Unit 15: Sizing of stand-alone PV systems based on the "worst month" method

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Table of contents

1. About this document

This material is part of the course package created for TRICALCAR project. For information on TRICALCAR, please consult the introductory module or, www.wilac.net/tricalcar/. This material was originally developed inSpanish for the TRICALCAR project.

1.1 Degree of difficulty

The degree of difficulty of this unit is "basic".

1.2 information about the icons

In this unit you will find 5 types of icons whose meaning is described below:

Central concept	Important practice recommended	Exercise	Intellectual property	Intellectual property

1.3 Acknowledgments and intellectual propertyz

In 1998, the organization Engineering without Borders (Spanish Federation) published the first version of a handbook titled "Manual de Energía Solar Fotovoltaica y Cooperación al Desarrollo". The handbook was written and published by members of the NGO and experts of the Institute of Energy Solar of the Polytechnical University of Madrid. By curiosities of life, none of the members of the editorial team kept the document in electronic format and more editions were never made. They have passed almost ten years from that very first edition and this document is an effort to rescue and to extend the handbook.

As part of this rescue operation I want to thank to the coordinators of the first original edition and my mentors in my years at University: Miguel Ángel Eguido Aguilera, Mercedes Montero Bartolomé y Julio Amador. This new work is licensed under Creative Commons Attribution Share Alike. We hope that this material becomes a new departure point for new editions including new contributions by the community.

2. Introduction

The objective of unit is to be able to choose and "size" the elements of a stand-alone photovoltaic installation. The system sizing implies (at least) to decide the number and type of solar panels required to capture the solar energy, the capacity of the battery that will store the energy for the days of little sun, and to be able also to determine the required characteristics of the rest of the elements that integrate the system (regulator, converter, cables, etc). During the system sizing you will decide the number of days of autonomy of your system, a measure of the reliability of your installation.

The system sizing calculations are important because the size of elements of the installation must be balanced and respect certain proportions. If we install more solar panels to produce more energy, the batteries should be dimensioned to be able store it, if the bank of batteries is too small and the loads are not using the energy, the energy needs to be thrown away. A regulator of a smaller amperage than needed, or one single cable conductor with an insufficient section can be cause of failure or fire and to render the installation unusable. The size of the elements is specially important if you are thinking to install the batteries and panels at the top of communication towers.

> *You should never forget the limitations of the photovoltaic energy to produce and store electrical energy, a light bulb that is left on by negligence during days can be fatal. The "fuel" of the photovoltaic systems, the solar radiation, have a difficult to predict behaviour. In fact, it is never possible to be absolutely sure (as in 100% sure) that a stand-alone system is going to be able to provide the necessary energy at any moment.*

Solar systems are designed for a certain consumption and if the user exceeds the planned limits constantly the provision of energy will fail.

The design method that we propose consists of considering the energy requirements, and based on them to calculate a system that works the maximum amount of time so it is the most trustworthy (reliable) as possible. Logically, whatever more panels and batteries installed, more energy will be able to be collected and to be stored. This increase of reliability of the installation will also have an increase in cost.

There are photovoltaic installations, as the provision of energy to telecommunication equipment that is part of the backbone of a radio network, in which the reliability factor is more important that the cost. In a client installation a low cost is going to be a determining factor. To find a balance between cost and reliability is not a easy task, and whatever decision you take, the really important thing is that you are able to determine what it is expected from your design and at what price.

Diverse procedures of calculation exist to ensure certain reliability at the minimum cost, but they require access to a lot of statistical data of solar radiation that is normally not available in many regions.

We propose a much more simple method, known as the **"method of the worst month"**, that consists in calculating the dimensions of the stand-alone system so it can work in the month in which the demand of energy is greater with respect to the solar energy available.

It is the worst month, as the month with the bigger ratio of demanded energy versus available energy. The method is widely used as it is simple and provides satisfactory results.

