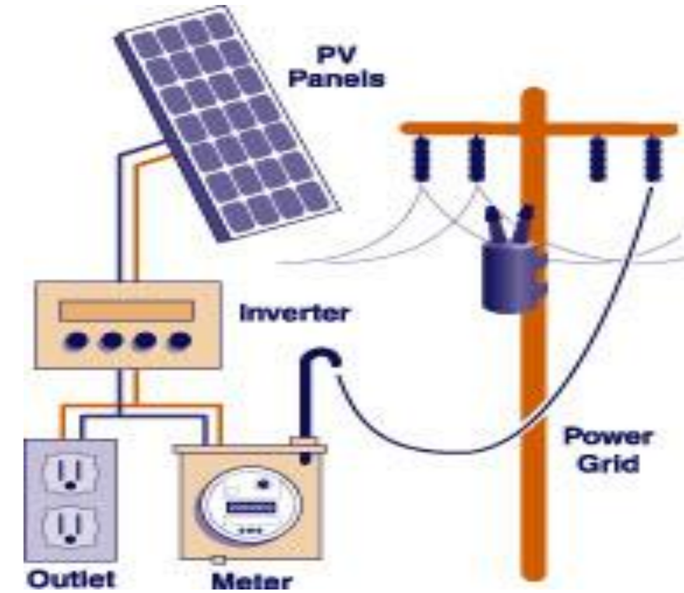
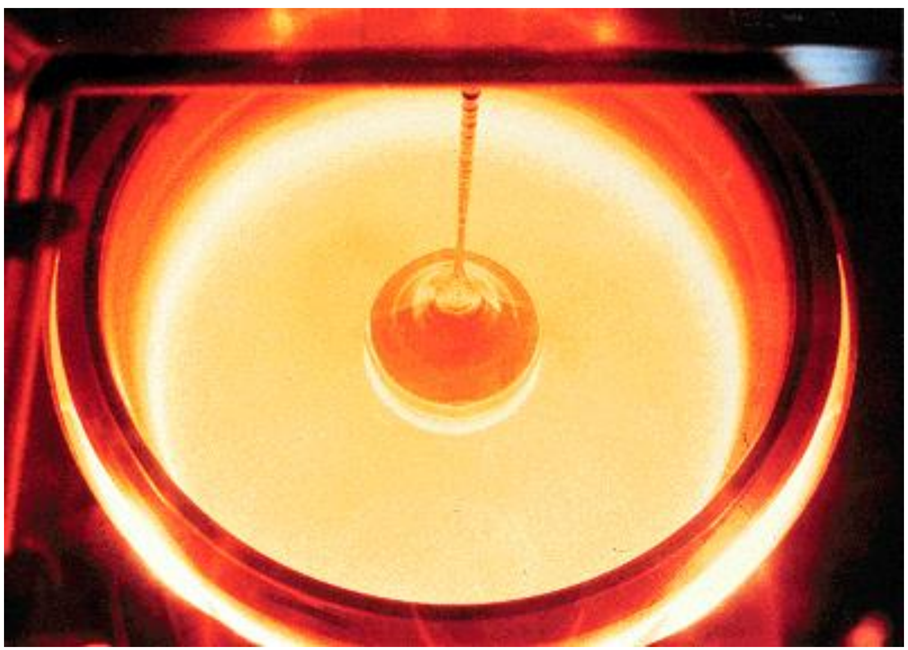
L8 part 2

Photovoltaic Materials and characteristics





ENEE5307 Renewable Energy & PV Energy Systems

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BZU-2021

Introduction

- **A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be *photovoltaic*.**
- **A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it.**
- **If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current.**
- **The driving force to power photo-voltaics comes from the sun, and it is interesting to note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand.**

History (1839)

- **In 1839 when a 19-year-old French physicist, Edmund Becquerel, was able to cause a voltage to appear when he illuminated a metal electrode in a weak electrolyte solution .**
- **In 1876,** ***Adams*** and ***Day*** were the first to study the photovoltaic effect in solids .
- They were able to build cells made of selenium that were 1% to 2% efficient.

History (early 1900s)

- **In 1904, As part of his development of quantum theory, <u>Albert Einstein</u> published a theoretical explanation of the photovoltaic effect, which led to a Nobel Prize in 1923.**
- About the same time, in what would turn out to be a cornerstone of modern electronics in general, and photovoltaics in particular, a Polish scientist by the name **of Czochralski began** to develop a method to grow perfect crystals of silicon.
- By the 1940s and 1950s, the Czochralski process began to be used to make the first generation of single-crystal silicon photo-voltaics, and that technique continues to dominate the photovoltaic (PV) industry today.

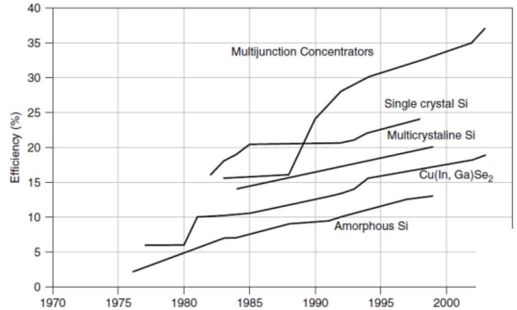
History (1950s)

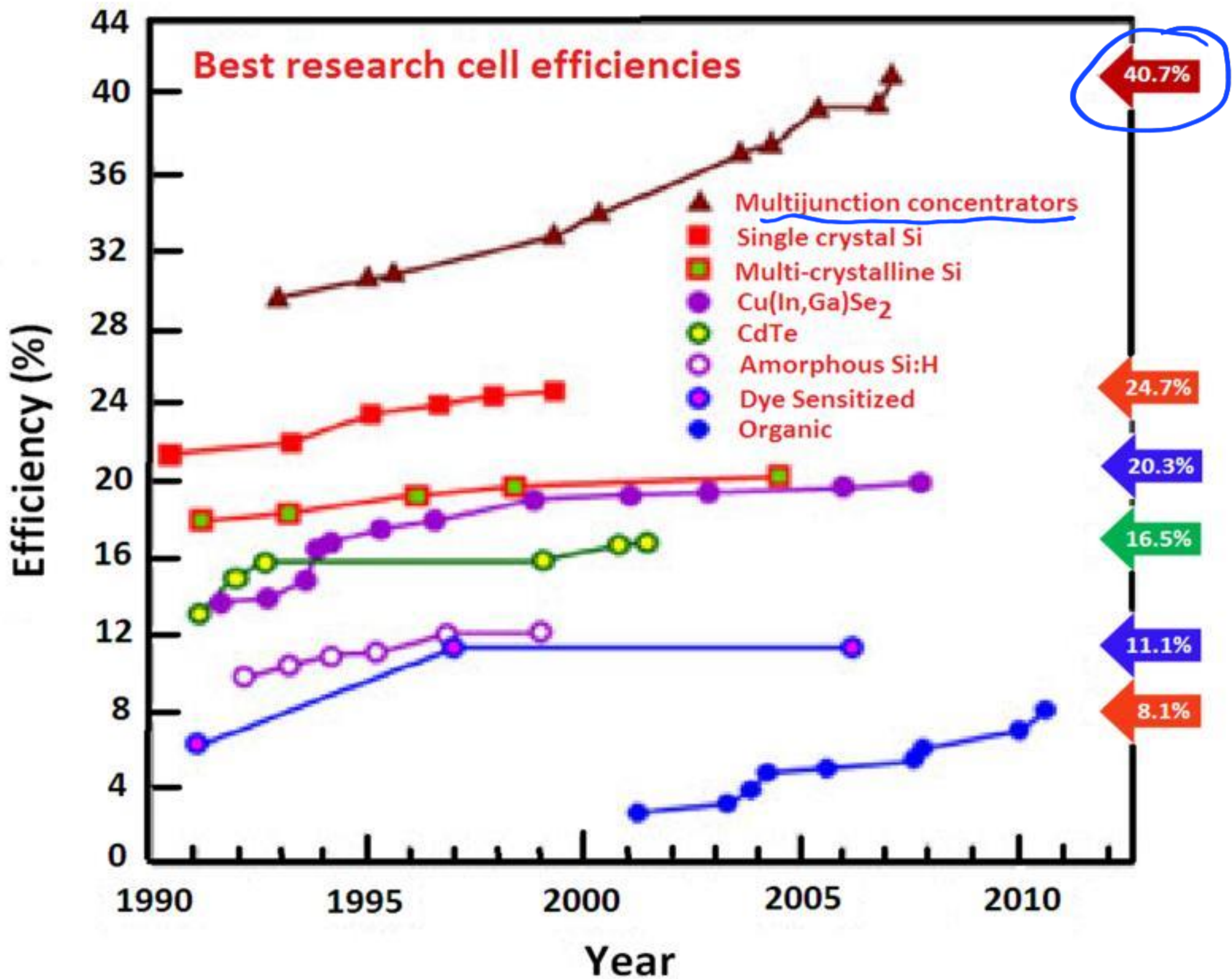
- In the 1950s there were several attempts to commercialize PVs, but their cost was prohibitive.
- The real emergence of PVs as a practical energy source came in **1958** when they were first used in **space** for the Vanguard I satellite.
- For space vehicles, cost is much less important than weight and reliability, and solar cells have ever since played an important role in providing onboard power for satellites and other space craft.
- Spurred on by the emerging energy crises of the 1970s, the development work supported by the space program began to pay off back on the ground

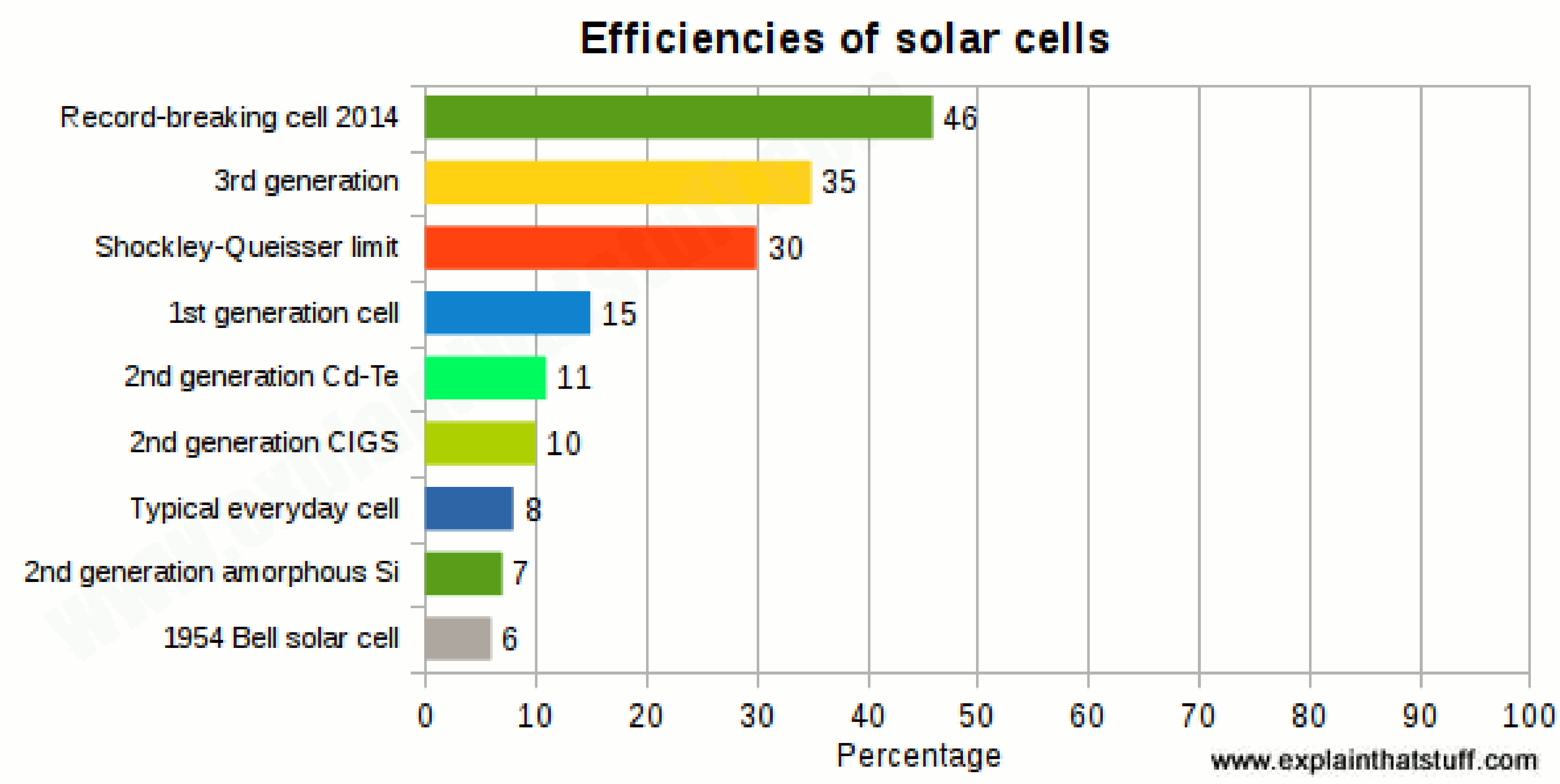
History (1980s)

- By the late 1980s, higher efficiencies and lower costs brought PVs closer to reality, and they began to find application in many off-grid terrestrial applications such as pocket calculators, highway lights, signs and emergency call boxes, rural water pumping, and small home systems.
- The cost of photovoltaic power did drop dramatically in the 1990s, and it is becoming competitive with other power sources

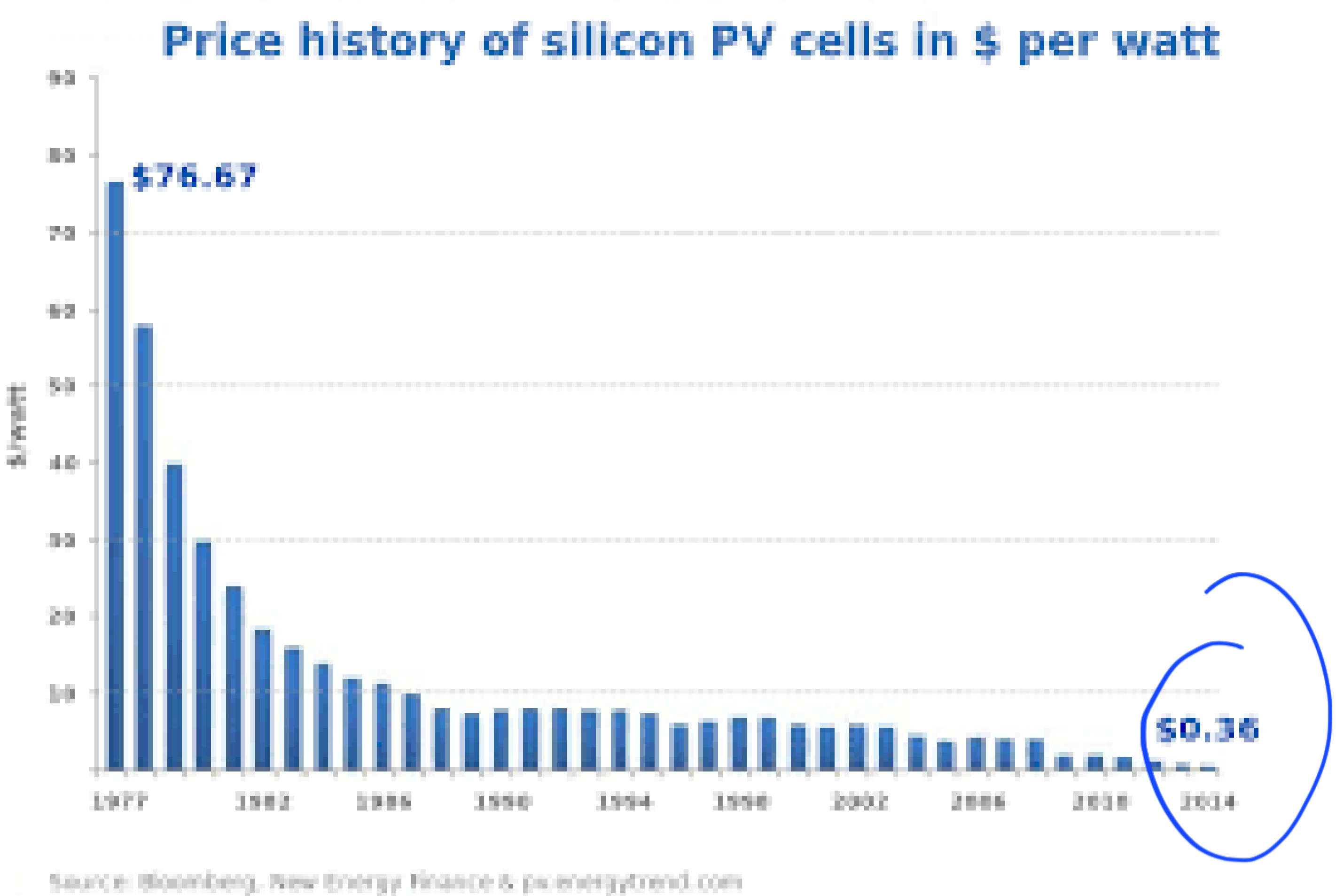
Efficiency of PV cells





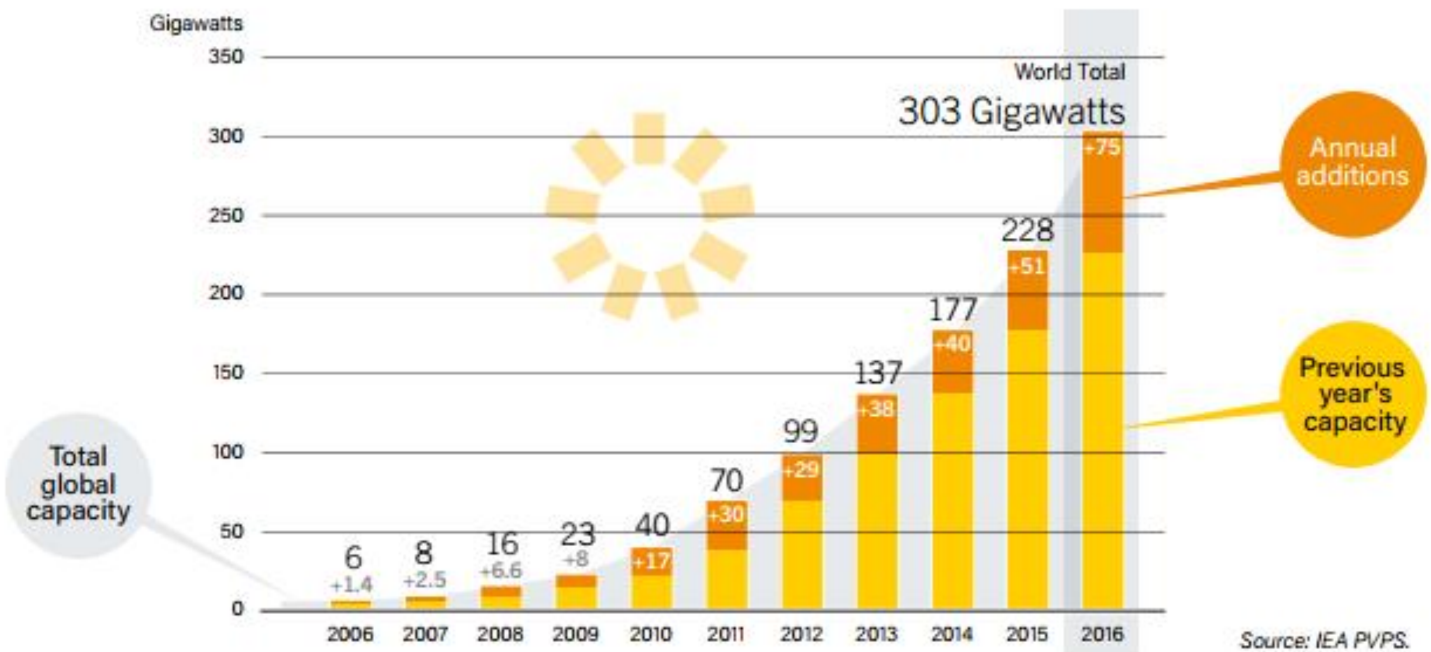


Efficiencies of solar cells
Record-breaking cell 2014
3rd generation
Shockley-Queisser limit
1st generation cell
2nd generation Cd-Te
2nd generation CIGS
Typical everyday cell
2nd generation amorphous Si
1954 Bell solar cell
46
35
30
15
11
10
8
7
6
0
10
20
30
40
50
60
70
80
90
100
Percentage
www.explainthatstuff.com

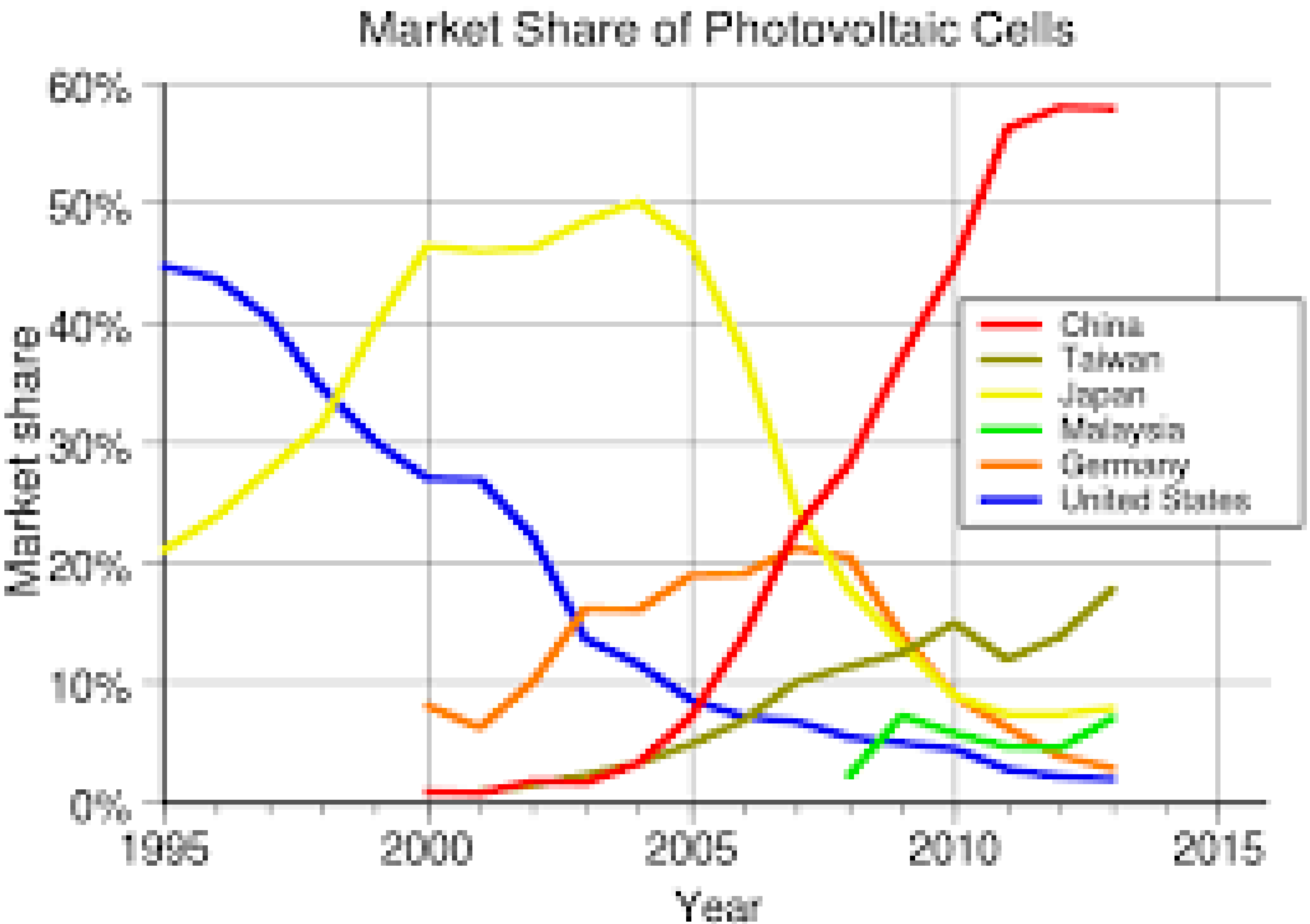

Price history of silicon PV cells in $ per watt
$/watt
$76.67
$0.36
1977
1982
1986
1990
1994
1998
2002
2006
2010
2014
Source: Bloomberg, New Energy Finance & pv.energytrend.com

Global PV Capacity

Solar PV Global Capacity and Annual Additions, 2006-2016

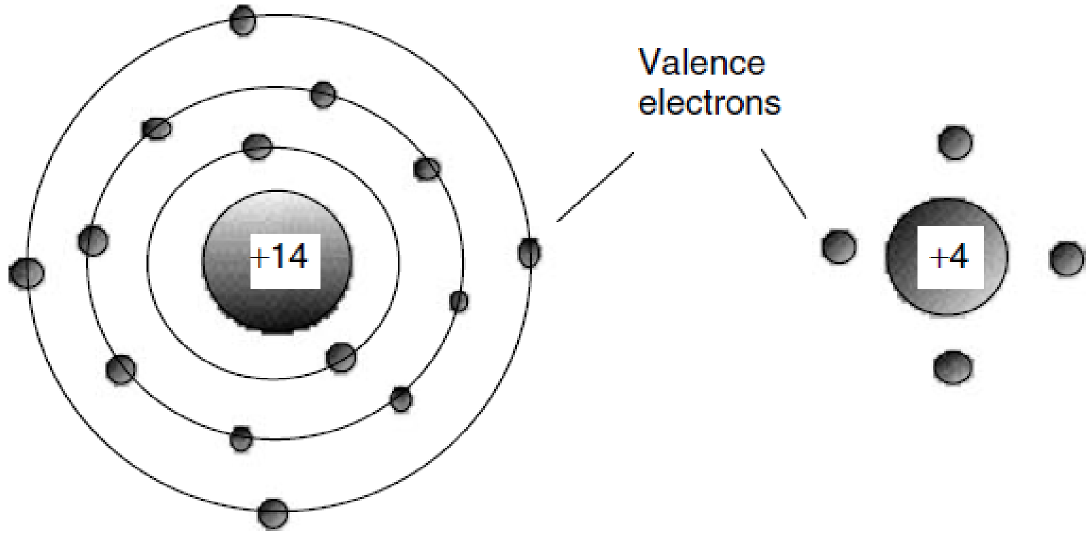


During 2016, at least **75 GW** of solar PV capacity was added worldwide – equivalent to the installation of more than **31,000 SOLAR PANELS EVERY HOUR.**

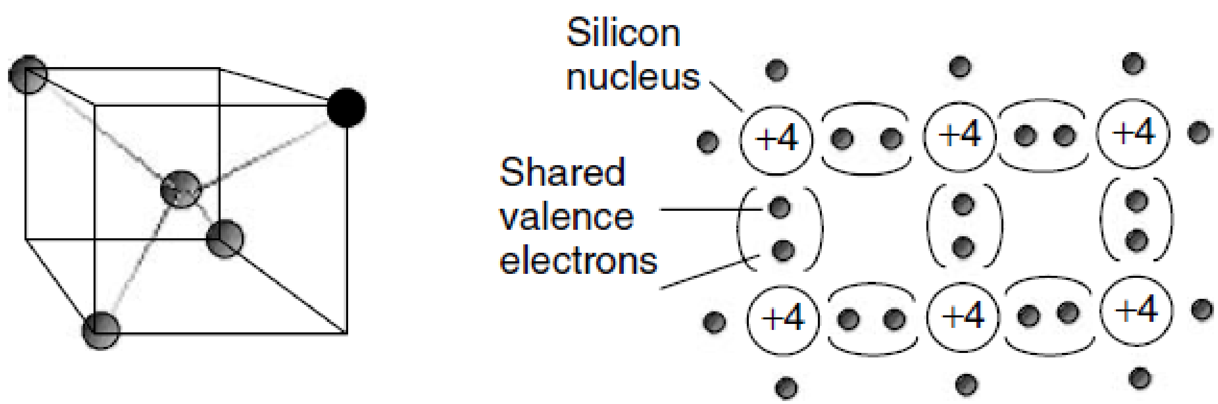


Market Share of Photovoltaic Cells
60%
50%
40%
30%
20%
10%
0%
Market share
1995
2000
2005
2010
2015
Year
China
Taiwan
Japan
Malaysia
Germany
United States

- **Silicon Atom and crystal are shown**



(a) Actual (b) Simplified

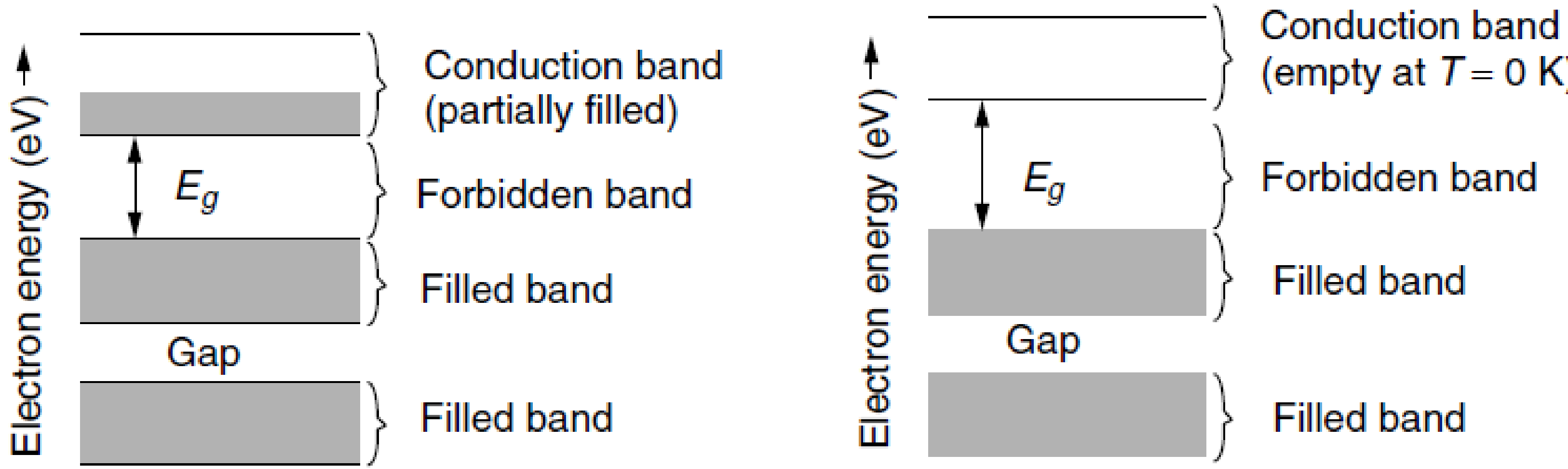


(a) Tetrahedral (b) Two-dimensional version

<u>Band Gap Energy</u>

- The energy that an electron must acquire to jump across the forbidden band to the conduction band is called the band-gap energy, designated *Eg*.
- **The units for band-gap energy are usually electron-volts (eV), where one electron-volt is the energy that an electron acquires when its voltage is increased by 1 V** (1 eV = 1.6 × 10^−19 J).

