Renewable Energy Systems (12210588)

5. Photovoltaic Systems

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Lecture 5

How Solar Energy Works

- The **photons** (particles from light), hit the solar cell and some are absorbed in the area of the junction, **freeing** the **electrons** in the silicon crystal
- If the photons contain enough **energy**, the **electrons** will **converge** the electric field at the junction and will **move** freely through the silicon atoms in the cell and **move** into an external circuit as energy
- As they **move** through the external circuit they **release** their energy as electricity then **return** to the solar cell

http://www.solarinnova.net/en/products/photovoltaic/cells

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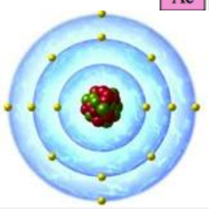
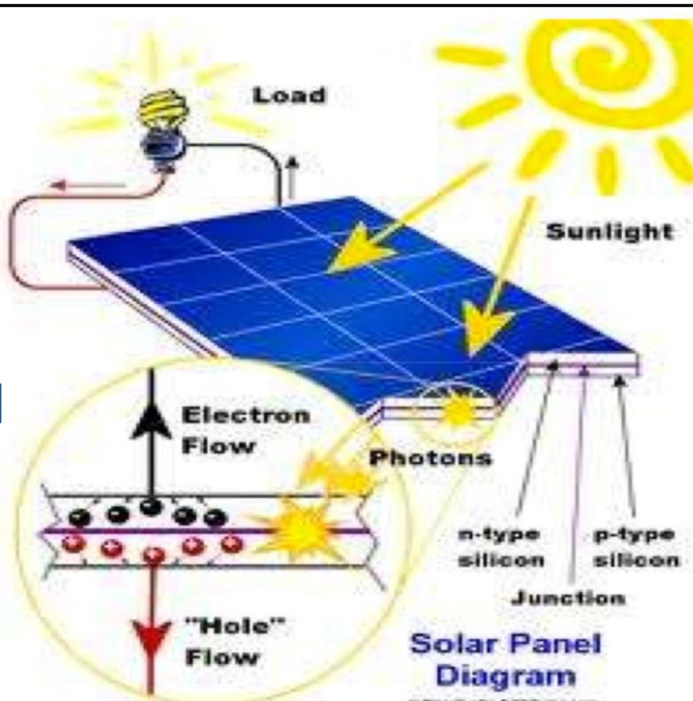
PV cells are mostly made of Silicon

↓Period / Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

http://en.wikipedia.org/wiki/Silicon



Solar panel



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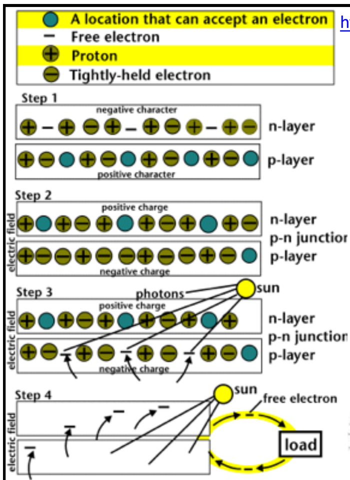
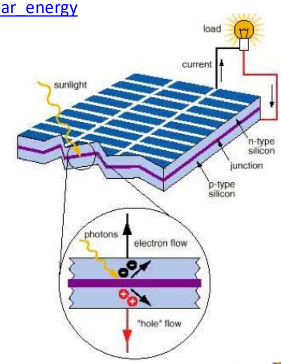
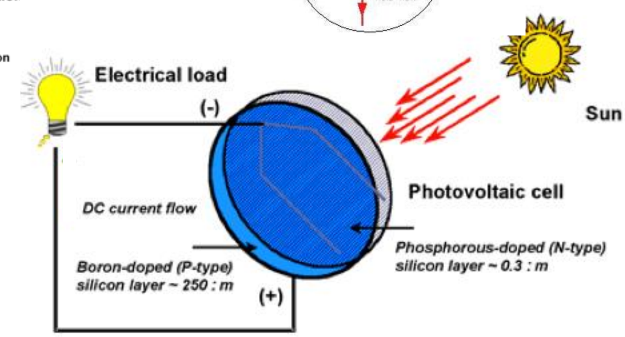


