Solar System Sizing

From Open Electrical

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Introduction

This calculation outlines the sizing of a standalone solar photovoltaic (PV) power system. Standalone PV systems are commonly used to supply power to small, remote installations (e.g. telecoms) where it isn't practical or cost-efficient to run a transmission line or have alternative generation such as diesel gensets.

Although this calculation is biased towards standalone solar PV systems, it can also be used for hybrid systems that draw power from mixed sources (e.g. commercial PV, hybrid wind-PV systems, etc). Loads must be adjusted according to the desired amount that the solar PV system will supply.

This calculation is based on crystalline silicon PV technology. The results may not hold for other types of solar PV technologies and the manufacturer's recommendations will need to be consulted.

Figure 1. Solar PV array

Why do the calculation?

This calculation should be done whenever a solar PV power system is required so that the system is able to adequately cater for the necessary loads. The results can be used to determine the ratings of the system components (e.g. PV array, batteries, etc).

When to do the calculation?

The following pre-requisite information is required before performing the calculation:

- Loads required to be supported by the solar PV system
- Autonomy time or minimum tolerable downtime (i.e. if there is no sun, how long can the system be out of service?)
- GPS coordinates of the site (or measurements of the solar insolation at the site)
- Output voltage (AC or DC)

Calculation Methodology

The calculation is loosely based on AS/NZS 4509.2 (2002) (http://infostore.saiglobal.com/store/Details.aspx?ProductID=315646) "Standalone power systems - System design guidelines". The methodology has the following six steps:

- Step 1: Estimate the solar irradiation available at the site (based on GPS coordinates or measurement)
- Step 2: Collect the loads that will be supported by the system
- Step 3: Construct a load profile and calculate design load and design energy
- Step 4: Calculate the required battery capacity based on the design loads
- Step 5: Estimate the output of a single PV module at the proposed site location
- Step 6: Calculate size of the PV array

Step 1: Estimate Solar Irradiation at the Site

The first step is to determine the solar resource availability at the site. Solar resources are typically discussed in terms of solar radiation, which is more or less the catch-all term for sunlight shining on a surface. Solar radiation consists of three main components:

- **Direct or beam radiation** is made up of beams of unscattered and unreflected light reaching the surface in a straight line directly from the sun
- **Diffuse radiation** is scattered light reaching the surface from the whole sky (but not directly from the sun)
- **Albedo radiation** is is light reflected onto the surface from the ground

Solar radiation can be quantitatively measured by irradiance and irradiation. Note that the terms are distinct - "irradiance" refers to the density of the **power** that falls on a surface (W / m^2) and "irradiation" is the density of the

energy that falls on a surface over some period of time such as an hour or a day (e.g. Wh / m^2 per hour/day).

In this section, we will estimate the solar radiation available at the site based on data collected in the past. However, it needs to be stressed that solar radiation is statistically random in nature and there is inherent uncertainty in using past data to predict future irradiation. Therefore, we will need to build in design margins so that the system is robust to prediction error.

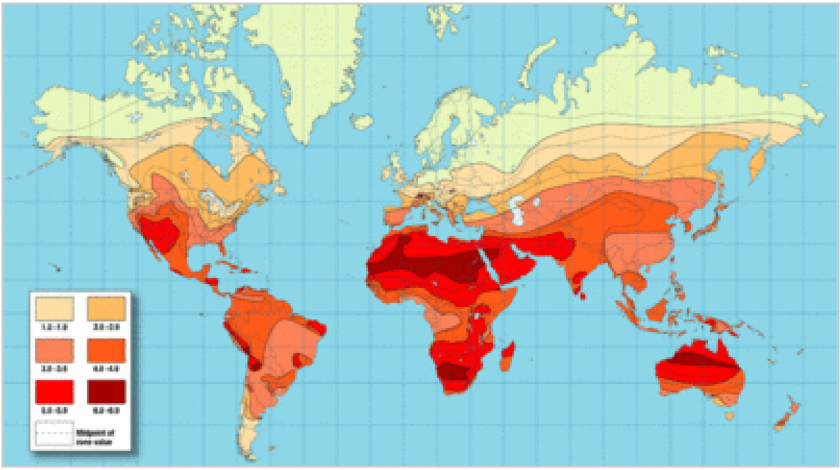


Figure 2. World solar irradiation map

Baseline Solar Irradiation Data

The easiest option is to estimate the solar irradiation (or solar insolation) by inputting the GPS coordinates of the site into the NASA Surface Meteorology and Solar Resource (http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi) website.

