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Calculations for a Grid-Connected Solar Energy System

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Introduction

Whether you live on a farm or ranch, in an urban area, or somewhere in between, it is likely you and your family rely on electricity. Most of us receive our electrical power from a local utility. A growing trend has been to generate our own electrical power. Solar energy systems have grown in popularity are available for residential, agricultural, and commercial applications.

Of the various types of solar photovoltaic systems, grid-connected systems --- sending power to and taking power from a local utility --- is the most common. According to the Solar Energy Industries Association (SEIA) (SEIA, 2017), the number of homes in Arizona powered by solar energy in 2016 was 469,000. The grid-connected system consists of a solar photovoltaic array mounted on a racking system (such as a roof-mount, pole mount, or ground mount), connected to a combiner box, and a string inverter. The inverter converts the DC electrical current produced by the solar array, to AC electrical current for use in the residence or business. Excess electricity not used by the solar owner enters the utility electrical grid and is used by other consumers.

Figure 1. A grid-tied system is used to produce energy for the user during the day, sends excess energy to the local utility, and relies on the utility to provide energy at night. The system pictured is a small-scale PV demonstration featuring all of the components: a PV array and combiner box mounted on a racking system, a DC disconnect switch, a string inverter (red and white unit), an AC disconnect switch, and an AC service panel. Collectively, these are referred to as the Balance of System (BOS).

Power & Energy

A review of electrical terminology is useful when discussing solar PV systems. There are two types of electrical current. In residential electrical systems, Alternating Current (AC) is used. The current reverses direction moving from 0 volts to 120 volts in one direction, and immediately, reversing the direction. Typical residential voltages are 120 and 240.

In solar photovoltaic systems, Direct Current (DC) electricity is produced. The current flows in one direction only, and the current remains constant. Batteries convert electrical energy into chemical energy are used with direct current. Current is the movement of electrons along a conductor. The flow rate of electrons is measured in amperage (A). The solar industry uses the capital letter "I" to represent current. The force or pressure to move the electrons through the circuit is measured in voltage (V). The higher the quantity of voltage, the more pressure there is to push the electrical current. The total amount of power produced by a solar module is measured in watts (W). Power (measured in Watts) is calculated by multiplying the voltage (V) of the module by the current (I). For example, a module rated at producing 20 watts and is described as max power (Pmax). The rated operating voltage is 17.2V under full power, and the rated operating current (Imp) is 1.16A. Multiplying the volts by amps equals watts (17.2 x 1.16 = 19.95 or 20).

Power and energy are terms that are often confused. In terms of solar photovoltaic energy systems, power is measured in units called watts. Watts is a function of volts

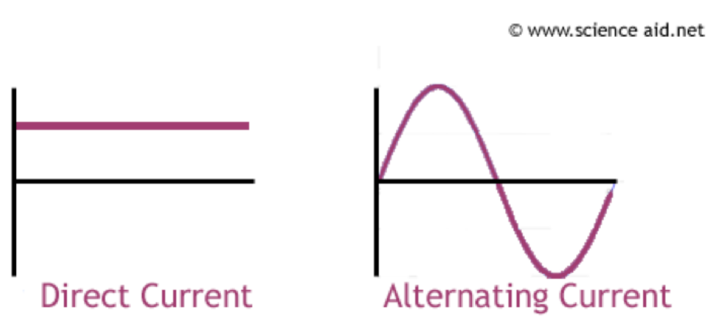

Figure 2. Direct current (DC) flows in one direction at a constant voltage. Alternating current (AC) flows in both directions, going from "0" to "120 volts", then reversing direction, dropping back to "0" and increasing to "120 volts". This cycle is repeated 60 times per second (hertz).

