Renewable Energy
Lecture 15: Pv System Sizing

Grade: 4th Class

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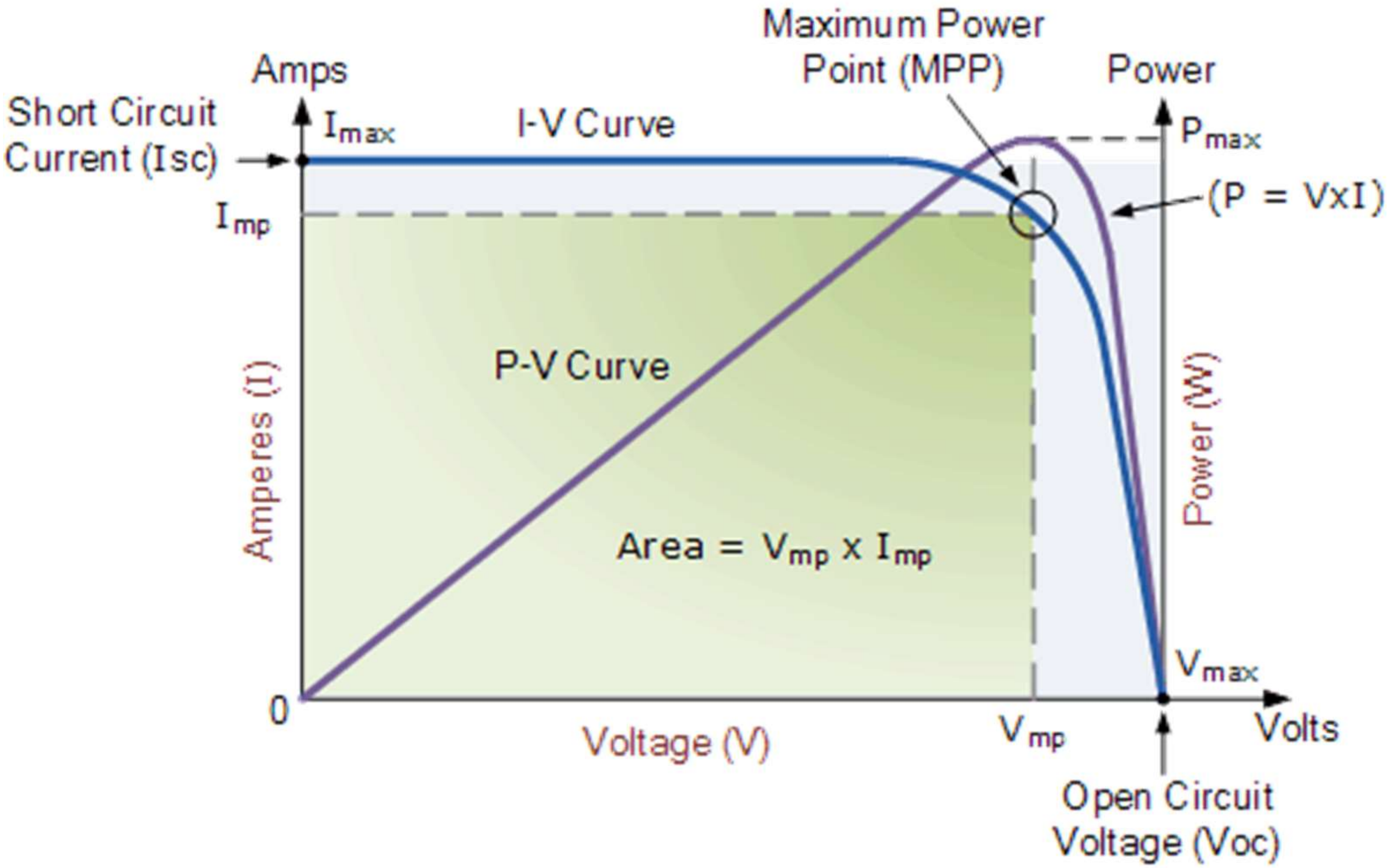
Solar Cell I-V Characteristic

Solar Cell I-V Characteristic Curves show the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array giving a detailed description of its solar energy conversion ability and efficiency. Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's output performance and solar efficiency.

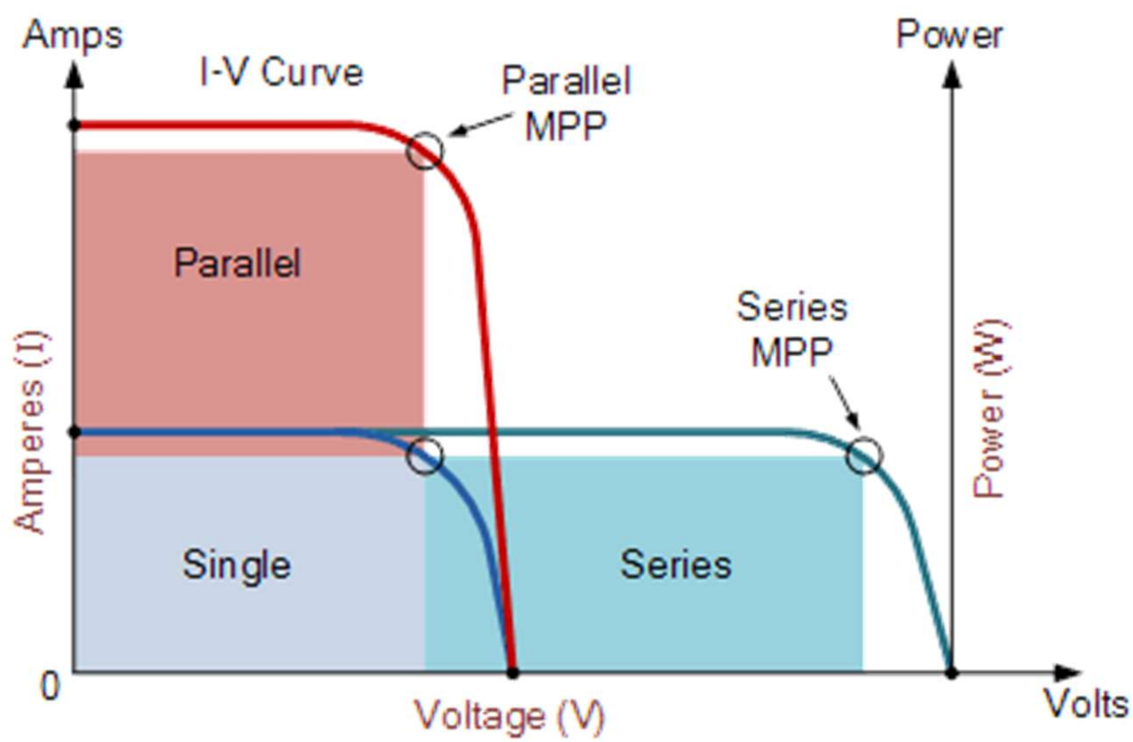
I-V curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible.