http://www.station57.org/solar_energy



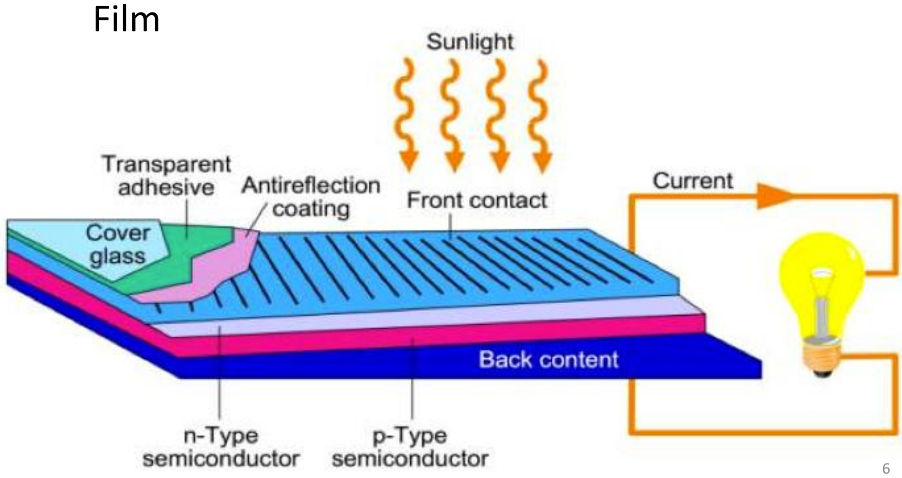
Photovoltaic cell



http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/how_pv_cells_work.htm

PV panels

- Mostly Silicon
- Crystalline, Microcrystalline, Amorphous & Thin Film



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Solar cell efficiency factors

Energy conversion efficiency

A solar cell's energy **conversion efficiency η** is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of the **maximum power point, P_m,** divided by the input **light irradiance** (**E**, in W/m^2) under standard test conditions (STC) and the surface **area** of solar cell (**A_c** in m^2).

$$\eta = \frac{P_m}{E\,A_c}$$

Castellano, R.N. 2010. Solar Panel Processing. Old City Publishing Inc., PA, USA.

Solar panel STC ratings

- **STC** stands for Standard Test Conditions
- **STC** specifies a **temperature** of **25°C** and an **irradiance** of **1000 W/m^2** with an air mass 1.5 (AM1.5) spectrum
- These correspond to the irradiance and spectrum of **sunlight incident** on a clear day upon a sun-facing 37°-tilted surface with the sun at an angle of 41.81° above the horizon
- Thus, under these conditions a solar cell of 12% efficiency with a 100 cm^2 (0.01 m^2) surface area can be expected to produce approximately 1.2 watts of power

https://www.intermtnwindandsolar.com/solar-panel-efficiency-understanding-stc-and-ptc-ratings/ 8

Solar panel PTC ratings

- **PTC** stands for Photovoltaics for Utility Scale Application Test Conditions
- If you want to know how PV panels will perform in the **real world**, look for their PTC ratings
- Under **PTC**, **lighting** conditions are the same as the STC, but the solar module is heated to a more realistic operating **temperature** of **45 °C**
- Since PV modules in the real world are exposed to **wind**, PTC testing keeps the air moving at **1.0 m/s**
- Generally, if no PTC value is listed in the specifications for a PV panel, you can expect it to be about **10** to **15% less efficient** than the STC rating

https://www.intermtnwindandsolar.com/solar-panel-efficiency-understanding-stc-and-ptc-ratings/ 9

