = Total energy required daily
SV = System voltage

The battery bank capacity is derived from

$$C_{bank\_required} = C_{required\_daily} \times \frac{T_{autonomy}}{DOD_{max}} \quad (5)$$

where,

$C_{bank\_required}$ = actual amount of battery capacity required
$T_{autonomy}$ = days of autonomy
DOD_{max} = maximum depth of discharge

Revised battery capacity:

$$C_{revised\_bank\_required} = \frac{C_{bank\_required}}{f_{tempbat}} \quad (6)$$

where,

$C_{revised\_bank\_required}$ = the revised battery bank capacity required
$f_{tempbat}$ = temperature correction factor of battery

Total bank discharge current:

$$I_{bank\_disch} = \frac{1}{SV} \times \left[\sum DC\ power + \sum \frac{AC\ power}{PF}\right] \quad (7)$$

where,

I_{bank_disch} = discharge current of battery bank

Number of batteries string in series:

$$N_{series\_bank} = \frac{SV}{nominal\ battery\ voltage} \quad (8)$$

where,

N_{series_bank} = number of batteries in series string

Number of batteries string in parallel:

$$N_{parallel\_bank} = \frac{C_{revised\_bank\_required}}{C_{per\_battery}} \quad (9)$$

where,

$N_{parallel\_bank}$ = number of battery strings in parallel
$C_{per\_battery}$ = Capacity of battery selected (Ah)

PV MODULE SIZING

Basically, the number of PV module is calculated based on user requirement. The output from PV modules should be sufficient to support the energy requirement of the building. There are 122 types of PV module available in the database and the new data specification can be added manually. To calculate the size of PV module, two

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methods can be used which are either to use the standard charge controller or by using the charge controller with MPPT.

SIZING BASED ON STANDARD CHARGE CONTROLLER

For this method, the PWM charge controller is used as standard charge controller. There are 11 different kinds of PWM charge controller and user can select any from the list to get the prediction of module configuration. The output will display the number of PV modules connected in series as well as parallel. Total number of PV module required can be calculated using formula below:

Temperature derating factor:

$$T_{cell} = T_{ambient} + \left[\left(\frac{NOCT-20}{0.8}\right) \times G\right] \quad (10)$$

$$f_{temp} = 1 + \left[\gamma_{Imp} \times (T_{cell} - T_{STC})\right] \quad (11)$$

where,

T_{cell} = cell effective temperature (°C)
f_{temp} = derating factor for temperature
γ_{Imp} = temperature coefficient of current
T_{stc} = temperature at STC (25°C)
G = solar irradiance (kW/m^2)

Corrected output current:

$$I_{corrected} = I_{mp\_stc} \times f_{temp} \times f_{mm} \times f_{dirt} \quad (12)$$

where:

$I_{corrected}$ = corrected current at real operating condition
I_{mp_stc} = output current of maximum power at STC
f_{temp} = temperature derating factor
f_{mm} = derating factor for manufacturer tolerance
f_{dirt} = derating factor for dirt

Number of modules connected in series:

$$N_S = \frac{SV}{nominal\ module\ voltage} \quad (13)$$

Number of modules connected in parallel:

$$N_P = \frac{E_{required\_daily} \times f_o}{SV \times I_{corrected} \times PSH \times \mu_{coul\ batt}} \quad (14)$$

where,

f_o = over-supply coefficient
PSH = PSH for specified tilt angle (h)
μ_{coul_batt} = coulombic efficiency of the battery

SIZING BASED ON MPPT CHARGE CONTROLLER

Similarly, user can select the appropriate type of MPPT charge controller. PV module. There are 14 types of MPPT controller listed in the MS Excel database. The software output will show the PV configuration array recommended. For this type of PV module sizing, the calculation steps are more complicated. The total number of PV module is determined using formula below:

Temperature derating factor:

$$T_{cell} = T_{ambient} + \left[\left(\frac{NOCT-20}{0.8}\right) \times G\right] \quad (15)$$

$$f_{temp} = 1 + \left[\frac{\gamma_{pmp}}{100} \times (T_{cell} - T_{stc})\right] \quad (16)$$

where,

T_{cell} = cell effective temperature (°C)
f_{temp} = derating factor for temperature
γ_{Imp} = temperature coefficient of current (% per °C)
T_{stc} = temperature at STC (25°C)