In this method the reliability is taken into consideration by fixing the maximum number of days that the system can work without receiving solar radiation and all the consumption is made solely at the expense of the energy stored in the battery. This number of days is known as the maximum number of days of autonomy (N). In brief N, is related to the number of consecutive cloudy days when the panels do not collect practically energy.

At the time of choosing *N*, it is necessary to consider several factors: the climatology of the place, the type of installation or its economic and social relevance (illumination of houses, hospital, factory, radio link, etc). Remember that the greater it is the *N*, the greater the investment. It is also important to evaluate all possible logistical costs of equipment replacement, it is not the same to change a discharged battery from an installation in the middle of a city that from the top a telecommunication tower that is several hours or days of walking distance.

Fixing the value of N, it is not an easy tasks as there are many factors involved, and many of them cannot be evaluated easily. Institution and experience play an important role in this part of the system sizing. A few tips can be provided here, for critical telecommunications equipment a good number is N = 5, whereas for low cost client equipment it is possible to be reduced the autonomy to N = 3.

At the end of this guide, we have included several tables that will facilitate the collection of required data and the sizing of the system. The next sections will explain in detail what information you need to collect and estimate and how to use the method of the "worst month".

3. General data

- **Latitude of the place** . With positive sign in the North hemisphere and negative in the South.
- **Data of solar radiation** . For the method of the "worst month" it is enough to know twelve values, one for every month. The twelve numbers are the monthly average values of daily

global irradiation on horizontal plane (G_{dm} (0), in kWh/m^2 × day). The monthly value results from the sum of the values of global irradiation of every day of the month divided by the number of days of the month.

If you have the data in Jules (J), you can apply the following conversion (1 J = 2,78 × 10^{-7} kWh).

The irradiation data G_{dm} (0) of many places of the world is gathered in tables and data bases. It is also recommendable to check for that information in a weather station close to your implementation site but do not be surprise if you can not find the data in electronic format. A good idea is to ask to companies that install photovoltaic systems in the region, there experience can be of great value.

Another alternative is to use the information of the number of sun hours per day (without clouds). The number of sun hours is available in tourist areas; just have in mind that you will need to convert that information to $G_{dm}(0)$ values. The method to convert from sun-hours to solar radiation is outside of the scope of this unit.

Another important concept that you should not confuse with "sun hours" is the one of number of "peak sun hours".

The number of peak sun hours has nothing to do with the number of hours without clouds, but the amount of daily irradiation. A day of 5 hours of sun without clouds does not necessary has those hours when the sun is at its zenit.

A peak sun hour is a normalized value of solar radiation of 1000 W/m² at 25 C. So when we refer to 5 hours of *peak sun hours*, we are talking of a daily solar radiation of 5000 W/m².

4. Electrical characteristics of system components

The electrical characteristics of the components of your system needs to be provided by the manufacturer. It is advisable to take your our own measures to notice possible deviations with respect to the nominal values. Unfortunately, deviation from promised values can be big and quality assurance of solar panels and batteries is another complex task.

These are the monimum values that you need to gather before starting your system sizing:

4.1 Panels

You need to know the voltage V_{Pmax} and the intensity/current I_{Pmax} in the point of maximum power in standard conditions.

4.2 Batteries

> *Nominal capacity (for 100 hours discharge) C_{NBat} operational voltage V_{NBat} and, either the maximum deep of discharge DoD_{max} or useful capacity C_{UBat}.*
>
> *You also need to know the type of battery that you plan to use, sealed lead-acid, gel, AGM, modified traction etc.*

The type of battery is important when deciding the cut-off set points in the regulator.

4.3 Regulator

Nominal tension V_{NReg}, and the maximum current that can operate I_{maxReg}.