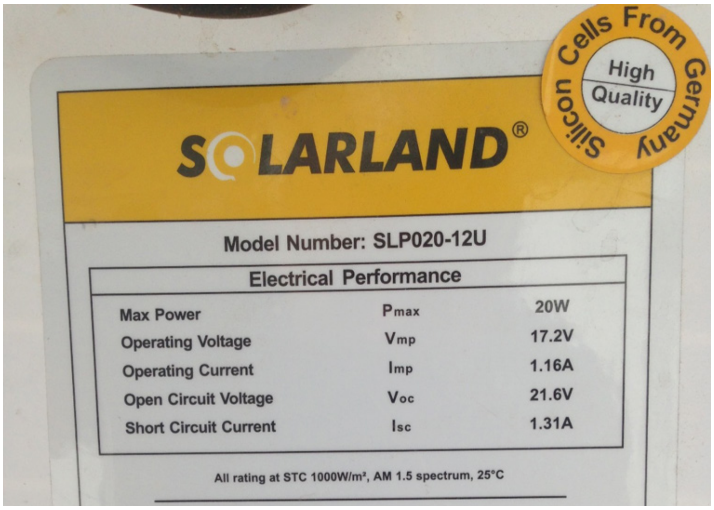

Figure 3. This solar module is rated to produce 17.2 volts and 1.16 amps will produce 19.95, or 20-watts of power under 1,000 W/m2 of solar irradiance (full sun)..

multiplied by amps (Watts = Volts x Amps). Electrical power is often measured in units of kilowatts. A kilowatt equals 1,000 watts. Your electric bill uses kilowatts to quantify the amount electricity you use. To measure how much energy is used, the component of time (how long the power is used) is brought into the equation, Watts X Hours = Watt-hours (Wh). To measure how much energy is used when a 100-watt light bulb is on for 5 hours, the solution is 100 watts x 5 hours = 500 watt-hours. A Kilowatt-Hour (kWh) is equal to 1,000 Wh. If the same light is left on for 10 hours, the energy consumed is equal to 100-watt x 10 hours = 1,000 watt-hours, or 1 kilowatt-hour (kWh).

Energy Use

To determine total energy usage of a resident or building, the owner will refer to their local utility bill. This value will vary depending on the size of residence or building, number of occupants, number of appliances, lights, and electrical heating and cooling systems. Monthly energy use values will vary with geographic location, time of year, and energy use habits of the occupants. Spring and summer months with higher temperatures result in frequent use of air conditioning systems resulting in higher energy consumption. If electricity is the sole power source and is provided by a local utility, a grid-connected system can be designed to offset all (100%) or a partial amount of the electrical needs. The size of the system will vary and is affected by multiple variables: location, space, and cost.

According to Clean Technica (Abdelhamid, 2016), 6 kW solar PV systems in size are typical in Arizona. System costs will vary based on size and complexity. A 6 kW system in 2016 was would cost about $21,000.00, or about $3.50 per watt.

Solar Insolation and Peak Sun Hours

In the solar energy industry, calculations are made using the amount of sun energy provided by the sun over the period of a day. The intensity (brightness) of the sun is referred to solar insolation. When the sun is at its brightest during the day the light intensity is measured using an irradiance meter (or pyranometer) and measured in Watt per meter squared (W/m2). The target value is 1,000W/m2. This value is typical of sunlight intensity at 12:00 noon, when the sun is highest in the sky.

Peak sun-hours is equal to the number of hours the insolation value is at 1,000W/m2. For example, a geographic region with a PSH of 3.5 is interpreted as solar insolation reaches 1,000W/m2 for of 3. 5 hours per day. This PSH value is generally higher in the southern part of the United States, including Arizona. The amount of peak sun-hours (PSH) for the region needs to be determined and is used in making a system sizing calculation. The average daily peak sun-hour per day value for fixed-plate solar array installation at latitude will be used. Data for four locations in Arizona are provided by the National Renewable Energy Laboratory (NREL). Table 1 displays the four locations in Arizona. This value is used in system sizing calculation.

Derate Factors

Each system has efficiency losses. High ambient temperature can result in loss of voltage produced by an array. Dust on the surface of an array results in energy loss. Each component of a solar PV system has efficiency losses. System wiring has efficiency losses. Available online PV system sizing programs will factor in these efficiency losses when making calculations for system sizing. The solar industry refers to these as derate factors. Examples of specific derate factors include: inverter efficiency, module power tolerance, and wiring losses. The Table 2 (SEI, 2012) illustrates how an overall derate factor is calculated:

The overall derate factor is arrived at by multiplying all the individual derate values together: (0.95 x 0.96 x 0.98 x 0.995 x 0.98 x 0.99 x 0.95 x 0.98 x 0.90 = 0.722). Additional derate factors include temperature losses, and inverter efficiencies. These are included calculations for solar array sizing.