Energy Bands

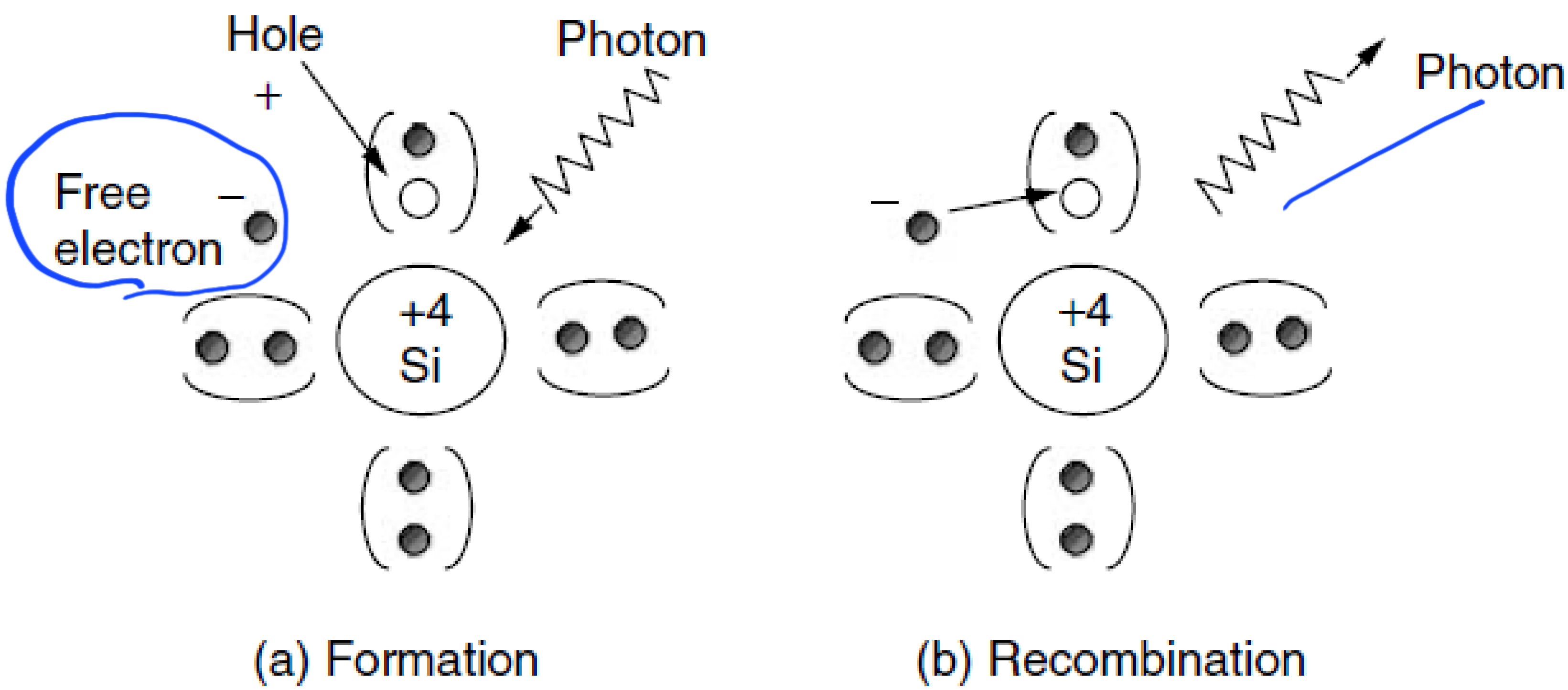


(a) Metals (b) Semiconductors

- Energy bands for (a) metals and (b) semiconductors.
- Metals have partially filled conduction bands, which allows them to carry electric current easily.
- Semiconductors at absolute zero temperature have no electrons in the conduction band, which makes them insulators.

eV – electron volt is a unit of energy equal to approximately 1.6×10^{-19} joules

- The band-gap *Eg* for silicon is 1.12 eV, which means an electron needs to acquire that much energy to free itself from the electrostatic force that ties it to its own nucleus—that is, to jump into the conduction band.
- Where might that energy come from?
- We already know that a small number of electrons get that energy thermally.
- For photovoltaics, the energy source is photons of electromagnetic energy from the sun.
- When a photon with more than 1.12 eV of energy is absorbed by a solar cell, a single electron may jump to the conduction band.
- When it does so, it leaves behind a nucleus with a +4 charge that now has only three electrons attached to it.
- That is, there is a net positive charge, called a *hole*, associated with that nucleus



A photon with sufficient energy can create a hole–electron pair as in (a).
The electron can recombine with the hole, releasing a photon of energy (b).

Photon Energy

- Thus, photons with enough energy create hole–electron pairs in a semiconductor.
- Photons can be characterized by their **wavelengths** or their **frequency** as well as by their **energy**; the three are related by the following:
- $$c = \lambda \nu$$
- where c is the speed of light (3 × 10^8 m/s),
- ν - is the frequency (hertz),
- λ - is the wavelength (m), and
- $$E = h\nu = hc/\lambda$$
- Where E is the energy of a photon (J) and h is Planck's constant (6.626 × 10^−34 J-s).

- **Example: photon to create hole –electron pair in Silicon**

What is the maximum wavelength can a photon have to create hole-electron pairs in Silicon?

What minimum frequency is that?

Si has a band-gap of 1.12 eV (1 eV=1.6x10^-19 J)

micron

Solution. From (8.2) the wavelength must be less than

$$\lambda \leq \frac{hc}{E} = \frac{6.626 \times 10^{-34}\ \mathrm{J \cdot s} \times 3 \times 10^{8}\ \mathrm{m/s}}{1.12\ \mathrm{eV} \times 1.6 \times 10^{-19} \mathrm{J/eV}} = 1.11 \times 10^{-6}\ \mathrm{m} = 1.11\ \mu\mathrm{m}$$

and from (8.1) the frequency must be at least

$$\nu \geq \frac{c}{\lambda} = \frac{3 \times 10^{8}\ \mathrm{m/s}}{1.11 \times 10^{-6}\ \mathrm{m}} = 2.7 \times 10^{14}\ \mathrm{Hz}$$

Summary

- **For a silicon photovoltaic cell, photons with wavelength greater than 1.11 μm have energy less than the 1.12 eV band-gap energy needed to excite an electron.**
- On the other hand, photons with wavelengths shorter than 1.11 μm have more than enough energy to excite an electron.
- Since one photon can excite *only* one electron, any extra energy above the 1.12 eV needed is also dissipated as waste heat in the cell.
- The band gaps for other photovoltaic materials—gallium arsenide (GaAs), cadmium telluride (CdTe), and indium phosphide (InP), in addition to silicon—are shown later.
- **These two phenomena relating to photons with energies above and below the actual band gap establish a maximum theoretical efficiency for a solar cell. To explore this constraint, we need to introduce the solar spectrum.**

Solar Spectrum (AM=1.5)

- Photons with wavelengths above 1.11 μm don't have the 1.12 eV needed to excite an electron, and this energy is lost.
- Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV is wasted as well.

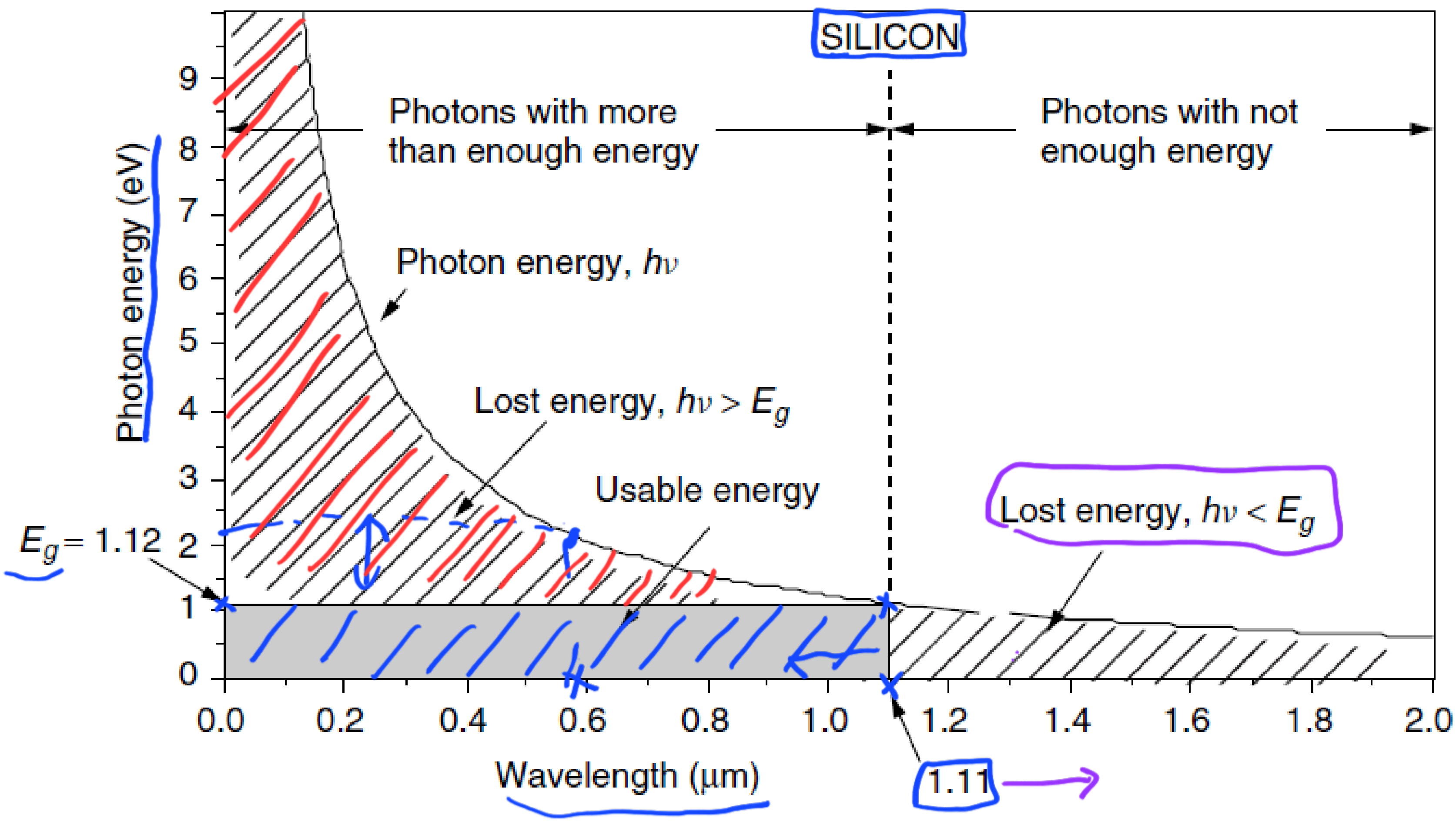
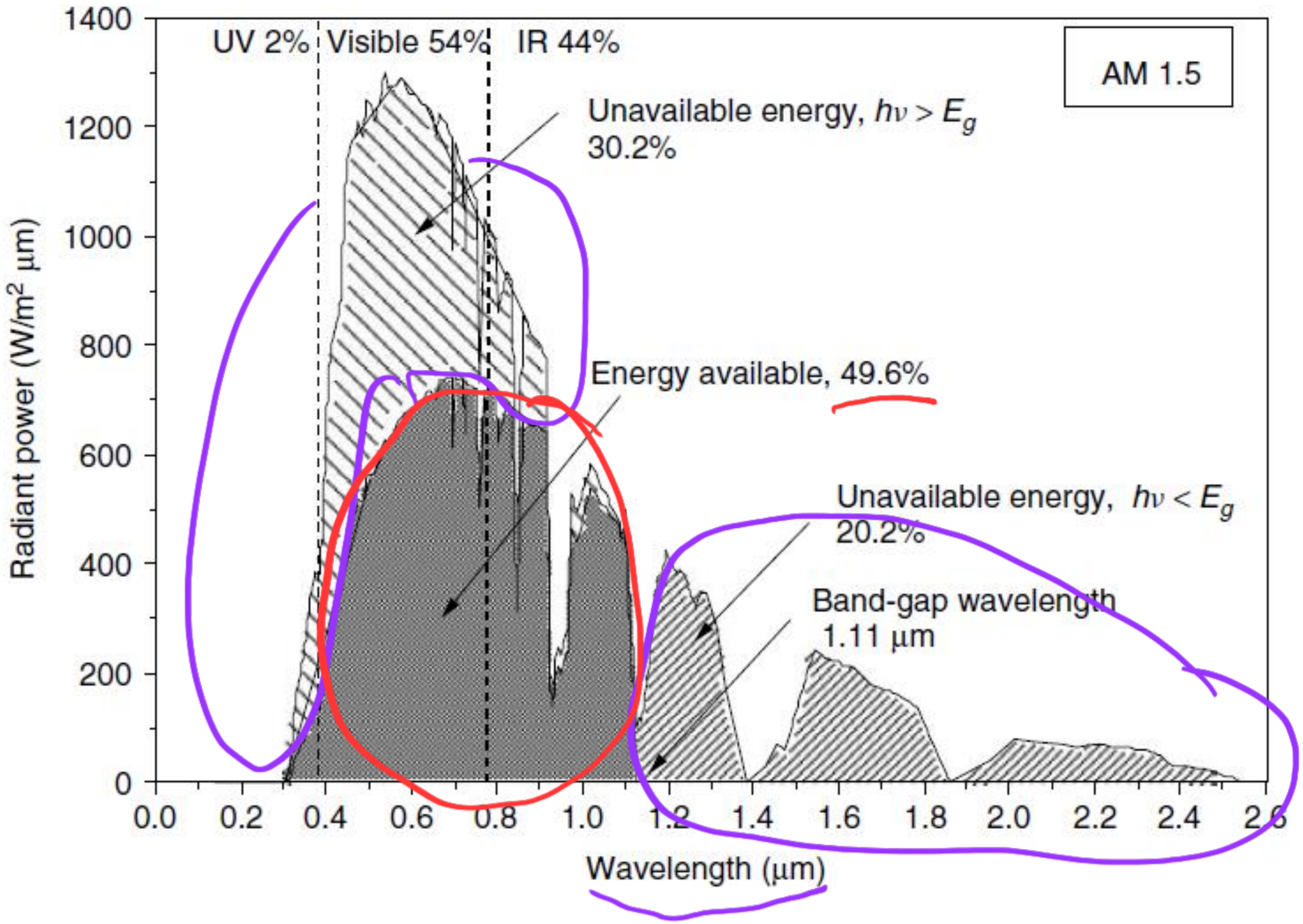


TABLE 8.2 Band Gap and Cut-off Wavelength Above Which Electron Excitation Doesn't Occur

Quantity	Si	GaAs	CdTe	InP
Band gap (eV)	1.12	1.42	1.5	1.35
Cut-off wavelength (μm)	1.11	0.87	0.83	0.92



- Photons with wavelengths longer than 1.11 μm don't have enough energy to excite electrons (20.2% of the incoming solar energy);
- Those with shorter wavelengths can't use all of their energy, which accounts for another 30.2% unavailable to a silicon photovoltaic cell.

Photovoltaic Efficiency

- The remaining 49.6% represents the maximum possible fraction of the sun's energy that could be collected with a silicon solar cell.
- **That is, the constraints imposed by silicon's band gap limit the efficiency of silicon to just under 50%.**
- There are other constraints to PV efficiency, mainly black-body radiation losses and recombination.
- Cells in the sun get hot, which mean their surface radiate energy proportional to the fourth power of their temperature
- This accounts for 7% losses
- Hole saturation effects in silicon can result in another 10% losses …(see main reference book)

Photovoltaic Efficiency

- Notice that the efficiencies of Si PV cells are well below the 49.6% due to other factors such as:

- 1. Recombination of holes and electrons before they can contribute to current flow.
- 2. Photons that are not absorbed in the cell either because they are reflected off the face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.
- 3. Internal resistance within the cell, which dissipates power.

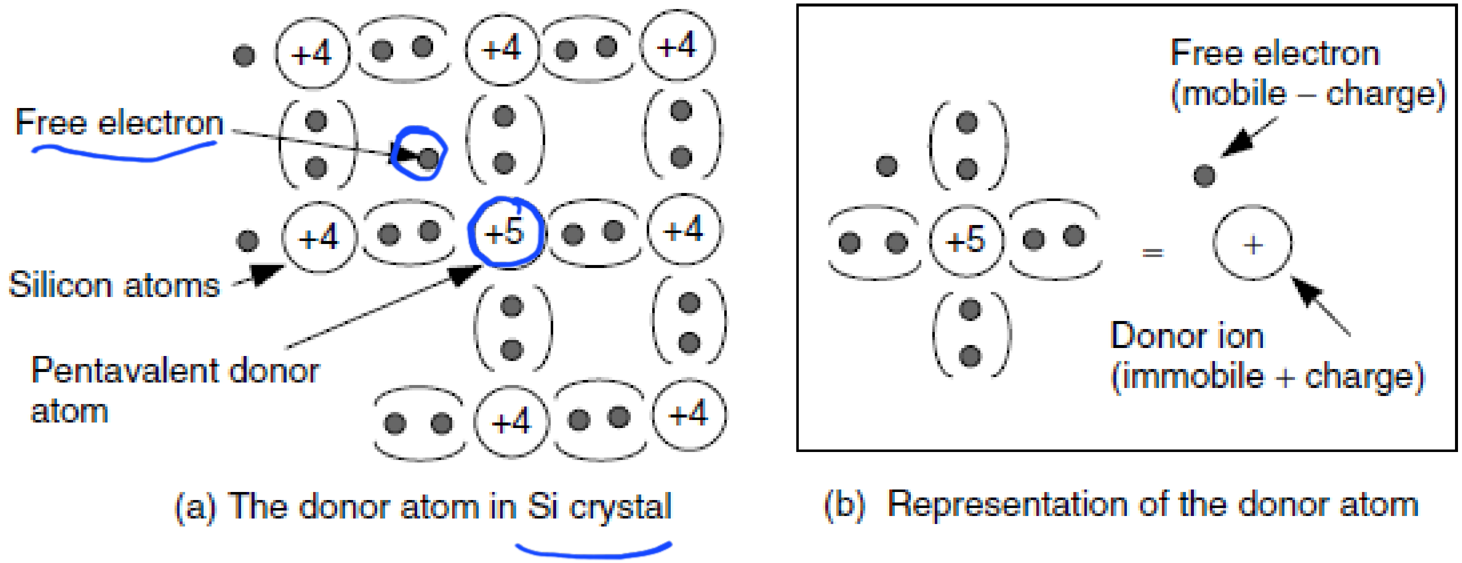
The p-n Junction (reminder)

- As long as a solar cell is exposed to photons with energies above the bandgap energy, hole–electron pairs will be created.
- The problem is, of course, that those electrons can fall right back into a hole, causing both charge carriers to disappear.
- **To avoid that recombination, electrons in the conduction band must continuously be swept away from holes.**
- In PVs this is accomplished by creating a built-in electric field within the semiconductor itself that pushes electrons in one direction and holes in the other.

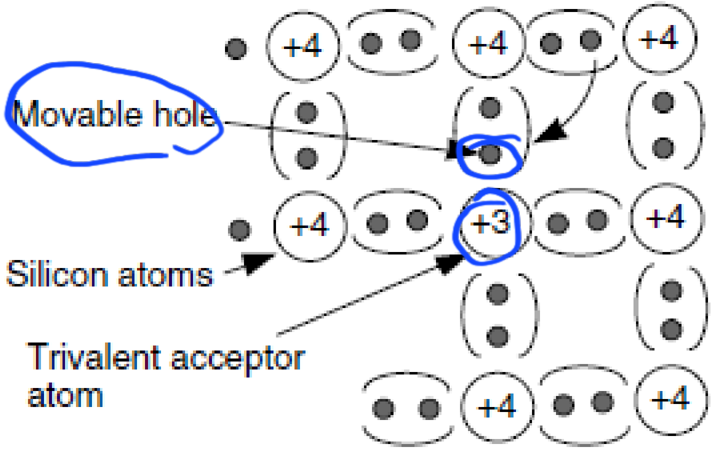
Electric Field

- To create the electric field, two regions are established within the crystal.
- On one side of the dividing line separating the regions, pure (intrinsic) silicon is purposely contaminated with very small amounts of a trivalent element from column III of the periodic chart;
- On the other side, pentavalent atoms from column V are added.

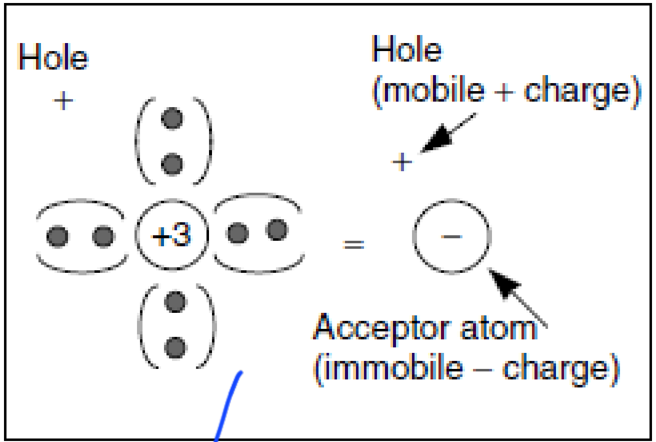
n-type



An *n*-type material.
(a) The pentavalent donor.
(b) The representation of the donor as a mobile negative charge with a fixed, immobile positive charge

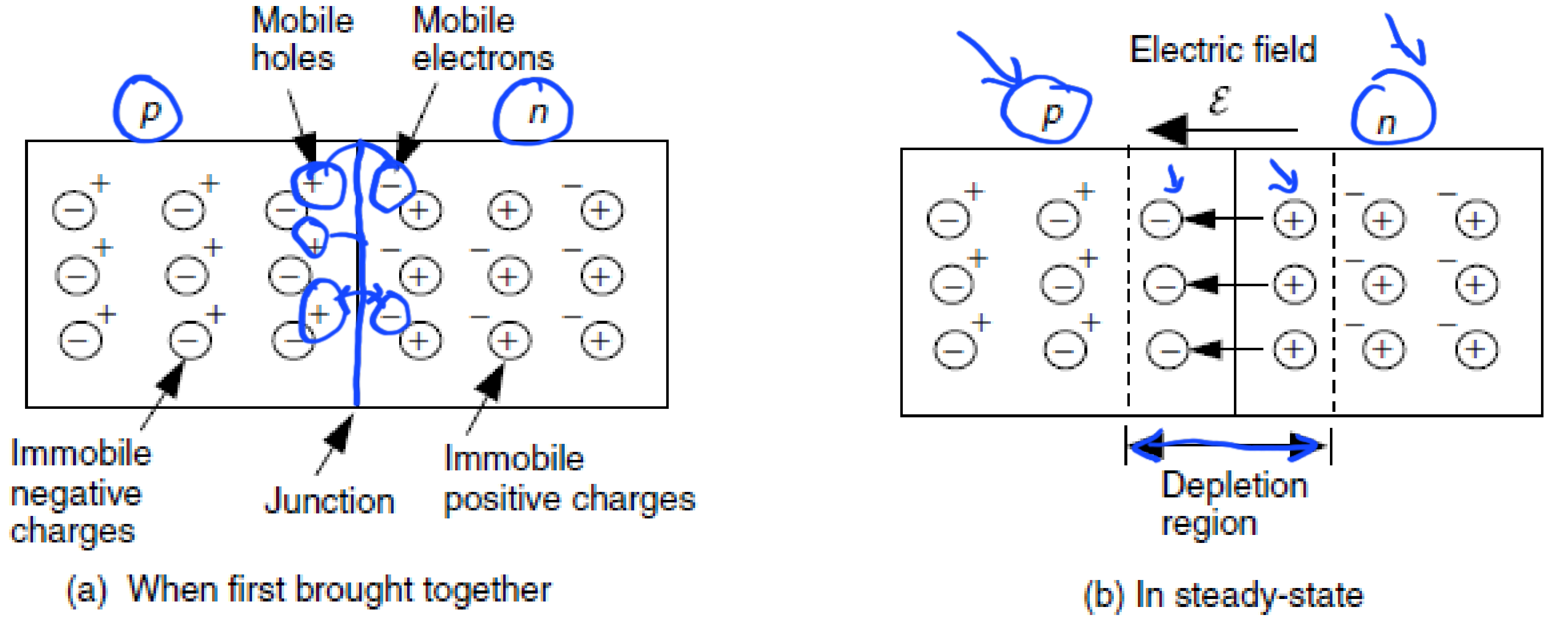


(a) An acceptor atom in Si crystal



(b) Representation of the acceptor atom

In a *p*-type material, trivalent acceptors contribute movable, positively charged holes leaving rigid, immobile negative charges in the crystal lattice.



(a) When a *p*–*n* junction is first formed, there are mobile holes in the *p*-side and mobile electrons in the *n*-side.

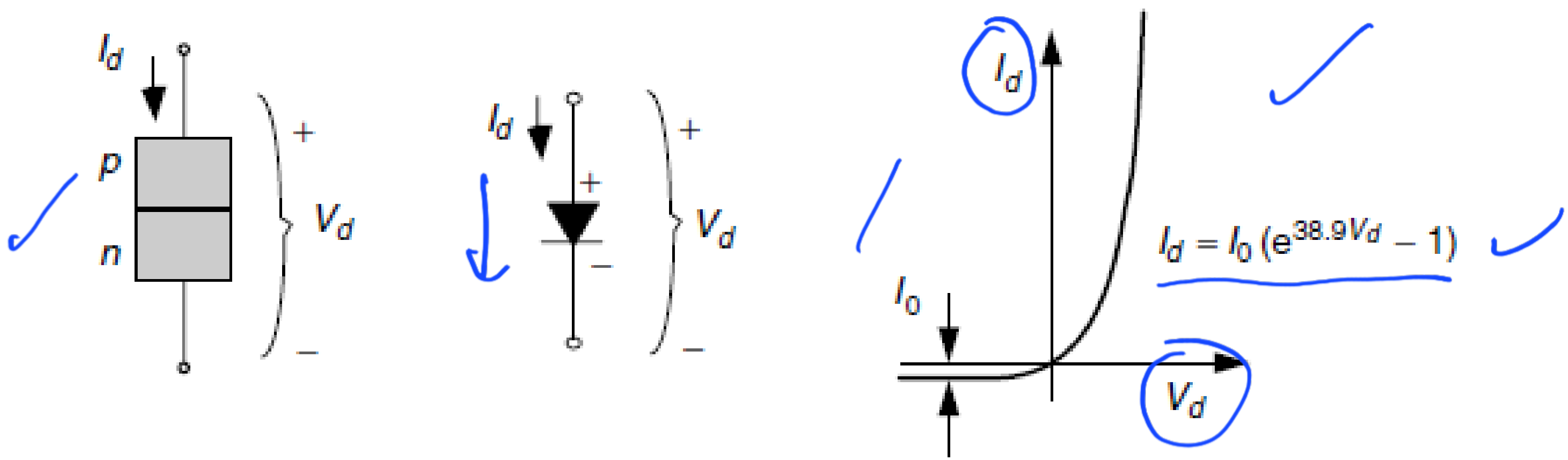
(b) As they migrate across the junction*, an electric field builds up that opposes, and quickly stops, diffusion.

- As the diffusion process continues, the electric field countering that movement increases until eventually (actually, almost instantaneously) all further movement of charged carriers across the junction stops.
- This is a pn junction (Diode)

The *p–n* Junction Diode

- Anyone familiar with semiconductors will immediately recognize that what has been described thus far is just a common, conventional *p–n* junction diode.
- :

$$I_d = I_0(e^{qV_d/kT} - 1)$$



(a) *p–n* junction diode

(b) Symbol for real diode

(c) Diode characteristic curve

- where Id is the diode current in the direction of the arrow (A), Vd is the voltage across the diode terminals from the p-side to the n-side (V), I0 is the reverse saturation current (A), q is the electron charge (1.602 × 10^−19C), k is Boltzmann's constant (1.381 × 10^−23 J/K), and T is the junction temperature (K).

$$\frac{qV_d}{kT} = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23}} \cdot \frac{V_d}{T(\mathrm{K})} = 11,600\frac{V_d}{T(\mathrm{K})}$$

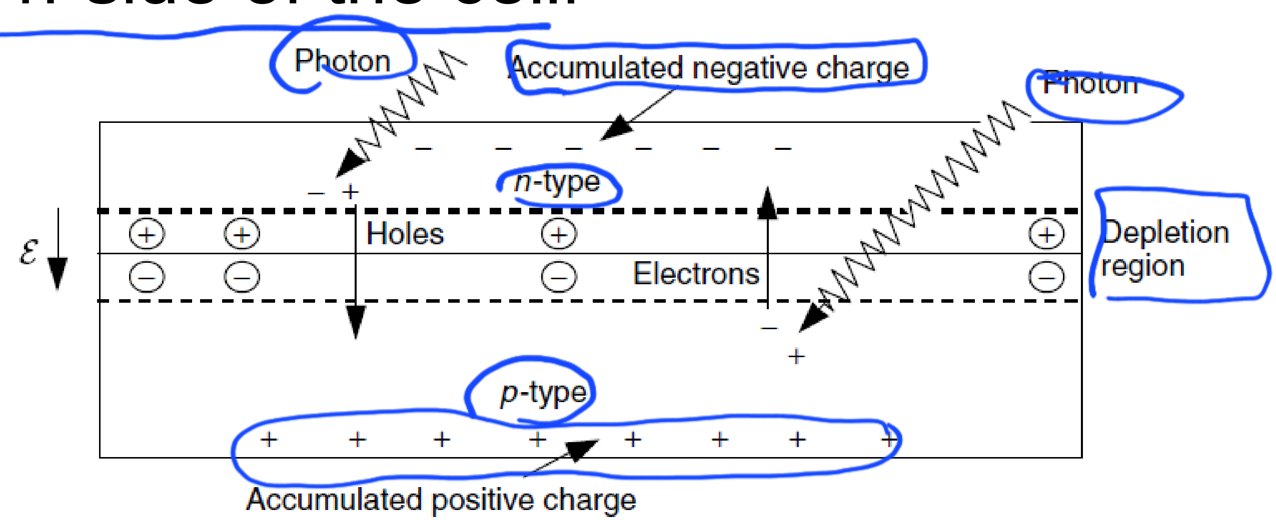
- A junction temperature of 25◦C is often used as a standard, which results in the following diode equation:

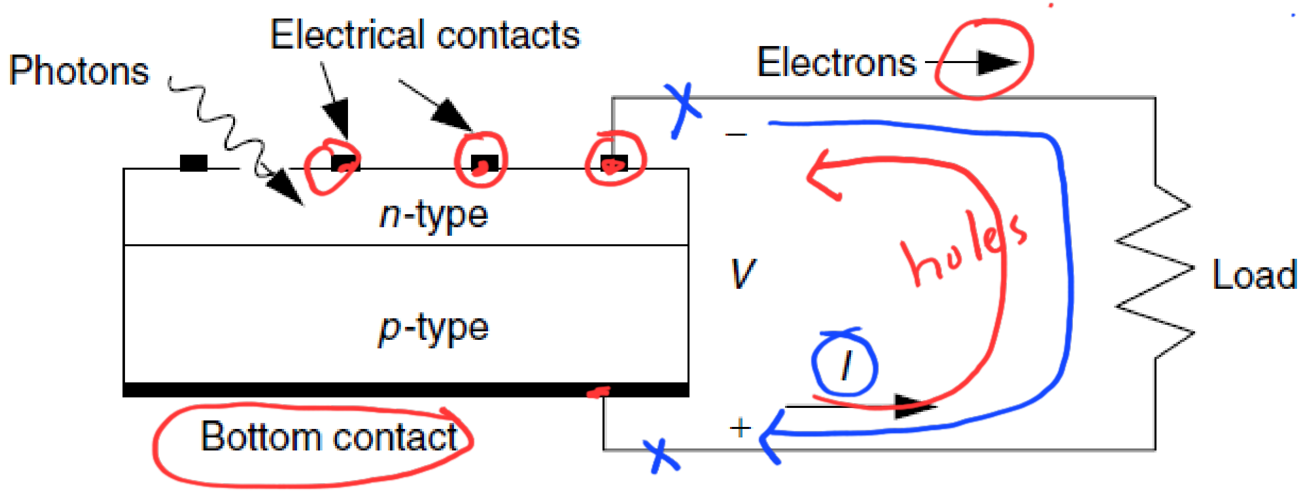
$\frac{1}{38.9} = 25.7\text{mV}$ ← V_T

$$I_d = I_0(e^{38.9V_d} - 1) \qquad (\text{at } 25^\circ\text{C})$$

A GENERIC PHOTOVOLTAIC CELL

- Let us consider what happens in the vicinity of a p–n junction when it is exposed to sunlight.
- As photons are absorbed, hole-electron pairs may be formed.
- When photons create hole–electron pairs near the junction, the electric field in the depletion region sweeps holes into the p-side and sweeps electrons into the n-side of the cell.





- If electrical contacts are attached to the top and bottom of the cell, electrons will flow out of the n-side into the connecting wire, through the load and back to the p-side as shown above.
- Since wire cannot conduct holes, it is only the electrons that actually move around the circuit. When they reach the p-side, they recombine with holes completing the circuit.
- Conventional current I is in the opposite direction.