DC/AC Converter/Inverter

If you are going to use any you need to know the *nominal voltage V_{NConv} , instantaneous Power P_{IConv} and Performance at 70% of maximum load h_{70} .*

4.4 Equipment or loads

For each of them it is necessary to know the nominal voltage V_{NC} and *the nominal power of operation P_C .*

In order to know the total energy that our installation is going to consume, it is also very important to consider *the average time of use* of each load, if it is daily, weekly, monthly or annual, and to consider any changes in the usage that might exist (seasonal, training or school periods, etc)

5. Two previous decisions

Apart from the electrical characteristics of the components and loads, it is necessary to have two more pieces of information before being able to do a system sizing. This two decisions are related to system autonomy and operational voltage.

- **N, number of days of autonomy**

You need to agree in value for *N* that takes care of the meteorological conditions, the type of installation and overall costs. It is very difficult to give you a concrete value of N for each part of the planet and installation but in the next table there are some recommended values. Take this values as a rough approximation, and consult with a experience designer to reach a final decision.

Winter	Domestic installation	Critical installation
very cloudy	5	10
variables	4	8
sunny	3	6

Table 1: Estimation of the number of days of autonomy

- V_N, **nominal voltage of the installation**

The components of your system need to be chosen to operate at a certain nominal voltage V_N.

> *Normally, the voltage is 12 or 24 Volts for the small systems and if the total power of consumption surpasses 3 kW, the voltage must be 48 or 120 V.*

The election of the value of the nominal voltage of the installation is not absolutely arbitrary and depends on, to a great extent, the availability of equipment in the market.

- If the equipment allows it, try to fix the nominal voltage to 12 or 24 V. Some wireless communications boards as Mikrotik's routerboards accept a wide range of input voltage (between 11 and 60 V DC).
- If you need to power several types of equipment that work at different nominal voltages, make a calculation what is the tension that minimizes the overall power consumption including the looses for power conversion in DC/DC and DC/AC converters.

6. Procedure of calculation

Before entering into detail, let us have a global idea of how the overall sizing process of calculation takes place. There are three main steps that need to be followed:

> **1º Solar Energy Available (the offer)**
>
> Based on statistical data of solar radiation, and the orientation and the optimal inclination of the solar panels we calculate the solar energy available. The estimation of solar energy available is done in monthly intervals, reducing the statistical data to 12 values. This estimation is a good compromise between precision and simplicity.

> **2º Electrical Energy Required (the demand)**
>
> We study the power consumption characteristics of the equipment chosen and their estimated usage. We calculate the electrical energy required per monthly basis. The electrical energy demand is calculated taking into consideration the expected fluctuations of usage. Factors to take into consideration are the variations between winter-summer, rainy period-dry season, school-vacation period etc. The result is 12 values of energy demand.

3º System sizing (the result)

With the data from the "worst month", the one in which the relation between the solar demanded energy and the energy available is greater, we calculate:

- The current that the array of panels needs to provide and therefore, the number of panels.
- The necessary energy storage capacity and, therefore, the number of batteries.
- The electrical characteristics of the regulator.
- The length and the necessary sections of cables for the electrical connections.

6.1 Orientation of the panels

Unless the sky is totally covered, most of the energy coming from the sun arrives in straight line. The solar module will capture more energy if it is "facing" the sun, perpendicular to the straight line between the position of the installation and the sun. "Unfortunately", the sun is not steady and we need to find a optimal position for our panels.

The orientation of the panels is determined by two angles, the azimuth a (angle that measures the deviation with respect to the south, in the north hemisphere, and with respect to the north, in the South hemisphere) and the inclination or elevation $ß$ (angle formed by the surface of the module and the horizontal plane).

6.1.1 Azimuth

You should have the module turned towards the terrestrial equator (facing south in the north hemisphere, and north in the south) so that during the day the panel catches the biggest amount of possible radiation (a = 0).

It is very important that the panels or part of them are under shade!. Study the elements that surround to array of panels (trees, buildings, walls, etc), and possible shades of a row of panels can on the others.