Table 1. Peak Sun-Hours of Arizona Locations by Latitude

	Flagstaff	Prescott	Phoenix	Tucson
Latitude	35.13º	34.65º	33.43º	32.12º
Average Daily Peak Sun Hour	6.0	6.1	6.5	6.5

Table 2. List of Derate Factors to use for Grid-Connected System

Calculator for Overall-DC to-AC Derate Factor		
Derate Factors	**Derate Value**	**Range of Acceptable Values**
Module power tolerance	0.95	0.88-1.05
Inverter and transformer	0.96	0.88-0.98
Module mismatch	0.98	0.97-0.995
Diodes and connections	0.995	0.99-0.997
DC wiring	0.98	0.97-0.99
AC wiring	0.99	0.98-0.993
Soiling	0.95	0.30-0.995
System downtime	0.98	0.00-0.995
Shading	0.90	0.00-1.00
Overall dc-to-ac derate factor	**0.722**	
Source: Solar Energy International		

Calculating Array Size

A formula is available for calculating the size of the solar PV array. The variables are electrical energy usage, peak sun-hours (PSH), and system derate factors. The first step is to determine the average daily solar PV production in kilowatt-hours. This amount is found by taking the owner's annual energy usage and dividing the value by 365 to arrive at an average daily use. This will tell us how much energy we will need on a daily basis. For example, a residence has an annual energy usage of 6,000 kWh. Divide this value by 365 to arrive at the average daily consumption. The owner needs to determine how much of their energy usage they wish to offset with solar PV energy production. Available space for an array, site quality (shading), and system cost are the immediate factors. We will use 100% for this example.

Assuming the resident uses 6,000 kWh of electrical energy, then the average daily consumption is (6,000 kWh ÷ 365 days) 19.2 kWh. The goal is to offset all (100%) electricity used with solar PV. The system with an inverter, will need to produce 19.2 ac kWh per day. This value will be divided by the average peak sun-hours (PSH) for the geographic location. System losses (derate factors) will be applied. The final value is the calculated solar PV array size in kilo-watts.

Avg. daily PV production in kWh	÷	Avg. peak sun hours per day	÷	Temperature losses	÷	Inverter efficiency	÷	General system derate factor	=	PV array size in kW
19.2	÷	6.5	÷	0.88	÷	0.96	÷	0.774	=	4.52

Flipping the equation, if an existing PV array size in kW is known, it is possible to calculate the average daily PV production in kWh.

PV array size in kW	X	Avg. peak sun hours per day	X	Temperature losses	X	Inverter efficiency	X	General system derate factor	=	Avg. daily PV production in kWh
4.52	X	6.5	X	0.88	X	0.96	X	0.774	=	4.52

The next step is to determine the amount of solar PV energy which can be produced from a specific space (location). Assuming the owner plans to install the array on the south-facing roof of their residence, a general rule is one kilowatt (1 kW) of solar PV module will fit in 100 square feet of space, or 10 watts per square foot. A typical residential roof will have plumbing vents, and may include a sky light, or air conditioning system mounted on it. Space needs to be left for access to service these items. Some locations and jurisdictions may require walking space (up to 36 inches) around the perimeter of the array for fire access. This reduces the amount of usable roof space for an array. As an example, assuming a roof has a usable space of 500 square feet, the available area in square feet is multiplied by the value 10 watts/ft2.

500 sq. ft. x 10 watts/ft2 = 5,000 watts of solar PV, or 5 kW. Plugging this value into the equation from above:

PV array size in kW	X	Avg. peak sun hours per day	X	Temperature losses	X	Inverter efficiency	X	General system derate factor	=	Avg. daily PV production in kWh
Inverter efficiency	X	6.5	X	0.88	X	0.96	X	0.774	=	21.25

The average daily PV production of 21.25 kWh can be obtained from a system this size. This is enough to meet the calculated PV array size of 4.52 kW.