Photovoltaic Effect

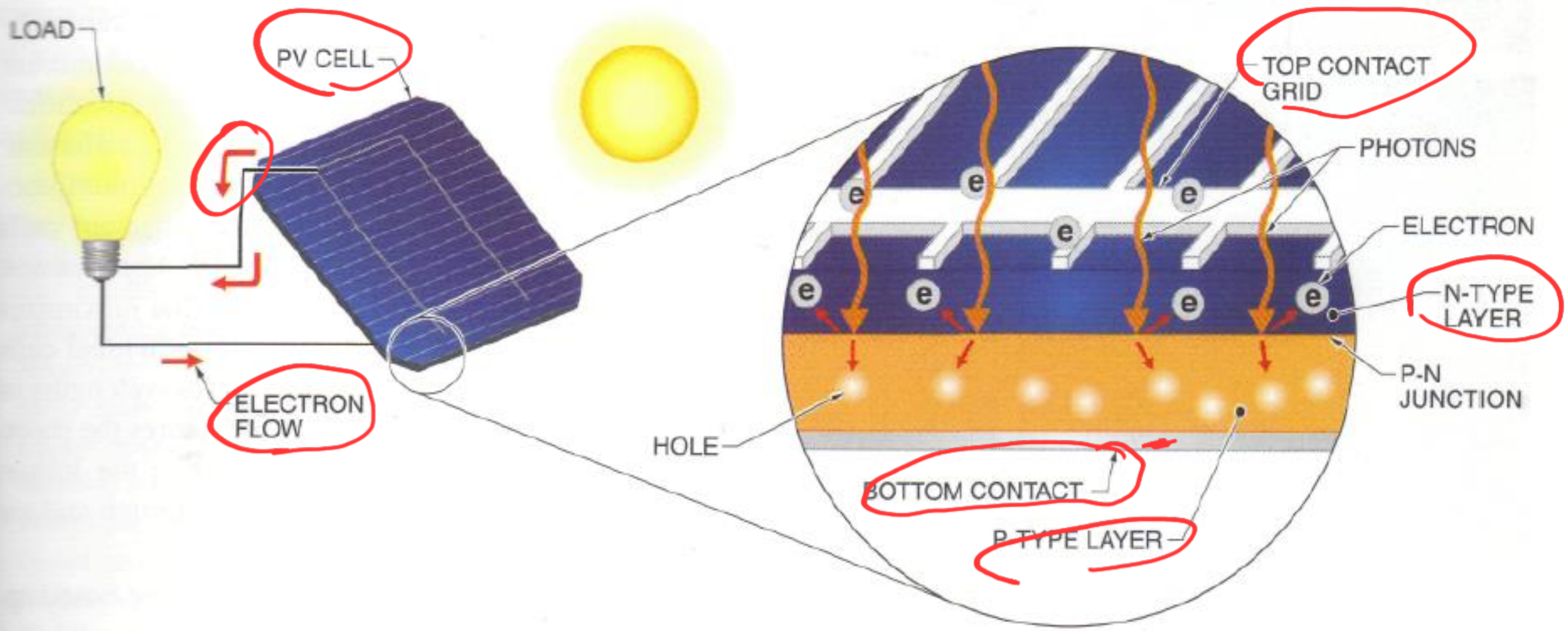
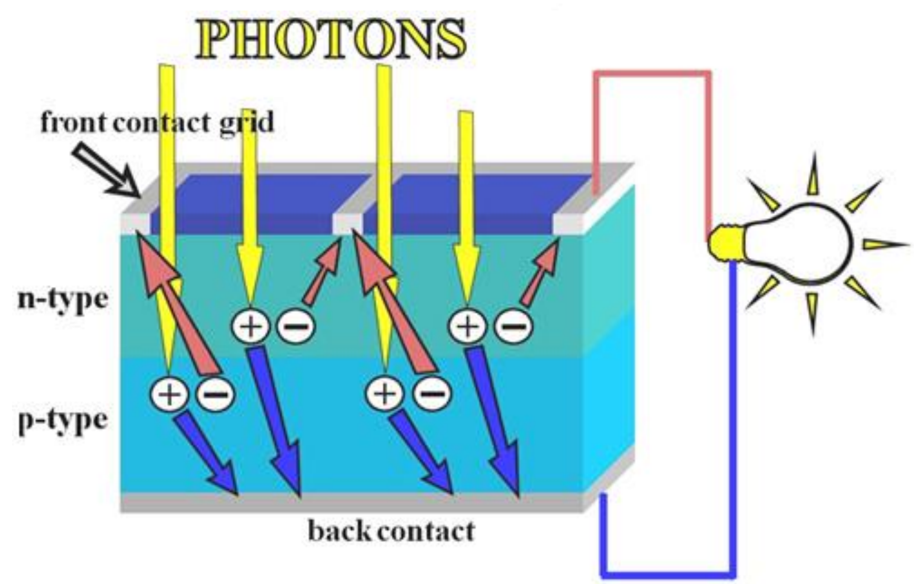


Figure 5-3. *The photovoltaic effect produces free electrons that must travel through conductors in order to recombine with electron voids, or "holes."*

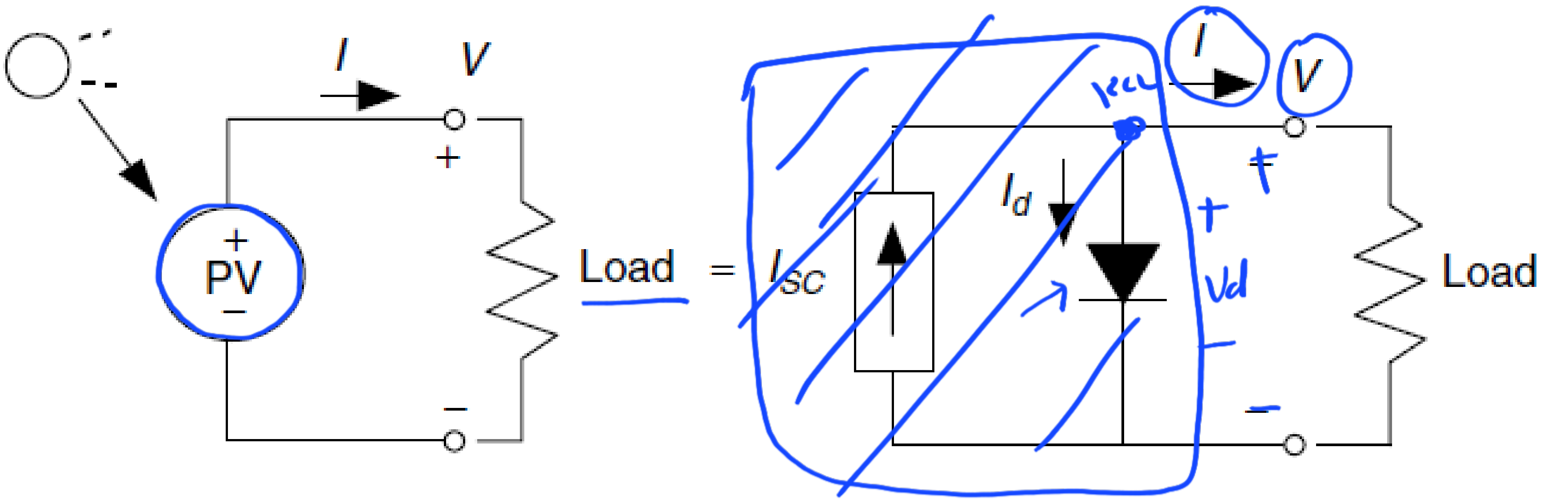


Can you turn the PV cell off?

- The process of electrons and holes being separated by photon energy, and doing work before recombining , occurs continuously while PV cells are exposed to light
- **There is no way of turning off a PV device other than completely covering the top surface with no light reaching the cells**

- See animations:
- https://www.youtube.com/watch?v=PROhNDen3nk
- https://www.youtube.com/watch?v=UJ8XW9AgUrw

The Simplest Equivalent Circuit for a Photovoltaic Cell



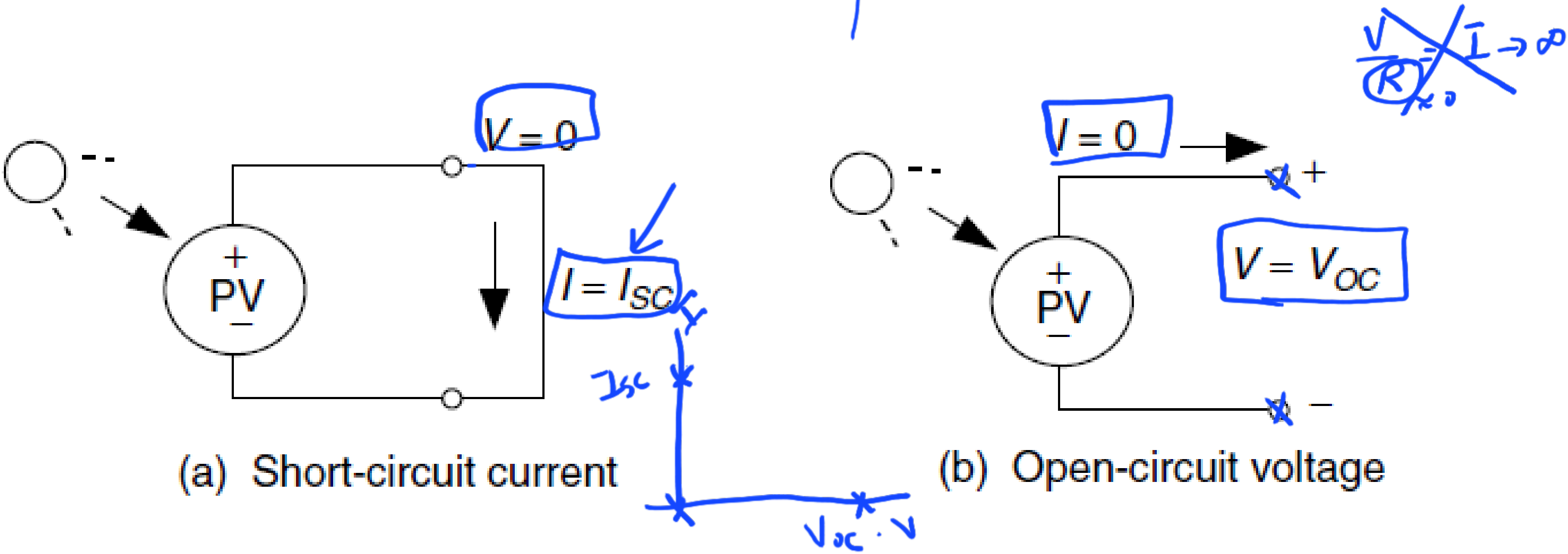
A simple equivalent circuit for a photovoltaic cell consists of a current source driven by sunlight in parallel with a real diode.

I_{sc} ?
I_d
I

→ KCL → $I + I_d = I_{sc}$ (? = const)

$\leftarrow I = I_{sc} - I_d$

$V = V_d$



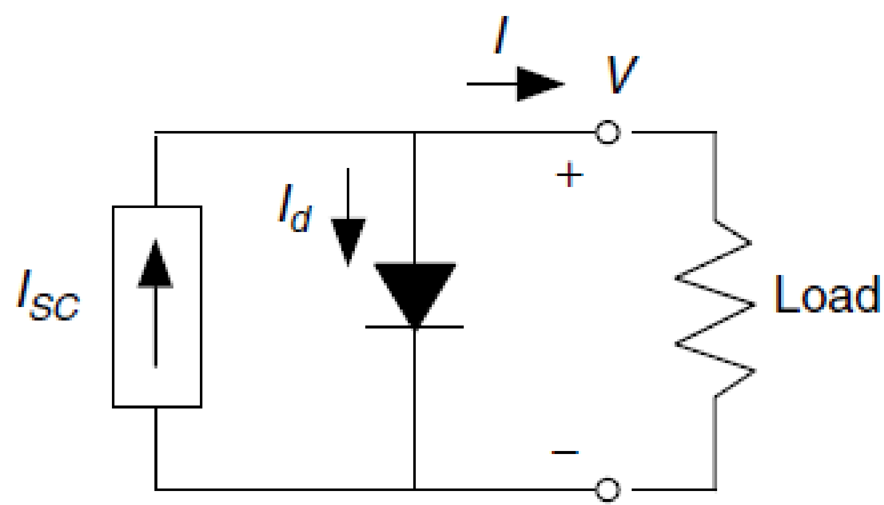
There are two conditions of particular interest for the actual PV and for its equivalent circuit

(1) the current that flows when the terminals are shorted together (the short-circuit current, *Isc*) and

(2) the voltage across the terminals when the leads are left open (the open-circuit voltage, *Voc*)

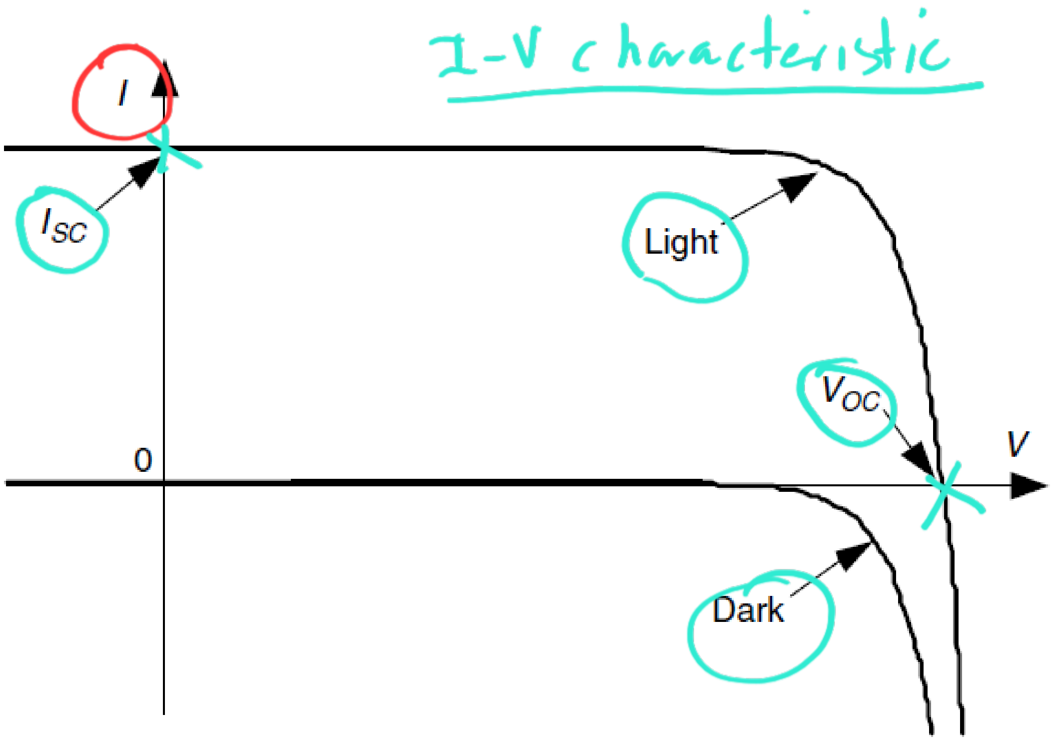
- When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since $V_d = 0$, so all of the current from the ideal source flows through the shorted leads.
- Since that short-circuit current must equal I_{SC}, the magnitude of the ideal current source itself must be equal to I_{SC}.
- Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown.
- Start with
- $I = I_{SC} - I_d$

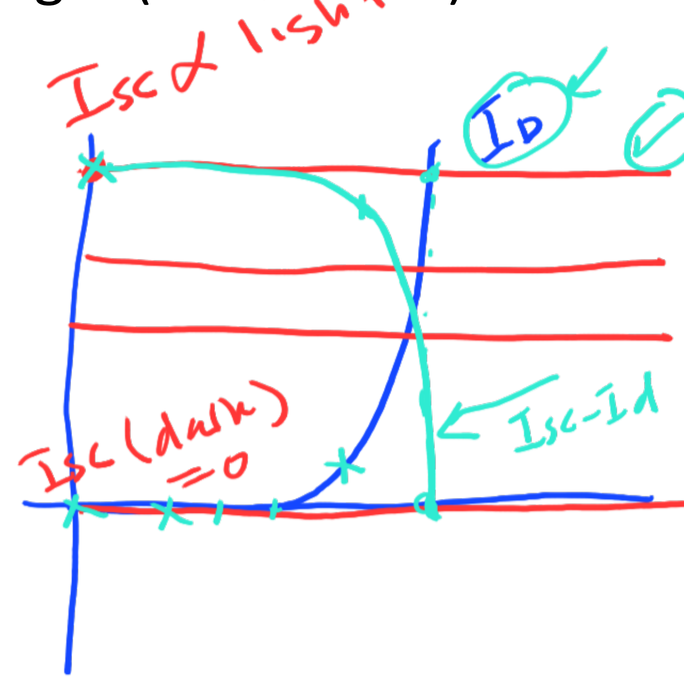
$$I = I_{SC} - I_0 \left(e^{qV/kT} - 1\right)$$



$$I = I_{SC} - I_0 \left(e^{qV/kT} - 1 \right)$$

- It is interesting to note that the second term above is just the diode equation with a negative sign.
- That means that a plot of I is just *ISC* added to the diode curve turned upside-down.
- Figure below shows the current–voltage relationship for a PV cell when it is dark (no illumination) and light (illuminated)





- When the leads from the PV cell are left open, *I* = 0 and we can solve for the open-circuit **voltage *Voc***:

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

- And at 25∘C,

$$I = I_{SC} - I_0(e^{38.9\ V} - 1)$$

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

constant

Short circuit current: Isc

- In both of these equations, short-circuit current, *Isc*, is directly proportional to solar insolation, which means that we can now quite easily plot sets of PV current–voltage curves for varying sunlight.
- Also, quite often laboratory specifications for the performance of photovoltaics are given per cm^2 of junction area, in which case the currents in the above equations are written as current densities.
- Both of these points are illustrated in the following example.

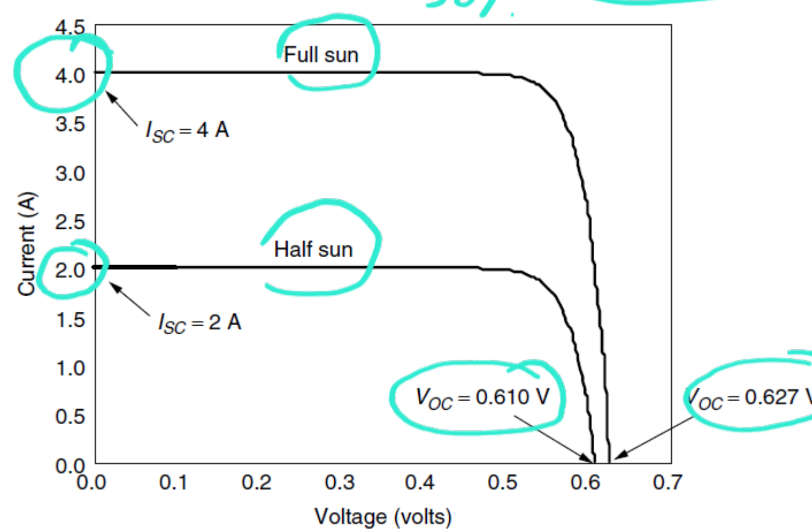
Example 8.3 The I–V Curve for a Photovoltaic Cell. Consider a 100-cm^2 photovoltaic cell with reverse saturation current $I_0 = 10^{-12}$ A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

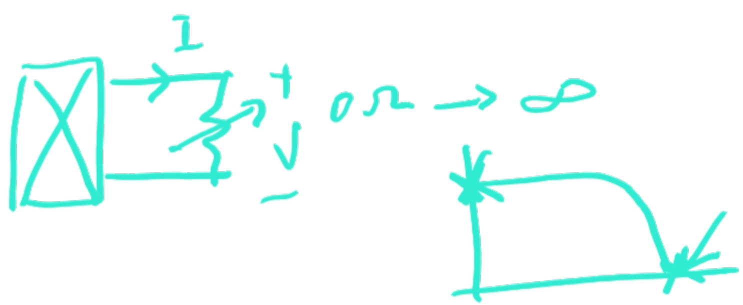
Solution. The reverse saturation current I_0 is 10^{-12} A/cm^2 $\times$ 100 cm^2 $= 1 \times 10^{-10}$ A. At full sun I_{SC} is 0.040 A/cm^2 $\times$ 100 cm^2 $=$ 4.0 A.

$$V_{OC} = 0.0257 \ \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 2$ A and the open-circuit voltage is

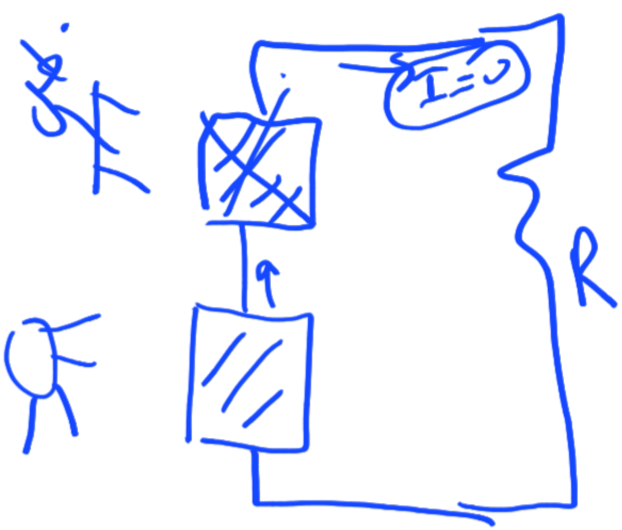
$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$

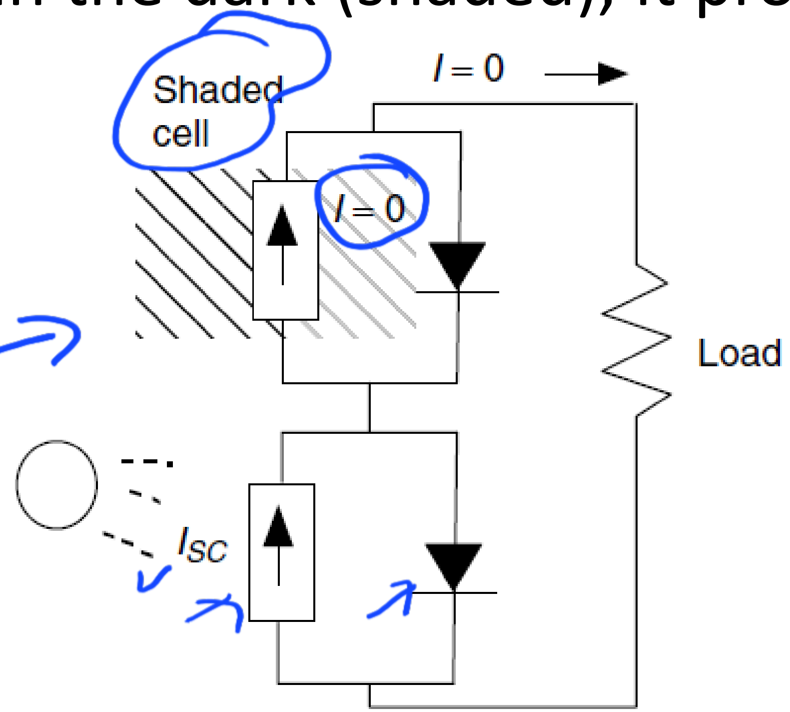




A More Accurate Equivalent Circuit for a PV Cell

- There are times when a more complex PV equivalent circuit than the one shown in previously is needed.
- For example, consider the impact of shading on a string of cells wired in series (Figure below shows two such cells).
- If any cell in the string is in the dark (shaded), it produces no current.





- In our simplified equivalent circuit for the shaded cell, the current through that cell's current source is zero and its diode is back biased so it doesn't pass any current either (other than a tiny amount of reverse saturation current).
- This means that the simple equivalent circuit suggests that no power will be delivered to a load if any of its cells are shaded!
- This is not correct , a more complex model can deal with this problem

The simple equivalent circuit of a string of cells in series suggests no current can flow to the load if any cell is in the dark (shaded).

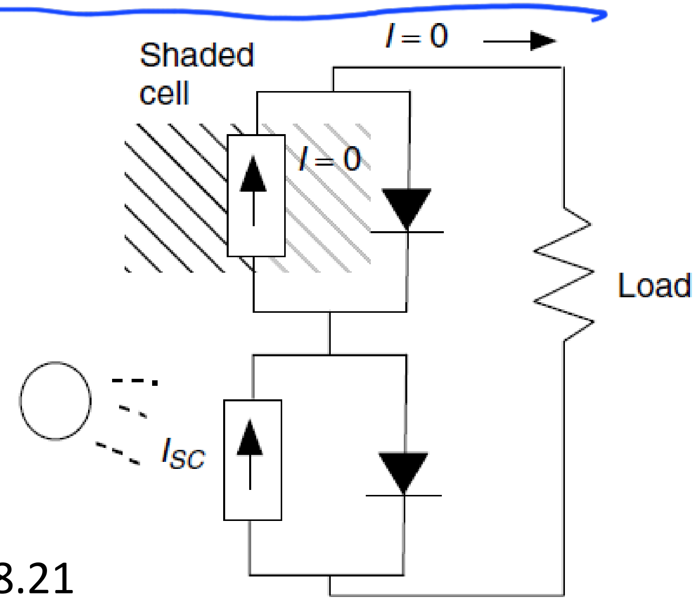


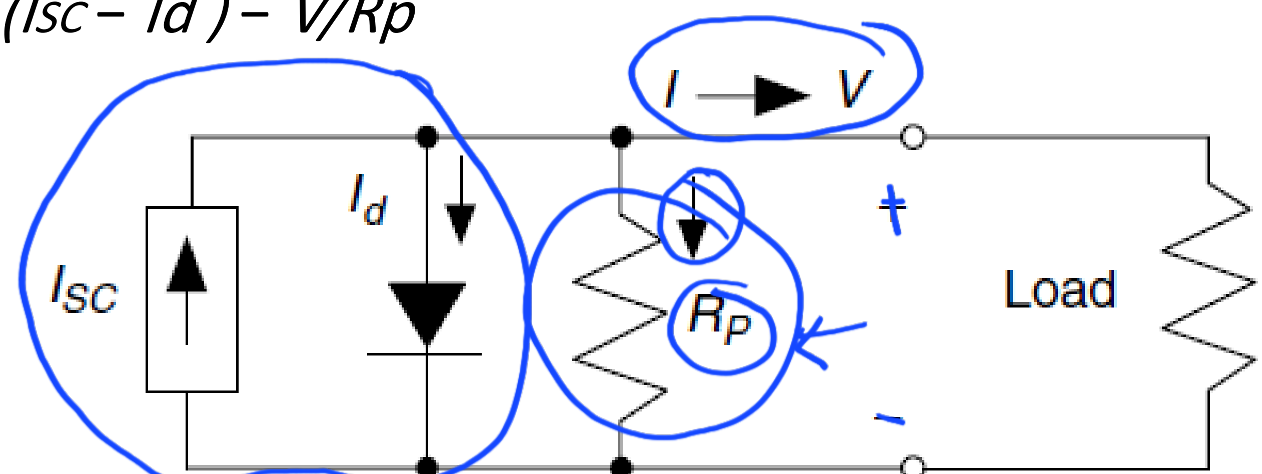
Fig. 8.21

A More Accurate Equivalent Circuit for a PV Cell

- While it is true that PV modules are very sensitive to shading, the situation is not quite as bad as that.
- So, we need a more complex model if we are going to be able to deal with realities such as the shading problem.
- A PV equivalent circuit that includes some parallel leakage resistance *Rp* is shown
- The ideal current source *Isc* in this case delivers current to the diode, the parallel resistance, and the load:

$$I = (I_{SC} - I_d) - V/R_P$$

$I = I_{sc} - I_d - I_{R_P}$, $I_{R_P} = \frac{V}{R_P}$



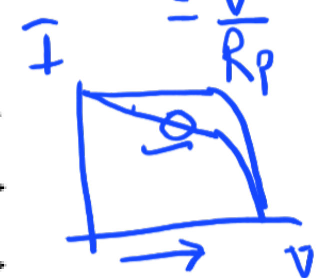
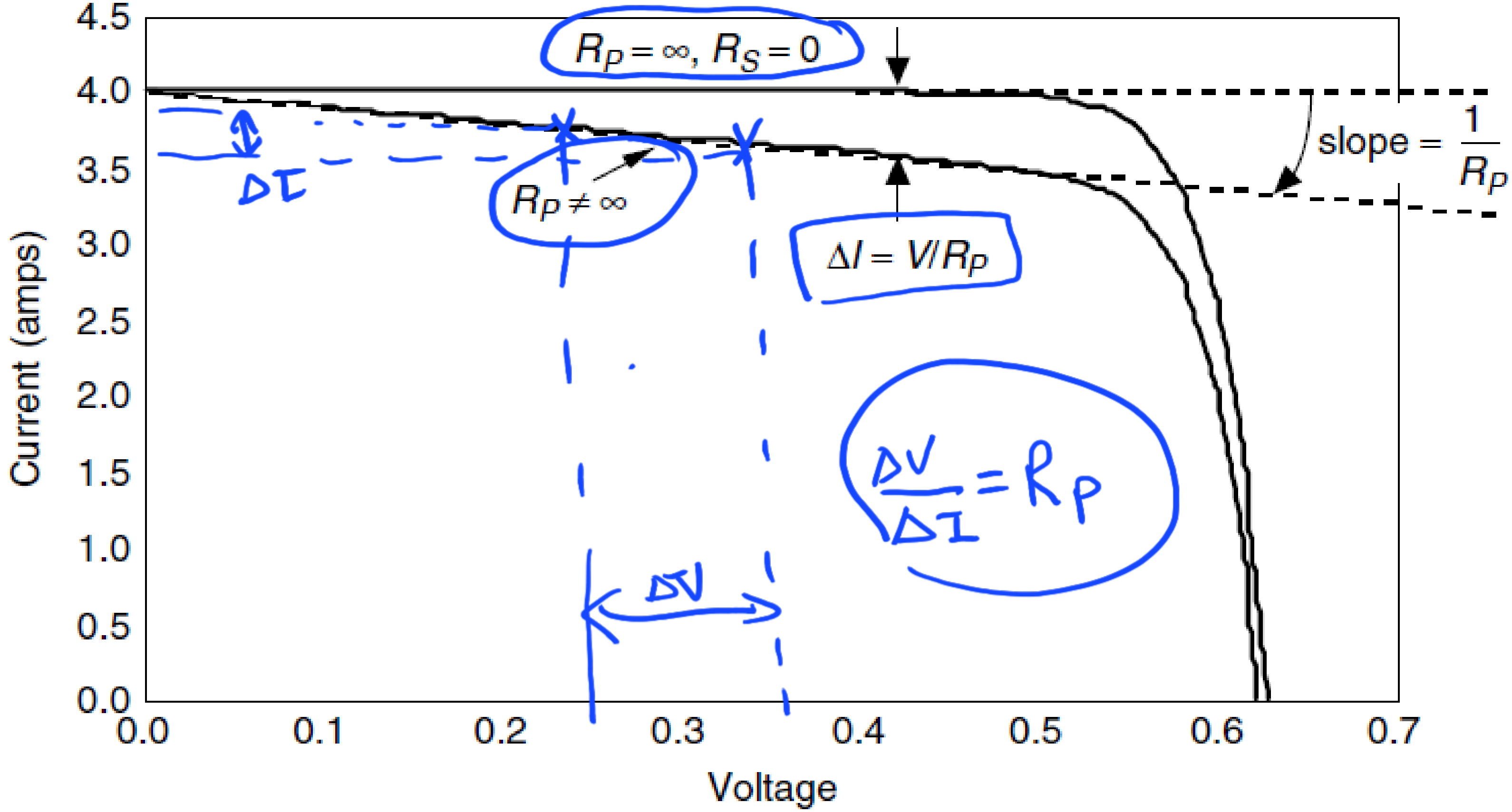


Figure 8.22



Modifying the idealized PV equivalent circuit by adding parallel resistance causes the current at any given voltage to drop by V/R_P.