Solar Cell I-V Characteristic



Solar Cell I-V Characteristic

Solar Cell I-V Characteristic Curve for a single solar cell or panel. But many photovoltaic arrays are made up of smaller PV panels connected together. Then the I-V curve of a PV array is just a scaled up version of the single solar cell I-V characteristic curve as shown.



Solar Array Parameters

•**V_{OC} = open-circuit voltage** – This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition). This value is much higher than Vmp which relates to the operation of the PV array which is fixed by the load. This value depends upon the number of PV panels connected together in series.

•**I_{SC} = short-circuit current** – The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition). This value is much higher than Imp which relates to the normal operating circuit current.

•**MPP = maximum power point** – This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = Imp x Vmp. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).

Solar Array Parameters

FF = fill factor – The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions and the product of the open-circuit voltage multiplied by the short-circuit current, (VOC x ISC) This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8.

%eff = percent efficiency – The efficiency of a photovoltaic array is the ratio between the maximum electrical power that the array can produce compared to the amount of solar irradiance hitting the array. The efficiency of a typical solar array is normally low at around 10-12%, depending on the type of cells (monocrystalline, polycrystalline, amorphous or thin film) being used.

Simple definitions:

- Voltage: Electrical pressure
- Current: Electrical flow
- Power: Rate at which electricity is used
- Energy: Amount of electricity used

Relationships:

- Power = Voltage × Current
- Energy = Power × Time Units:
- Voltage is measured in Volts = V
- Current is measured in Amps = A
- Power is measured in Watts = W
- Energy is measured in Wh or more often kWh

Simple definitions:

SOLAR POWER

Measured in power per unit area and most often in watts per square meter. 1000 watts per square meter is called “peak sun”, which is a typical sunny day near noon

SOLAR ENERGY

Since: power × time = energy

Then: solar power × time = solar energy

If we have peak sun conditions of 1000 watts per square meter for one hour, then we have a “peak sun hour” or a “sun hour”.

Different locations have different amounts of solar energy.

Peak sun hours per day is also often called insolation. Insolation is incident solar radiation.

HOW TO CALCULATE ENERGY USAGE FOR AN OFF- GRID

You have a 12V 2A light bulb that will run for 3 hours per day.

You also have a 100W radio repeater that will be on 100% of the time.

How much energy in kWh does the cabin use in a day?

Answer:

12V × 2A = 24W

24W × 3 hours = 72Wh of energy per day for the lights.

100W × 24 hours per day = 2400Wh repeater

Total energy = 2400Wh + 72Wh = 2472Wh/day

Energy is kWh not kW/h or kW

BATTERY MATH

When talking about battery capacity, the term Amp Hour is commonly used. An Ah is an amp for an hour. Amp hours are easily converted to Wh.

$Ah \times V = Wh$

A 6 volt battery that has 100 Ah has:

$6V \times 100Ah = 600Wh$

A 12V battery with 100Ah has:

$12V \times 100Ah = 1200Wh$

TYPES OF DC CONNECTIONS (SERIES AND PARALLEL)

Often times PV is hooked up in groups of solar modules where the positive lead of one module is connected to the negative lead of the next module. That is called a series connection.

With PV and batteries, series connections increase voltage.

Even within a solar PV module itself, the solar cells are connected in series to increase voltage. Parallel connections do not increase voltage and increase only current with PV.

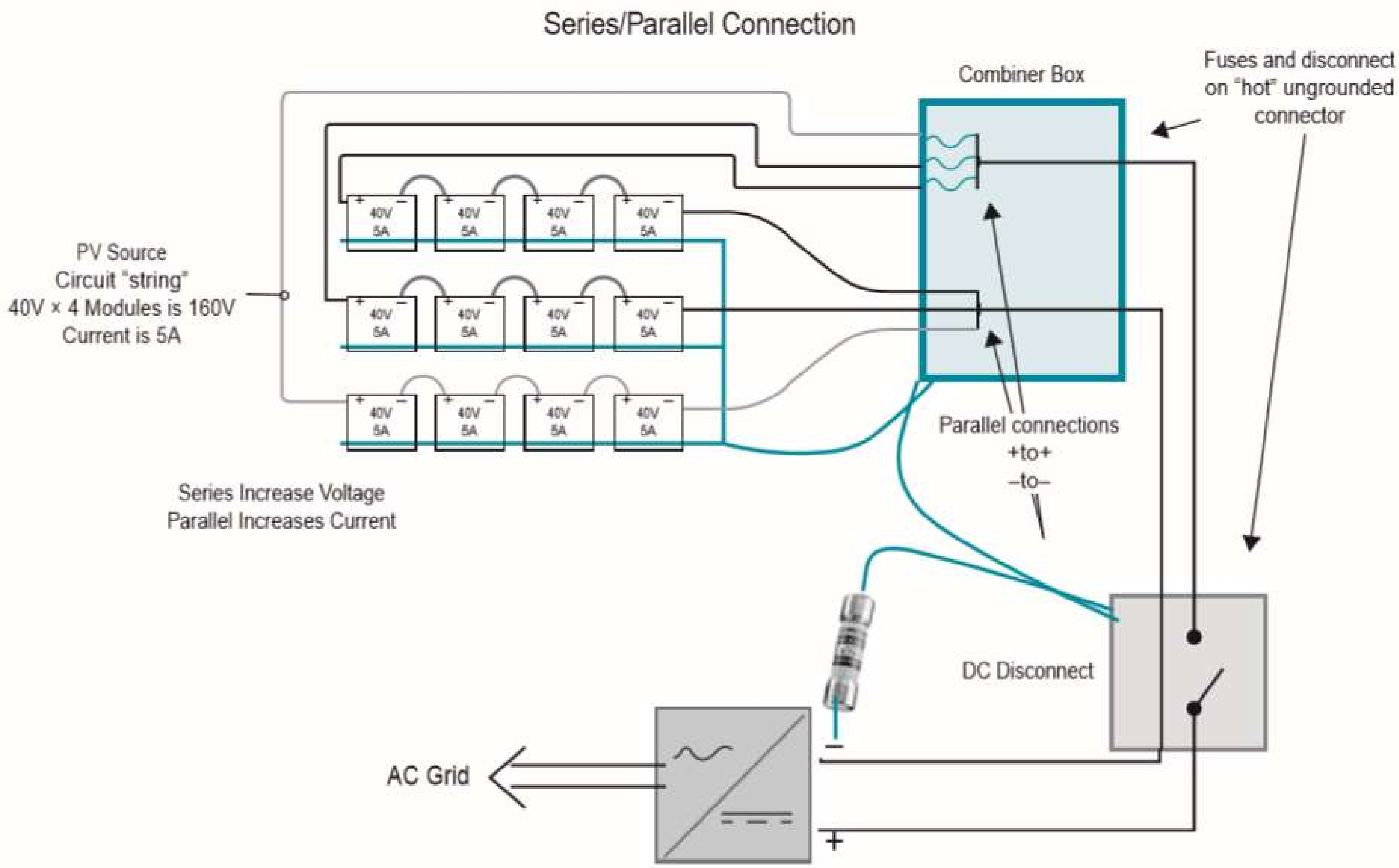
Series: Positive to negative and increases voltage.