Another Example:

Home consumes 4,000 kWh per year. Average PSH per day for a south-facing array = 6.5
Overall average system efficiency factor 66%.

To calculate the array size needed to offset annual energy consumption, divide the annual kWh consumption by 365. The result is the average daily consumption in kWh. Divide this amount by average daily peak sun hours (PSH) to get approximate array size in kW. Divide this amount by the system's efficiency derate factor.

4,000 kWh/yr ÷ 365 days/yr. = 10.96 kWh/day

10.96 kWh/day ÷ 6.5 sun-hours/day = 1.69 kW

1.69 kW ÷ 0.66 efficiency factor = 2.55 kW array

With a cost of $3.50/Watt (installed) the estimated array cost is:

2,500 watt x $3.50/watt = $8,750.00

Solar Module Selection

Once the size of the array has been selected, determining the number of solar modules needed to produce the power is the next step. Modules are marketed by the amount of power (in watts) produced. The larger the amount of watts per module, the fewer the modules required. For example, for a 2,000 watt system, it would make more sense (economically) to install larger 175-watt modules than smaller 20-watt modules (2,000 watts ÷ 175-watt/module = 11.43 or 12 modules; whereas 2,000 watts ÷ 20-watt/module = 100 modules). Not only would the amount of racking material would be higher, but the labor time for installation would be greater. For additional information regarding solar modules, refer to the factsheet, Demystifying The Solar Module, (AZ1701-2017) (Franklin, 2017).

Module availability and price are two factors that need to be considered. System installers typically buy modules in bulk to reduce the cost per unit. This minimizes the type and amount of racking material required. When available space is a factor, the most efficient module should be selected. Crystalline modules are more efficient than thin-film modules. Though cheaper, it would take more space using thin-film to achieve the same amount of power produced by crystalline modules.

Using the 2.5kW size array example, assume the available module is rated at 240-watts/module.

2,500 watts ÷ 240-watts/module = 10.41 modules. Since a part of a module is not possible, it is recommended to round up to 11 modules.

Looking at specifications for Module A:

STC Power (Pmp)	240 W
Maximum power voltage (Vmp)	29.86 V
Maximum power current (Imp)	8.10 A
Open-circuit voltage (Voc)	36.45 V
Shor-circuit current (Isc)	8.59 A
Temperature coefficients:	
TkVoc	-0.32%/ o C
TkVmp	-0.42%/o C

An array with a series string of 11 modules is capable of producing 2,640 watts, or 2.64 kW. Larger systems will likely have more than one string of modules. Each string is wired in series to build the voltage. This is referred to as a source circuit. As the strings are connected to a combiner box, they are wired in parallel to build system current. At this point, an output circuit is created.

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Inverter Sizing

The next step in grid-connected system sizing is determining the size of the inverter. The role of the inverter is to convert DC electricity produced by the solar array to AC electricity used by the residence. Selection of the inverter is based on: PV array capacity the inverter can handle (in watts), output voltage (240 volts is typical for residential systems), and the DC input voltage range. An inverter has a DC input voltage window. The goal is to design a system where the DC voltage produced remains within the voltage range. An example, an inverter has a range of 230 V to 600 V. The critical factor is temperature. A high ambient temperature, which results in high solar cell temperatures, can result in array voltage loss, while low ambient temperature can result in increased array voltage production. Failure to attain the minimum voltage due to high temperatures results in inverter shutdown. Likewise, exceeding the maximum voltage due to low temperatures also results in the inverter going offline, and possible inverter damage.

The calculations to be performed for the following:

1. What is the minimum number of modules in series?
2. What is the maximum number of modules in series?
3. How many source circuits can be wired in parallel?

To begin with, the record high and low temperatures for the location need to be referenced. The solar industry commonly refers to the data available from the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE). For the low temperature, the ASHRAE Extreme Annual Mean Minimum Design Dry Bulb Temperature values are used. For the high temperature, the ASHRAE 2% Annual Design Dry Bulb Temperature, with a temperature adder to account for increased module temperatures for roof-mounted systems is utilized.