Factors that affect solar panel efficiency

- Although **PTC ratings** offer a realistic view of photovoltaic output, they do **not** indicate **exact** energy production
- Several specific **factors** — known as **derate factors** — can reduce the amount of solar electricity created by a PV system
- Some factors, like **shading** on the photovoltaic panels, can be eliminated through the PV installation process.
- Other factors, including **energy conversion losses**, **wiring inefficiencies** and **module heating**, are unavoidable
- Module **efficiency ratings** reflect system performance in the "**perfect world**" of the lab environment
- Overall, **derate factors** typically **decrease** solar panel **efficiency** by about **14 %**.

https://www.intermtnwindandsolar.com/solar-panel-efficiency-understanding-stc-and-ptc-ratings/ 10

PV panel types

1. Monocrystalline

Monocrystalline solar cells are created from a single crystal and are cut from a block of crystal which has only grown in one direction (one plane). Single crystalline is more difficult to manufacturer, making a more expensive option with greater efficiency than the multicrystalline (polycrystalline cells)

2. Polycrystalline (Multicrystalline)

Polycrystalline solar cells are created from a multifaceted crystal which is cut from a block of crystal grown in multiple directions, making them slightly less efficient for the same size cells, meaning having a larger surface area for the same output

3. Amorphous Thin Film

Amorphous thin film panels are cheaper to manufacturer and the latest technologies are making them more efficient pushing them up to over 130 watt barrier, requiring larger areas for the same desired effect

Usually, mono from 170Wp to 245Wp and poly from 200Wp to 280Wp, making the modules a more financially viable prospect

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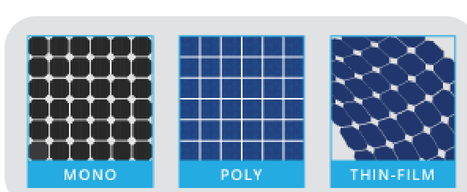
The major types of solar panels

Solar panel type	Advantages	Disadvantages
Monocrystalline	▪ High efficiency/performance ▪ Aesthetics	▪ Higher costs
Polycrystalline	▪ Low cost	▪ Lower efficiency/performance
Thin-film	▪ Portable and flexible ▪ Lightweight ▪ Aesthetics	▪ Lowest efficiency/performance



https://www.energysage.com/solar/101/types-solar-panels/

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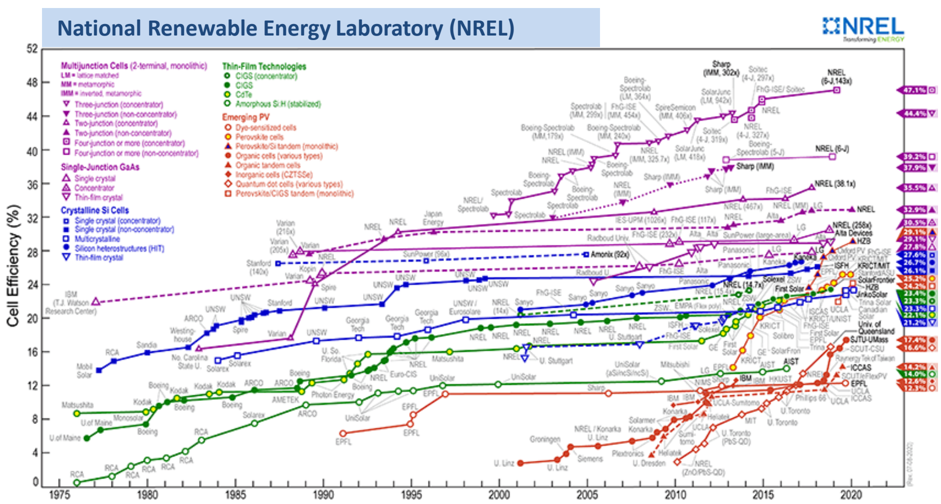
Best research-cell efficiency



https://www.nrel.gov/pv/cell-efficiency.html

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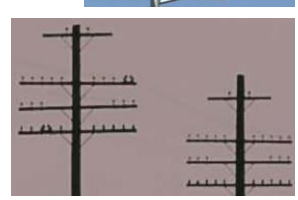
PV systems Applications