$I = (I_{SC} - I_d) - V/R_p$

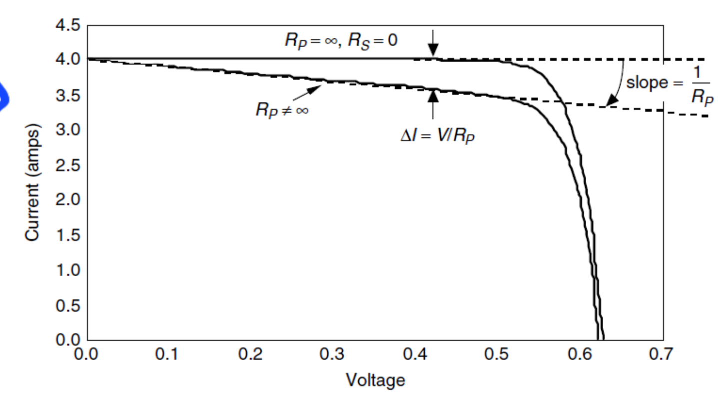
- The term in the parentheses is the same current that we had for the simple model.
- So, what the equation tells us is that at any given voltage, the parallel leakage resistance causes load current for the ideal model to be decreased by V/R_p as is shown I
- For a cell to have losses of less than 1% due to its parallel resistance, R_P should be greater than about

$$R_P > 100\ V_{OC}/I_{SC}$$

- Consider a large cell, with I_{SC} around 7 A and V_{OC} about 0.6 V, which says its parallel resistance should be greater than about 9 .

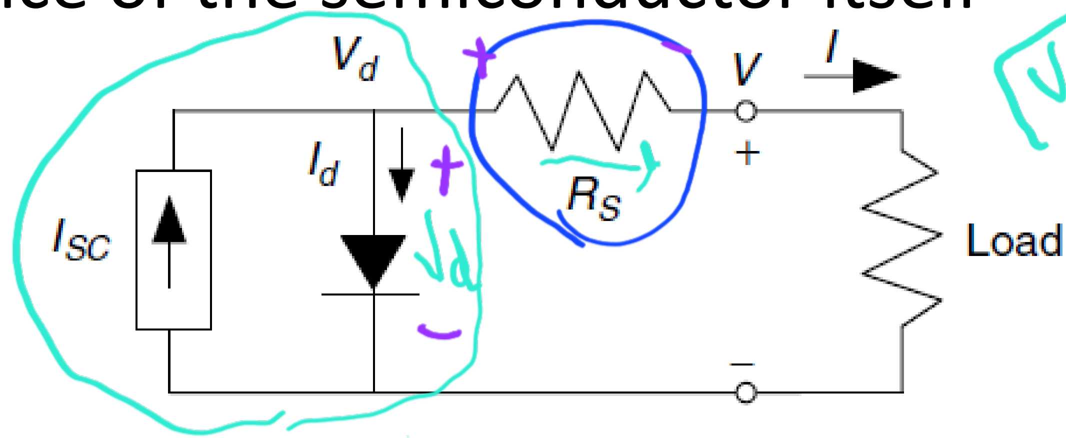
End of L9 24/3

L10 14/4 covered Project & review



Series Resistance

- An even better equivalent circuit will include series resistance as well as parallel resistance.
- Before we can develop that model, consider Fig. below in which the original PV equivalent circuit has been modified to just include some series resistance, *Rs*.
- Some of this might be contact resistance associated with the bond between the cell and its wire leads, and some might be due to the resistance of the semiconductor itself



Effect of Rs

- To analyze effect of series resistance, start with the simple equivalent circuit

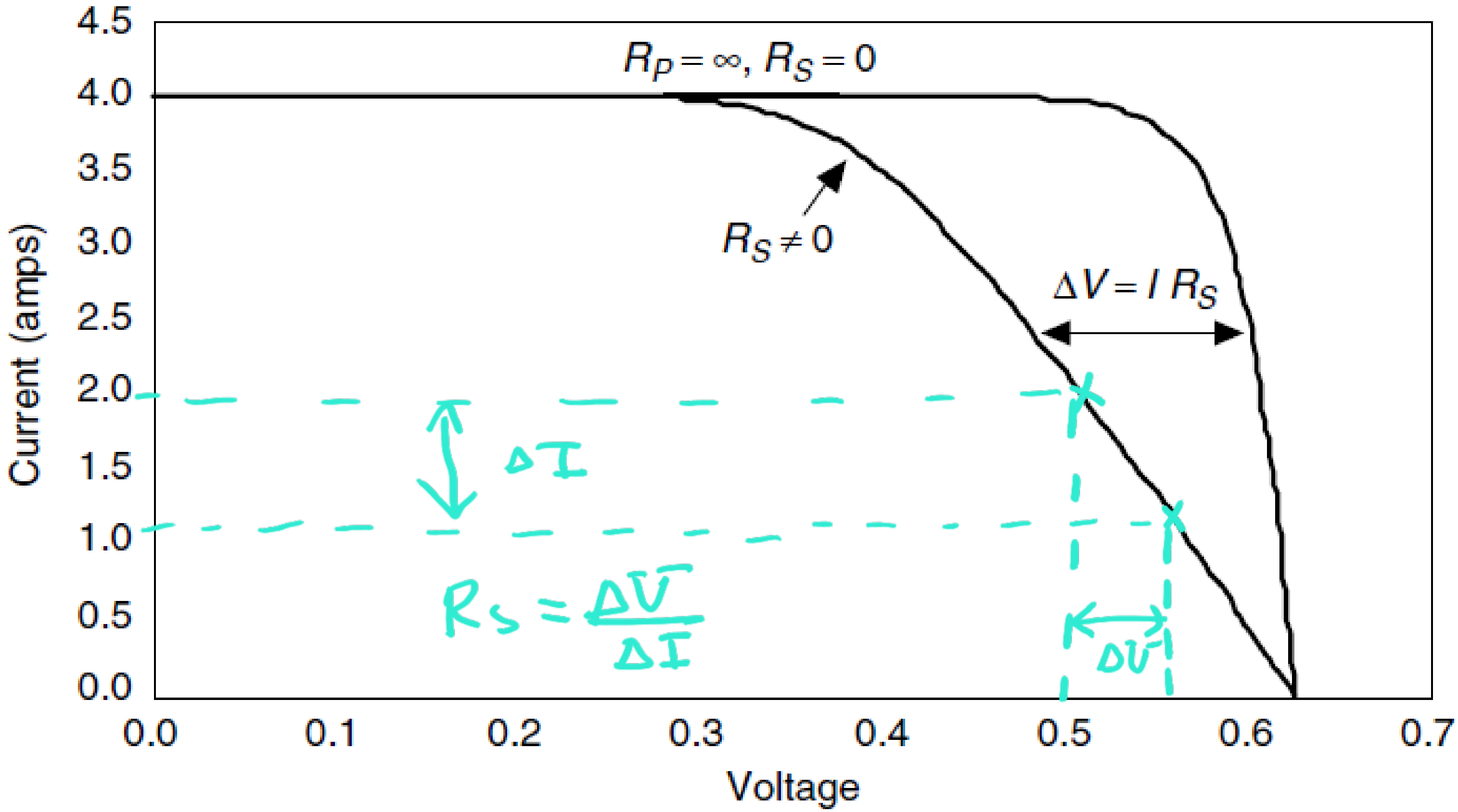
$$I = I_{SC} - I_d = I_{SC} - I_0\left(e^{qV_d/kT} - 1\right)$$

- and then add the impact of *RS*

$$V_d = V + I \cdot R_S$$

$$I = I_{SC} - I_0\left\{\exp\left[\frac{q(V + I \cdot R_S)}{kT}\right] - 1\right\}$$

- Equation above can be interpreted as the original PV *I*−*V* curve with the voltage at any given current shifted to the left by Δ*V* = *IRs* as shown in Fig. 8.25.



Adding series resistance to the PV equivalent circuit causes the voltage at any given current to shift to the left by $\Delta V = I R_S$.

- Rs must be as small as possible to avoid high losses and voltage drop across it

Generalized PV cell equivalent Circuit

- Finally, let us generalize the PV equivalent circuit by including both series and parallel resistances as shown in Fig. 8.26. We can write the following equation for current and voltage:

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left(\frac{V + I \cdot R_S}{R_P} \right)$$

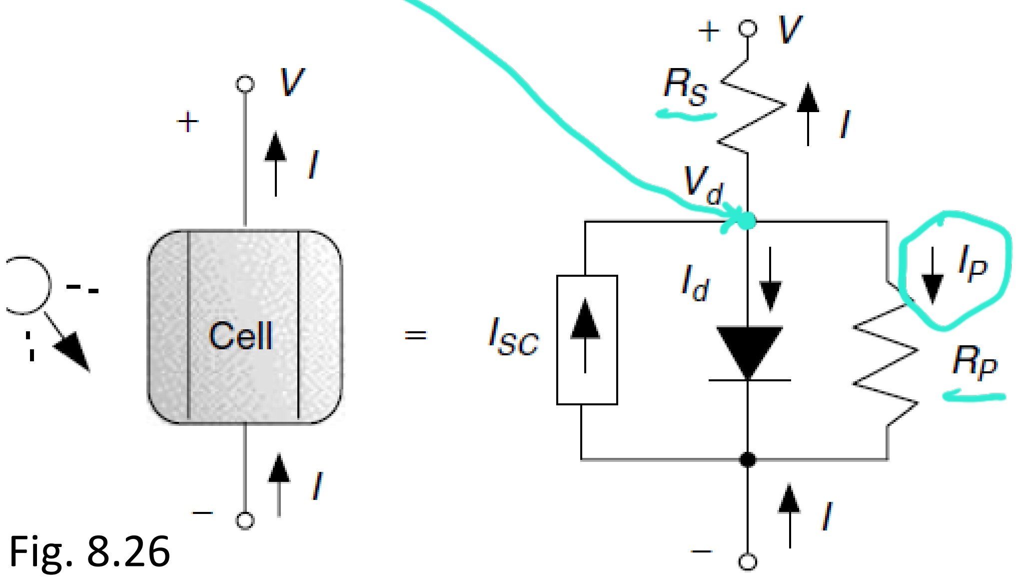


Fig. 8.26

A more complex equivalent circuit for a PV cell includes both parallel and series resistances. The shaded diode reminds us that this is a "real" diode rather than an ideal one.

- Under the standard assumption of a 25∘C cell temperature

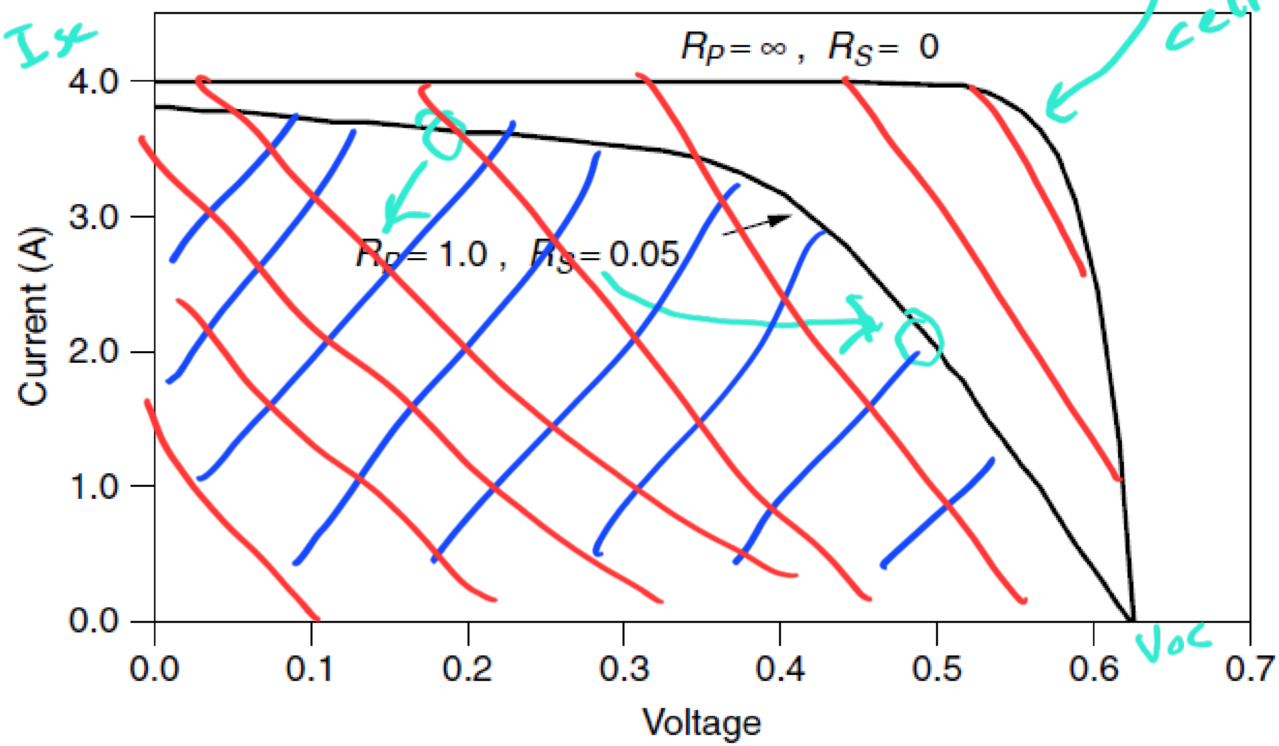
$$I = I_{SC} - I_0 \left[e^{38.9(V+IR_S)} - 1\right] - \frac{1}{R_P}(V + IR_S) \qquad \text{at } 25^\circ\text{C}$$

- Unfortunately, this is a complex equation for which there is no explicit solution for either voltage *V* or current *I*.
- A spreadsheet solution, however, is fairly straightforward and has the extra advantage of enabling a graph of *I* versus *V* to be obtained easily.
- The approach is based on incrementing values of diode voltage, *Vd*, in the spreadsheet.
- For each value of *Vd*, corresponding values of current *I* and voltage *V* can easily be found.

$$I_{SC} = I + I_d + I_P$$

$$I = I_{SC} - I_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

- Voltage across an individual cell then can be found from $V = V_d - I R_S$
- for an equivalent circuit with $R_S = 0.05$ and $R_P = 1$ is shown



PV Modules and Arrays

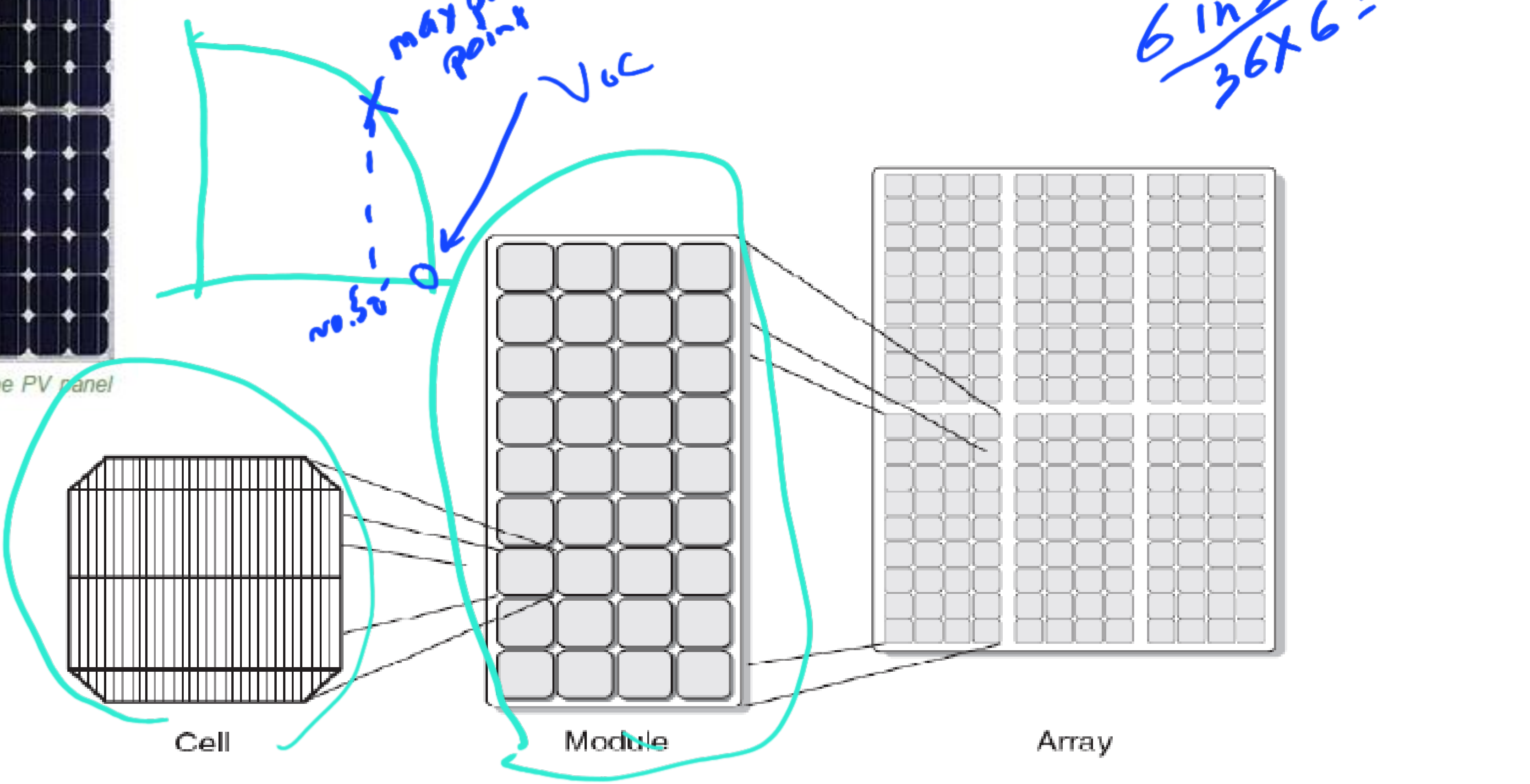
- The primary component common to all PV systems is the PV array which consists of individual modules that are connected to produce desired voltage, current, and power output
- Modules and arrays produce **DC power** ,which can be used to charge batteries, directly power DC loads, or converted to AC power by inverters to power AC loads or to interface with electric utility grid

PV Modules and Arrays

- The voltage of PV modules varies somewhat with **temperature**, and the current varies proportionately to **solar irradiance**, so power output is rarely constant
- PV systems usually require means to store or condition power so it can be used effectively by electrical loads

Cells, Modules, Arrays

Monocrystalline PV panel



Source: [ABS Energy Research, 2009 or [Dr. Harald Schutzeeichel, 2009]

Cell Materials

- Crystalline Silicon is most common base raw material for silicon cell production is at least 99.9% pure polysilicon, a product refined from quartz and silica sands
- Various grades of polysilicon can be used in PV cell production and affect the quality and efficiency of cells
- Crystalline silicon (C-Si) cells currently offer the **best ratio of performance to cost** and utilize many of the raw materials and process used by semiconductor industry

Cell Materials

- Gallium Arsenide (GaAs) cells are more efficient than C-Si cells , but the high cost and toxicity have limited their use to space applications so far
- Multi-junction cell: a cell that maximizes efficiency by using layers of individual cells that each respond to different wavelengths of solar energy; the top layer captures the short wave while longer wave lengths is absorbed by the lower layer

Cell Materials

- Thin-Film PV devices: module based approach to cell design
- A thin film module is a module –like PV device with its entire substrate coated in thin layers of semiconductor material using chemical vapor deposition techniques and then laser-scribed to delineate individual cells and make electrical connection between them
- Amorphous Silicon (a-Si) ; copper indium, gallium selenide (CIGS) and cadmium telluride (CdTe) are among competing thin film technologies

- Thin-Film modules are less costly to produce and use less raw materials than C-Si and may not be as durable in the field

Photo-Electrochemical Cell

- A cell that relies on chemical process to produce electricity from light, rather than using semiconductors
- Photo-Electrochemical cells include dye-sensitized cells ,and polymer (plastic) cells and are sometimes called organic cells
- Engineering challenges in developing these cells are considerable, some are expected to impact commercial markets in the next decade

Solar Cell Construction

- Materials
  - Crystalline Silicon
  - Gallium Arsenide (more expensive)
- Grown into large single-crystal ingots

سبائك

- Sawed into thin wafers

عملية نشر للطبقات

- 2 wafers are bonded together (p-n junction)
- Wafers grouped into panels or arrays

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

Wafer Manufacturing

- The manufacture of commercial silicon modules involves fabricating silicon wafers, transforming the wafers into cells, and assembling cells into modules.
- A *wafer* is a thin, flat disk or rectangle of base semiconductor material.
- Wafers are 180 μm to 350 μm thick and are made from p-type silicon.
- Crystalline silicon cell wafers are produced in three basic types:

1) Monocrystalline , 2) polycrystalline, and 3) ribbon silicon.

- Each type has advantages and disadvantages in terms of efficiency, manufacturing , and costs.

PV Materials Efficiencies

PV Material Efficiencies*

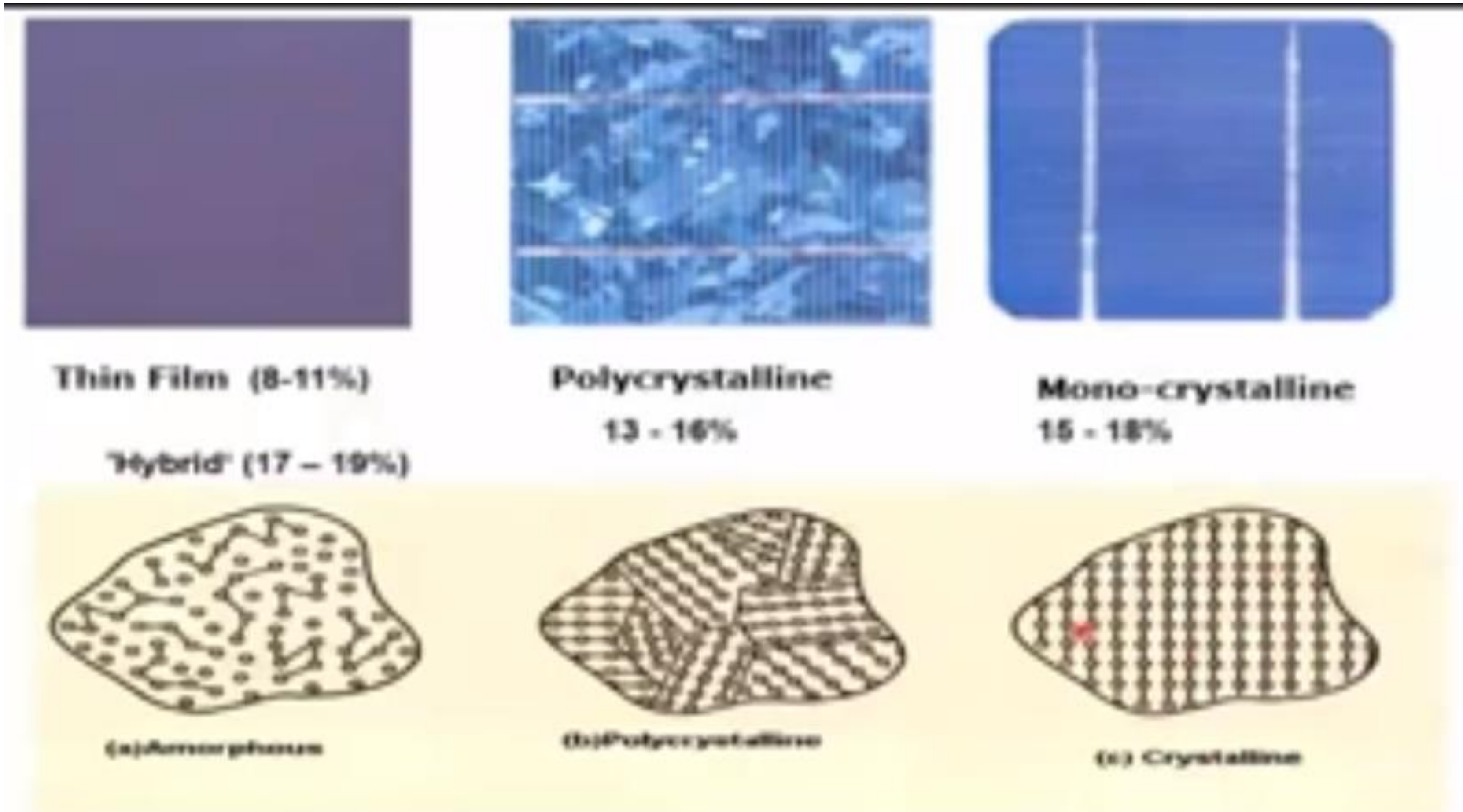
MATERIAL	TYPICAL EFFICIENCIES	BEST LABORATORY EFFICIENCY
Multijunction gallium arsenide (GaAs)	33 to 38†	40.7†
Monocrystalline silicon	14 to 17	24.7
Polycrystalline silicon	11.5 to 14	20.3
Copper indium gallium selenide (CIGS)	9 to 11.5	19.9
Cadmium telluride (CdTe)	8 to 10	16.5
Amorphous silicon (a-Si)	5 to 9.5	12.1
Dye-sensitized (Grätzel)	4 to 5	11.1
Polymer (Organic)	1 to 2.5	5

* in %

† in concentrating applications

Source: NREL

Figure 5-4. *Various PV materials and technologies produce different efficiencies.*

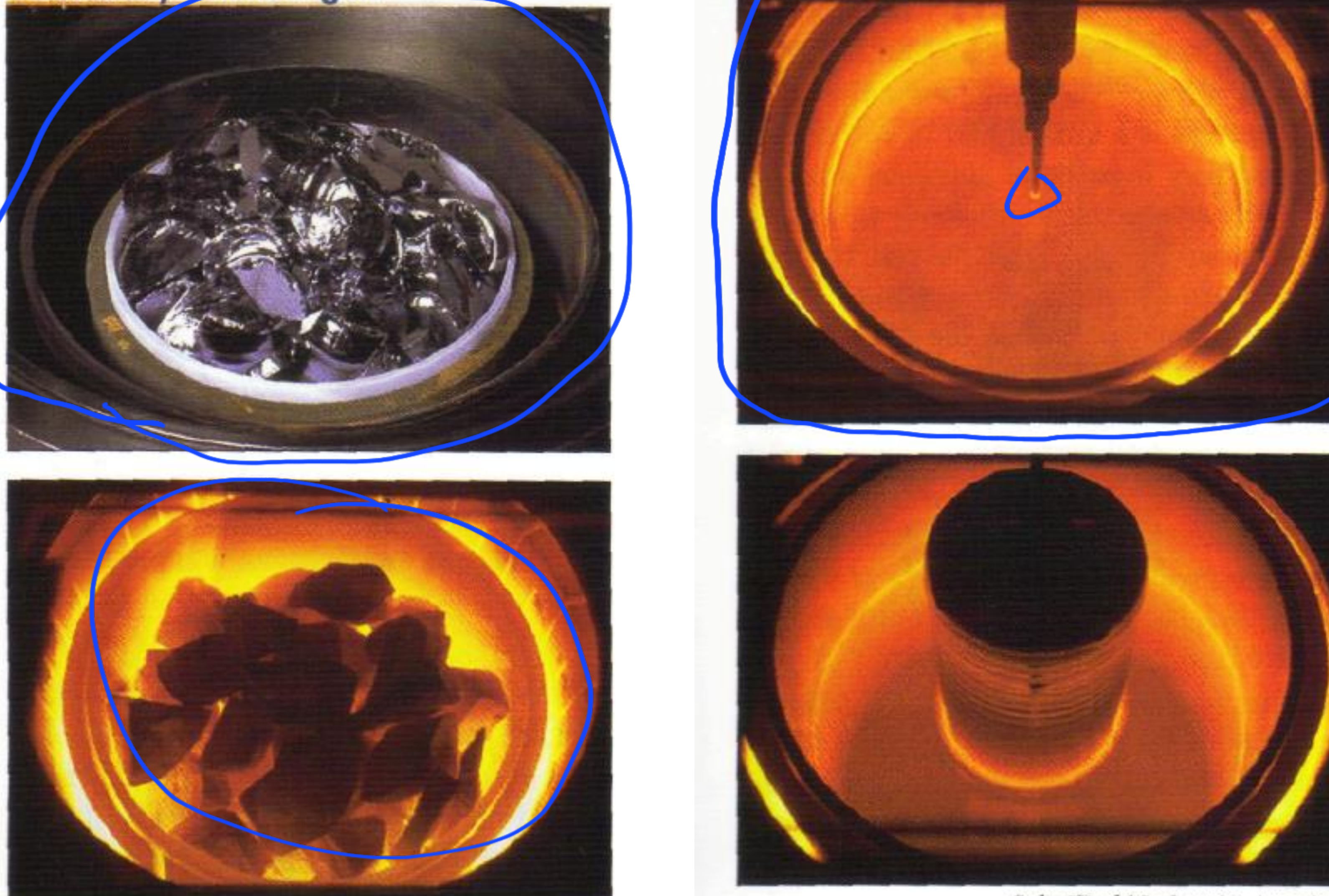

Thin Film (8-11%)
Polycrystalline
13 - 16%
Mono-crystalline
15 - 18%
"Hybrid" (17 – 19%)
(a)Amorphous
(b)Polycrystalline
(c) Crystalline

Mono-crystalline Silicon

- A *mono-crystalline wafer is* a silicon wafer made from a single silicon crystal grown in the form of a cylindrical ingot. See **Figure** next slide.
- Chunks of highly pure polysilicon are melted in a crucible, along with boron.
- A small seed crystal is dipped into the molten bath and slowly rotated and withdrawn.
- Over a period of many hours, the seed crystal grows into a large cylindrical crystal up to 40" in length and 8" in diameter

wafer (رقاقة) ingot (سبيكة)