For any given set of GPS coordinates, the website provides first pass estimates of the monthly minimum, average and maximum solar irradiation (in $kWh / m^2 / day$) at ground level and at various tilt angles. Collect this data, choose an appropriate tilt angle and identify the best and worst months of the year in terms of solar irradiation. Alternatively, for US locations data from the National Solar Radiation Database (http://www.nrel.gov/rredc/solar_data.html) can be used.

The minimum, average and maximum daytime temperatures at the site can also be determined from the public databases listed above. These temperatures will be used later when calculating the effective PV cell temperature.

Actual solar irradiation measurements can also be made at the site. Provided that the measurements are taken over a long enough period (or cross-referenced / combined with public data), then the measurements would provide a more accurate estimate of the solar irradiation at the site as they would capture site specific characteristics, e.g. any obstructions to solar radiation such as large buildings, trees, mountains, etc.

Solar Irradiation on an Inclined Plane

Most PV arrays are installed such that they face the equator at an incline to the horizontal (for maximum solar collection). The amount of solar irradiation collected on inclined surfaces is different to the amount collected on a horizontal surface. It is theoretically possible to accurately estimate the solar irradiation on any inclined surface given the solar irradiation on an horizontal plane and the tilt angle (there are numerous research papers on this topic, for example the work done by Liu and Jordan in 1960).

However, for the practical purpose of designing a solar PV system, we'll only look at estimating the solar irradiation at the **optimal tilt angle**, which is the incline that collects the most solar irradiation. The optimal tilt angle largely depends on the latitude of the site. At greater latitudes, the optimal tilt angle is higher as it favours summertime radiation collection over wintertime collection. The Handbook of Photovoltaic Science and Engineering (http://www.amazon.com/Handbook-Photovoltaic-Science-Engineering-Antonio/dp/0471491969) suggests a linear approximation to calculating the optimal tilt angle:

$$\beta_{opt} = 3.7 + 0.69|\phi|$$

Where β_{opt} is the optimal tilt angle (deg)

ϕ is the latitude of the site (deg)

The handbook also suggests a polynomial approximation for the solar irradiation at the optimal tilt angle:

$$G(\beta_{opt}) = \frac{G(0)}{1 - 4.46 \times 10^{-4} \times \beta_{opt} - 1.19 \times 10^{-4} \times \beta_{opt}^2}$$

Where $G(\beta_{opt})$ is the solar irradiation on a surface at the optimal tilt angle (Wh / m^2)

$G(0)$ is the solar irradiation on the horizontal plane (Wh / m^2)
β_{opt} is the optimal tilt angle (deg)

Alternatively, the estimated irradiation data on tilted planes can be sourced directly from the various public databases listed above.

Solar Trackers

Solar trackers are mechanical devices that can track the position of the sun throughout the day and orient the PV array accordingly. The use of trackers can significantly increase the solar irradiation collected by a surface. Solar trackers typically increase irradiation by 1.2 to 1.4 times (for 1-axis trackers) and 1.3 to 1.5 times (for 2-axis trackers) compared to a fixed surface at the optimal tilt angle.

Non-Standard Applications

A solar irradiation loss factor should be used for applications where there are high tilt angles (e.g. vertical PV arrays as part of a building facade) or very low tilt angles (e.g. North-South horizontal trackers). This is because the the solar irradiation is significantly affected (detrimentally) when the angle of incidence is high or the solar radiation is mainly diffuse (i.e. no albedo effects from ground reflections). For more details on this loss factor, consult the standard ASHRAE 93, "Methods of testing to determine the thermal performance of solar collectors" (http://www.techstreet.com/standards/ASHRAE/93_2010?product_id=1703551) .

Step 2: Collect the Solar Power System Loads

The next step is to determine the type and quantity of loads that the solar power system needs to support. For remote industrial applications, such as metering stations, the loads are normally for control systems and instrumentation equipment. For commercial applications, such as telecommunications, the loads are the telecoms hardware and possibly some small area lighting for maintenance. For rural electrification and residential applications, the loads are typically domestic lighting and low-powered apppliances, e.g. computers, radios, small tv's, etc.