- Home solutions
- Solar street lights
- Solar water pumping system
- Garden lights
- Solar vehicles
- HVAC systems

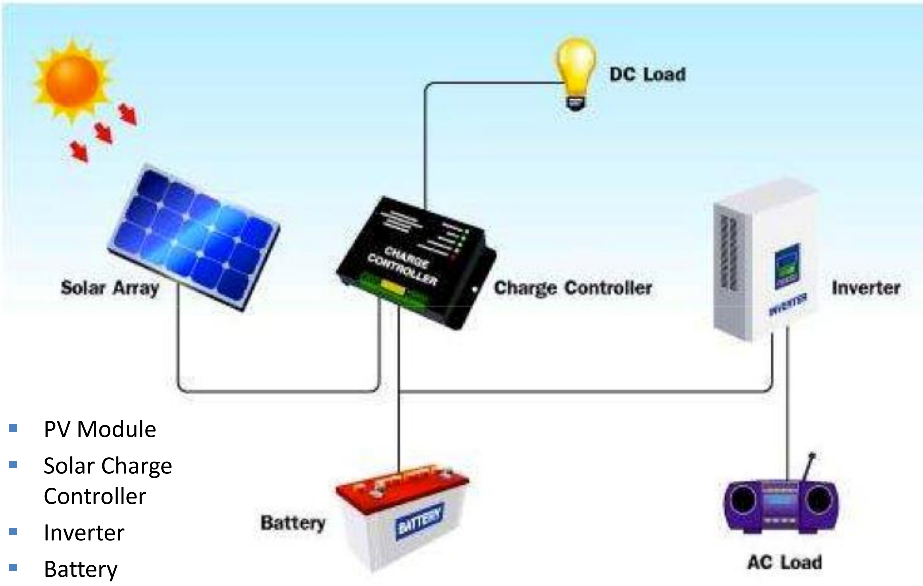
Battery systems

- Telecom towers
- Medical
- Electric vehicle
- Petrol & Diesel VS Hybrid



https://himaxelectronics.com/product-item/14-4v-prius-hev-hybrid-car-replacement-battery/

PV Components



- PV Module
- Solar Charge Controller
- Inverter
- Battery
- Loads (AC and DC)

https://silverbattery.in/products/solar-batteries/

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Inverter sizing

- An inverter is used in the system where AC power output is needed. The **input rating** of the inverter should never be lower than the total watt of appliances. The inverter must have the same **nominal voltage** as your battery
- For **stand-alone** systems, the inverter must be large enough to handle the total amount of Watts you use at one time. Inverter size should be **25 - 30%** bigger than total Watts of appliances
- In case of appliance type is **motor** or **compressor** then inverter size should be minimum **3 times** the capacity of those appliances and must be added to the inverter capacity to handle surge current during starting
- For **grid tie** systems, the input rating of the inverter should be same as PV array rating to allow for safe and efficient operation

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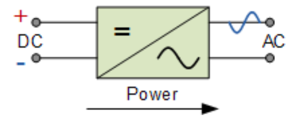
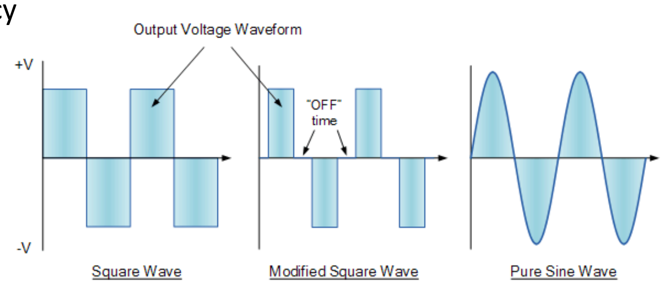
Basic Types of Inverters



- **Stand-alone solar system**
  - Square wave inverters: cheap of low quality output
  - True sine wave inverters: standard for commercial uses of high quality output to operate sensitive devices
  - Modified sine wave inverters: cheap of good conversion efficiency



- **Solar Inverters**
  - Grid tie inverters

https://www.alternative-energy-tutorials.com/solar-power/solar-power-inverter.html 17

Charge controllers

A **charge controller** or **charge regulator** is basically a voltage and/or current regulator to keep batteries from overcharging. It regulates the voltage and current coming from the solar panels going to the battery.