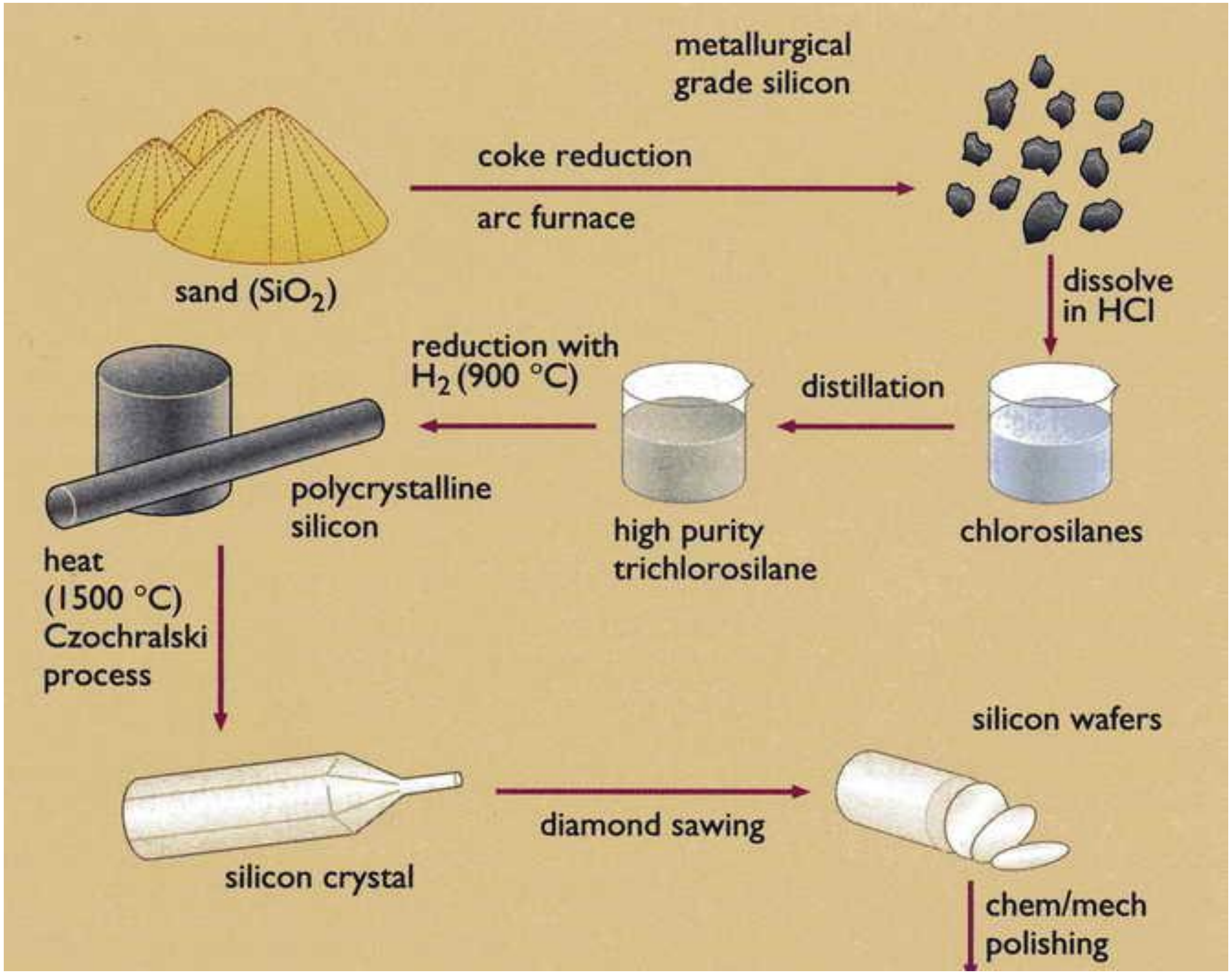
Monocrystalline Ingots



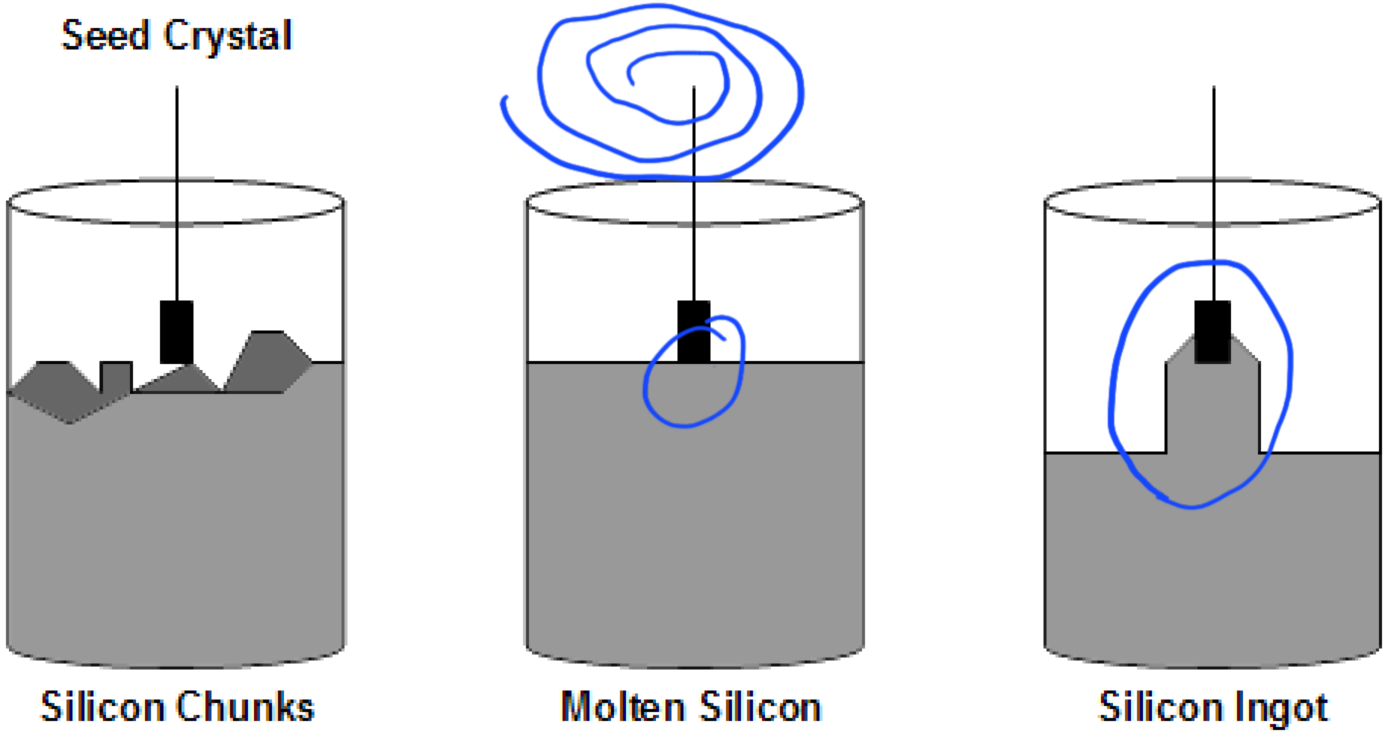
SolarWorld Industries America

Figure 5-5. *Monocrystalline silicon wafers are sawn from grown cylindrical ingots.*

Creating Silicon Wafers



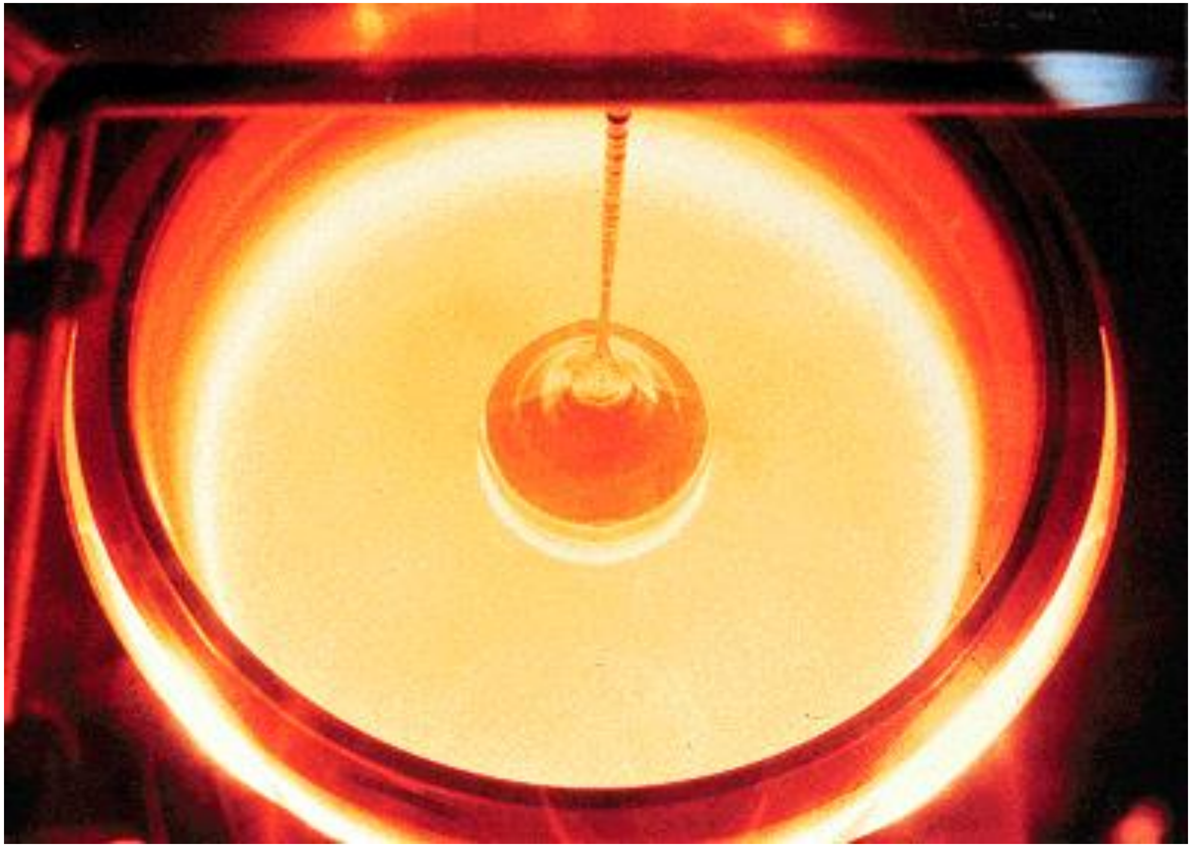
Growing Silicon Ingots



Czochralski Process

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

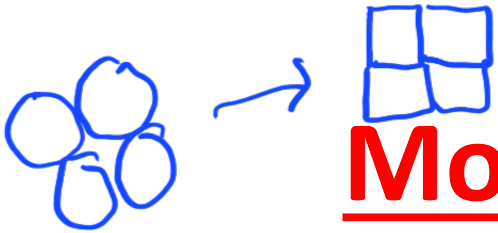
Drawing a Silicon Ingot



http://www.answers.com/topic/silicon

Silicon Ingots & Wafers

http://www.sumcosi.com/english/products/products2.html



Monocrystalline Silicon

- Because the ingot is round, the edges are often cropped to a more rectangular or square shape, which allows cells to be packed more closely in a module.
- Individual wafers are then cut from the ingot using diamond wire saws.
- Commercial monocrystalline cells have efficiencies on the order of 14% to 17%, with some laboratory samples having efficiencies as high as about 25%.

Polycrystalline Silicon

- *A polycrystalline wafer (رقاقة)* is a silicon wafer made from a cast silicon ingot (سبيكة)that is composed of many silicon crystals.
- Molten silicon is poured into a crucible to form an ingot, which is slowly and carefully cooled over several hours.
- During cooling, many silicon crystals form and grow as the molten material solidifies.
- The cast ingot is then sectioned with wire saws to form square or rectangular wafers.

Polycrystalline Silicon

- Polycrystalline wafers can sometimes be distinguished from monocrystalline wafers by their square corners and the grain boundaries appearing on the wafer surface.
- While polycrystalline cells have slightly lower efficiencies (11.5% to 14%) than monocrystalline cells, their lower manufacturing costs and denser packing in modules makes them competitive with monocrystalline modules.

Polycrystalline Ingots

DOE/NREL, John Wohlgemuth—Solarex

Figure 5-6. *Polycrystalline silicon wafers are sawn from cast rectangular ingots.*

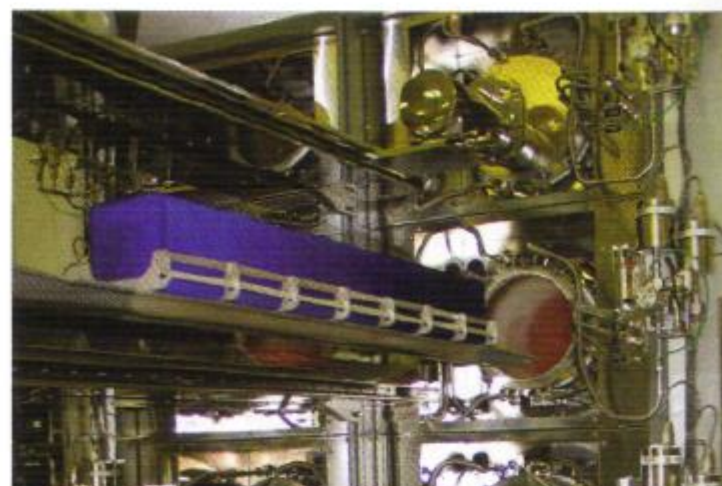
Ribbon Silicon

- A *ribbon wafer* is a silicon wafer made by drawing a thin strip from a molten silicon mixture.
- The melted material is pulled between parallel dies where it cools and solidifies to form a continuous multicrystalline ribbon.
- The ribbon is then cut at specific intervals to form rectangular-shaped wafers.
- While cells produced from ribbon silicon wafers have slightly lower efficiencies (11% to 13%) than other silicon cells, this process is less expensive because there is less material waste and it does not require ingot sawing.

Cell Fabrication

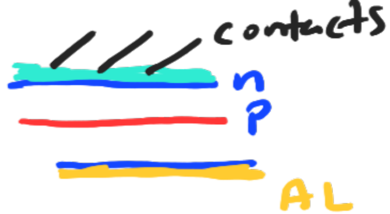
- Once a crystalline silicon wafer is produced, it must go through additional processing to become a functional PV cell.
- **Etching:** first the wafers are dipped in a sodium hydroxide solution to etch the surface and remove imperfections introduced during the sawing process.
- The textured surface increases surface area, allows subsequent coatings to adhere better, and minimizes reflected sunlight.

- **Phosphorous Diffusion**: After the wafers are cleaned they are placed on racks and into a diffusion furnace, where phosphorous gas penetrates the outer surfaces *of the cell, creating a thin n-type semiconductor* layer surrounding the original p-type semiconductor material. See **Figure** 5-8.



SolarWorld Industries America

Figure 5-8. *Diffusion of phosphorous gas creates a thin n-type semiconductor layer over the entire surface of a p-type wafer.*



قص الاطراف

- **Edge Abrasion** : the edge of the wafer is then abraded to remove the n-type material.
- **Coating**: Antireflective coatings are then applied to the top surface of the cell to further reduce reflected sunlight and improve cell efficiency.
- **Electrical Contacts:** After the coatings dry, grid patterns are screen printed on the top surface of the cell with silver paste to provide a point for electron collection and the electrical connection to other cells.
- These grid lines generally include two or more main strips across the cell, with finer lines emanating from the main strips across the cell surface.
- The configuration of these grid patterns is a critical part of cell design,

Electrical Contacts

- The configuration of these grid patterns is a critical part of cell design, because they must be of sufficient size and distribution to be able to efficiently collect and conduct current away from the cell, but must be minimized to avoid covering much of the cell surface, which lowers the effective cell surface area exposed to sunlight.
- Finally, the entire back surface of the cell is coated with a thin layer of metal, typically aluminum, which alloys with the silicon and neutralizes the n-type semiconductor layer on the back surface.
- This results in the bottom surface of the cell being the positive connection, while the top surface is negative

Testing

- After cells are produced, each is electrically tested under simulated sunlight and sorted according to its current output.
- This sorting *process largely eliminates problems with* current mismatch among series-connected cells and allows manufacturers to produce modules that are of the same physical size but have different power ratings.

Cell Fabrication

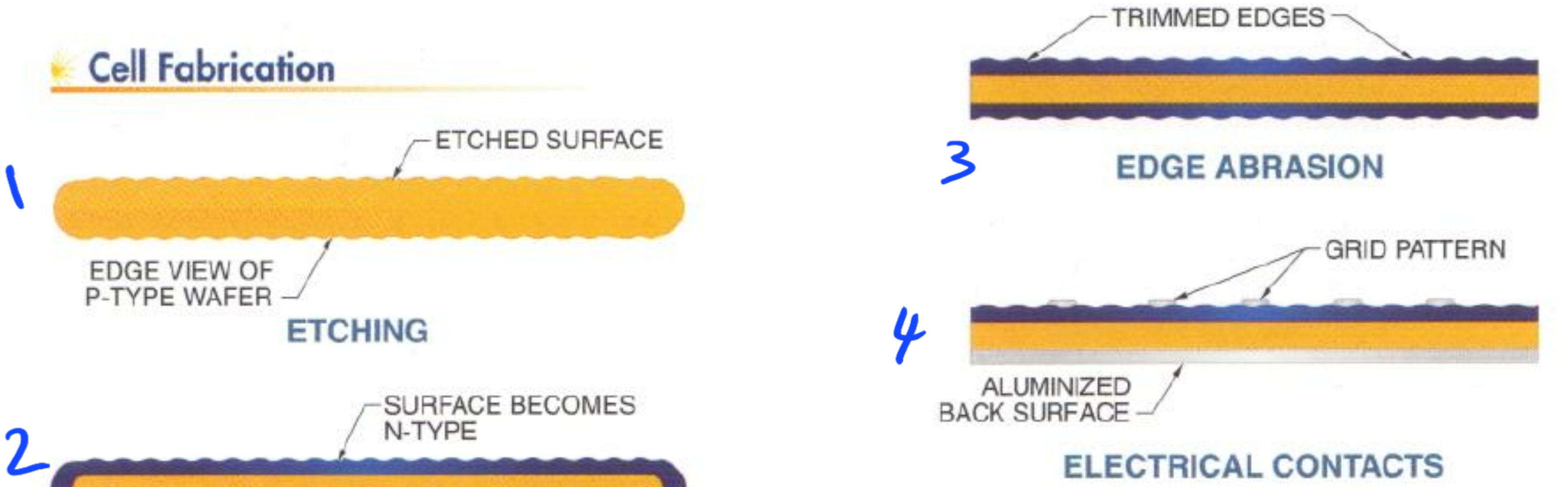
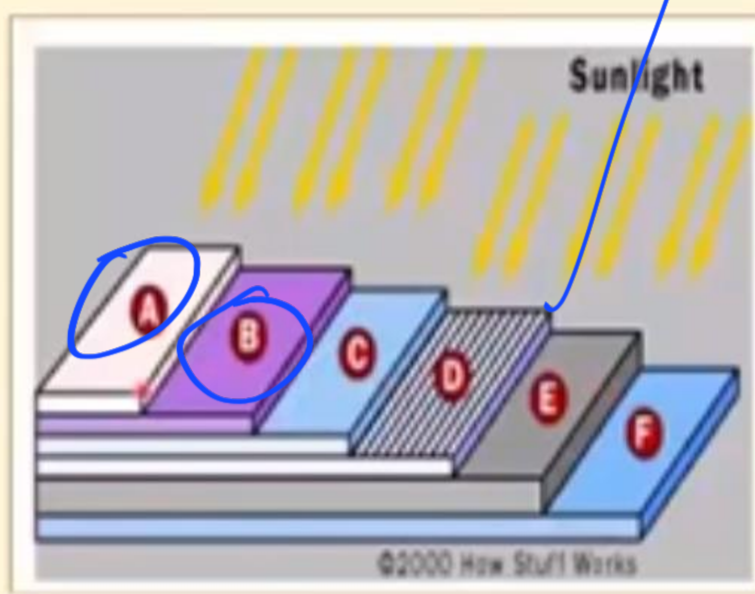
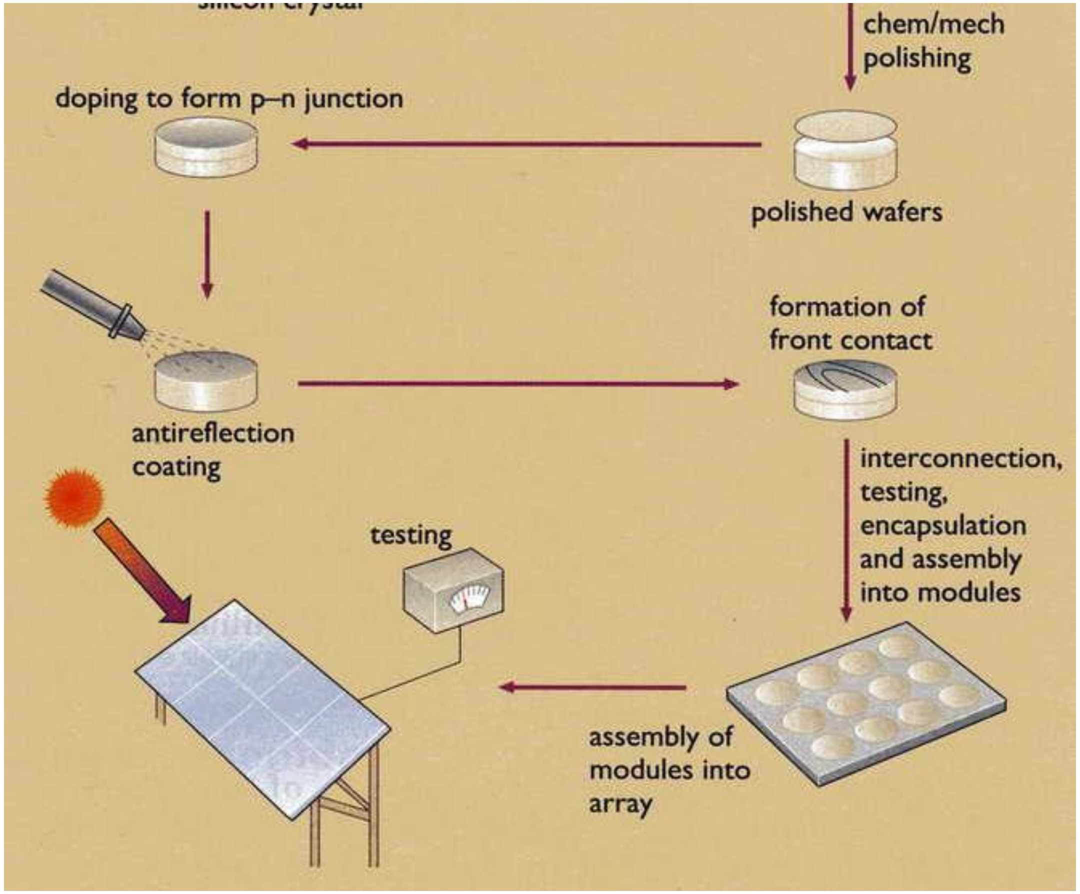


Figure 5-7. *Several steps are involved in turning silicon wafers into PV cells.*

A. A layer of glass for protection
B. Antireflective coating
C. Contact grid
D. Highly purified N-Type Silicon
E. P-Type Silicon
F. Back Contact.



Creating PV Cells



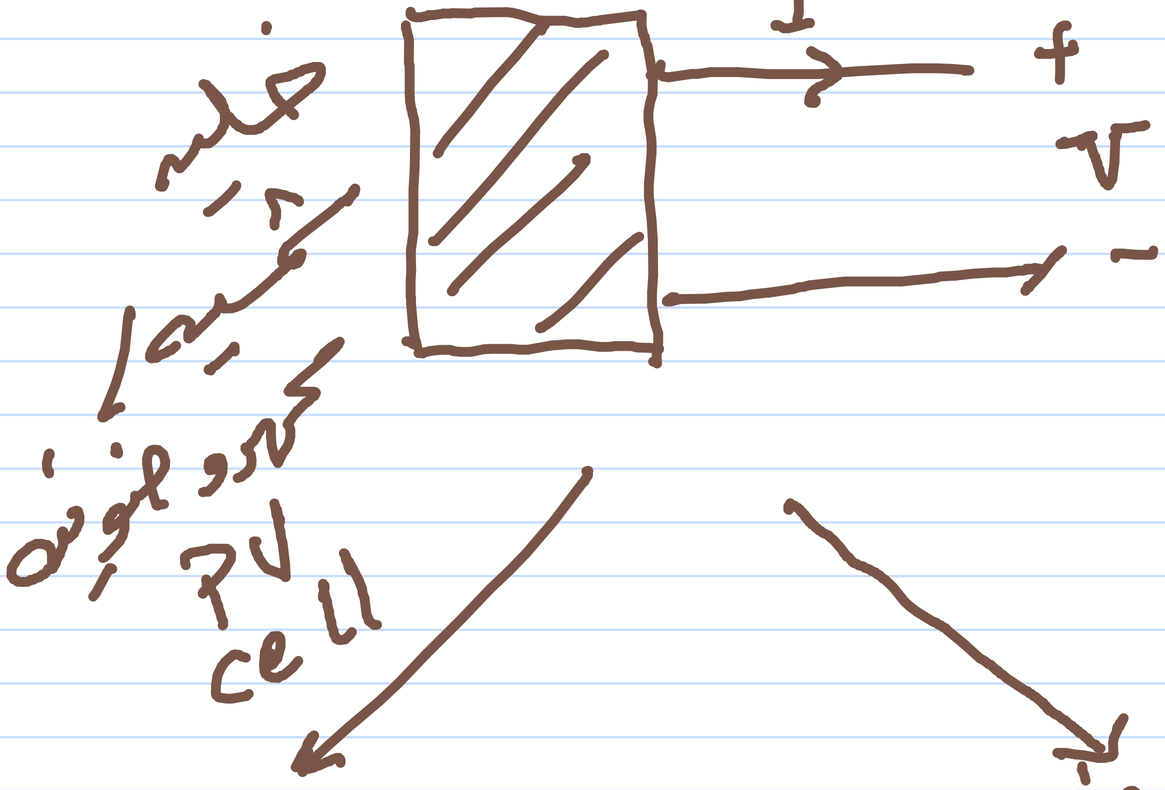
How Solar Cells are Made see movie book CD