Parallel: All of the positives are connected to one place and all of the negatives to another.

With alternating current, we can also have series and parallel connections.

TYPES OF DC CONNECTIONS (SERIES AND PARALLEL)

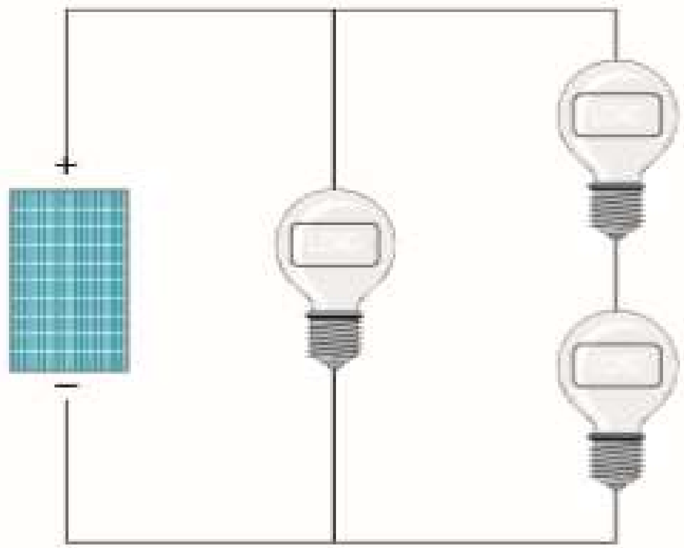
Figure 3.5 Diagram of a PV system, including series and parallel connections



In a negative grounded system, inside inverter there is a connection between negative and ground. If more than one amp goes through this connection, there is a ground fault and device deactivates inverter.

TYPES OF DC CONNECTIONS (SERIES AND PARALLEL)

Figure 3.6 Series and parallel connections. Light bulbs on the right are connected in series to each other. Light bulb in the middle is connected in parallel with the other bulbs.



TYPES OF DC CONNECTIONS (SERIES AND PARALLEL)

Why we transmit electricity with high voltage:

Voltage × Current = Power

Higher current causes voltage drop and power loss on transmission lines, so if we can transmit our power with high voltage and low current, then we have fewer losses.

A 1kW 12V battery based system would have 4 times more losses than a 1kW 24V battery based system or 16 times the losses of a 1kW 48V system if we were using the same conductors (wires).

ESTIMATING HOW MUCH PV FITS IN A GIVEN SPACE

If you covered 100 square meters with 15.6% efficient PV, you would have 156W/square meter × 100 square meters = 15,600W = 15.6kW of PV

In reality, you would need extra space around the edges and chimneys, since you usually cannot fit PV in every space.

Some designers estimate 100W to 120W/square meter, to leave room for roof penetrations, walkways and space for firefighters. Do not use dissimilar PV modules in series.

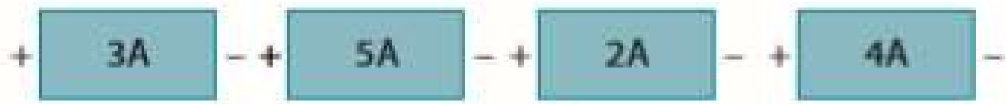
ESTIMATING HOW MUCH PV FITS IN A GIVEN SPACE

When PV is connected in series, you will have what is sometimes called “the Christmas light effect”. If one module has less current, then it will limit the amount of current to flow through the whole series connected PV source circuit (string).

Before there were bypass diodes in PV modules, when a cell was shaded all of the current from all of the other cells and modules would try to push through the shaded cell. This would create heat (from resistance) and could be a fire hazard. Also it would be terrible for performance.