Charge controllers have two basic categories:

- **Pulse Width Modulation (PWM)**: PWM comes into play when the battery bank is full. PWM is used in locations that may also have a lot of constant, dependable sunshine — in deserts or the tropics. It is used in smaller, cost-sensitive systems
- **Maximum power point tracking (MPPT)**: They can adjust (or track) the input voltage and current of the PV array to find the optimum operating voltage that will generate the most power at a given moment. Generally, MPPT is more expensive and desirable since it can maximize output under challenging conditions.

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https://www.solarpowerworldonline.com/2019/12/how-to-select-a-solar-charge-controller/

Pros and Cons of Both Types of Controllers

	PWM	MPPT
Pros	1/3 – 1/2 the cost of a MPPT controller	Highest charging efficiency (especially in cool climates)
	Longer expected lifespan due to fewer electronic components and less thermal stress	Can be used with 60-cell panels
	Smaller size	Possibility to oversize array to ensure sufficient charging in winter months
Cons	PV arrays and battery banks must be sized more carefully and may require more design experience	2-3 times more expensive than a comparable PWM controller
	Cannot be used efficiently with 60-cell panels	Shorter expected lifespan due to more electronic components and greater thermal stress

https://www.phocos.com/wp-content/uploads/2019/11/Guide-Comparing-PWM-MPPT-Charge-Controllers.pdf

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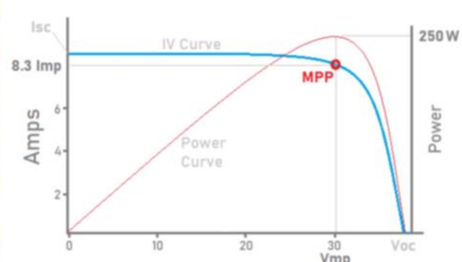
Characteristics of charge controllers

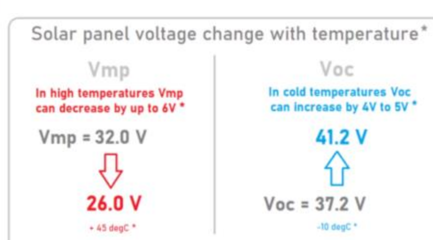
ELECTRICAL CHARACTERISTICS	
Maximum Power (Pmax)*	235 W
Tolerance of Pmax	+5%/-0%
PTC Rating	211.8 W
Type of Cell	Polycrystalline silicon
Cell Configuration	60 in series
Open Circuit Voltage (Voc)	37.2 V
Maximum Power Voltage (Vpm)	29.3 V
Short Circuit Current (Isc)	8.60 A
Maximum Power Current (Ipm)	8.02 A
Module Efficiency (%)	14.4%
Maximum System (DC) Voltage	600 V (UL)/1000V (IEC)
Series Fuse Rating	15 A
NOCT	47.5°C
Temperature Coefficient (Pmax)	-0.485%/°C
Temperature Coefficient (Voc)	-0.36%/°C
Temperature Coefficient (Isc)	0.053%/°C

*Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (ASTM E892 global spectral irradiance) at a cell temperature of 25°C.

Define these conditions?

https://www.thesolarplanner.com/pv_panel_features.html





https://www.cleanenergyreviews.info/blog/mppt-solar-charge-controllers

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Battery capacity

Battery **state of charge (SOC)** or **battery capacity %** is calculated using battery current, efficiency, and Peukert constant. To accurately measure battery **SOC**, a “**shunt**” is used to measure the current and rate of charge and discharge.