First Exam material Ends Here

L11-PV model 19/4/202

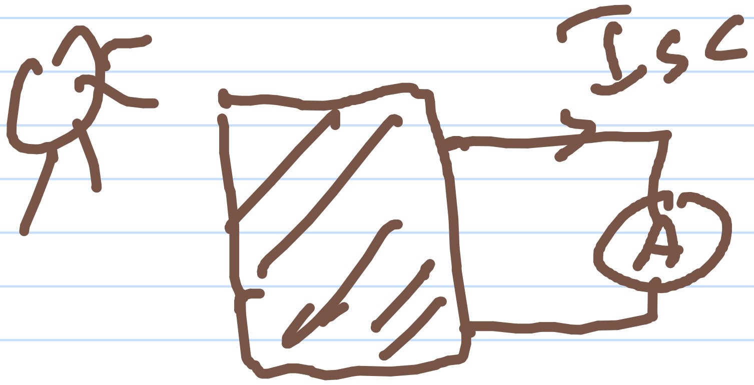
ENEE 5307

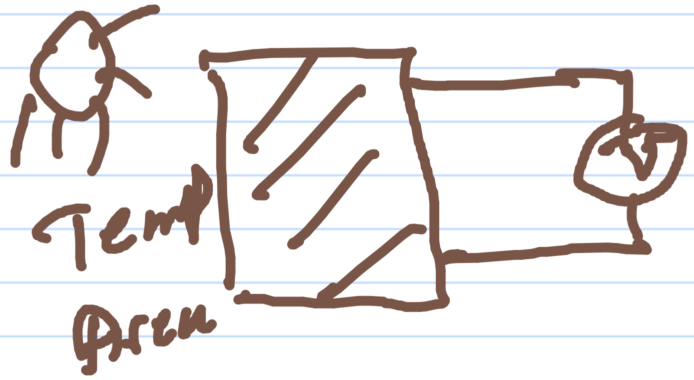
14/4/2021



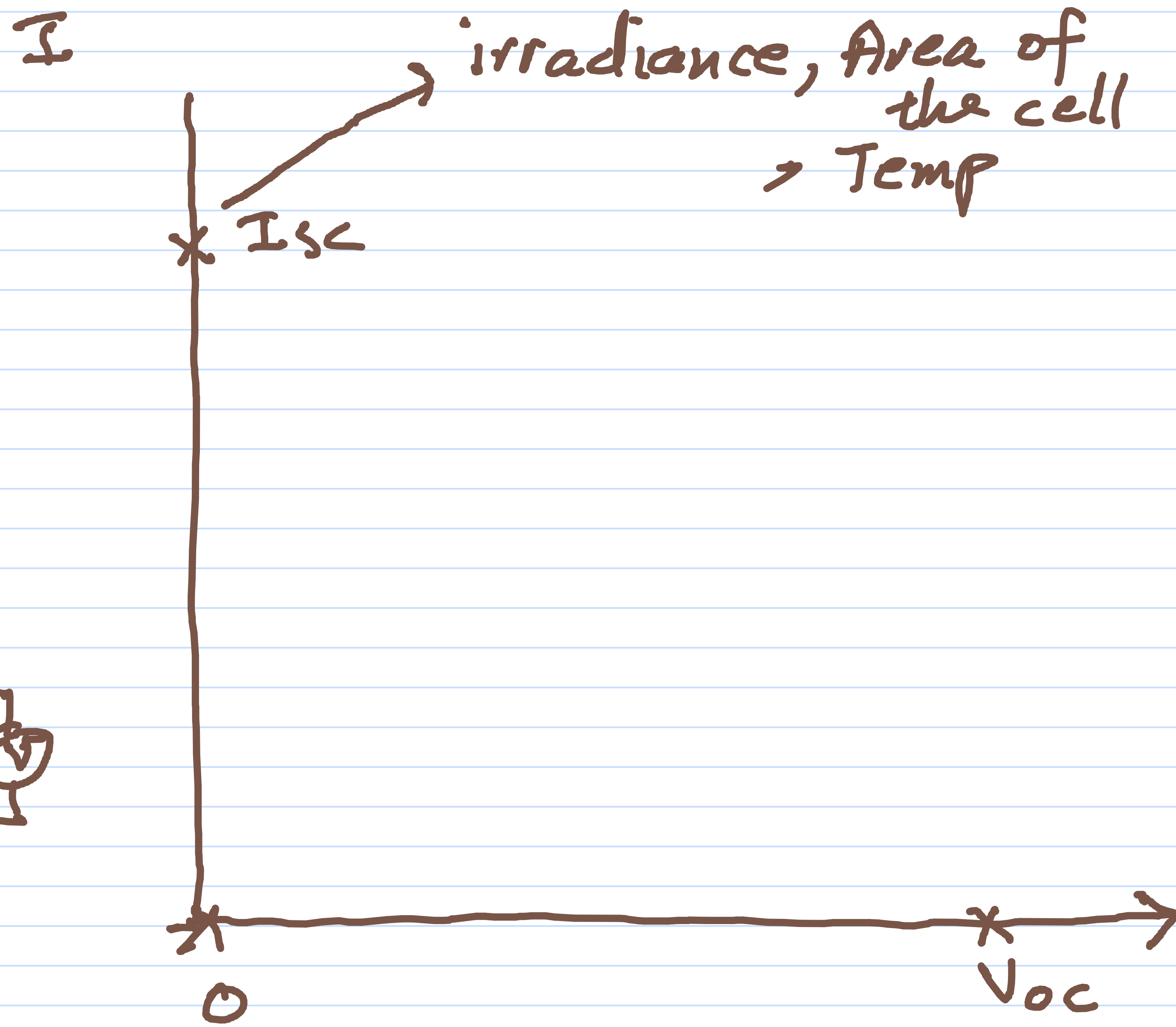
if $V = 0$
$I = I_{sc}$

if $I = 0$
$V = V_{oc}$

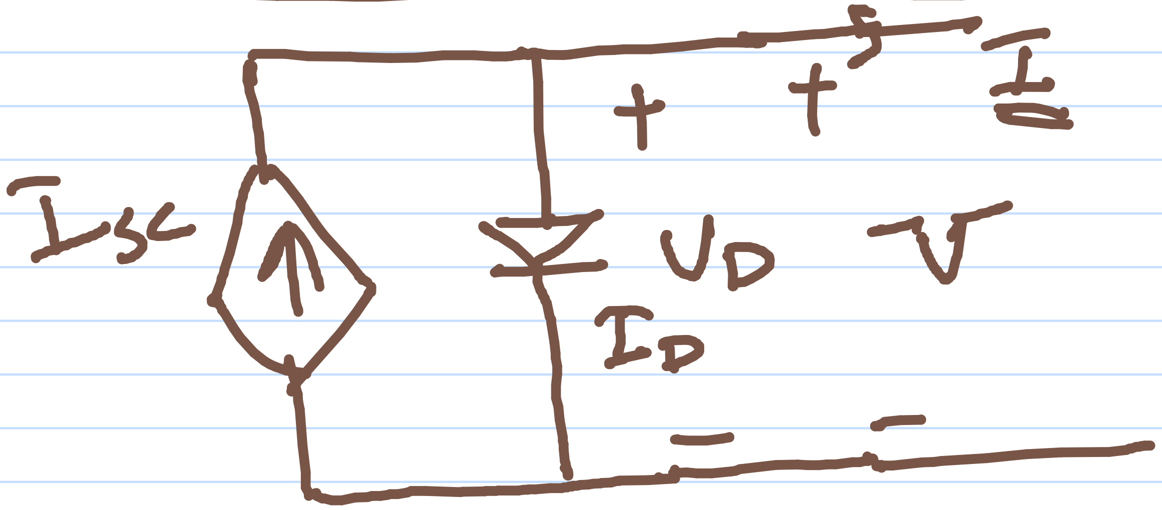




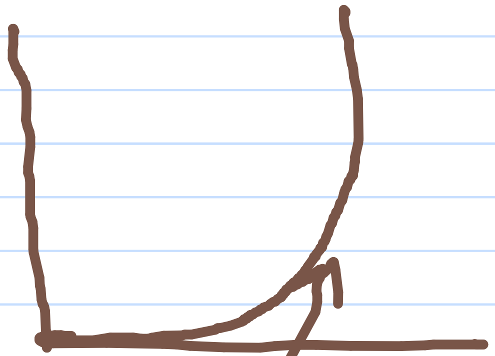
The main characteristic is I-V curve



1) Simple Equivalent circuit



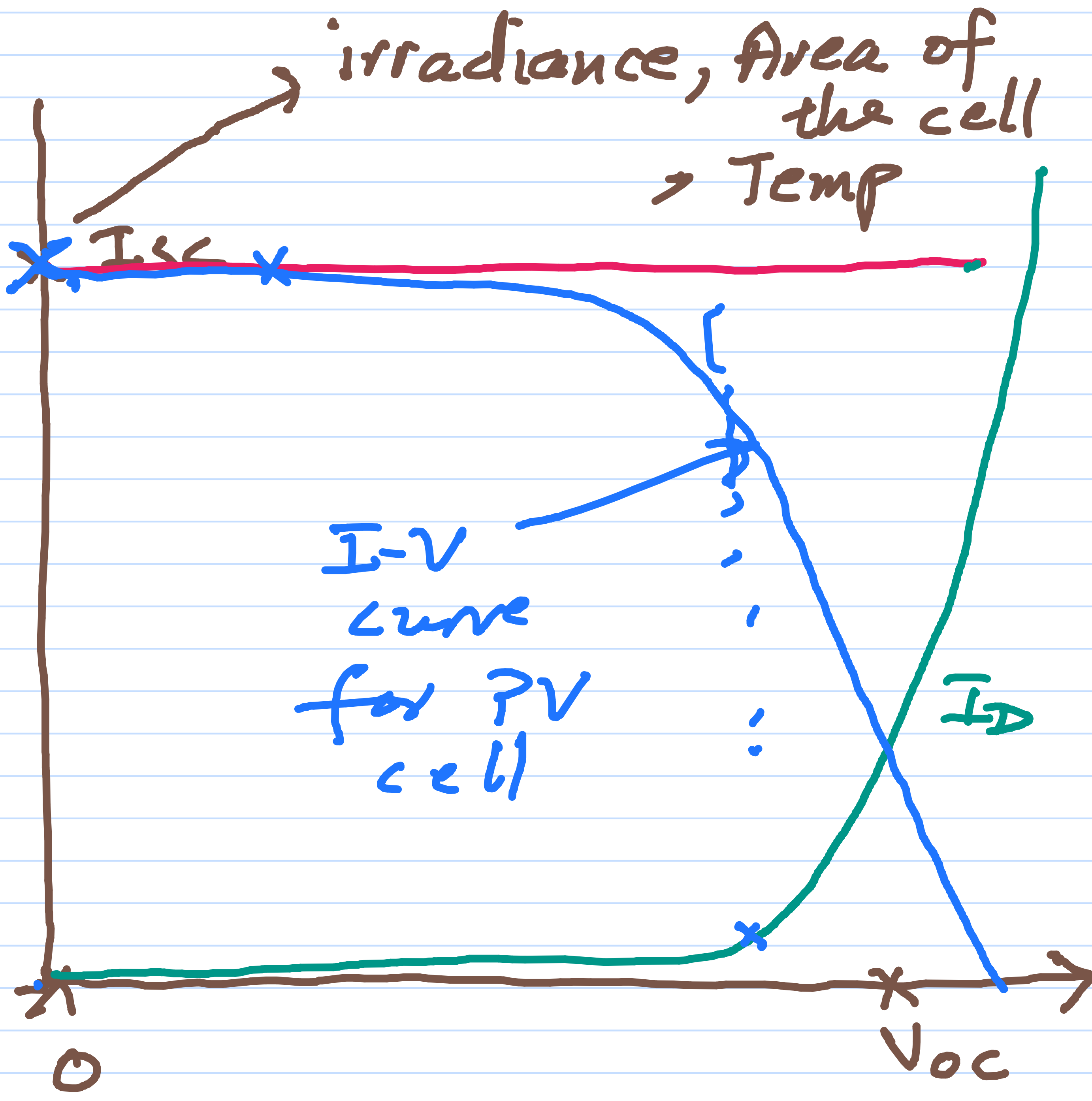
$I_D = f(V_D) \rightarrow$ exponential



$I = I_{sc} - I_d$

$= const - I_D$

The main characteristic is I-V curve

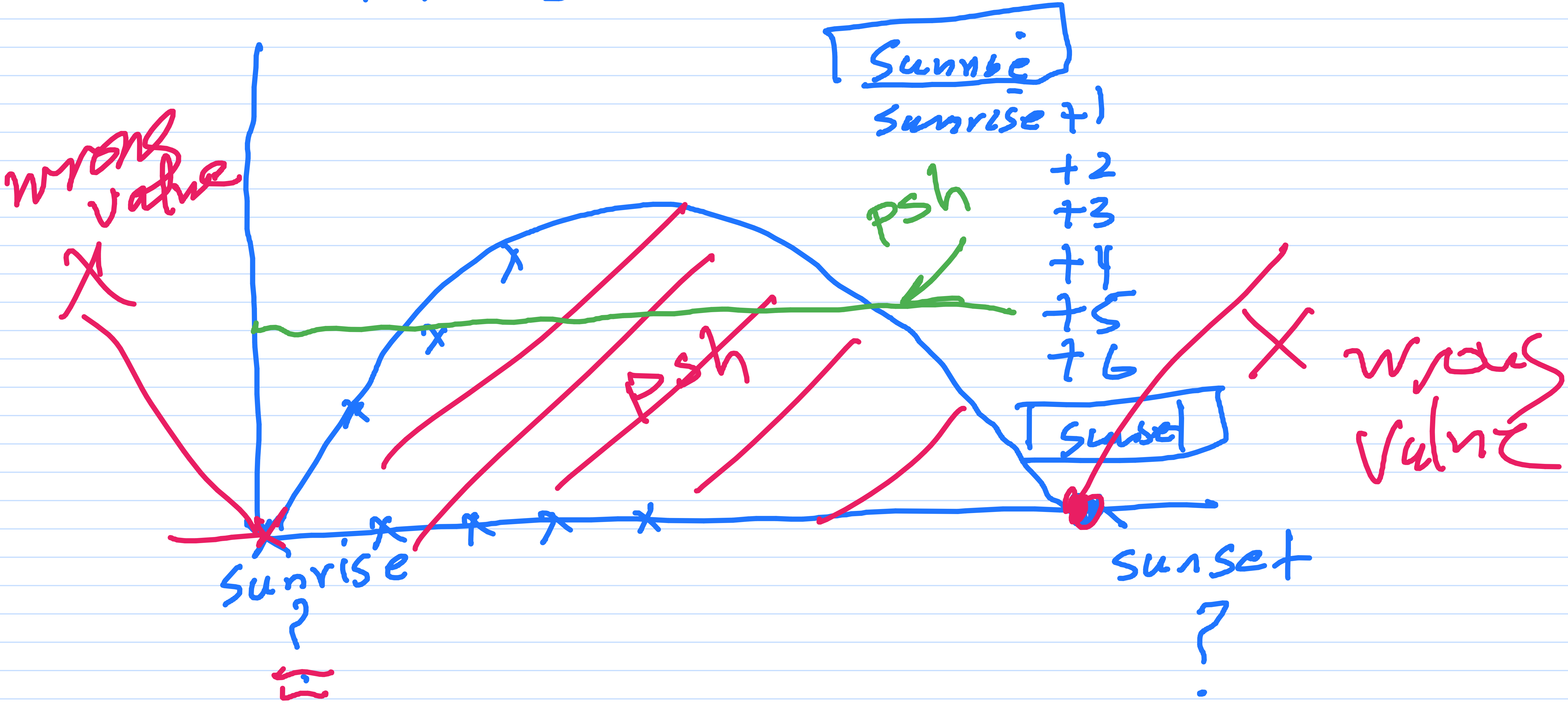


Project

for each n, L = latitude, $\phi_c = 0$

$n = 1$ $= 32°$

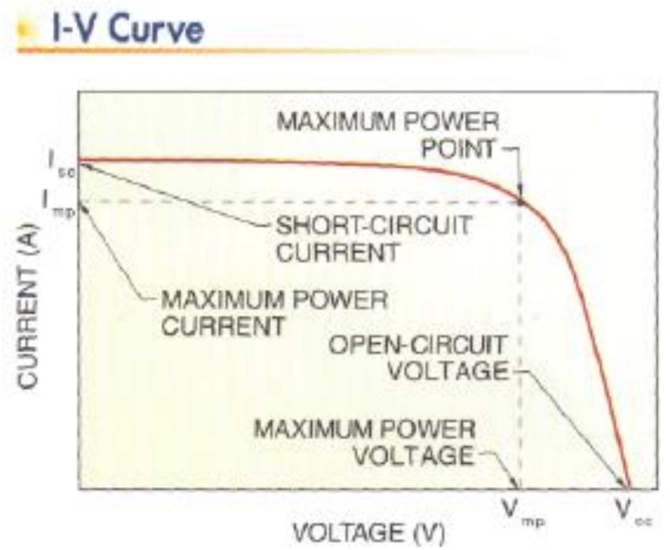
↓ Clear sky irradiance

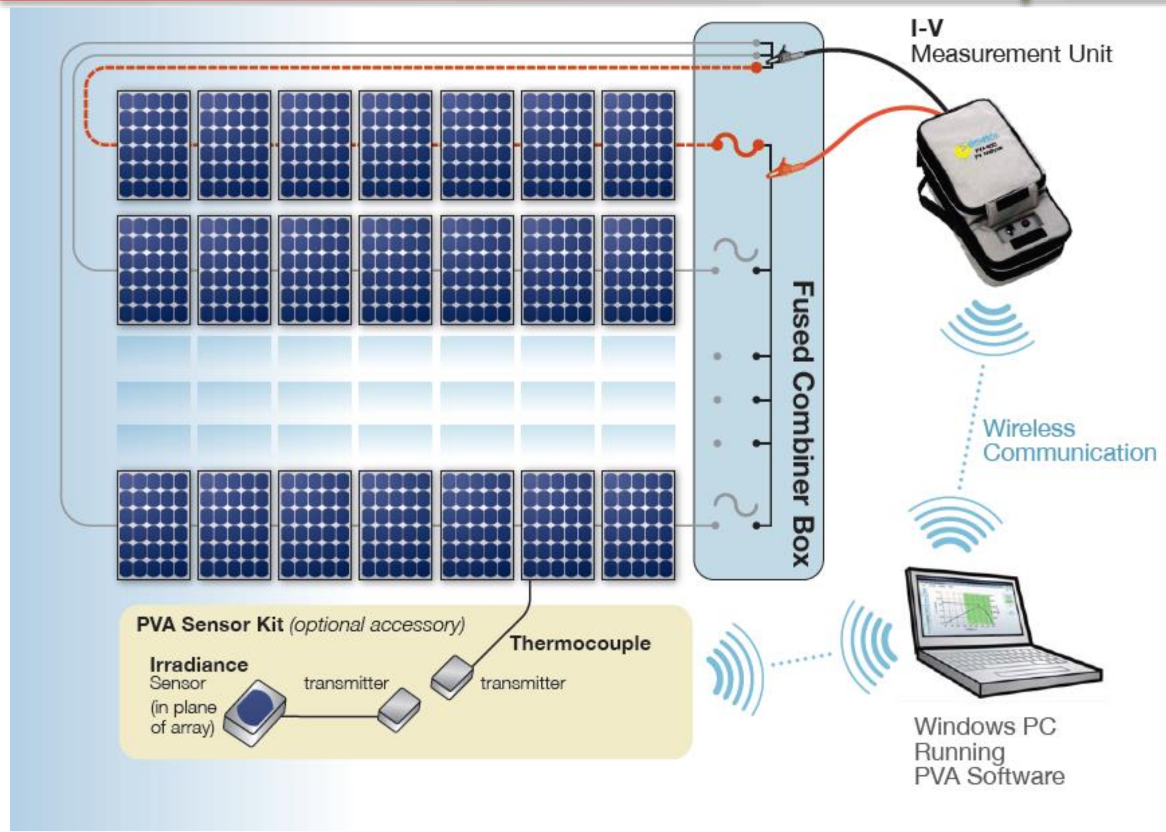


I-V Characteristic

19/4

L12



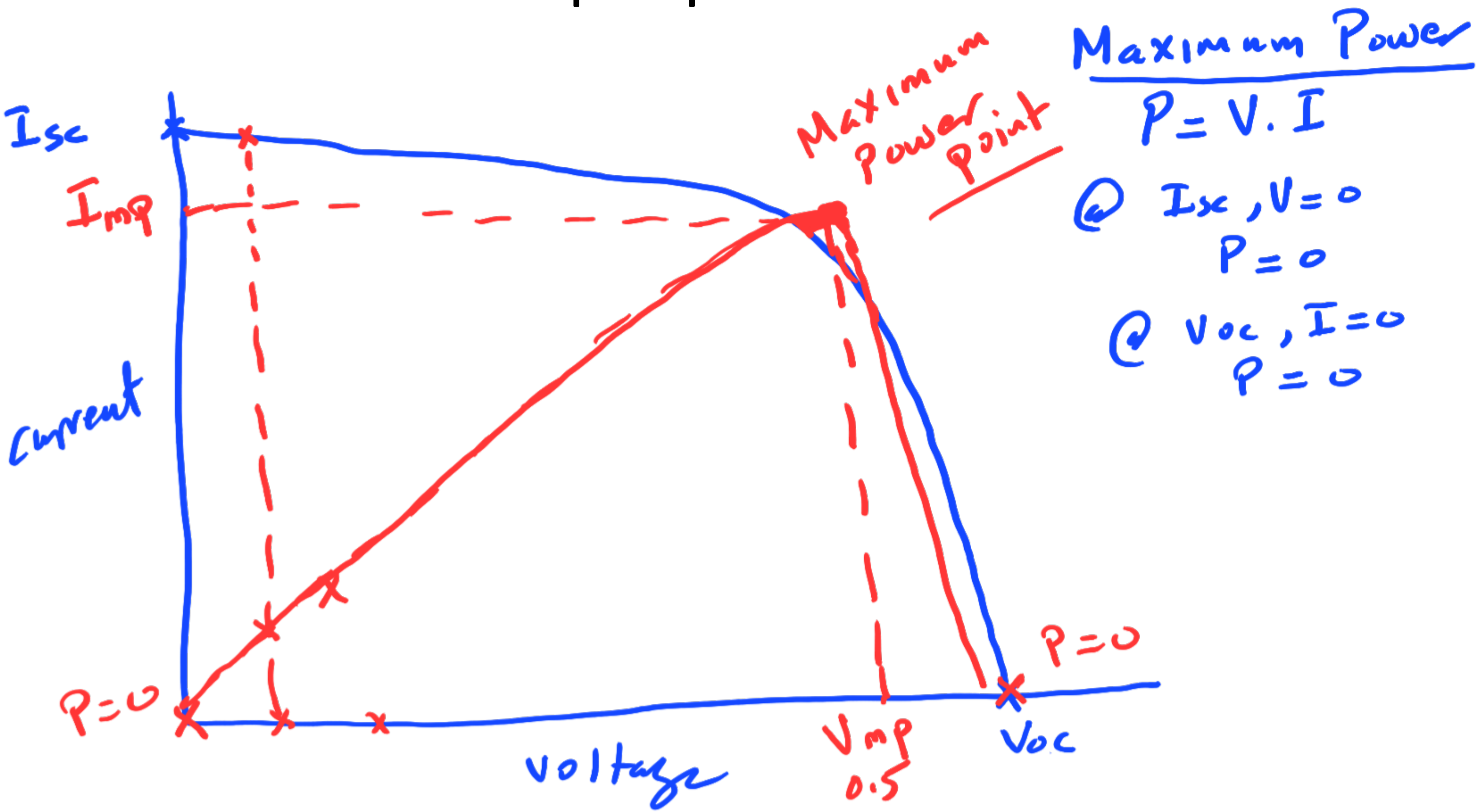


ENEE5307 Renewable Energy & PV Systems

Nasser Ismail
BZU-2020

The *current-voltage (I-V) characteristic*

- The *current-voltage (I-V) characteristic is the* basic electrical output profile of a PV device.

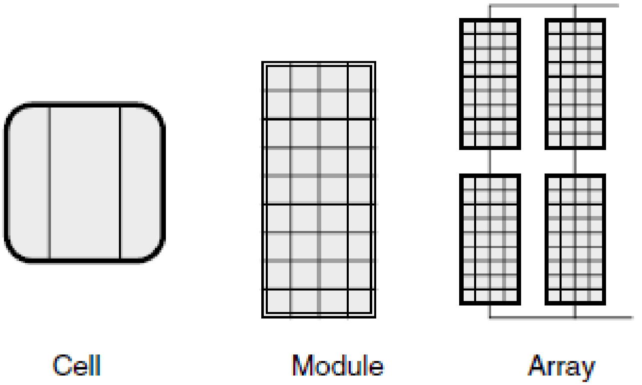


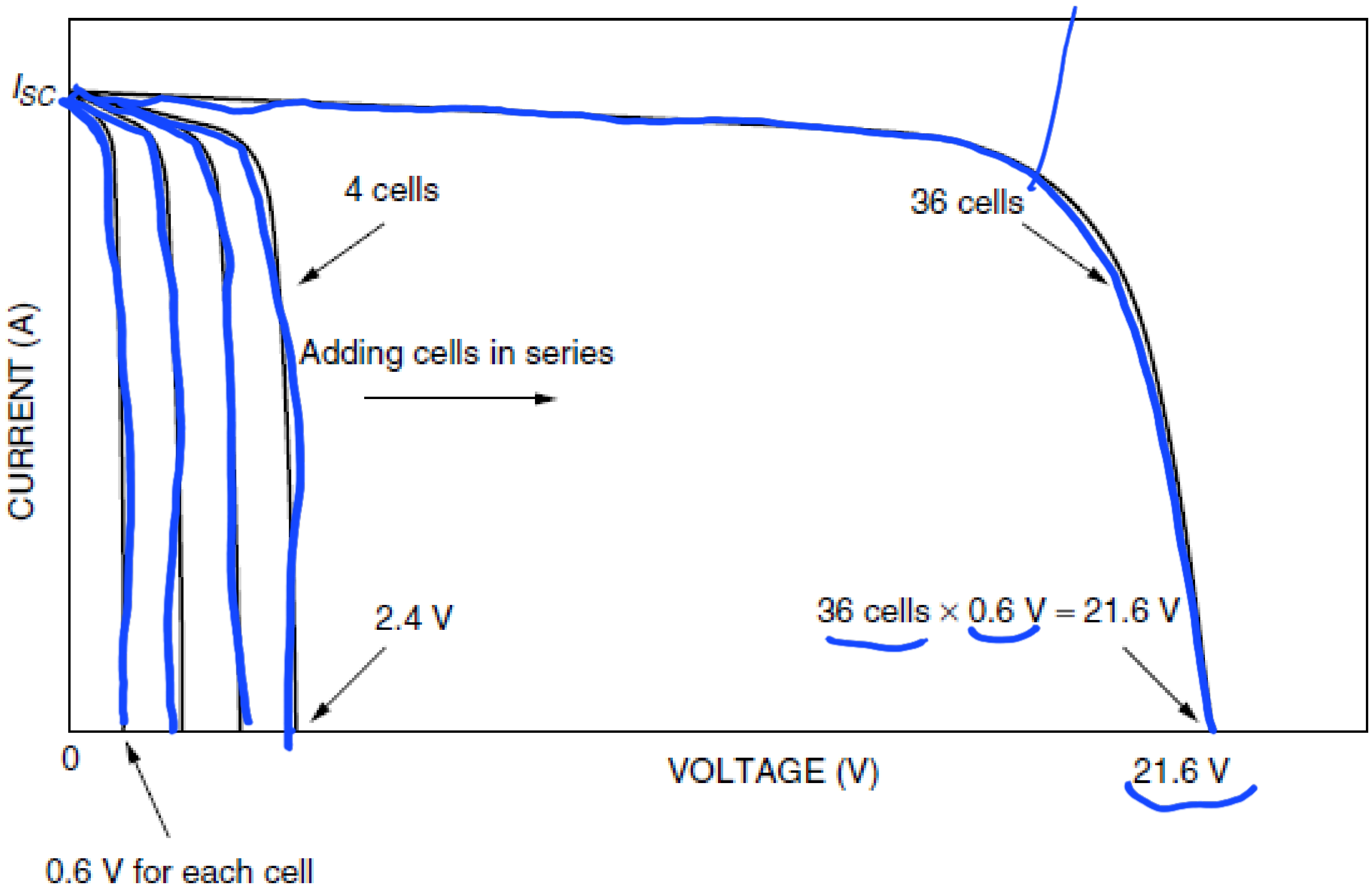
FROM CELLS TO MODULES TO ARRAYS

- Individual cells produce about 0.5 V,
- The basic building block for PV applications is a *module* consisting of a number of pre-wired cells in series, all encased in tough, weather-resistant packages.
- A typical module has 36 cells in series and is often designated as a “12-V module” even though it is capable of delivering much higher voltages than that.
- 12-V modules may be desirable in certain very simple battery charging systems.
- Large 72-cell modules are now quite common, some of which have all of the cells wired in series, in which case they are referred to as 24-V modules.

FROM CELLS TO MODULES TO ARRAYS

- Some 72-cell modules can be field-wired to act either as 24-V modules with all 72 cells in series or as 12-V modules with two parallel strings having 36 series cells in each.
- **Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of which is power.**
- ***An important element in PV system design is deciding how many modules should be connected in series and how many in parallel to deliver whatever energy is needed.***
- Such combinations of modules are referred to as an *array*.



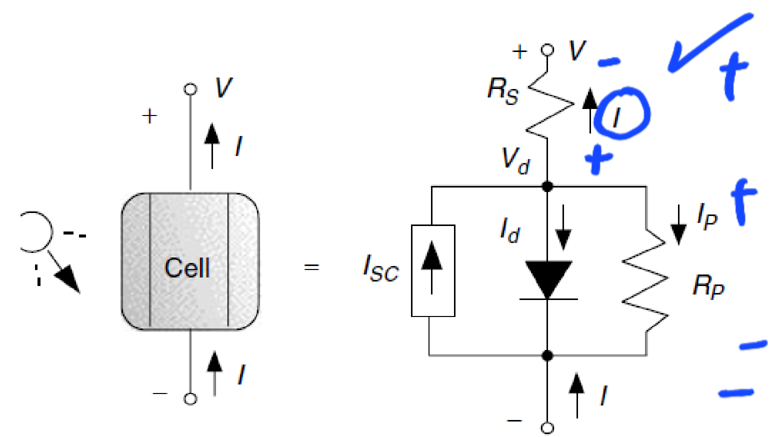


For cells wired in series, their voltages at any given current add.
A typical module will have 36 cells.

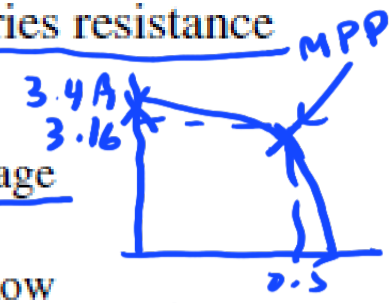
$$V_{module} = n(V_d - I R_S)$$

1 cell

n is number of modules

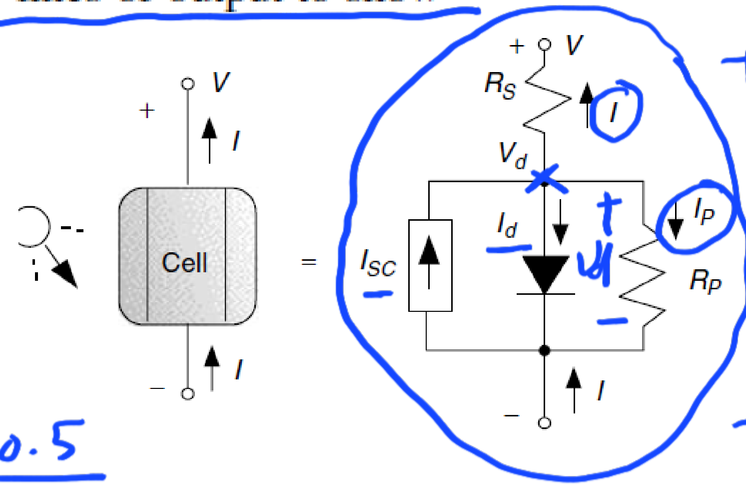


Example 8.4 Voltage and Current from a PV Module. A PV module is made up of 36 identical cells, all wired in series. With 1-sun insolation (1 kW/m^2), each cell has short-circuit current $I_{SC} = 3.4$ A and at 25°C its reverse saturation current is $I_0 = 6 \times 10^{-10}$ A. Parallel resistance $R_P = 6.6\ \Omega$ and series resistance $R_S = 0.005\ \Omega$.



a. Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V.

b. Set up a spreadsheet for I and V and present a few lines of output to show how it works.



- Solution:

a. using $V_d = 0.5$ V

$$\rightarrow I = I_{sc} - \underbrace{I_0\left(e^{38.9 V_d} - 1\right)}_{I_d} - \frac{V_d}{R_P}$$

$$= 3.4 - 6\times 10^{-10}\left(e^{38.9\times 0.5} - 1\right) - \frac{0.5}{6.6}$$

$$= 3.16 \text{ A}$$

$$V_{module} = n(V_d - I R_s) = 36(0.5 - 3.16\times 0.005) = 17.43 \text{ V}$$

Power delivered is therefore

$$P\,(\text{watts}) = V_{\text{module}}\, I = 17.43 \times 3.16 = 55.0\ \text{W}$$

b. A spreadsheet might look something like the following:

Number of cells, $n = 36$

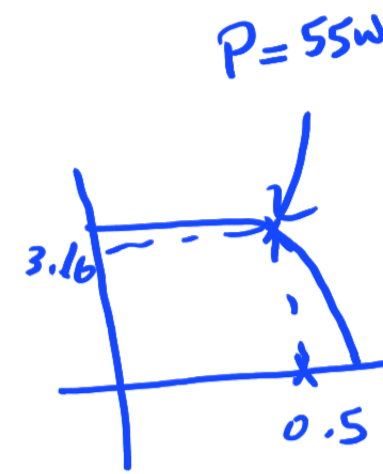
Parallel resistance/cell R_P (ohms) = 6.6

Series resistance/cell R_S (ohms) = 0.005

Reverse saturation current I_0 (A) = 6.00E-10

Short-circuit current at 1-sun (A) = 3.4

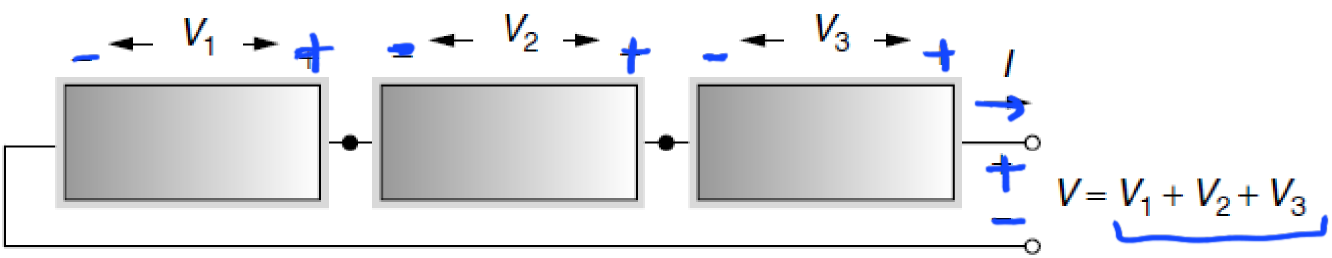
V_d	$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - \frac{V_d}{R_p}$	$V_{\text{module}} = n(V_d - IR_S)$	P (watts) $= V_{\text{module}} I$
0.49	3.21	17.06	54.80
0.50	3.16	17.43	55.02
0.51	3.07	17.81	54.75
0.52	2.96	18.19	53.76
0.53	2.78	18.58	51.65
0.54	2.52	18.99	47.89
0.55	2.14	19.41	41.59

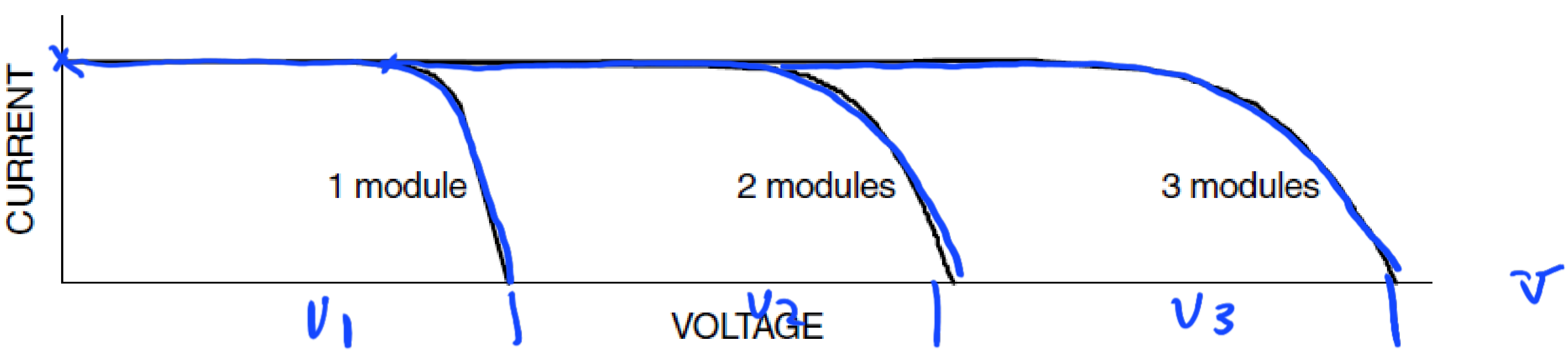


Notice that we have found the maximum power point for this module, which is at $I = 3.16$ A, $V = 17.43$ V, and $P = 55$ W. This would be described as a 55-W module. ← Maximum Power Point ≡ rated Power of the Module

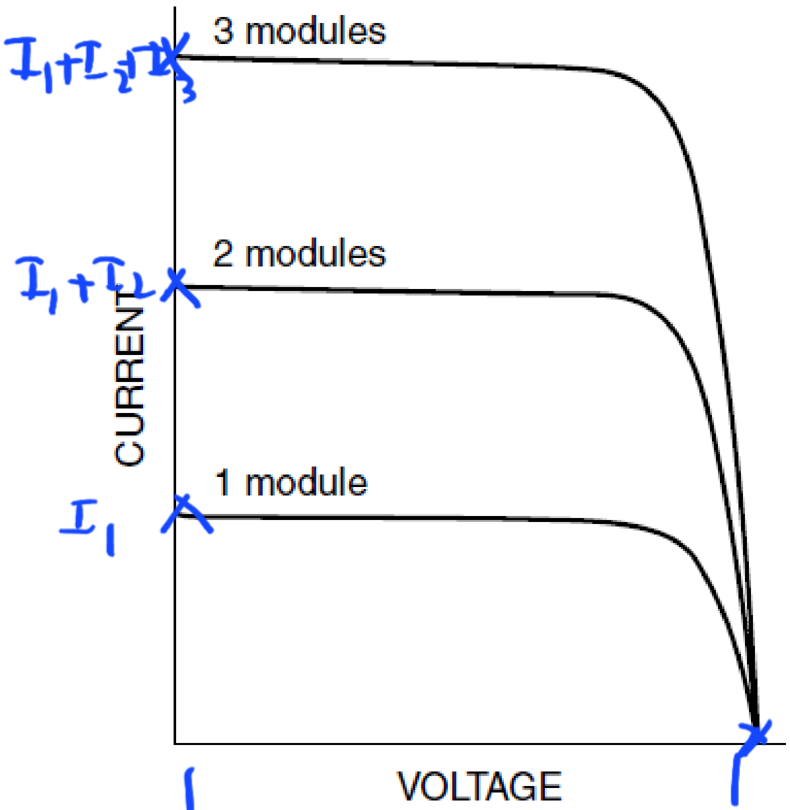
From Modules to Arrays

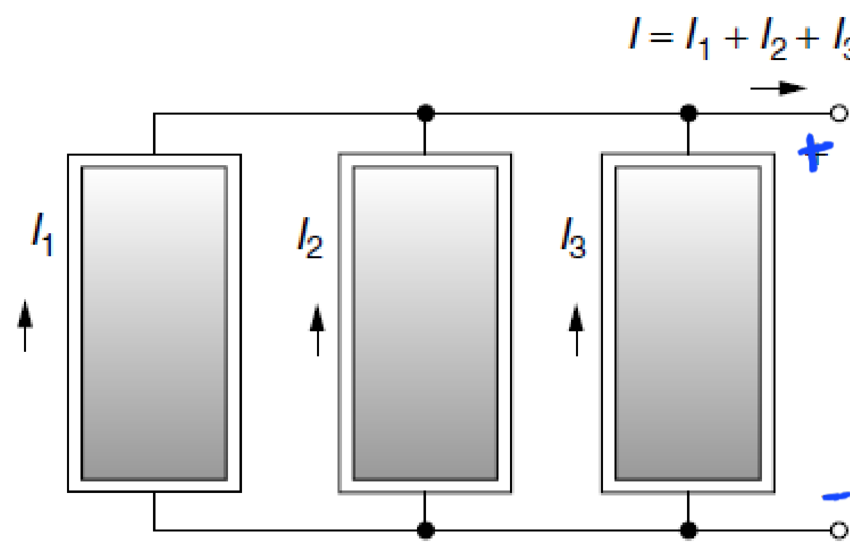
- Modules can be wired in series to increase voltage, and in parallel to increase current.
- Arrays are made up of some combination of series and parallel modules to increase power.
- For modules in series, the $I-V$ curves are simply added along the voltage axis.