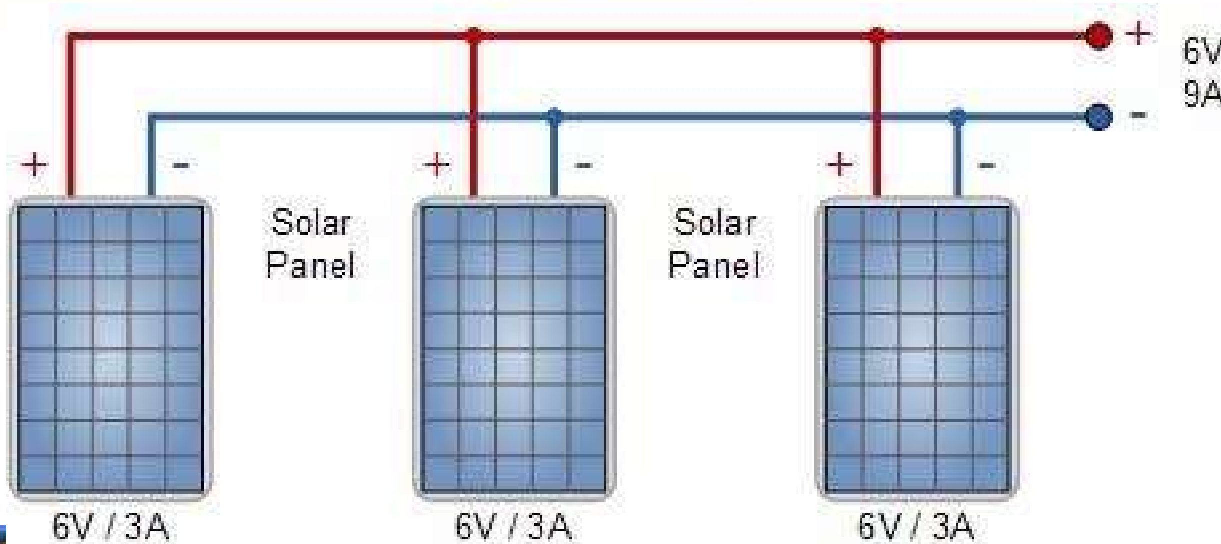
PV Module Series and Parallel Connection

Module Mismatch is Bad

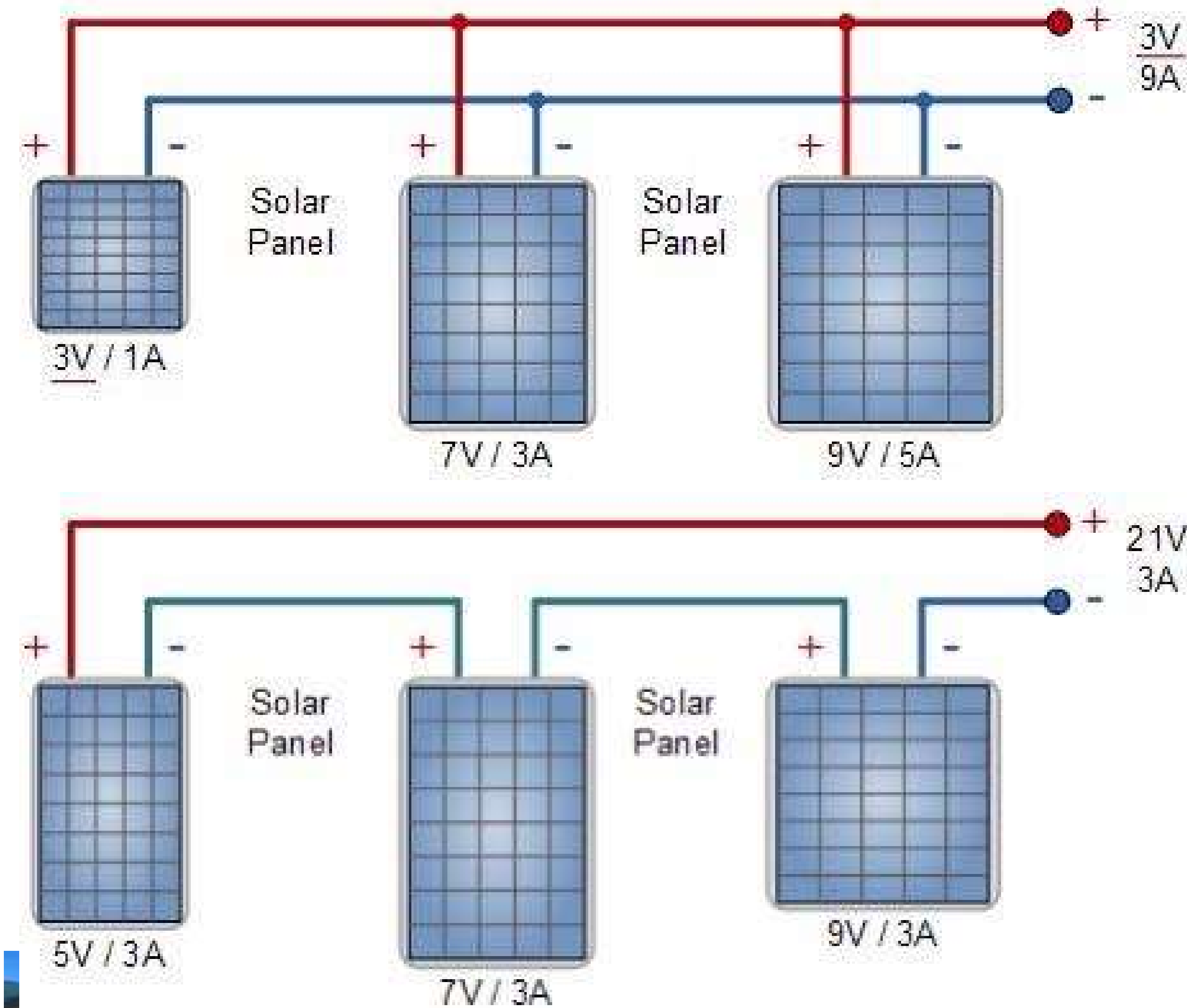


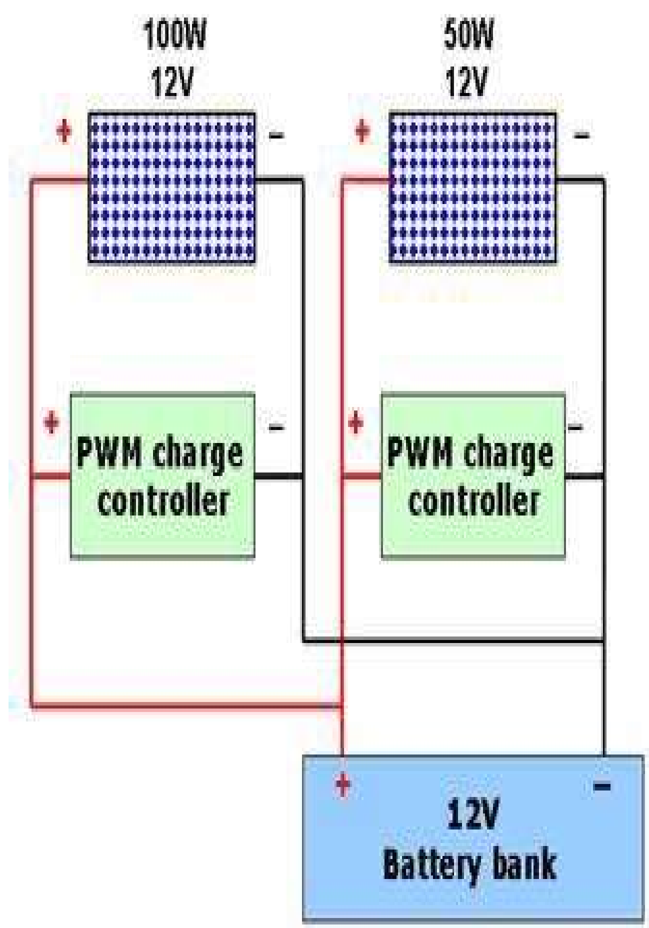
Hook up these modules
in series and you get 2A