Peukert exponent is based on **Peukert law** which states: “As the rate of discharge increases, the battery’s capacity decreases.” Battery capacity changes according to the rate of discharge.

Battery type	Peukert exponent	Application
Lithium (e.g., Lithium Iron Phosphate)	1.00 – 1.05	Efficiency and warranty
Lead-acid gel (sealed) (SLA)	1.1 – 1.25	withstand high temps
Lead-acid AGM (Absorbed Glass Mat)	1.1 – 1.2	resist vibration
Lead-acid flooded (FLA)	1.2 – 1.5	most cost-effective

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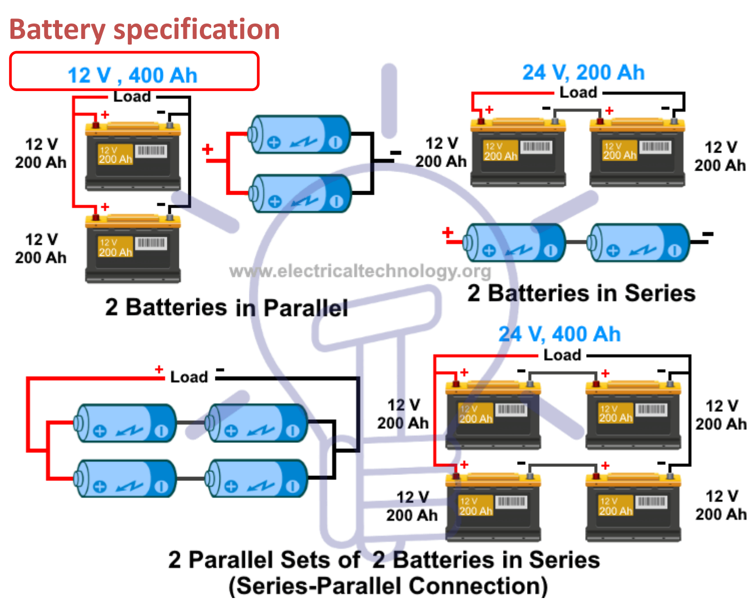
https://www.cleanenergyreviews.info/blog/mppt-solar-charge-controllers, https://www.wholesalesolar.com/blog/lead-acid-vs-lithium-batteries

Batteries Connection



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https://www.electricaltechnology.org/2013/11/series-parallel-and-series-parallel-connection-of-batteries.html

Solar PV system sizing I

1. Determine power consumption demands

The first step in designing a solar PV system is to find out the total power and energy consumption of all loads that need to be supplied by the solar PV system as follows:

1.1 Calculate total Watt-hours per day for each appliance used

Add the Watt-hours needed for all appliances together to get the total Watt-hours per day which must be delivered to the appliances.

1.2 Calculate total Watt-hours per day needed from the PV modules

Multiply the total appliances Watt-hours per day times **1.3** (the energy lost in the system) to get the total Watt-hours per day which must be provided by the panels

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Solar PV system sizing II

2. Size the PV modules

Different size of PV modules will produce different amount of power. To find out the sizing of PV module, the total peak watt produced is needed. The peak watt (W_p) produced depends on size of the PV module and the climate of the site location.

2.1 Divide the total peak watt by 5.5 sunshine hours/day

Assume the average annual solar insolation is 5.5 kWh/m^2/day and the solar irradiance is 1000 W/m^2.

2.2 Calculate the number of PV panels for the system

Divide the answer obtained in item 2.1 by the rated output Watt-peak of the PV modules available to you.

- Increase any fractional part of result to the next highest full number and that will be the number of PV modules required

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Solar PV system sizing III

3. Battery sizing

3.1 Calculate total Watt-hours per day used by appliances.

3.2 Divide the total Watt-hours per day used by 0.85 for battery loss.

3.3 Divide the answer obtained in item 3.2 by 0.6 for depth of discharge (DOD).

DOD is an alternate method to indicate a battery's state of charge (SOC). The DOD is the complement of SOC: as one increases, the other decreases. As a battery may actually have higher capacity than its nominal rating, it is possible for DOD value to exceed the full value (e.g., 55 Ah or 110% for a 50 Ah one).