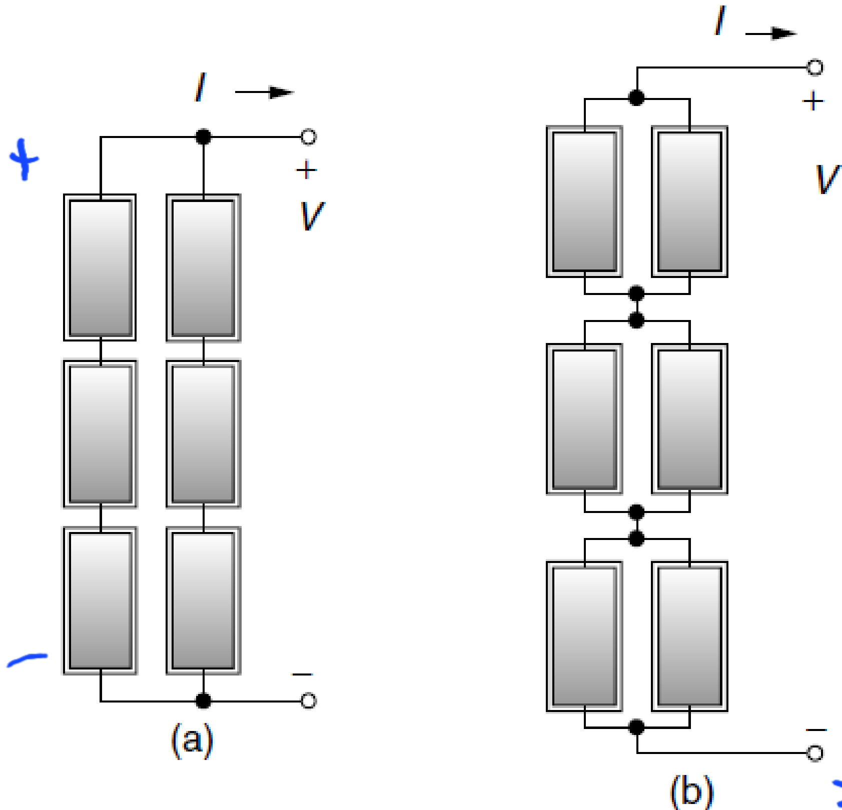




- For modules in parallel, the same voltage is across each module and the total current is the sum of the currents.
- That is, at any given voltage, the $I-V$ curve of the parallel combination is just the sum of the individual module currents at that voltage







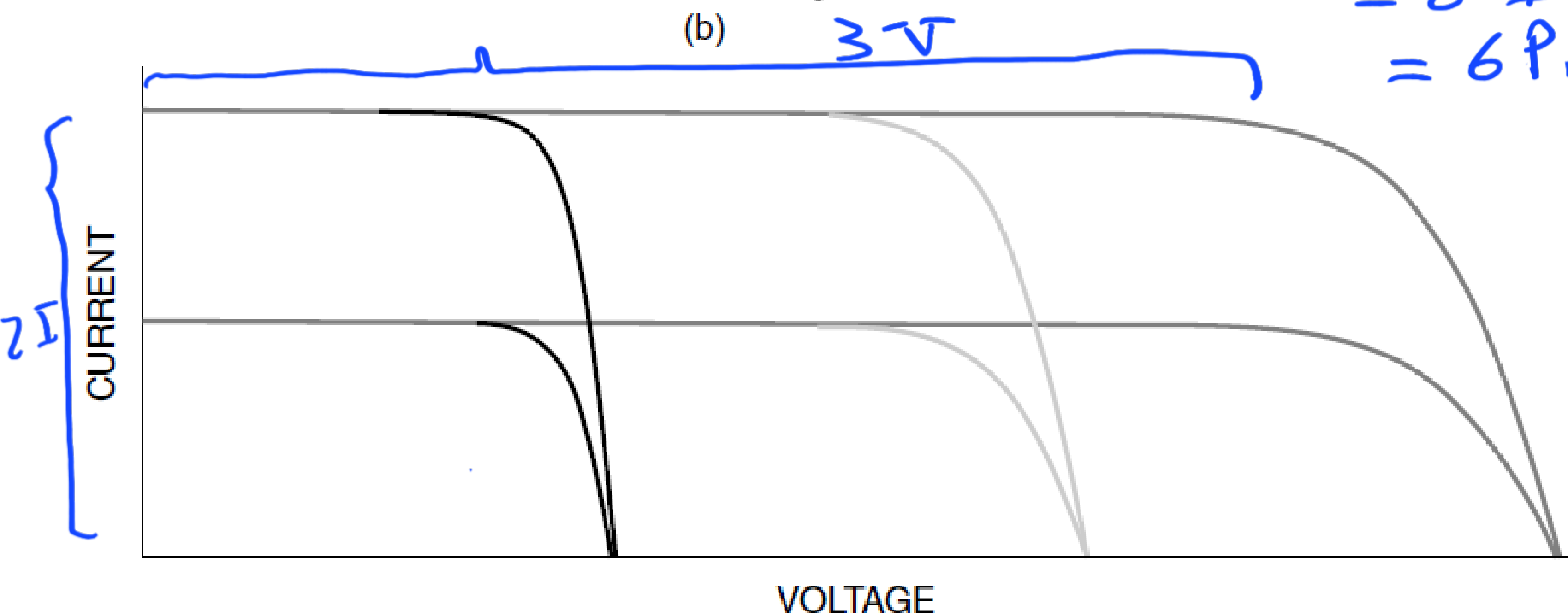
Two ways to wire an array with three modules in series and two modules in parallel.

Both I-V curves are the same

$P_{array} = 2I \times 3V$

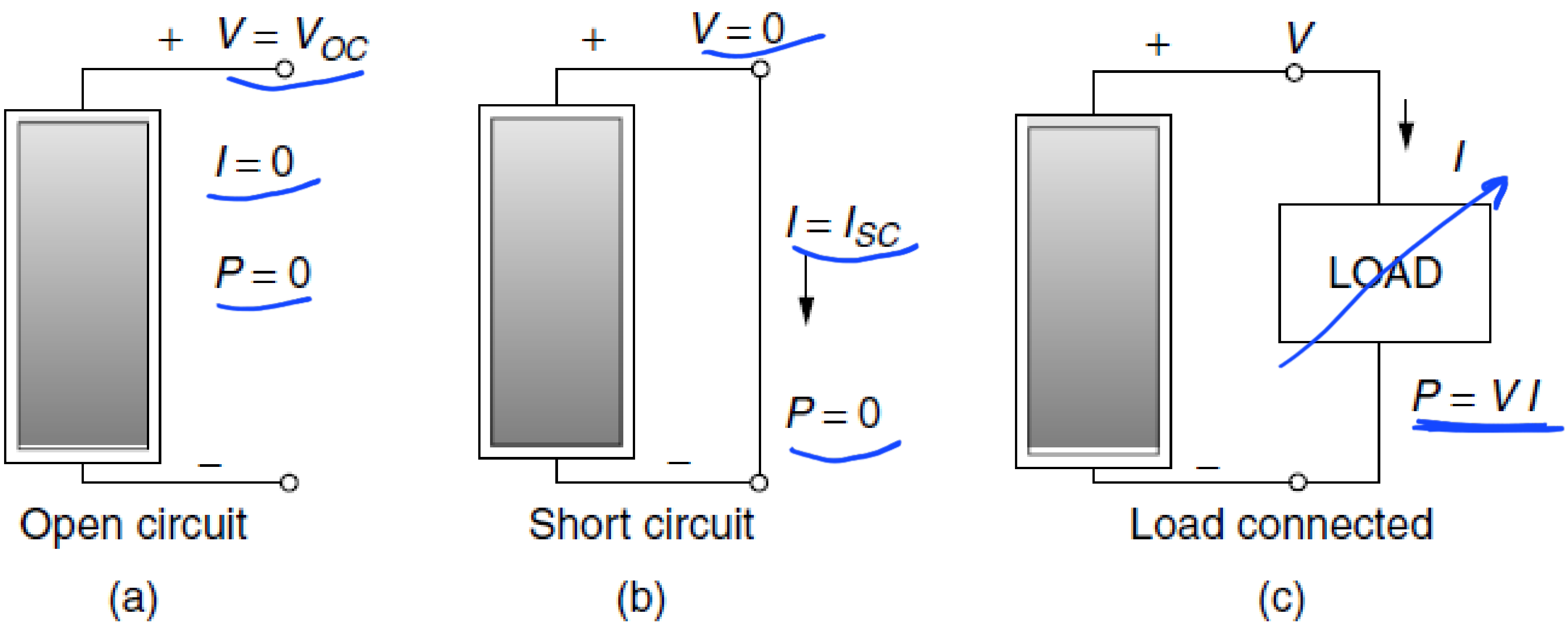
$= 6 IV$

$= 6 P_{module}$

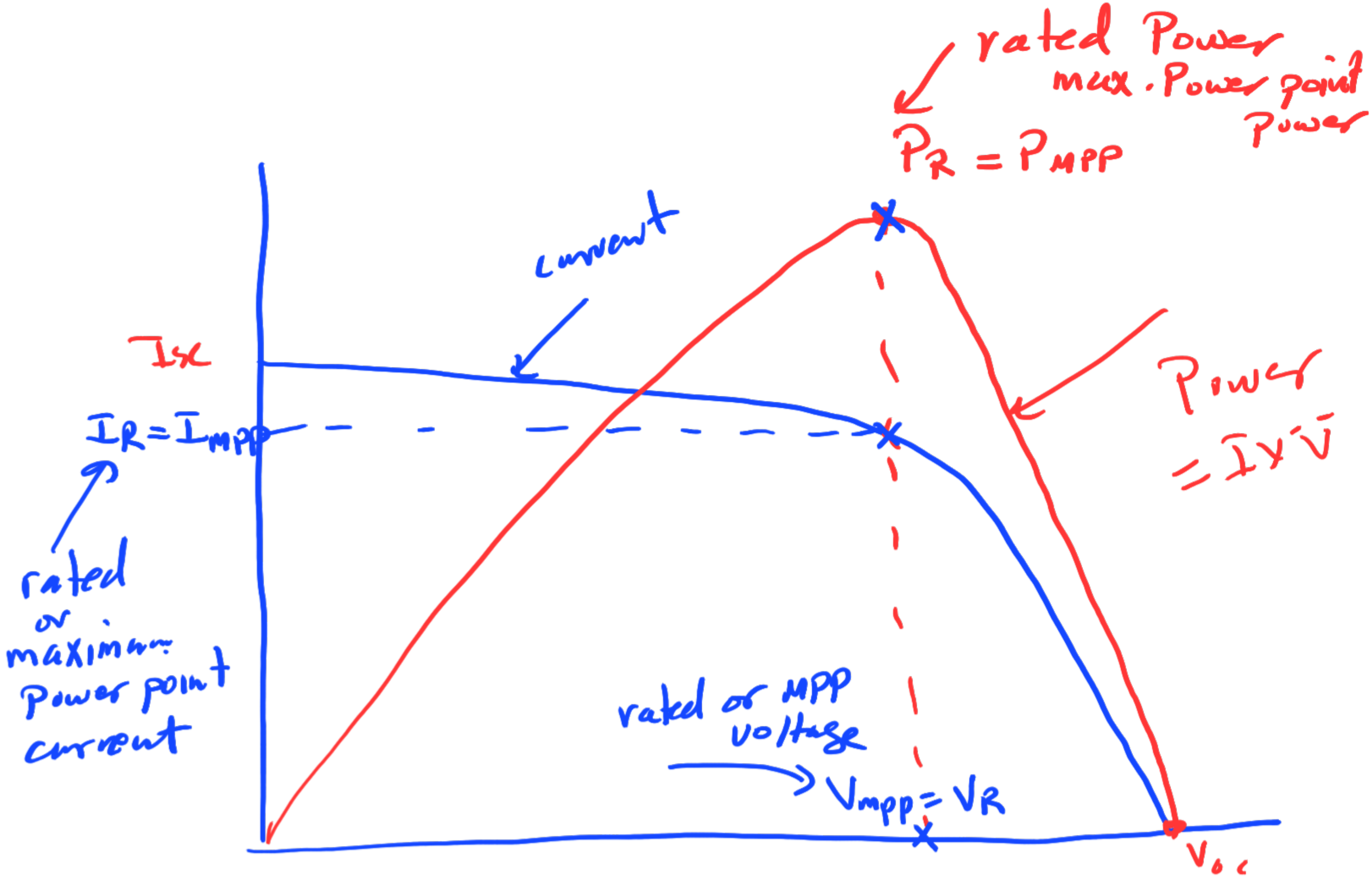


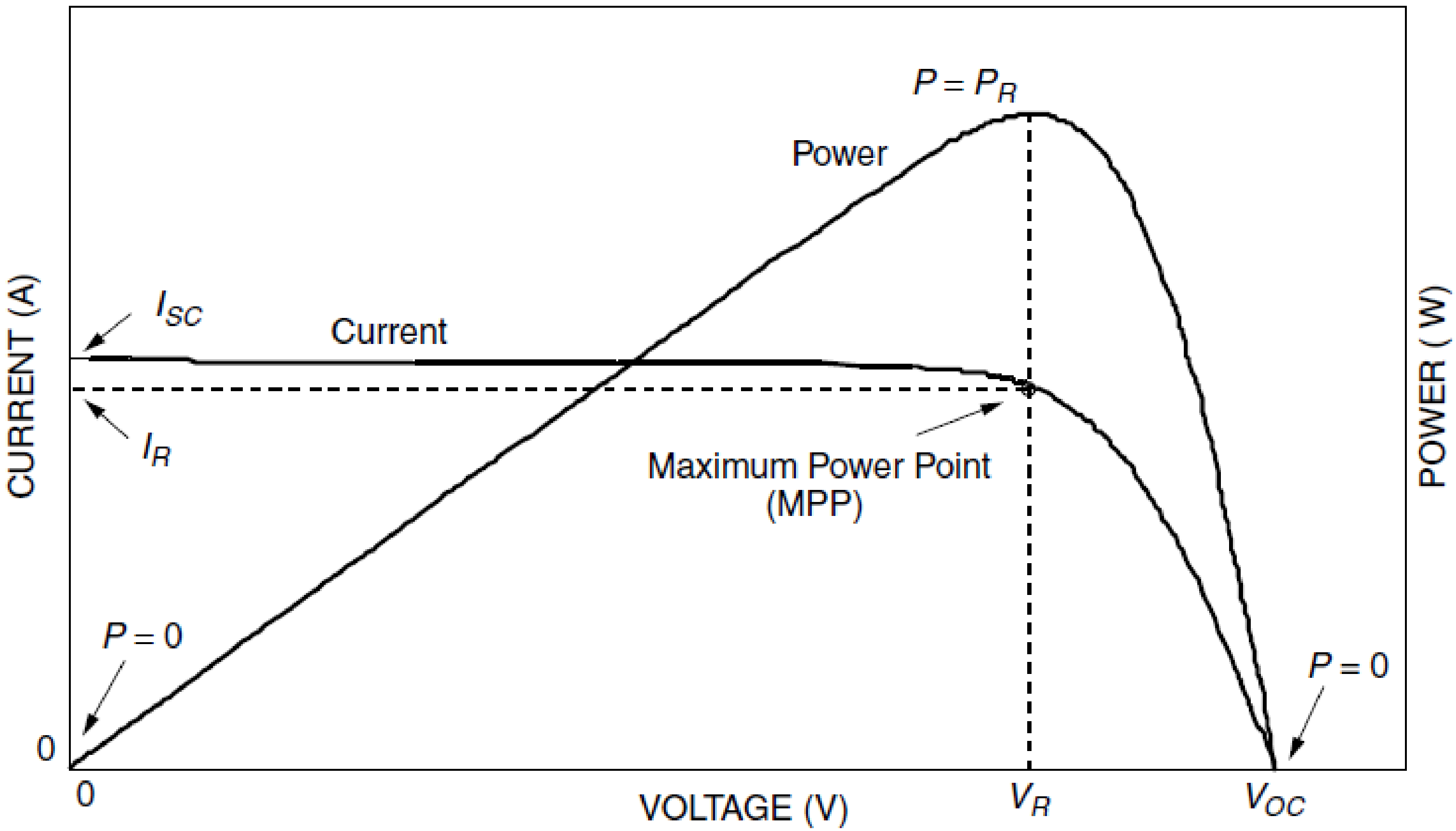
THE PV I–V CURVE UNDER STANDARD TEST CONDITIONS (STC)

- Before the load is connected, the module sitting in the sun will produce an **open-circuit voltage Voc**, but no current will flow.
- If the terminals of the module are shorted together (which doesn't hurt the module at all, by the way), **the short-circuit current Isc** will flow, but the output voltage will be zero.
- In both cases, since power is the product of current and voltage, no power is delivered by the module and no power is received by the load.
- When the load is actually connected, some combination of current and voltage will result and power will be delivered.
- To figure out how much power, we have to consider the I –V characteristic curve of the module as well as the I –V characteristic curve of the load.

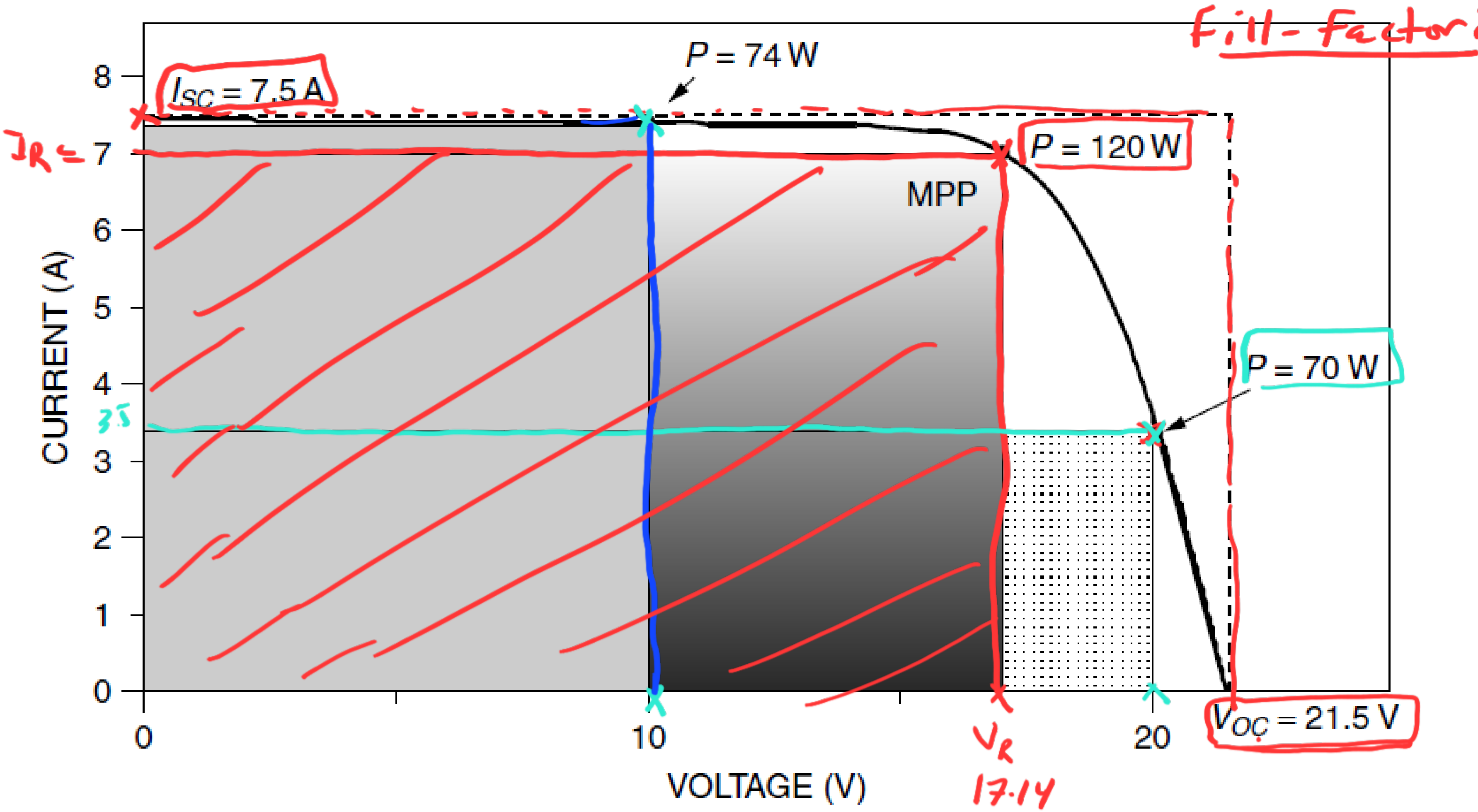


- No power is delivered when the circuit is open (a) or shorted (b).
- When the load is connected (c), the same current flows through the load and module and the same voltage appears across them.


rated Power
max. Power point
Power
PR = PMPP
current
Isc
IR = IMPP
rated
or
maximum
Power point
current
Power
= I x V
rated or MPP
voltage
Vmpp = VR
Voc



The $I-V$ curve and power output for a PV module.
At the maximum power point (MPP) the module delivers the most power that it can under the conditions of sunlight and temperature for which the $I-V$ curve has been drawn.



- The maximum power point (MPP) corresponds to the biggest rectangle that can fit beneath the *I* – *V* curve.
- The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides ***Voc*** and ***ISC***.

Fill Factor

- Fill factors around 70–75% for crystalline silicon solar modules are typical, while for multijunction amorphous-Si modules, it is closer to 50–60%.

$$\textbf{Fill Factor (FF)} = \frac{\textbf{Power at MPP (i.e. Rated Power)}}{V_{OC} I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

$$= \frac{V_{mpp} \times I_{mpp}}{V_{oc} \cdot I_{sc}}$$

- Since PV $I-V$ curves shift all around as the amount of insolation changes
- And as the temperature of the cells varies, standard test conditions (STC) have been established to enable fair comparisons of one module to another.

Standard Test Conditions :STC

- **STC: include a solar irradiance of 1 kW/m^2 (1 sun) , spectral distribution, corresponding to an air mass ratio of 1.5 (AM 1.5).**
- The standard cell temperature for testing purposes is 25°C (it is important to note that 25° is cell temperature, not ambient temperature).
- Manufacturers always provide performance data under these operating conditions,
- The key parameter for a module is its rated power; $P_{DC,STC}$.
- Power adjustments to take into account temperature effects will be done later
- Also the actual ac power that the module and inverter combination will deliver will be estimated.

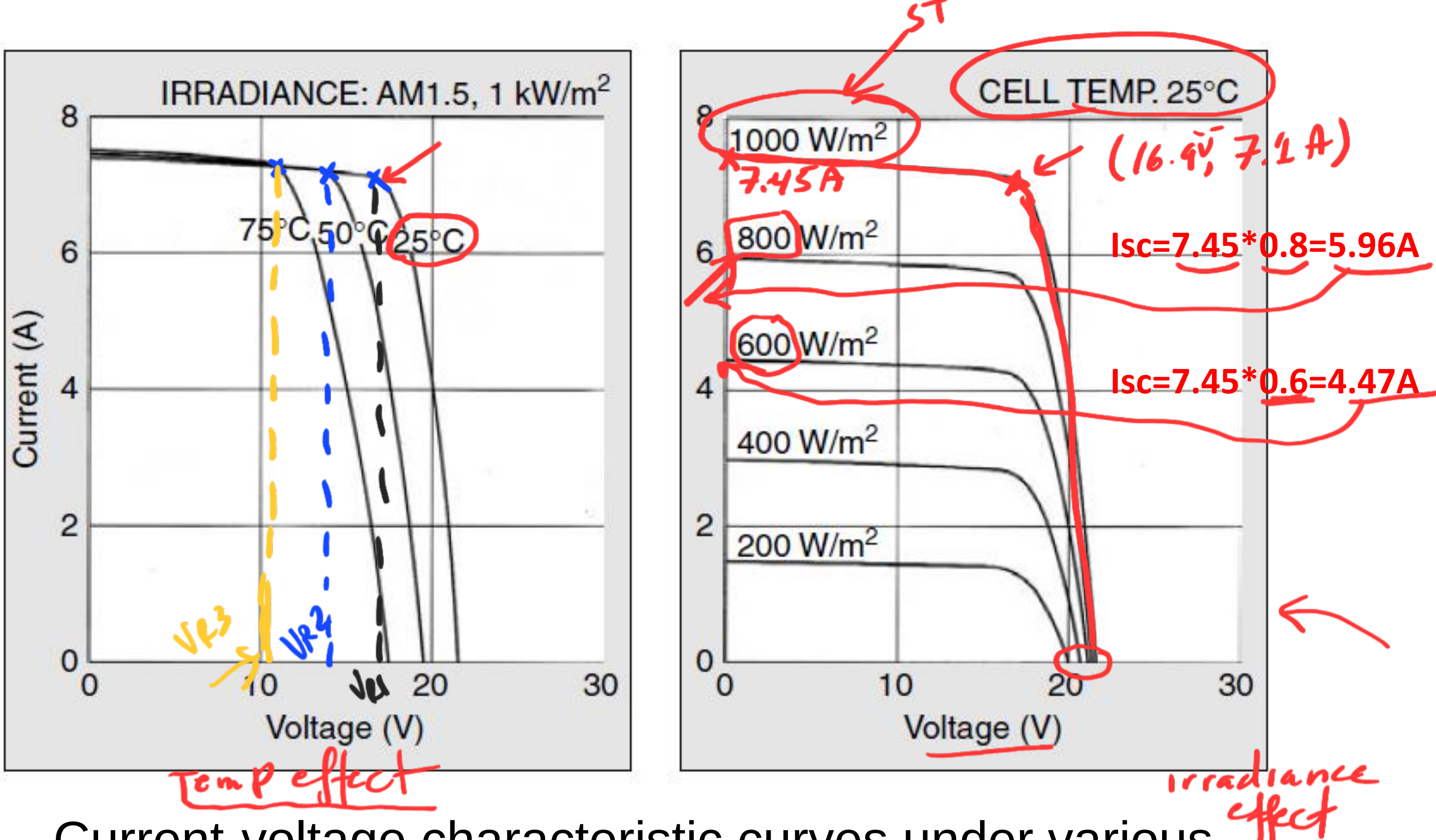
TABLE 8.3 Examples of PV Module Performance Data Under Standard Test Conditions (1 kW/m^2, AM 1.5, 25°C Cell Temperature)

Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current at rated power (A)	7.1	4.77	4.45	3.88	2.41
Open-circuit voltage V_{OC} (V)	21.5	43.1	42.8	23.8	23.3
Short-circuit current I_{SC} (A)	7.45	5.46	4.75	4.80	2.68
Length (mm/in.)	1425/56.1	1575/62.05	1587/62.5	1366/53.78	1293/50.9
Width (mm/in.)	652/25.7	826/32.44	790/31.1	741/29.18	329/12.9
Depth (mm/in.)	52/2.0	46/1.81	50/1.97	31.8/1.25	54/2.1
Weight (kg/lb)	11.9/26.3	17/37.5	15.4/34	9.2/20.2	14.8/32.6
Module efficiency	12.9%	12.7%	12.0%	6.3%	9.4%

IMPACTS OF TEMPERATURE AND INSOLATION ON $I-V$ CURVES

- Manufacturers will often provide $I-V$ curves that show how the curves shift as insolation and cell temperature changes.
- An example for the Kyocera 120-W multicrystal-silicon module described in Table 8.3. is given
- Notice as insolation drops, short-circuit current drops in direct proportion.
- **Cutting insolation in half, for example, drops I_{SC} by half.**
- **Decreasing insolation also reduces V_{OC}, but it does so following a logarithmic relationship that results in relatively modest changes in V_{OC}.**

as seen before



Current-voltage characteristic curves under various cell temperatures and irradiance levels for the Kyocera KC120-1 PV module.

Temp Effect

- As cell temperature increases, the open-circuit voltage decreases substantially while the short-circuit current increases only slightly.
- **Photovoltaics, perhaps surprisingly, therefore perform better on cold, clear days than hot ones**.
- For crystalline silicon cells, V_{OC} drops by about **0.37%** for each degree Celsius increase in temperature and I_{sc} increases by approximately **0.05%.**
- The net result when cells heat up is the MPP slides slightly upward and toward the left with a decrease in maximum power available of about **0.5%/◦C.**
- Given this significant shift in performance as cell temperature changes, it should be quite apparent that temperature needs to be included in any estimate of module performance.

NOCT

- Cells vary in temperature not only because ambient temperatures change, but also because insolation on the cells changes. Since only a small fraction of the insolation hitting a module is converted to electricity and carried away, most of that incident energy is absorbed and converted to heat.
- To help system designers account for changes in cell performance with temperature, manufacturers often provide an indicator called the NOCT, which stands for nominal operating cell temperature.
- The NOCT is cell temperature in a module when ambient is 20◦C, solar irradiation is 0.8 kW/m^2, and windspeed is 1 m/s. To account for other ambient conditions, the following expression may be used:

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8} \right) \cdot S$$

- where *Tcell* is cell temperature (◦C), *Tamb* is ambient temperature, and *S* is solar insolation (kW/m^2).

Impact of Cell Temperature on Power for a PV Module.