Operating Voltage Limit:

$$V_{max\_oc} = V_{oc\_stc} + \left[\gamma_{voc} \times (T_{min} - T_{STC})\right] \quad (17)$$

$$V_{max\_mp} = V_{mp\_stc} + \left[\gamma_{vmp} \times (T_{min} - T_{STC})\right] \quad (18)$$

Corrected power output:

$$P_{mod\_corrected} = P_{mp\_stc} \times f_{temp} \times f_{mm} \times f_{dirt} \quad (19)$$

where,

$P_{mod\_corrected}$ = corrected output power of module (Wp)
P_{mp_stc} = rated power at STC (Wp)
f_{mm} = manufacturing tolerance (dimensionless)
f_{dirt} = derating factor for dirt

Sub-system efficiency:

$$\mu_{pv\_ss} = \mu_{pv\_batt} \times \mu_{controller} \times \mu_{wh\_batt} \quad (20)$$

where,

μ_{pv_ss} = PV sub-system efficiency
μ_{pv_batt} = PV cable efficiency
$\mu_{controller}$ = MPPT charge controller efficiency
μ_{wh_batt} = battery watt-hour efficiency

The number of modules connected in series string with the safety margin of 5% is given by

$$N_S = \frac{0.95 \times V_{max\_window\_cc}}{V_{max\_mp}} \quad (21)$$

where,

N_S = max. number of modules per string
$V_{max\_window\_cc}$ = max. window voltage of the charge controller (V)
V_{max_mp} = max. voltage at max. power at effective cell temperature

and the number of modules connected in parallel string:

$$N_P = \frac{N_T}{N_S} \quad (22)$$

where,

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N_P = number of strings of modules connected in parallel required

Hence, the total number of modules is:

$$N_T = \frac{E_{required\_daily} \times f_o}{P_{mod\_corrected} \times PSH \times \mu_{pv\_ss}} \quad (23)$$

where,

N_T = total number of modules required
f_o = over-supply coefficient

CHARGE CONTROLLER SIZING

As mentioned, the tool allows the user to choose between two types of charge controller, either PWM or MPPT type controller. The selection of charge controllers is based on maximum charging current from the PV array and the total current rating of the charge controller. The tools will calculate the possible minimum number of charge controller based on the number of batteries required using formula below:

Total current rating of charge controller with the safety factor value of 1.25 is given by

$$I_{controller\_rating} = 1.25 \times I_{sc\_stc} \times N_P \quad (24)$$

where,

$I_{controller\_rating}$ = controller current rating
I_{sc_stc} = short circuit current at STC
N_P = number of parallel strings

Number of charge controller:

$$N_{controller} = \frac{I_{controller\_rating\_calculated}}{I_{controller\_rating\_datasheet}} \quad (25)$$

where,

$N_{controller}$ = number of charge controller
$I_{controller\_rating\_calculated}$ = calculated total current rating of charge controller
$I_{controller\_rating\_datasheet}$ = current rating of charge controller from datasheet

RESULTS AND ANALYSIS

The result of this project consist of two parts based on different methods used for charge controller. The configuration of PV system sizing depends on the scenario of case and type of equipment chosen by the user. In this work, a residential building in Pekan Pahang is chosen as study case to validate the feasibility of developed software. The load of residential building is used to calculate the load demand for a period of one year. The amount energy produced by the PV system is calculated based on the value of load profile and efficiency of the inverter chosen. Figures-2 shows the main page of the PV system design tool for sizing the standalone PV system, calculation of load profile and database of PV modules respectively. Figure-3 shows the program for designing the standalone PV system.

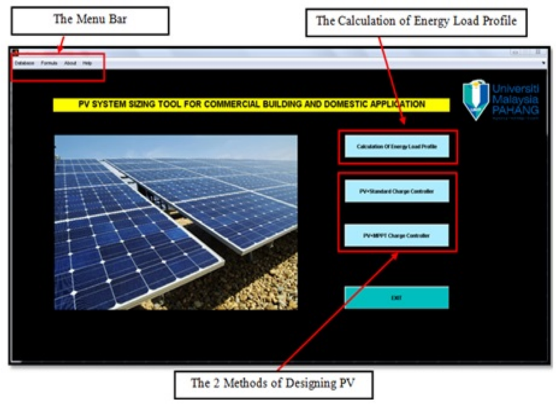

Figure-2. Main page of PV design tool.