This is similar to what happens with shading or
different orientations within a string

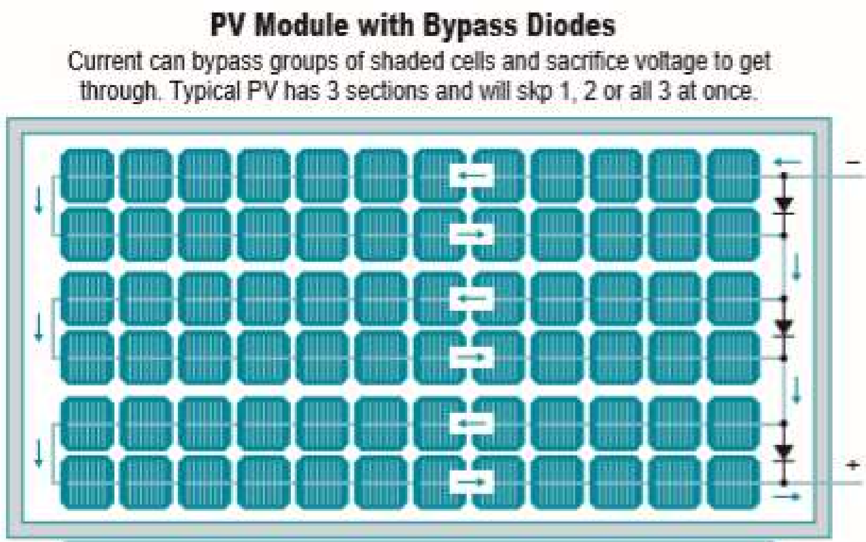


PV Module Series and Parallel Connection





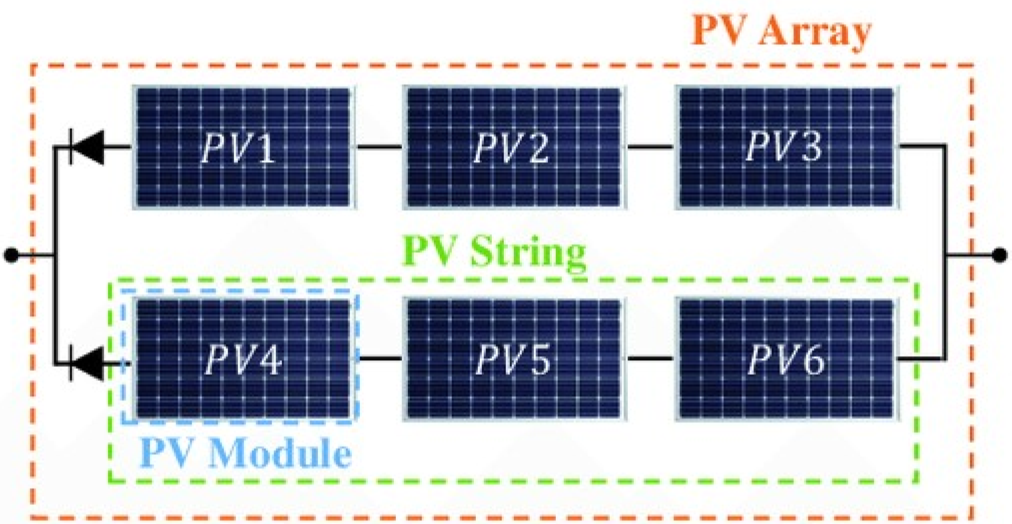
Pv module with Bypass Diodes



Bypass diodes will bypass a group of cells. The group of cells being bypassed would not create voltage, but would let the current through. Bypass diodes sacrifice voltage for current.

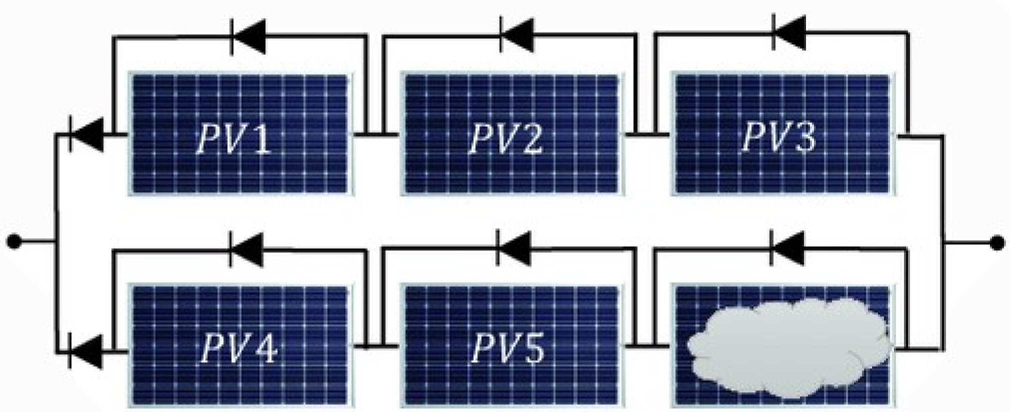
A bypass diodes analogy would be: When there is an accident on the freeway, you take the frontage road. Bypass diodes are wired in parallel to a group of cells so there is another pathway for current to take when there is a shaded cell.