Step 3: Construct a Load Profile

Refer to the Load Profile Calculation for details on how to construct a load profile and calculate the design load (S_d) and design energy (E_d). Typically, the "24 Hour Profile" method for constructing a load profile is used for Solar Power Systems.

Step 4: Battery Capacity Sizing

In a solar PV power system, the battery is used to provide backup energy storage and also to maintain output voltage stability. Refer to the Battery Sizing Calculation for details on how to size the battery for the solar power system.

Step 5: Estimate a Single PV Module's Output

It is assumed that a specific PV module type (e.g Suntech STP070S-12Bb) has been selected and the following parameters collected:

- Peak module power, P_{stc} (W-p)
- Nominal voltage V_n (Vdc)
- Open circuit voltage V_{oc} (Vdc)
- Optimum operating voltage V_{mp} (Vdc)
- Short circuit current I_{sc} (A)
- Optimum operating current I_{mp} (A)
- Peak power temperature coefficient γ (% per deg C)
- Manufacturer's power output tolerance f_{man} (%)

Manufacturers usually quote these PV module parameters based on Standard Test Conditions (STC): an irradiance of 1,000 W / m^2, the standard reference spectral irradiance with Air Mass 1.5 (see the NREL site (http://rredc.nrel.gov/solar/spectra/am1.5/) for more details) and a cell temperature of 25 deg C. Standard test conditions rarely prevail on site and when the PV module are installed in the field, the output must be de-rated accordingly.

Effective PV Cell Temperature

Firstly, the average effective PV cell temperature at the installation site needs to be calculated (as it will be used in the subsequent calculations). It can be estimated for each month using AS\NZS 4509.2 equation 3.4.3.7:

$$T_{cell,eff} = T_{a,day} + 25$$

Where $T_{cell,eff}$ is the average effective PV cell temperature (deg C)

$T_{a,day}$ is the average daytime ambient temperature at the site (deg C)

Standard Regulator

For a solar power system using a standard switched charge regulator / controller, the derated power output of the PV module can be calculated using AS\NZS 4509.2 equation 3.4.3.9(1):

$$P_{mod} = V_{ave} I_{T,V} \times f_{man} \times f_{dirt}$$

Where P_{mod} is the derated power output of the PV module using a standard switched charge controller (W)

V_{ave} is the daily average operating voltage (Vdc)
$I_{T,V}$ is the module output current based on the daily average operating voltage, at the effective average cell temperature and solar irradiance at the site - more on this below (A)
f_{man} is the manufacturer's power output tolerance (pu)
f_{dirt} is the derating factor for dirt / soiling (Clean: 1.0, Low: 0.98, Med: 0.97, High: 0.92)

To estimate $I_{T,V}$, you will need the IV characteristic curve of the PV module at the effective cell temperature calculated above. For a switched regulator, the average PV module operating voltage is generally equal to the average battery voltage less voltage drops across the cables and regulator.

MPPT Regulator

For a solar power system using a Maximum Power Point Tracking (MPPT) charge regulator / controller, the derated power output of the PV module can be calculated using AS\NZS 4509.2 equation 3.4.3.9(2):

$$P_{mod} = P_{stc} \times f_{temp} \times f_{man} \times f_{dirt}$$

Where P_{mod} is the derated power output of the PV module using an MPPT charge controller (W)

P_{stc} is the nominal module power under standard test conditions (W)
f_{man} is the manufacturer's power output tolerance (pu)
f_{dirt} is the derating factor for dirt / soiling (Clean: 1.0, Low: 0.98, Med: 0.97, High: 0.92)
f_{temp} is the temperature derating factor - see below (pu)

The temperature derating factor is determined from AS\NZS 4509.2 equation 3.4.3.9(1):

$$f_{temp} = 1 - \gamma \left(T_{cell,eff} - T_{stc} \right)$$

Where f_{temp} is temperature derating factor (pu)

γ is the Power Temperature Coefficient (% per deg C)
$T_{cell,eff}$ is the average effective PV cell temperature (deg C)
T_{stc} is the temperature under standard test conditions (typically 25 deg C)

Step 6: Size the PV Array

The sizing of the PV array described below is based on the method outlined in AS/NZS 4509.2. There are alternative sizing methodologies, for example the method based on reliability in terms of loss of load probability (LLP), but these methods will not be further elaborated in this article. The fact that there is no commonly accepted sizing methodology reflects the difficulty of performing what is an inherently uncertain task (i.e. a prediction exercise with many random factors involved).