Table 3 lists the record low and high temperatures for the following Arizona locations.

The record high in Tucson is 47o C (117o F), and the record low is - 9o C (16o F).

Table 3. Record High and Low Temperature Values for Select Arizona Locations

	Flagstaff	Phoenix	Prescott	Tucson
Record Low Temp	-34° C	-4° C	-23° C	-9° C
Record High Temp	37° C	50° C	40° C	47° C
Source: www.plantmaps.com				

The goal of this part of the calculation is to determine the maximum number of modules to be wired in series. The open-circuit voltage (Voc) of the source circuit cannot exceed the inverter's maximum DC input voltage during cold temperatures. For this example, the maximum input voltage is 450 volts.

Calculating the temperature-corrected maximum open-circuit voltage for the single module:

Module Vocmax = Voc x [1 + (Tmin – Tstc) x (TkVoc)]

= 36.45 V x [1 + (-9o C – 25o C) x (-0.32 %/oC)]

= 36.45 V x [1 + (-34 x -0.0032)]

= 36.45 V x [1 +0.1088]

= 36.45 V x 1.1088

= 40.52 V

This means that at the coldest temperature the module's voltage is actually 11% higher.

Table 4. Adder for estimating solar module cell temperature

Pole or Ground	25° C
Tilted rack on roof	30° C
Roof mount	35o C
Source: Osterberg, 2013	

Dividing the maximum inverter input voltage of 450 volts by the module temperature-corrected Voc will provide the maximum number of modules to be wired in series.

= 450 V ÷ 40.52

= 11.11

= 11 modules

The 11.11 value is rounded down to 11. Rounding up would result in exceeding the 450 V maximum. On the coldest days, when the temperature is low, the array voltage will not exceed the inverter max voltage. The next step is to determine the minimum number of modules based on the temperature-corrected minimum module voltage. On the hottest days, the array voltage will decrease. If the minimum number of modules is not calculated correctly, the drop in module voltage may result in the inverter minimum voltage not being met, and the inverter going offline. The module temperature coefficient for voltage max power (Vmp) is used. For this module, the temperature coefficient indicates for every one degree change in temperature, the Vmp decreases 0.42%. The formula is:

Module Vmpmin = Vmp x [1 + ((Tadd +Tmax – Tstc) x (TkVmp))]

Interpreting the equation variables,

- Vmp = the module rated Vmp at Standard Test Condition (STC)
- Tadd = the temperature adder value specific to an array mounting system, 35o C for a roof-mounted array
- Tmax = maximum expected temperature in degree C
- Tstc = the STC temperature at 25o C
- TkVmp = the temperature coefficient of Vmp as listed in the module specs

= 29.86 V x [1 + ((35o C + 47o C – 25o C) x (-0.42%/o C)]

= 29.86 V x [1 + (57 x (-0.0042)]

= 29.86 V x [1 + (-0.2394)]

= 29.86 V x 0.7606

= 22.71 V

This calculation shows the minimum module Vmp which may occur if operating on the hottest day in Tucson, Arizona. This value is 24% less than the rated Vmp of the module.

205 V ÷ 22.71

= 9.03

= 10 modules

So the array string can have a minimum of 10 modules in a string and no more than 11 for the desired inverter.

Inverter Sizing

Inverters are available based on total wattage. Using the size of 4.52 kW calculated earlier, either a 4 or 5 kW inverter will be selected. The DC input voltage window is range of voltage, usually 203 V to 450 V. For the AC output voltage, it is desired to obtain 240 volts to meet the needs of larger household appliances, such as an electric range, or water heater.