Pv module with Bypass Diodes



Terminal Voltage
$= max((V_{PV1} + V_{PV2} + V_{PV3}), (V_{PV4} + V_{PV5} + V_{PV6}))$

Power Capacity
$= min(C_{PV1}, C_{PV2}, C_{PV3}) + min(C_{PV4}, C_{PV5}, C_{PV6})$



Terminal Voltage
$= V_{PV1} + V_{PV2} + V_{PV3}$

Power Capacity
$= min(C_{PV1}, C_{PV2}, C_{PV3}) + min(C_{PV4}, C_{PV5})$

BASIC SYSTEM SIZING FACTORS

Regardless if the system is utility interactive or stand-alone, the location and derating factors also are a factor in determining system size. To simplify system sizing, we can look to this basic grid tied example and go from there:

AC kW system size × derating × insolation = production

Example: PV system produces 4kW at 1000W per square meter of irradiance in a location that had 5 sun hours per day of insolation and had 10% losses from shading.

4kWac × 5PSH × 0.9 derating = 18kWh/day

- 0.9 derating is from the 10% losses. If you lose 10%, then you keep 90%.

BASIC SYSTEM SIZING FACTORS

Example1 : A 7kWdc PV system makes 5.5kWac when 1000W per square meter are shining on it. If this is in a location that will get an average of 4.5 peak sun hours (PSH) per day and there are 12% losses from shading, then about how much energy will this system produce in a month?

Answer: 5.5kWac × 4.5PSH × 0.88 derating × 30days

= 653kWh

Explanation:

System makes 5.5kWac (inverter output) under "peak sun conditions" of 1000W per square meter.
There are 4.5 peak sun hours of insolation, which means that the solar radiation is equivalent to 4.5 hours of 1000 watts per square meter. This is like if it were noon for 4.5 hours and then dark the rest of the day.
12% losses means that we lose 12% and we keep 88% of our production.

BASIC SYSTEM SIZING FACTORS

Example2 : If a 12V pump drew 5A for 2 hours, how much energy did it use and how many amp hours would it take from a 12V battery?

Energy calculation

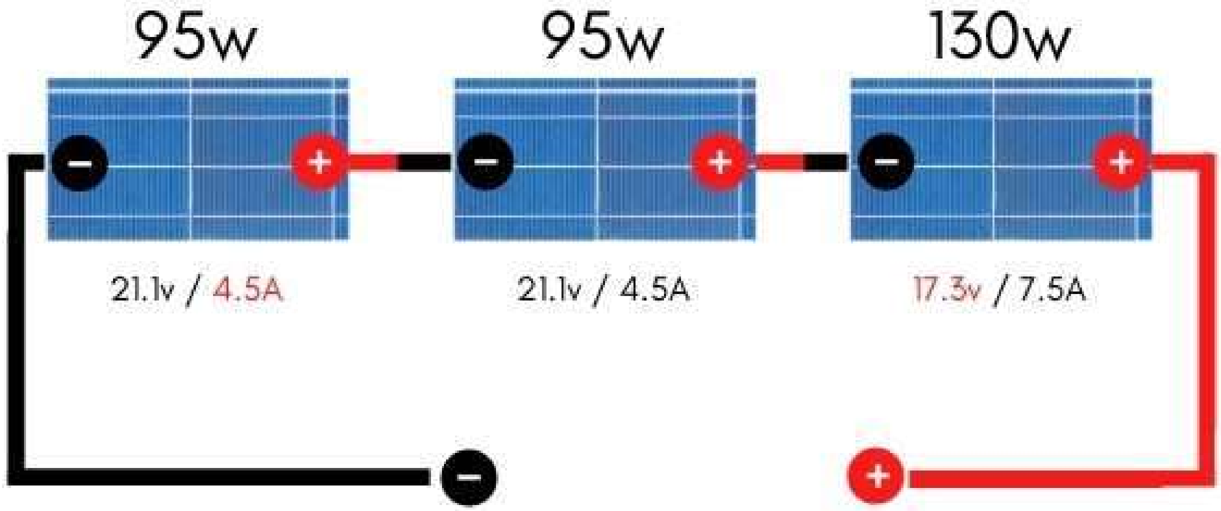
$12V \times 5A \times 2$ hours = 120Wh (not kWh)

There are different ways to calculate Ah for this problem.