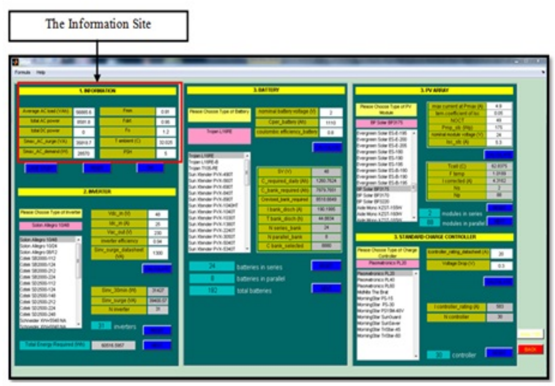

Figure-3. Standalone PV system design.

DESIGN BASED ON CASE STUDY

The design start with the calculation of the load profile of a building. User is required to fill in the load profile form to determine the total load demand. If the user already has the load profile of the building, they can directly insert the values in the sizing window. For example the load profile of case study is shown in Figure-4.

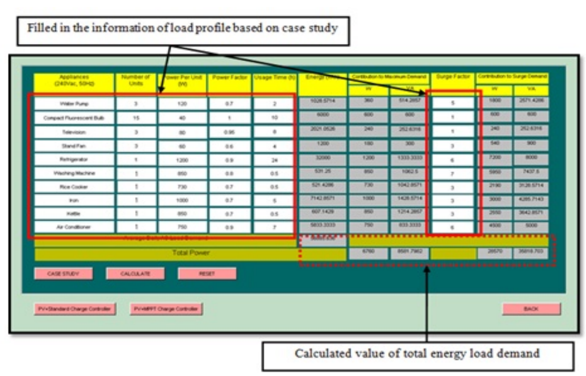

Figure-4. Calculation of energy load profile.

ANALYSIS OF THE PV SYSTEM DESIGN

To illustrate the ability of the tools, both types of PV modules are compared to analyze the performance of PV system in terms of energy prediction. Some of the information used in the case study are listed below:

Information:

- Average AC Load (VAH) = 56885.6
- Total AC Power = 8581.8 Wh
- AC surge load demand = 35818.7 VA
- maximum AC load demand = 28570 VA
- $f_{mm} = 0.91$
- $f_{dirt} = 0.95$
- $f_o = 1.2$
- $T_{ambient} = 32.025$ °C
- $PSH_{pa} = 5$h

Type of inverter:

- Solon Allegro 10/48

Type of battery:

- Trojan L16RE

Type of PV module:

- BP Solar BP3175
- SCHOTT ASE-320DGF/5D

Type of standard charge controller:

- Plasmatronics PL20

From the results obtained, the number of inverter Solon Allegro 10/48 required is 31 units. Meanwhile, type of battery chosen is Trojan L16RE and total number of battery needed is 192 units. The tool also recommended that 24 batteries are connected in series and 8 batteries in parallel. As for the type of PV module, the BP Solar BP3175 is selected and the configuration recommended is that 2 modules are connected in series and 88 strings of modules connected in parallel. For comparison, the PV module type SCHOTT ASE-320DGF/5D was also tested. The results recommended that 1 module is connected in series and 69 strings of modules are connected in parallel.

After sizing the PV system, the user can assess the performance of the system based on the type of inverter, battery, PV module and charge controller. In this study, meteorological data measured in Pekan area used as given in Table-1. The performance of the PV system designed is analyzed in terms of the types of PV module chosen towards the energy generated per year. For the PV system using BP Solar BP3175, the energy generated per year can be seen in Figure-5 while for SCHOTT ASE-320-DGF/5D, the result is shown in Figure-6. For both PV system, the graphs show that the predicted energy yield (kWhpa) increases when the PSH (h) is higher.

Table-1. Meteorological data of Pekan, Pahang, Malaysia.