It is acceptable to turn the panels ±20º towards the east or the west if needed (a = ±20º).

6.1.2 Inclination

Once you have fixed the azimuth, the parameter that is key in our calculations is the inclination of the panel, that we will express as the angle beta (ß).

The maximum height that reaches the sun every day varies according to the stations, having its maximum in the day of the summer solstice and its minimum in the winter solstice. The best of the situations will be when the panels tracks this variation but this is not possible for cost reasons. In some scenarios you can consider two fixed inclinations, one position for the months of summer and another for the months of winter, but in this case you need to have special support structures and only makes sense if there is a considerable increase of the consumption during the summer.

In installations with telecommunications equipment it is normal to have the panels with a fixed inclination. In most of the scenarios the demand of energy of the system is constant during the year and therefore the "worst month" will always be the one with less isolation.

The value of ß should maximize the ratio between offer and the demand of energy. This is translated, depending on the different scenarios, in:

- *For installations with constant or similar consumptions throughout the year, it is preferable to optimize the installation to the capture the maximum radiation during "the winter" months. You should use the absolute value of the latitude of the place (angle F) increased in 10° (ß = | F | + 10 °).*
- *For installations with inferior consumptions in winter the value of the latitude of the place can be used as the solar panel inclination. The system is optimized for the months of spring and autumn (ß = | F |).*
- *For installations that are only used during summer, you should use the absolute value of the latitude of the place (angle F) decreased in 10°(ß = | F | - 10°).*

It is also recommended that the inclination of the panel should never be less than 15° to avoid the accumulation of dust and/or humidity. In repeating telecommunication stations in areas where exists snow and ice it is very important to protect the panels and to incline them an angle superior to 65°.

6.2 Required current in the worst month

For every month you need to calculate the quotient I_m.

I_m is the maximum daily current that a array of panels operating at nominal voltage of V_N needs to provide in a day with a irradiation of G_{dm} in a month "m" and with an inclination of panels ß.

The I_m(WORST MONTH) will be the greater one of the I_m, and the system sizing is based on the data of that worth month.

The calculations of $G_{dm}(\beta)$ for a certain place can be made based on $G_{dm}(0)$ using conversion tables and or computer software as PVSYST or PVSOL.

Due to the losses in the regulator, batteries and that the panels do not always work in the point of maximum power a correction is applied and the required current I_{mMAX} is calculated as:

$$I_{mMAX} = 1,21 \, I_m \text{ (WORST MONTH)}$$

Once you have determined what is the worst month, and what is the value of I_{mMAX} and the total energy that you require E_{TOTAL}(WORST MONTH) you can proceed to the final calculations.

6.3 Final calculations

6.3.1 Number panels

The panels are designed to be part of a modular array, being possible to combine them in series, parallel or a mixed form. By combining the panels we can obtain the desired voltage and current.

When the panels are connected in series , the total voltage is equal to the sum of the individual voltages of each module while maintaining the same intensity; when connecting in parallel, they currents are summed together, remaining the same the voltage. It is important, to avoid any electrical deviations when connecting panels, ensuring that the array is composed of same type of panels and characteristics.

In general, you should try to acquire panels with V_{Pmax} a bit bigger than the nominal voltage of the system (12, 24 or 48 V). Remember that you need your panel to provide a few volts more than the nominal voltage of the battery to get it charged. If it is not possible to find a single panel that satisfies your requirements, you need to connect several panels in series to reach your desired voltage. The number of panels in series *Nps* is the next superior integer to the quotient between the nominal voltage of the system and the voltage of the panel.

$$Nps = V_N / V_{Pmax}$$

In order to calculate the number of panels in parallel (*Npp*), you need to divide the I_{mMAX} by the current of the panel I_{pmax} in the point of maximum power and take the next superior integer as N_{pp}

$$Npp = I_{mMAX} / I_{Pmax}$$

The total number of panels is the result of multiplying the number of panels in one series (to fix voltage) by the number of series in parallel (to fix current) *Nps x Npp*.