120Wh/12V = 10Ah $5A \times 2$ hours = 10Ah

Remember that Ah are just Amps $\times$ hours

BASIC SYSTEM SIZING FACTORS



Total voltage = 21.1v + 21.1v + 17.3v = 59.5v

Total current = 4.5A

Total power = 59.5v x 4.5A = 267.75w

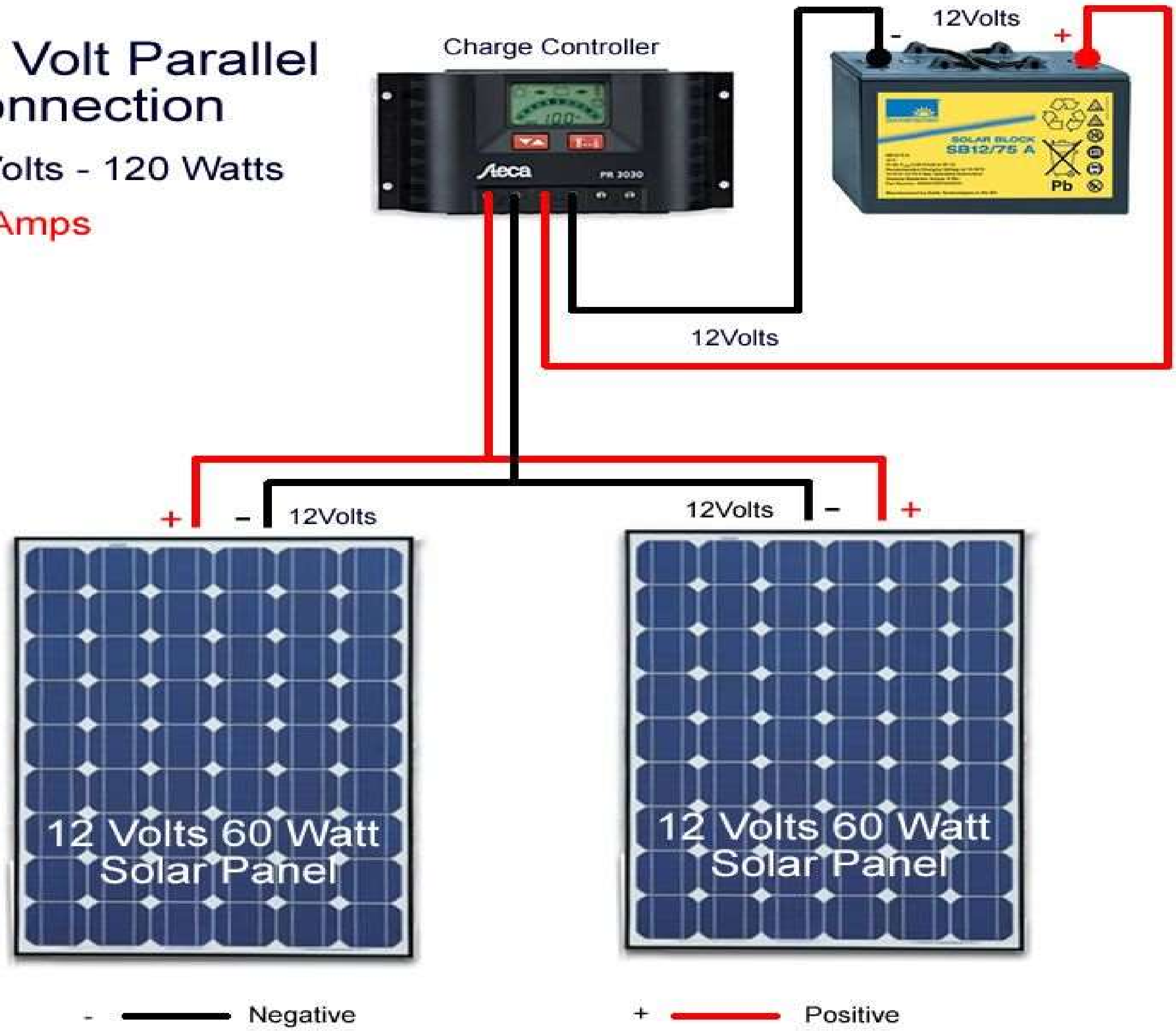
Loss = 16% of the 320w panels

BASIC SYSTEM SIZING FACTORS

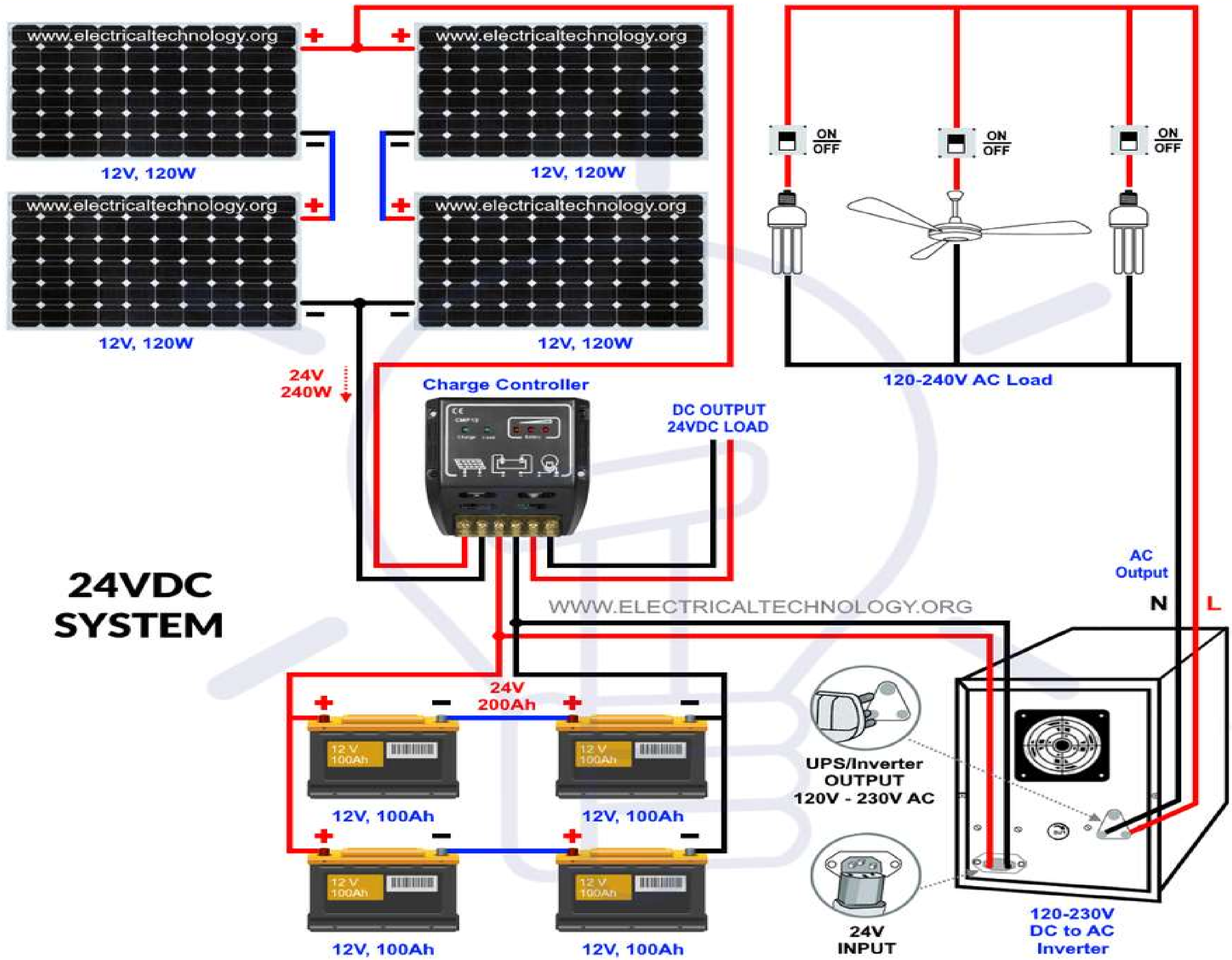
12 Volt Parallel Connection

12Volts - 120 Watts

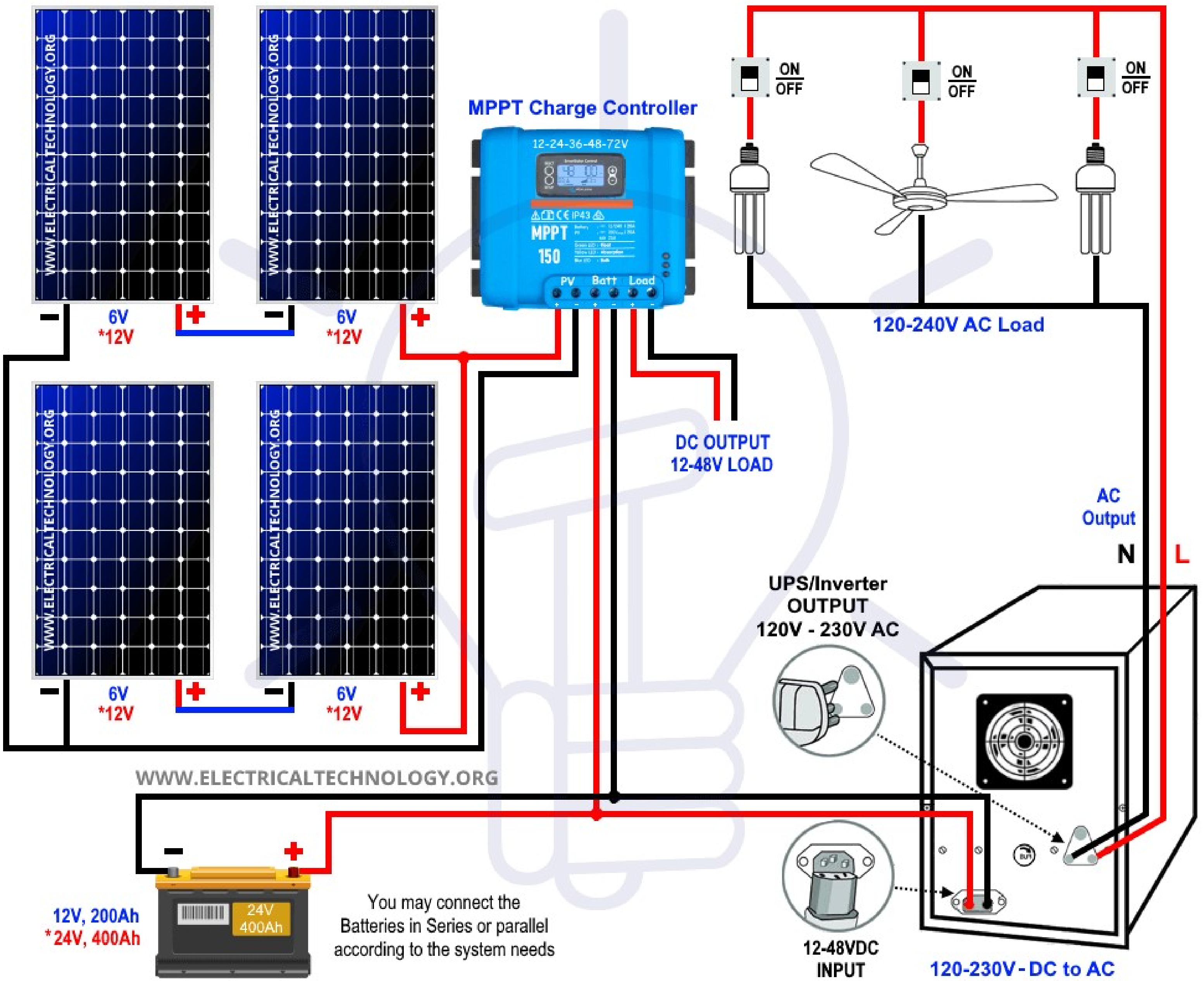
10 Amps



Solar Panels & Batteries in Series-Parallel Connection - 24V



How to Wire Solar Panels in Series-Parallel Connection



SYSTEM SIZING

Example3 : Calculate the annual energy output of the PV power plant which consist of 30 modules located at site having average daily global radiation of 4.1 [kwh/m2] and average ambient temperature is 35^{o} C . The specification of A PV module under the stander testing conditions are :

Number of cell	36 series	Short circuit current	9.2 A	NOC T	44 ^{o}C
Max power	150 W	Open circuit voltage	20.1 V		
Max power current	8.8 A	Max power voltage	17.1 V		

SYSTEM SIZING