Standard Regulator

The number of PV modules required for the PV array can be found by using AS\NZS 4509.2 equation 3.4.3.11(1):

$$N = \frac{E_d \times f_o}{P_{mod} \times G \times \eta_{coul}}$$

Where N is the number of PV modules required

P_{mod} is the derated power output of the PV module (W)
E_d is the total design daily energy (VAh)
f_o is the oversupply co-efficient (pu)
G is the solar irradiation after all factors (e.g. tilt angle, tracking, etc) have been captured (kWh / m^2 / day)

η_{coul} is the coulombic efficiency of the battery (pu)

The oversupply coefficient f_o is a design contingency factor to capture the uncertainty in designing solar power systems where future solar irradiation is not deterministic. AS/NZS 4509.2 Table 1 recommends oversupply coefficients of between 1.3 and 2.0.

A battery coulombic efficiency of approximately 95% would be typically used.

MPPT Controller

The number of PV modules required for the PV array can be found by using AS\NZS 4509.2 equation 3.4.3.11(2):

$$N = \frac{E_d \times f_o}{P_{mod} \times G \times \eta_{pvss}}$$

Where N is the number of PV modules required

P_{mod} is the derated power output of the PV module (W)
E_d is the total design daily energy (VAh)
f_o is the oversupply coefficient (pu)
G is the solar irradiation after all factors (e.g. tilt angle, tracking, etc) have been captured ($kWh / m^2 / day$)
η_{pvss} is the efficiency of the PV sub-system (pu)

The oversupply coefficient f_o is a design contingency factor to capture the uncertainty in designing solar power systems where future solar irradiation is not deterministic. AS/NZS 4509.2 Table 1 recommends oversupply coefficients of between 1.3 and 2.0.

The efficiency of the PV sub-system η_{pvss} is the combined efficiencies of the charge regulator / controller, battery and transmission through the cable between the PV array and the battery. This will depend on specific circumstances (for example, the PV array a large distance from the battery), though an efficiency of around 90% would be typically used.

Worked Example

A small standalone solar power system will be designed for a telecommunications outpost located in the desert.

Step 1: Estimate Solar Irradiation at the Site

From site measurements, the solar irradiation at the site during the worst month at the optimal title angle is 4.05 kWh/m^2/day.

Step 2 and 3: Collect Loads and Construct a Load Profile

For this example, we shall use the same loads and load profile detailed in the Energy Load Profile Calculation example. The load profile is shown in the figure right and the following quantities were calculated:

- Design load S_d = 768 VA
- Design energy demand E_d = 3,216 VAh

Step 4: Battery Capacity Sizing

For this example, we shall use the same battery sizes calculated in the Battery Sizing Calculation] worked example. The selected number of cells in series is 62 cells and the minimum battery capacity is 44.4 Ah.

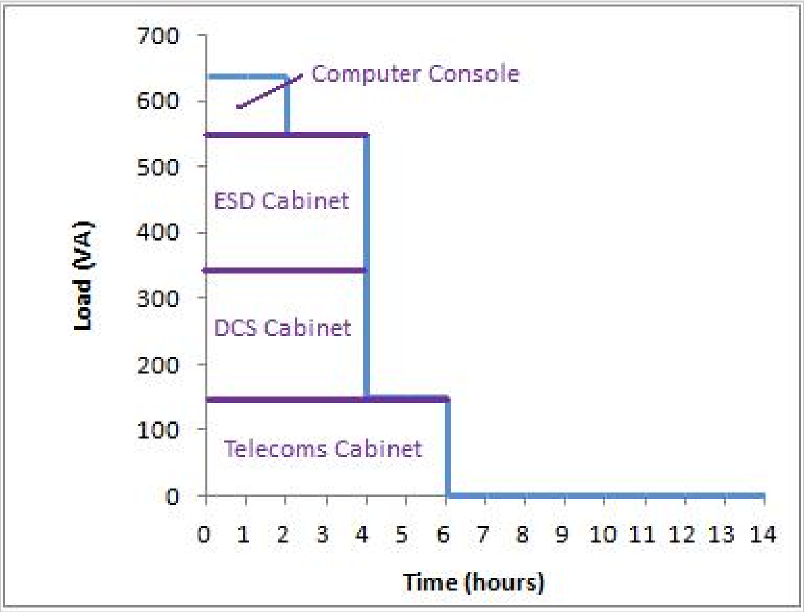


Figure 3. Load profile for this example

Step 5: Estimate a Single PV Module's Output

A PV module with the following characteristics is chosen:

- Peak module power, $P_{stc} = 120$ W-p
- Nominal voltage $V_n = 12$ Vdc
- Peak power temperature coefficient $\gamma = 0.38$ % per deg C
- Manufacturer's power output tolerance $f_{man} = 5$ %

Suppose the average daytime ambient temperature is 40C. The effective PV cell temperature is:

$$T_{cell,eff} = T_{a,day} + 25$$

$$= 40 + 25 = 65 \text{ deg C}$$

An MPPT controller will be used. The temperature derating factor is therefore:

$$f_{temp} = 1 - \gamma \left(T_{cell,eff} - T_{stc} \right)$$

$$= 1 - 0.0038 \times (65 - 25) = 0.848$$

Given a medium dirt derating factor of 0.97, the derated power output of the PV module is:

$$P_{mod} = P_{stc} \times f_{temp} \times f_{man} \times f_{dirt}$$

$$= 120 \times 0.848 \times 0.95 \times 0.97 = 93.77 \text{ W}$$

Step 6: Size the PV Array

Given an oversupply coefficient of 1.1 and a PV sub-system efficiency of 85%, the number of PV modules required for the PV array for a MPPT regulator is:

$$N = \frac{E_d \times f_o}{P_{mod} \times G \times \eta_{pvss}}$$

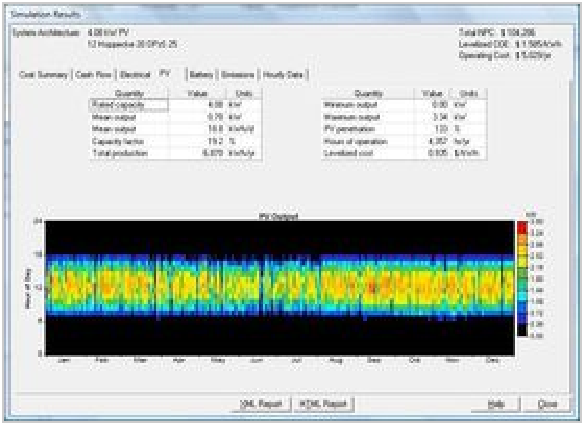
$$= \frac{3,216 \times 1.1}{93.77 \times 4.05 \times 0.85} = 10.9588 \text{ modules}$$

For this PV array, 12 modules are selected.

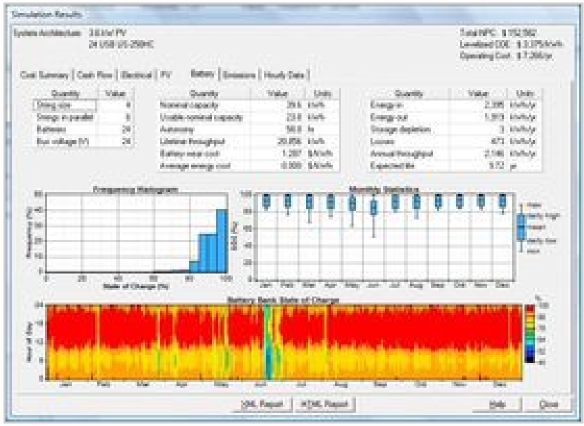
Computer Software

It is recommended that the solar PV system sized in this calculation is simulated with computer software. For example, HOMER (http://www.homerenergy.com/) is a popular software package for simulating and optimising a distributed generation (DG) system originally developed by the National Renewable Energy Laboratory (NREL).

Screenshots from HOMER software



PV Output



Battery Output

What Next?

With the sizing calculation completed, the solar PV equipment (PV array, batteries, charge controllers, etc) can be specified and a cost estimate or budget enquiry / requisition package issued. The approximate dimensions of the equipment (especially the PV array and batteries) can also be estimated and a design layout can be produced.

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