3.4 Divide the answer obtained in item 3.3 by the nominal battery voltage.

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Cont. Solar PV system sizing III

3. Battery sizing

3.5 Multiply the answer obtained in item 3.4 by days of autonomy to get the required Ampere-hour (Ah) capacity of deep-cycle battery.

- **Days of autonomy (DA):** the number of days that you need the system to operate when there is no power produced by PV panels
- **Battery Capacity (Ah) = ?**

$$\frac{\text{Total Watt-hours per day used by appliances} \times \text{DA}}{0.85 \times 0.6 \times \text{Nominal battery voltage}}$$

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Solar PV system sizing IV

4. Solar charge controller sizing

- According to standard practice, the sizing of solar charge controller is to take the **short circuit current** (I_{sc}) of the PV array, and multiply it by 1.3
- Solar charge controller rating = Total short circuit current of PV array x 1.3

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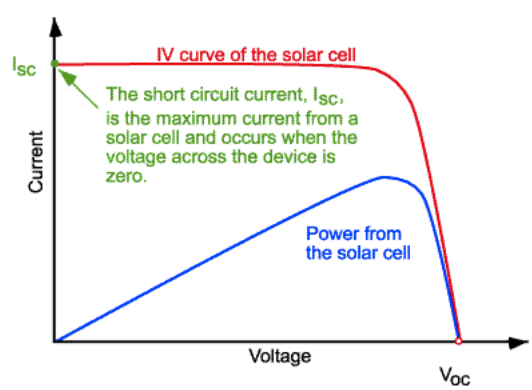
What is I_{SC}?

- The **short-circuit current** is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited)
- The short-circuit current depends on a number of **factors**:

1. area of the solar cell
2. number of photons
3. spectrum of the incident light (e.g., AM1.5)
4. optical properties (absorption and reflection)
5. collection probability



Example

A house has the following electrical appliance usage:

Appliance	Wattage (Watt)	Quantity	House usage (hour)
Energy saver	18	1	4
Fan	60	1	2
Refrigerant	75	1	12

Solution

1. Determine power consumption demands

Total PV panels energy needed = 1,092 x 1.3

= 1,419.6 Wh/day

2. Size and number the PV panel

Total W_p of PV panel capacity needed = 1,419.6/ 5.5

= 258.1 W_p

Number of PV panels needed = 258.10 round up to whole number 260 (Now consider the input DC voltage of Inverter i.e., 12, 24, 48 V)

if we consider

24 V then 260/2 → 130w x 2 panels are required

Solution

3. Inverter sizing

- Total Watt of all appliances = 18 + 60 + 75
  = 153 W
- For safety, the inverter should be considered 25-30% bigger size
- The inverter size should be about 198.9 W or greater
  - 198.9 / 153 = 1.3

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Solution

4. Battery capacity

- Total appliances use = (18 W x 4 hours) + (60 W x 2 hours) + (75 W x 12 hours) = 1,092 Wh/d
- Nominal battery voltage = 12 V
- Days of autonomy = 3 days

Battery capacity = 1,092 x 3 / (0.85x0.6x12)

- Total Ampere-hours required is 535.29 Ah

So the battery should be rated 12 V 600 Ah for 3 day autonomy. For 24 VDC input we need 300Ahx2 batteries or other suitable battery bank

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Solution

5. Solar charge controller sizing

- PV module specification
  - Pm=130 Wp
  - Vm = 17.3 V dc
  - Im = 7.51 A
  - Voc = 21.8 V
  - Isc =7.85 A
- Solar charge controller rating = (2 panels in series 24 volt so current 7.5 A)
- So the solar charge controller should be rated 10 A at 12/24 V auto selection or greater