6.3.2 Capacity of the battery or accumulator

The battery determines the overall voltage of your the system and needs to have enough a capacity to provide energy to the loads when there is not enough solar radiation.

One important warning: in photovoltaic systems, the association in parallel is not recommendable. The degradation of the battery individual cells (2 V) does not take place in a homogeneous form, different cells will support more fatigue than others.

To estimate the capacity of our battery, we first calculate the required energy capacity of our system (*necessary capacity*, C_{Nec}). The necessary capacity depends on the energy available in the "worst month" and the desired number of days of autonomy *(N)* that we decided previously.

$$C_{NEC} \text{ (Ah)} = E_{TOTAL}(WORST\ MONTH)\ (Wh)/V_N(V).\ N$$

The nominal capacity of the battery C_{NOM} needs to be bigger than the C_{NEC} as we can not fully discharge a battery. To calculate the size of the battery we need to take into consideration what is the maximum deep of discharge *(DoD)* that the battery allows:

$$C_{NOM}(Ah) = C_{NEC}(Ah)/DoD_{MAX}$$

In order to calculate the number of batteries in series (*Nbs*), we divide the nominal voltage of our installation (V_N) between the nominal voltage of the battery (V_{NBat}):

$$Nbs = V_N / V_{NBat}$$

6.4 Regulator

One other important warning: never use a regulator in parallel, use always regulators in series.

For security reasons, a regulator needs to be able to operate with a current I_{maxReg} at least 20% greater than the maximum intensity that is provided by the array of panels:

$$I_{maxReg} = 1,2.\ N_{pp} \cdot I_{PMax}$$

6.5 DC/AC Inverter

The total energy needed for the AC equipment it is calculated including all the looses that introduces the DC/AC converter or inverter. When choosing an inverter, it is good to know that the performance of the inverters is not constant with the power. An inverter has better performance when operating close to its nominal power. Using an inverter of 1500 Watts to power a load of 25 Watts is extremely inefficient. In order to avoid this waste of energy it is important to consider not the peak power of all your equipments but the peak power of the equipments that are expected to work simultaneously.

6.6 Cables

Once you know the numbers panels, batteries and type of regulators and inverters that you want to use, it is necessary to calculate the length and the section of the cables needed to connect the different elements of the photovoltaic system.

> **The length** depends on the location of your the installation. A general rule is to try to minimize the length of the cables between the regulator and the panels and batteries. By having short cables we can minimize the voltage drop, the section of the cables and its cost.
>
> **The section** is chosen based on the length of cables and the current that circulates.

The goal is to minimize voltage drops. In order to calculate the section *S* of the cable it is necessary to know:

- *The maximum* current I_{MC} that is going to circulate in the cable. In the case of the panel-battery subsystem, it is the I_{mMAX} calculated for every month. In the battery-loads subsystem depends on the way that the loads are connected.

- *The voltage drop* (*Va-Vb*) that we consider permissible in the cable. The voltage drop that results of adding all possible individual drops is expressed as a percent of the nominal tension of the installation. Typical maximum values are:

Section of the PV System	Voltage Drop (% of V_N)
Panel Array-Battery	1%
Battery-converter	1%
Main line	3%
Main Line (illumination)	3%
Main Line (equipment)	5%

- *Typical acceptable voltage drops in cables*

The section of the cable comes determined by the Ohm Law:

$$S(mm^2) = r(\Omega mm^2/m)L(m)\ I_{mMAX}(A)/V_a - V_b(V)$$

where S is the section, r is resistivity (intrinsic property of the material: for copper, 0,01286 W ^{2}mm/m), and L the length.

> S is chosen taking into consideration the cables available in the market. You should choose the immediately superior section to the one that is obtained from the formula. For security reasons that are some minimum values, for the cable that connects panels and battery, this is a minimum of 6 mm^2. For the other sections, that minimum is 4 mm^2.