Solution :

Annual energy (AE)= ? , 30 modules , daily G = 4.1 [KWh/m²] ,

Ta =35 C°

$$G = 4.1\ (KWh/m^2) = \frac{4.1\ KWh/m^2}{12\ h} = 0.342\ KW/m^2$$

$$I_{sc}\,(G) = I_{sc}\,(\text{at } 1\ Kw/m^2) \times G\ (\text{in } KW/m^2)$$

$$I_{sc}\,(G) = 9.2 \times 0.342 = 3.143\ [A]$$

$$Tc = T\alpha + \left(\frac{NocT - 20}{0.8}\right) \times G$$

$$Tc = 35 + \left(\frac{44-20}{0.8}\right) \times 0.342 = 45.25\ ^{o}C$$

$$V_{oc}\,(Tc) = V_{oc} - 0.0023 \times \text{No. of cells} \times (Tc-25)$$

$$V_{oc}\,(Tc) = 20.1 - 0.0023 \times 36 \times (45.25-25) = 18.423\ [V]$$

SYSTEM SIZING

Solution :

$$FF = \frac{Pmax}{Voc \times Isc} = \frac{150}{20.1 \times 9.2} = 0.811$$

$$Pmax\ (G,Tc) = Isc\ (G) \times Voc\ (Tc) \times FF$$

$$Pmax\ (G,Tc) = 3.143 \times 18.423 \times 0.811$$

$$Pmax\ (G,Tc) = 46.975\ [W]$$

$$C_f = \frac{P\ operating\ cond}{Pstc} = \frac{46.975}{150} = 0.313$$

$$AE = No.\ of\ modules \times P\ max \times C_f \times h\ in\ year$$

$$AE = 30 \times 150 \times 0.313 \times 8760$$

$$AE = 12344985.873\ [Wh/\ year]$$

$$AE = 12.345\ [MWh/\ year]$$