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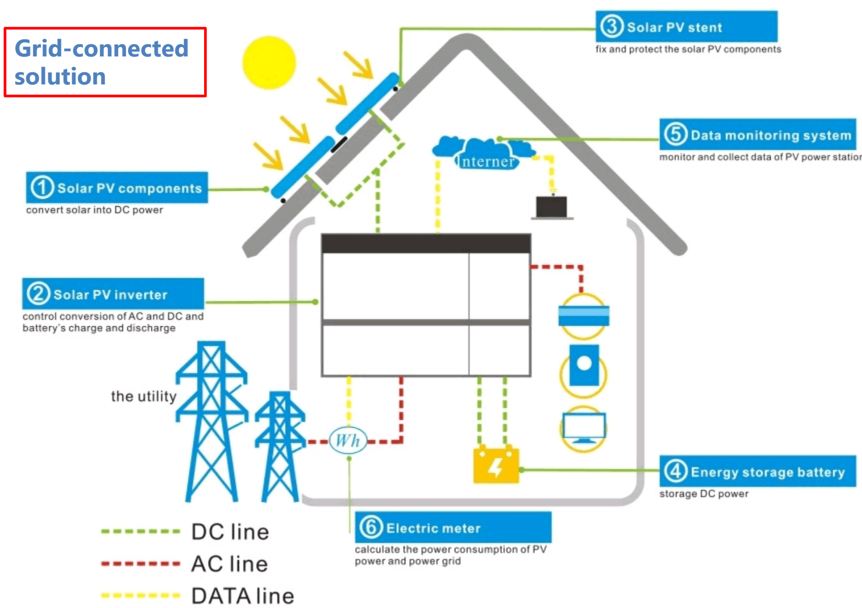
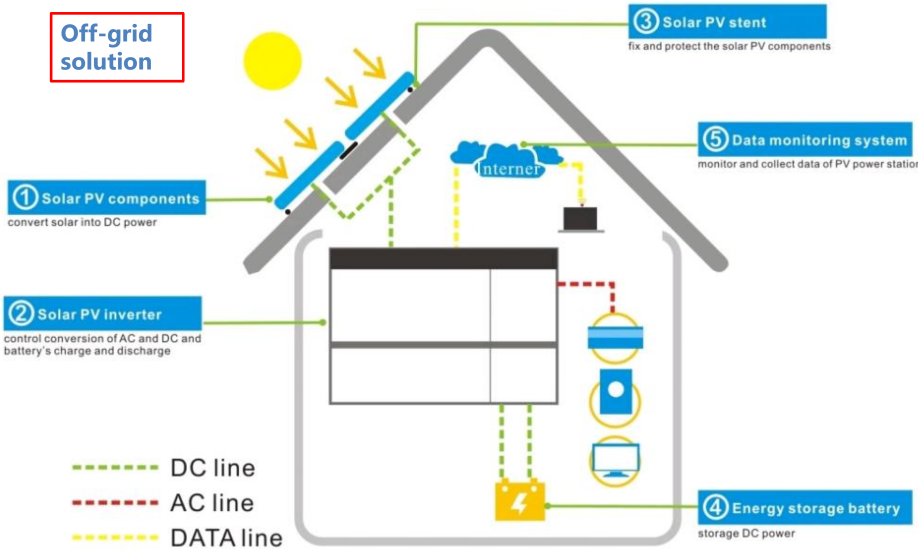
Household energy storage system's power solutions



https://himaxelectronics.com/household-energy-storage-systems-power-solutions/

Household energy storage system's power solutions



https://himaxelectronics.com/household-energy-storage-systems-power-solutions/

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United Nations Sustainable Development Goals (SDG)

SDG7: Ensure access to affordable, reliable, sustainable and modern energy

- While some **17%** of energy consumption is now met with **renewables**,
- **789** million people (**13%** of the globe) lack electricity
- **One** in **four** houses is not electrified in some developing countries

- Energy services are key to preventing disease and fighting pandemics, e.g., COVID-19
- Renewable energy sources can provide sustainable energy and clean freshwater to healthcare facilities

https://sdgs.un.org/goals/goal7

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