STAND ALONE SYSTEM SIZING

GENERAL DATA

Site Latitude (°)	

IRRADIATION DATA (Gdm(0), in kWh/m2 × day)

JN	FB	MR	AP	MY	JN	JL	AG	SP	OC	NV	DC

Irradiation worst month	

COMPONENTS CHARACTERISTICS

PANELS

VOLTAGE @ MAXIMUM POWER (Vpmax, V)	
CURRENT @ MAXIMUM POWER (Ipmax, A)	
PANEL TYPE/MODEL AND POWER (Wp)	

BATTERIES

NOMINAL CAPACITY @ 100 H (CN Bat)	
NOMINAL VOLTAGE (VN Bat)	
MAXIMUM DEEP OF DISCHARGE (DoD MAX) OR USABLE CAPACITY (CU Bat)	

REGULATOR

NOMINAL VOLTAGE (VN Reg)	
MAXIMUM CURRENT (Imax Reg)	

DC/AC INVERTER (IF NEEDED)

NOMINAL VOLTAGE (VN Conv)	
INSTANTENOUS POWER (PI Conv)	
PERFORMANCE @ 70% LOAD	

REALIABILITY AND SYSTEM OPERATIONAL VOLTAGE

DAYS OF AUTONOMY (N)	
NOMINAL VOLTAGE (VN Equip)	

LOADS

ESTIMATED ENERGY CONSUMED BY THE LOADS (DC)				
MONTH WITH BIGGER CONSUMPTION:				
EQUIPMENT DESCRIPTION	NUMBER OF UNITS (1)	NOMIMAL POWER (2)	USAGE HOURS-DAY (3)	ENERGY (Wh/día) E=(1) x (2) x (3)
ETOTAL DC (before any converter) =				

ESTIMATED ENERGY CONSUMED BY THE LOADS (AC)				
MONTH WITH BIGGER CONSUMPTION:				
EQUIPMENT DESCRIPTION	NUMBER OF UNITS (1)	NOMIMAL POWER (2)	USAGE HOURS-DAY (3)	ENERGY (Wh/día) E=(1) x (2) x (3)

ETOTAL AC (before any converter) =				
ETOTAL AC (after converter) = ETOTAL AC / h (70%)				

ELECTION OF WORST MONTH

PLACE:

LATITUDE:

NOMINAL VOLTAGE OF THE INSTALATION VN(V):

	JN	FB	MR	AP	MY	JN	JL	AG	SP	OC	NV	DC
INCLINATION ß												
Gdm (ß) (Kwh/m2 × day)												
ETOTAL (DC) (Wh/day)												
ETOTAL (AC) (Wh/day)												
ETOTAL (AC + DC)=												
Im (A) = ETOTAL (Wh/day) × 1kW/m2/ (Gdm(ß) x VN)												

WORST MONTH (SUMMARY)	
ImMAX (A)	
ImMAX (A) = 1' 21 x Im	
ETOTAL (AC + DC)	

FINAL CALCULATIONS

PANELS

PANELS SERIES (NPS)	NPS = VN / VPmax =	
PANELS PARALLEL (NPP)	NPP = ImMAX / IPmax =	
TOTAL NUMBER OF PANELS	NTOT = NPS x NPP =	

BATTERY

NECCESARY CAPACITY (CNEC)	CNEC =(ETOTAL(WORST MONTH)	

	PEOR))/VN).NAut =	
NOMINAL CAPACITY (CNOM)	CNOM = CNEC / DoDmax =	
NUMBER OF BATTERIES IN SERIES (NBS)	NBS = VN / VNBat =	

CABLES

	PANELES – BATTERIES	BATTERIES - CONVERTER	MAIN LINE
TENSION DROP (Va-Vb)			
SECTION (r. L.ImMAX/(Va-Vb))			

7. Intellectual Property Rights

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