Months	Solar Irradiance (W/m-2)	Daily Average PSH (h)	Monthly PSH (h)	Avg. Max. Ambient Temp. (°C)
Jan	758.9677	4.8	124.8	32.2
Feb	800.4643	5	125	30.2
Mar	778.1935	4.81	134.68	31.3
Apr	919.3333	5.1	142.8	33.4
May	858.6452	5.25	147	33.2
Jun	834.5217	5.2	150.8	31.1
Jul	862.5	5.35	149.8	32.9
Aug	843.1613	5.2	145.6	32.3
Sept	927.9	5.45	152.6	33.5
Oct	898.6774	5.35	149.8	31.2
Nov	811.2308	4.95	123.75	31.7
Dec	747.129	4.7	117.5	31.3

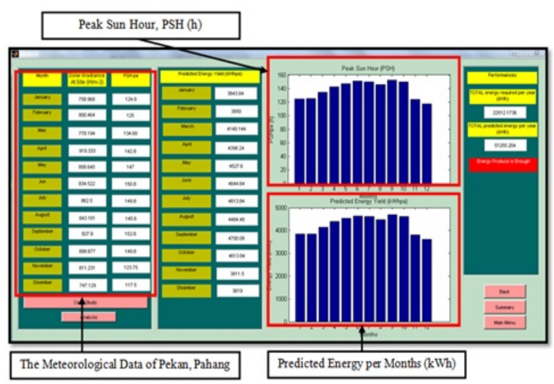

Figure-5. The performances of PV module design with BP Solar BP3175.

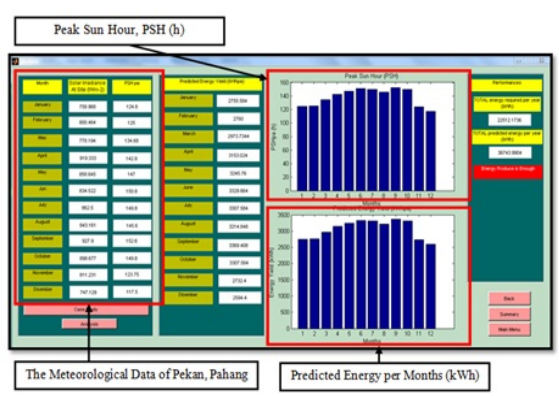

Figure-6. The performances of PV module design with SCHOTT ASE-320-DGF/5D.

Based on the type of PV modules, the energy produced will increase when the number of module increased as illustrated in Table-2. The energy predicted depends on the value of PSH, the configuration of PV module and the output power of PV module. In addition, the value of total energy predicted per year is compared with total energy required per year in order to evaluate ability of the system in supplying the energy. Result in Figure-7 shows the total energy predicted per year is higher than the total energy required. The energy produced by the PV system design is sufficient to cover the energy needed by the building.

Table-2. The energy produced based on different configuration of PV modules.

Types of PV module	BP Solar BP3175	SCHOTT ASE-320-DGF/5D
Types of inverter	Solon Allegro 10/48	Solon Allegro 10/48
Total yearly load demand (kWh)	22512.1736	22512.1736
Array configuration	2x88	1x69
Total No. of PV modules	176	69
Average total predicted energy (kWh)	51255.204	36743.990
Performances	Optimum	Not Optimum

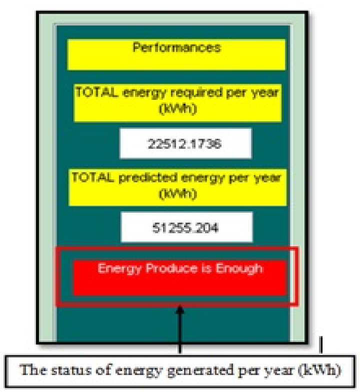

Figure-7. The energy generated per year (kWh).

CONCLUSIONS

In order to fulfil the electricity demand, the standalone PV system is an option to yield a feasible energy supply. The development of software tool to find the practical sizing of the PV system is important to assist users in minimizing the cost and time. In rural area of Pekan, Pahang; there is a potential to install the stand-alone PV system since the yearly solar irradiation and PSH are almost constant. The development of this software considers the solar irradiation, average ambient temperature and PSH of the installation site. User with minimal knowledge on designing a standalone PV system, conveniently can use this tool to develop their own PV system.

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