Inverter A

Maximum dc input voltage	500 V
DC minimum starting voltage	220 V
Continuous ac output power	4,600 W
DC input voltage window	205 V - 450 V
AC output voltage range	183 V – 229 V

Inverter B

Maximum dc input voltage	500 V
DC minimum starting voltage	255 V
Continuous ac output power	5,200 W
DC input voltage window	240 V - 450 V
AC output voltage range	211 V – 264 V

IPV Watts

An online software program such as PVWatts© Calculator (http://pvwatts.nrel.gov/pvwatts.php.),allows the user to select the option to select their geographic location using a city and state, or zip code. Multiple options to plug in different values including array size, tilt angle of array, orientation, and derate values. The result is a table of monthly and annual peak sun-hours, with corresponding AC energy production in kilowatt hours (kWh), along with the value of AC energy. An optional tool allows the user to see a sky-view of their location and a drawing tool to estimate the location and size of an array on a roof, for example

Station Identification				
City:	**Flagstaff**	**Phoenix**	**Prescott**	**Tucson**
Latitude:	35°	33.4°	34.5°	33°
Elevation:	2135m	337m	1540m	779m
PV System Specifications				
DC Rating:	1.0 kW	1.0 kW	1.0 kW	1.0 kW
DC to AC Derate Factor:	0.722	0.722	0.722	0.722
AC Rating:	0.7 kW	0.7 kW	0.7 kW	0.7 kW
Array Type:	Fixed	Fixed	Fixed	Fixed
Array Tilt:	35°	33.4°	34.5°	33°
Array Azimuth:	180°	180°	180°	180°

	Flagstaff		Phoenix		Prescott		Tucson	
Month	A	B	A	B	A	B	B	B
Jan	5.10	134	5.09	123	5.27	134	5.74	140
Feb	5.78	135	6.05	132	5.68	130	6.14	132
Mar	6.21	159	6.61	153	6.14	152	7.04	167
Apr	6.43	156	7.55	166	6.78	159	7.48	168
May	6.56	161	7.54	168	7.07	168	7.24	163
June	6.61	151	7.28	153	7.08	158	7.10	153
July	5.95	141	7.14	155	6.34	145	6.40	143
Aug	5.54	131	7.17	157	6.51	149	6.82	153
Sep	6.59	153	7.15	151	6.59	148	7.06	156
Oct	6.19	151	6.75	153	6.51	155	6.75	157
Nov	5.43	134	5.99	127	5.57	133	6.02	140
Dec	5.03	131	4.88	119	4.98	126	5.31	131
Year	5.95	1,737	6.57	1,757	6.21	1,756	6.59	1,802

Note: A = Solar Radiation (kWh/m2/day); B = AC Energy (kWh)

Conclusions

When sizing the grid-connected array system, the solar owner needs to consider size limitations. Available space for the array, including physical location if it will be mounted to the roof of the residence, the direction the roof is facing, the amount of shade on the roof during the day, the initial cost of the system, and the amount of energy required to produce are questions to consider. The first step is to review energy consumption habits. Look at a year's worth of electrical usage. An energy audit can help identify where energy conservation practices (such as improving insulation, using energy-efficient appliances, and switching to low-energy lighting) can reduce the kilowatt-hour usage. Next, is to locate the average daily peak sun-hours (PSH) for the array location. Be sure to use derate factors to calculate average daily production. Decide how much of your electrical energy use you desire to offset using solar energy --- 100%, 75%, or 50%. There are incentives available for solar users. A web site called the Database of State Incentives for Renewable & Efficiencies® (http://www.dsireusa.org/) can help the user search for programs available to them in their local community by searching with their zip code. These programs may be offered by local municipalities, state and federal agencies. Categories include financial incentives, regulatory policies, and technical assistance.

Online system sizing programs are available to help the future solar owner calculate the required DC wattage of the system. The programs gives the user options for adjusting the size, and includes the derate factors.

For more information about solar energy systems, additional solar factsheet titles available include:

- *Solar Photovoltaic (PV) Site Assessment (AZ1697-2017)*
- *Types of Solar Photovoltaic Systems (AZ1745-2017)*
- *Solar Photovoltaic (PV) System Components (AZ1742-2018)*
- *Mounting Your Solar Photovoltaic System (AZ1703-2017)*
- *Hand Tools Used for Solar Photovoltaic (PV) Systems (AZ1702-2017)*

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