- Estimate cell temperature, open-circuit voltage, and maximum power output for the 150-W BP2150S module under conditions of 1-sun insolation and ambient temperature 30◦C. The module has a NOCT of 47◦C.
- Solution: cell temperature is estimated to be

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^{\circ}}{0.8}\right) \cdot S = 30 + \left(\frac{47 - 20}{0.8}\right) \cdot 1 = 64^{\circ}\text{C}$$

- From Table 8.3, for this module at the standard temperature of 25◦C, *VOC* = 42.8 V. Since *VOC* drops by 0.37%/◦C, the new *VOC* will be about:

Temp. Coeffecient for Voc

$$V_{OC} = 42.8[1 - 0.0037(64 - 25)] = 36.7\ \text{V}$$

0.37% = 0.0037

ΔT = 39

= 39 × 0.0037

= 0.1443

= 42.8 (1 − 0.1443) = 36.7 V

$0.5\% = \frac{0.5}{100} = 0.005$

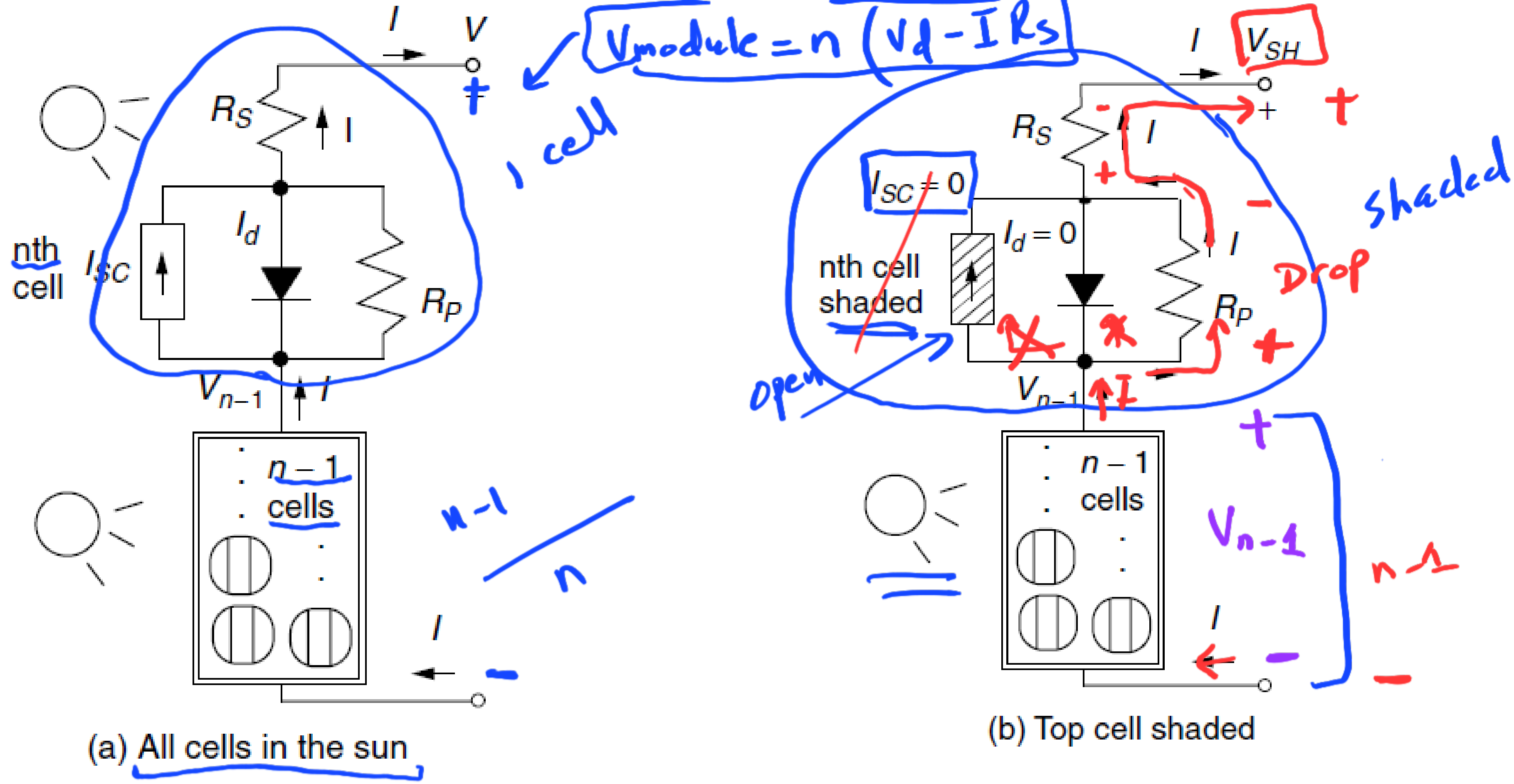
- With maximum power expected to drop about - 0.5%/◦C, this 150-W module at its maximum power point will deliver

$$P_{max} = 150\ W \cdot [1 - 0.005(64 - 25)] = 121\ W$$

- which is a rather significant drop of 19% from its rated power.

SHADING IMPACTS ON I –V CURVES

- The output of a PV module can be reduced dramatically when even a small portion of it is shaded.
- Unless special efforts are made to compensate for shade problems, even a single shaded cell in a long string of cells can easily cut output power by more than half.
- **External diodes,** purposely added by the PV manufacturer or by the system designer, can help preserve the performance of PV modules.
- The main purpose for such diodes is to mitigate the impacts of shading on PV $I-V$ curves.
- Such diodes are usually added in parallel with modules or blocks of cells within a module.



A module with n cells in which the top cell is in the sun (a) or in the shade (b)

$$V_{SH} = V_{n-1} - I(R_P + R_S)$$

With all n cells in the sun and carrying I, the output voltage was V so the voltage of the bottom $n - 1$ cells will be.

$$V_{n-1} = \left(\frac{n-1}{n}\right) V$$

$V_{module} = n \times V_{cell}$

$$V_{SH} = \left(\frac{n-1}{n}\right) V - I\,(R_P + R_S)$$

- The drop in voltage Δ V at any given current *I* , caused by the shaded cell, is given by:

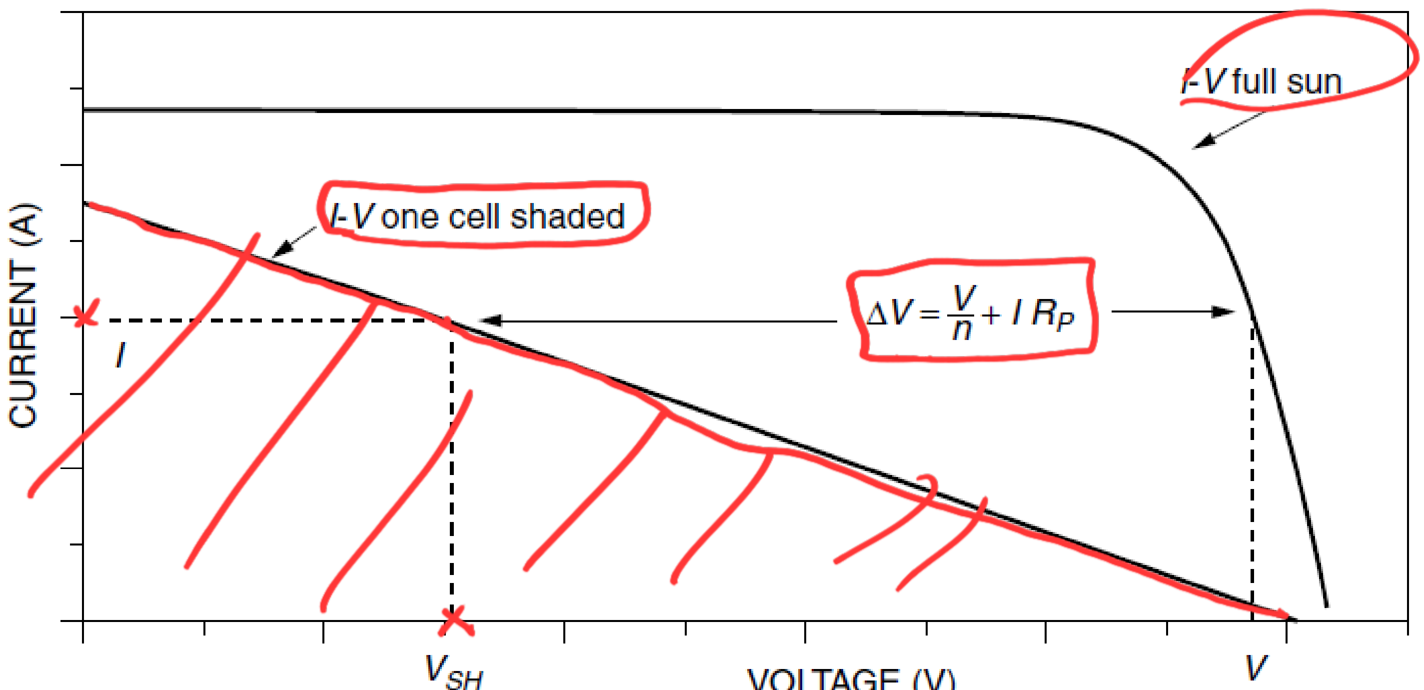
$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I\,(R_P + R_S)$$

$$\Delta V = \frac{V}{n} + I\,(R_P + R_S)$$

- If *R_P >> R_S , previous equation becomes*

$$\Delta V \cong \frac{V}{n} + I\,R_P$$

- At any given current, the $I-V$ curve for the module with one shaded cell drops by ΔV.
- The huge impact this can have is illustrated in



Example :
Impacts of Shading on a PV Module.

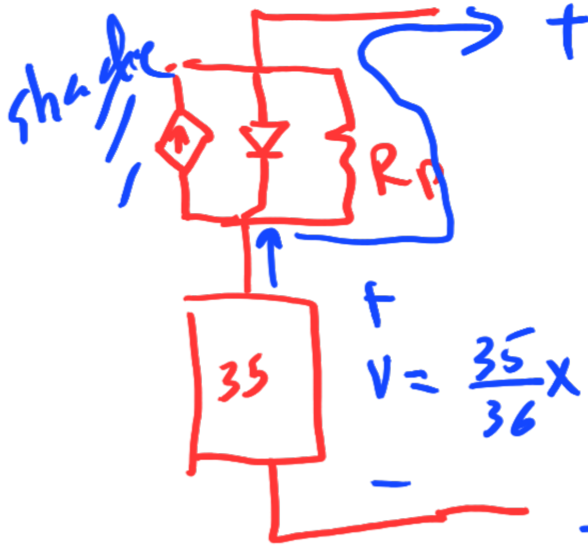
n=36

- The 36-cell PV module described in previous Example had a parallel resistance per cell of $R_P = 6.6$.
- In full sun and at current $I = 2.14$ A the output voltage was found there to be $V = 19.41$ V.
- If one cell is shaded and this current somehow stays the same, then:

a. What would be the new module output voltage and power?

b. What would be the voltage drop across the shaded cell?

c. How much power would be dissipated in the shaded cell?



V_{sh}

$V = \frac{35}{36} \times 19.41 = 18.87\ V$

−

$V_{module} = 19.41\ V$

$I = 2.14\ A$

$P = 41.516\ W$

normal

$\Delta V = \frac{V}{n} + 2.14 \times 6.6$

$= \frac{19.41}{36} + 2.14 \times 6.6 = 14.66\ V$

$V_{sh} = 19.41 - 14.66 = 4.75\ V$

$P_{shaded} = 4.75 \times 2.14 = 10.1\ W$

$\frac{19.41}{36}$

B) $V_c = I(R_p + R_s) = 2.14(6.6 + 0.005) = 14.14\ V$

Drop on shaded cell

C) $P_{dissipated} = V_c \times I = 14.14 \times 2.14 = 30.2\ W$

in shaded cell

Ended 21/4/2020

Example solution

Same Previous Example

A) The drop in module voltage will be:

$$\Delta V = \frac{V}{n} + I R_P$$

$$= \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

- The new output voltage will be 19.41 − 14.66 = 4.75 V.
- Power delivered by the module with one cell shaded would be :

  $P_{module} = V I = 4.75 \text{ V} \times 2.14 \text{ A} = 10.1 \text{ W}$
- For comparison, in full sun the module was producing 41.5 W

Solution continued

b) All of that 2.14 A of current goes through the parallel plus series resistance (0.005) of the shaded cell, so the drop across the shaded cell will be :

$$V_c = I\,(R_P + R_S) = 2.14(6.6 + 0.005) = 14.14\ V$$

- (normally a cell in the sun will add about 0.5 V to the module; this shaded cell subtracts over 14 V from the module).

C) The power dissipated in the shaded cell is voltage drop times current, which is

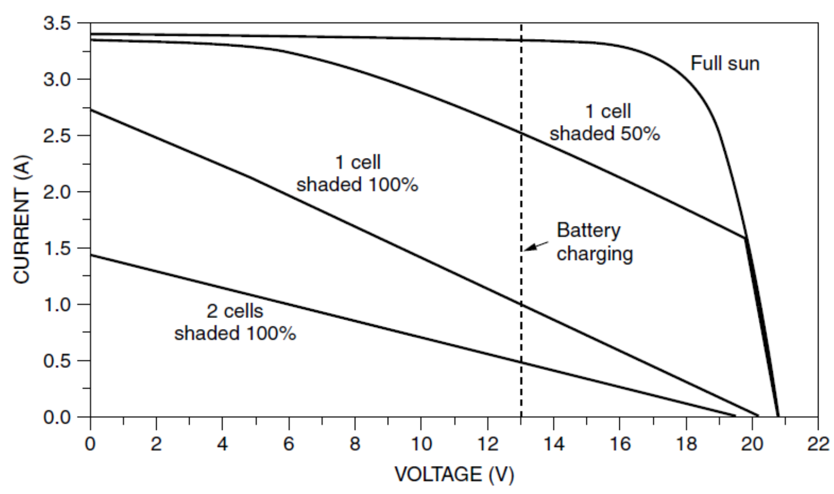
$$P = V_c I = 14.14\ \text{V} \times 2.14\ \text{A} = 30.2\ \text{W}$$

- All of that power dissipated in the shaded cell is converted to heat, which can cause a local hot spot that may permanently damage the plastic laminates enclosing

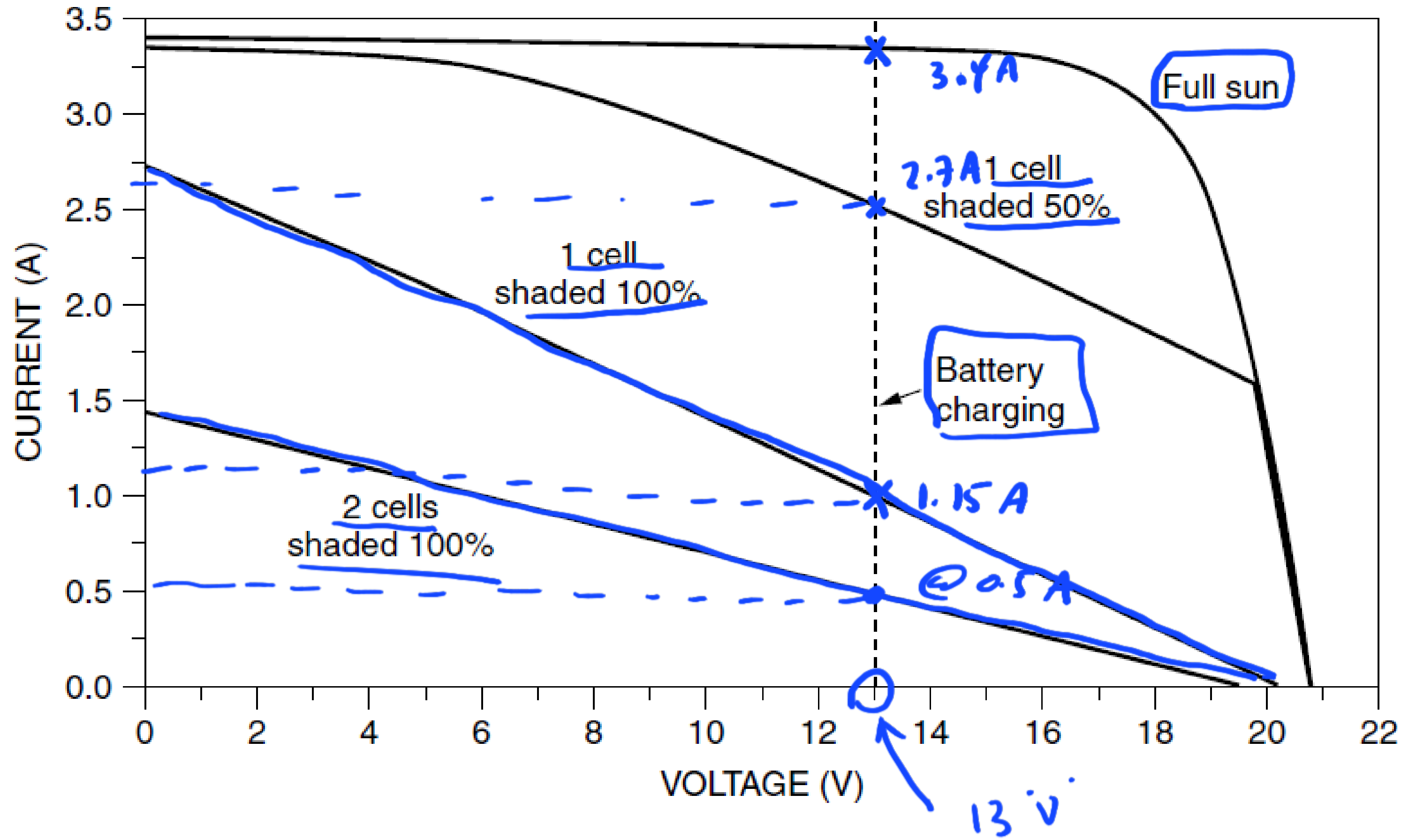
Impact of Shading

L13 24/4/2024

- The procedures demonstrated in previous Examples can be extended to develop $I-V$ curves under various conditions of shading.
- Figure below shows such curves for the example module under full-sun conditions and with one cell 50% shaded, one cell completely shaded, and two cells completely shaded.
- Also shown on the graph is a dashed vertical line at 13 V, which is a typical operating voltage for a module charging a 12-V battery. The reduction in charging current for even modest amounts of shading is severe. With just one cell shaded out of 36 in the module, the power delivered to the battery is decreased by about two-thirds!



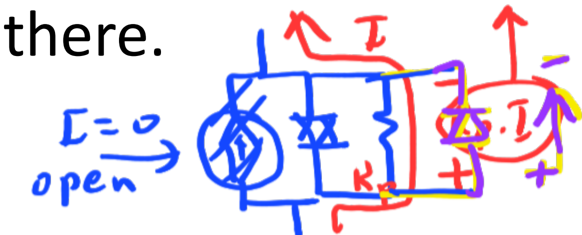
Impact of Shading



Effects of shading on the *I*–*V* curves for a PV module. The dashed line shows a typical voltage that the module would operate at when charging a 12-V battery; the impact on charging current is obviously severe.

Bypass Diodes for Shade Mitigation

- Previous Example shows not only how drastically shading can shift the *I*–*V* curve, but also how local, potentially damaging hot spots can be created in shaded cells.
- Figure 8.40 shows a typical situation. In Fig. 8.40a a solar cell in full sun operating in its normal range *contributes* about 0.5 V to the voltage output of the module, but in the equivalent circuit shown in 8.40b a shaded cell experiences a *drop* as current is diverted through the parallel and series resistances.
- This drop can be considerable (in previous Example it was over 14 V).
- The voltage drop problem in shaded cells could be to corrected by adding a *bypass diode* across each cell, as shown in Fig. 8.41.
- When a solar cell is in the sun, there is a voltage rise across the cell so the bypass diode is cut off and no current flows through it—it is as if the diode is not even there.



- The voltage drop problem in shaded cells could be to corrected by adding a *bypass diode* across each cell, as shown in Fig. 8.41. When a solar cell is in the sun, there is a voltage rise across the cell so the bypass diode is cut off and no current flows through it—it is as if the diode is not even there.
- When the solar cell is shaded, however, the drop that would occur if the cell conducted any current would turn on the bypass diode, diverting the current flow through that diode.
- The bypass diode, when it conducts, drops about 0.6 V. So, the bypass diode controls the voltage drop across the shaded cell, limiting it to a relatively modest 0.6 V instead of the rather large drop that may occur without it.

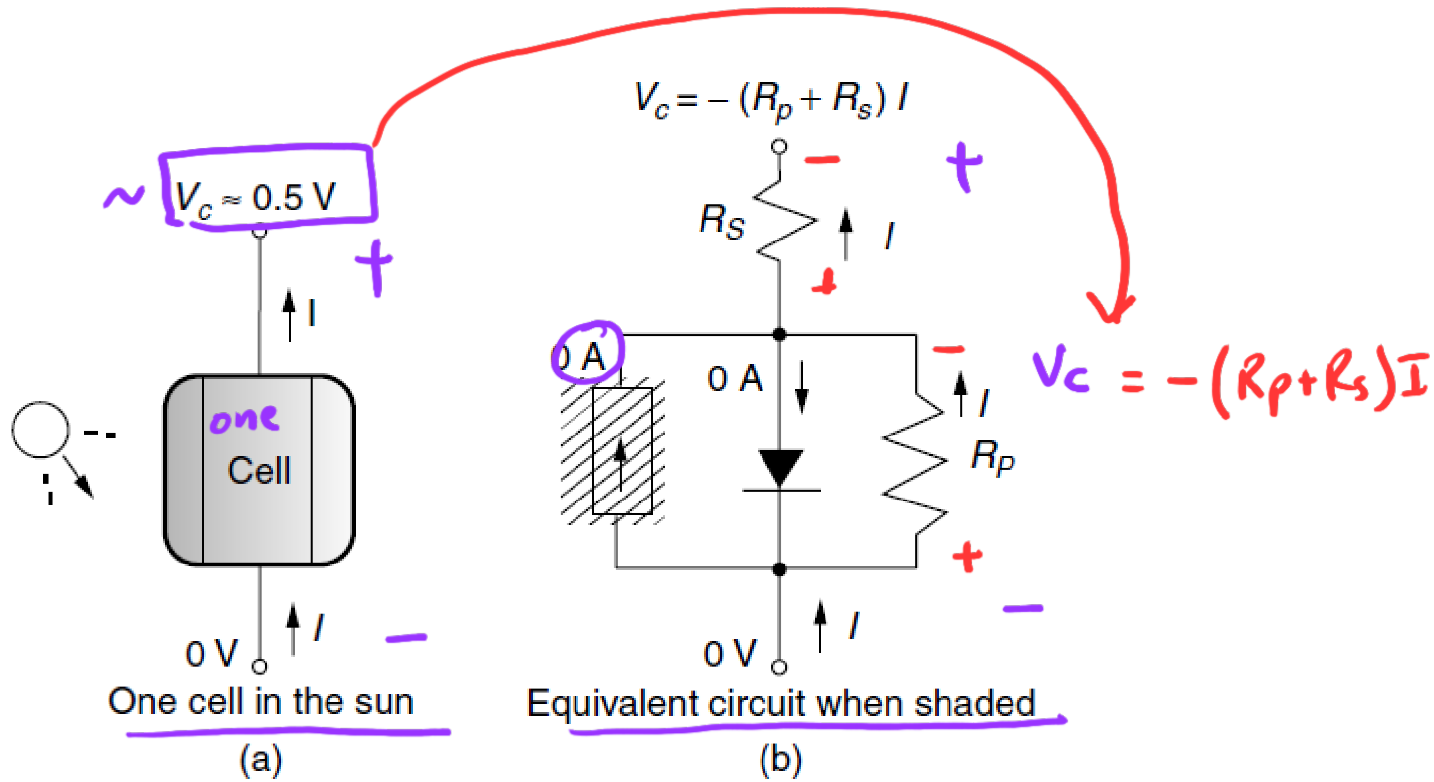


Figure 8.40

- In full sun a cell may contribute around 0.5 V to the module output;
- but when a cell is shaded, it can have a large voltage drop across it.

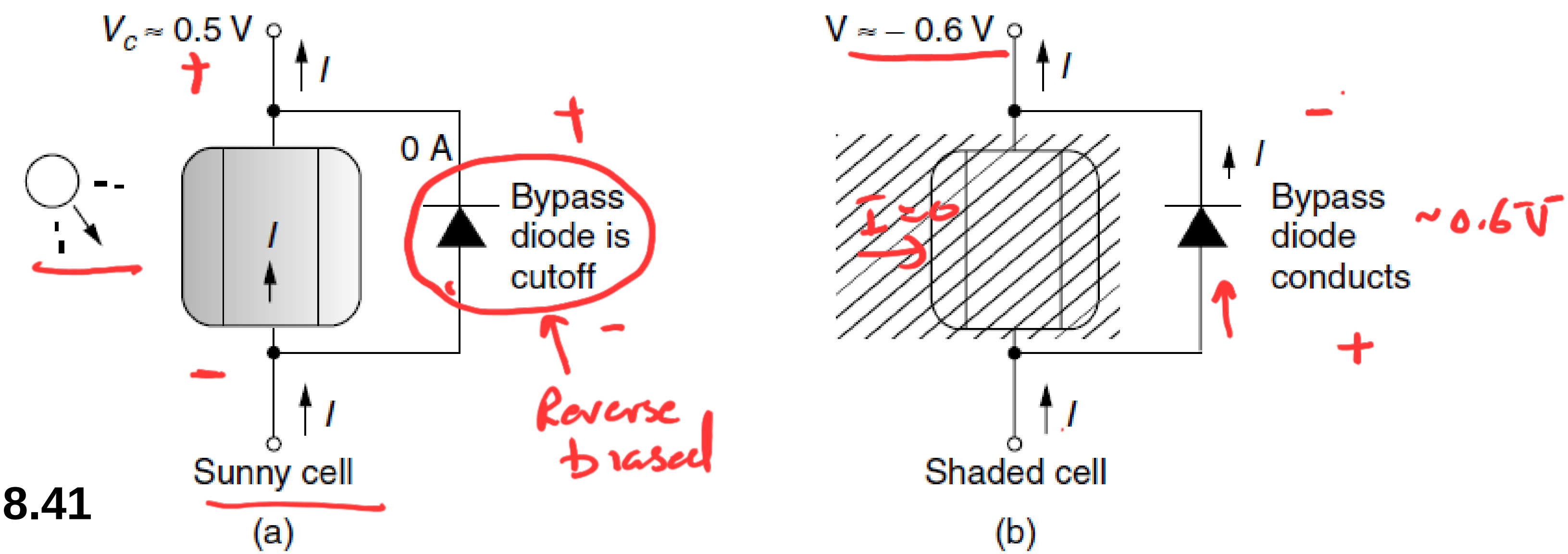


Figure 8.41

- Mitigating the shade problem with a bypass diode.
- In the sun (a), the bypass diode is cut off and all the normal current goes through the solar cell.
- In shade (b), the bypass diode conducts current around the shaded cell, allowing just the diode drop of about 0.6 V to occur.

Bypass Diodes Across Modules

- **In real modules, it would be impractical to add bypass diodes across every solar cell, but manufacturers often do provide at least one bypass diode around a module to help protect arrays, and sometimes several such diodes around groups of cells within a module.**
- **These diodes don't have much impact on shading problems of a single module, but they can be very important when a number of modules are connected in series.**
- **Just as cells are wired in series to increase module voltage, modules can be wired in series to increase array voltage.**
- **Also, just as a single cell can drag down the current within a module, a few shaded cells in a single module can drag down the current delivered by the entire string in an array.**
- **The benefit already demonstrated for a bypass diode on a single cell also applies to a diode applied across a complete module.**

- To see how bypass diodes wired in parallel with modules can help mitigate shading problems, consider Fig. 8.42, which shows $I-V$ curves for a string of five modules).
- The graph shows the modules in full sun as well as the $I-V$ curve that results when one module has two cells completely shaded. Imagine the PVs delivering charging current at about 65 V to a 60-V battery bank.
- As can be seen, in full sun about 3.3 A are delivered to the batteries. However, when just two cells in one module are shaded, the current drops by one-third to about 2.2 A.
- With a bypass diode across the shaded module, however, the $I-V$ curve is improved considerably as shown in the figure.

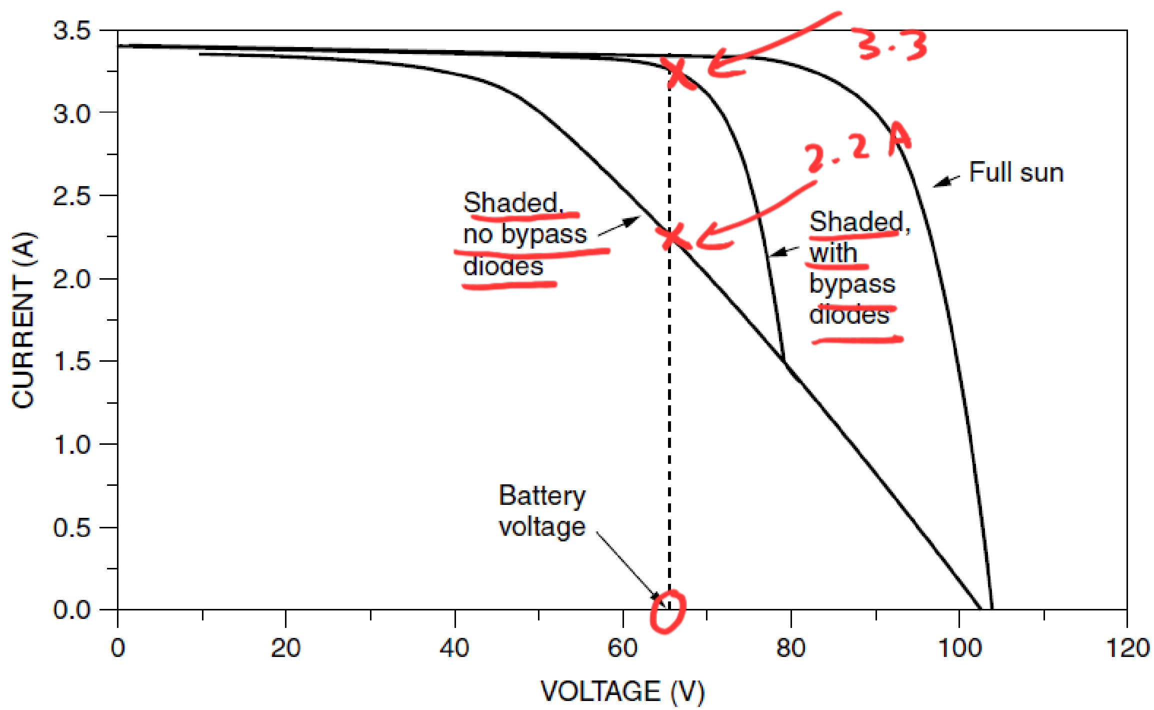


Fig. 8.42

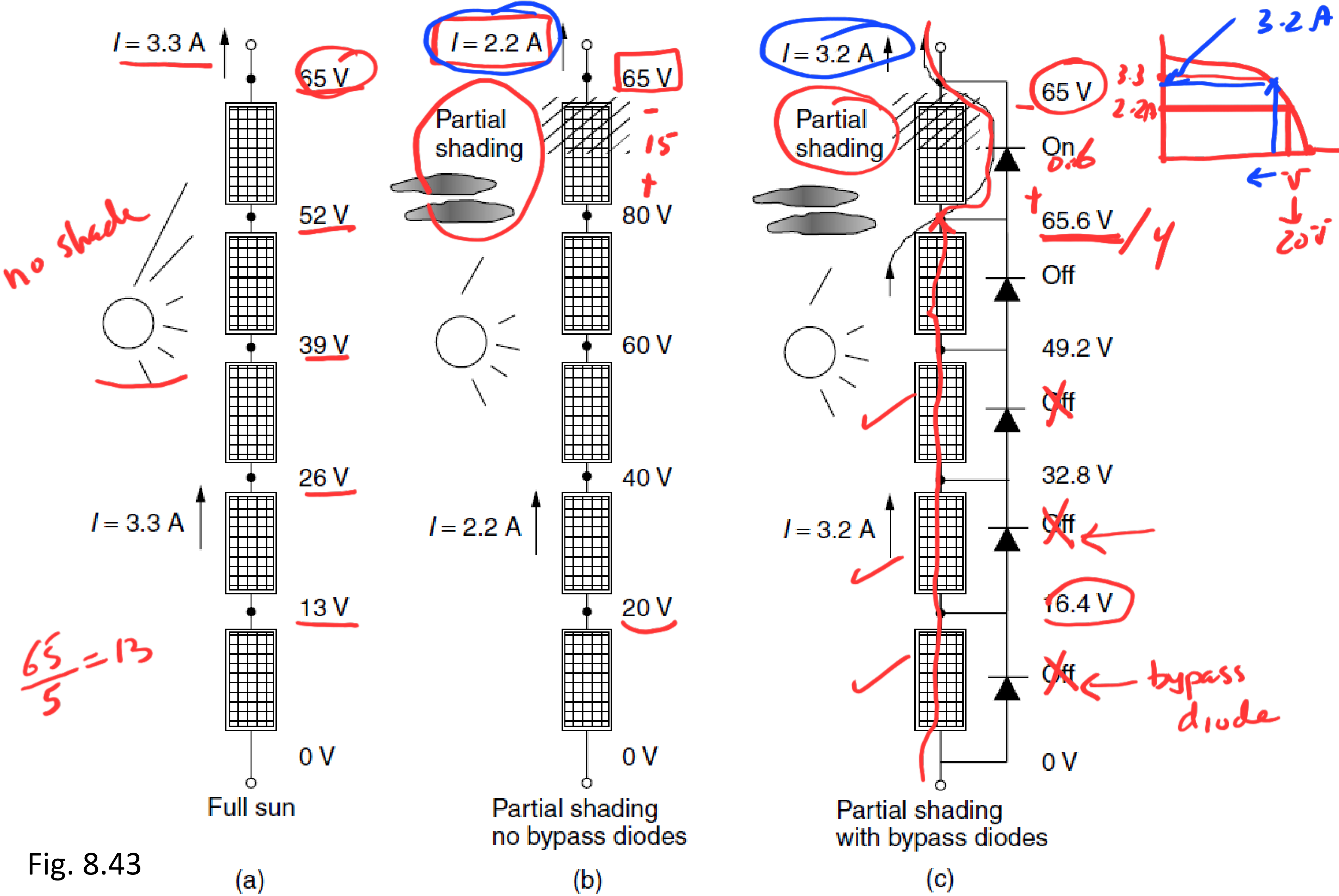


Fig. 8.43

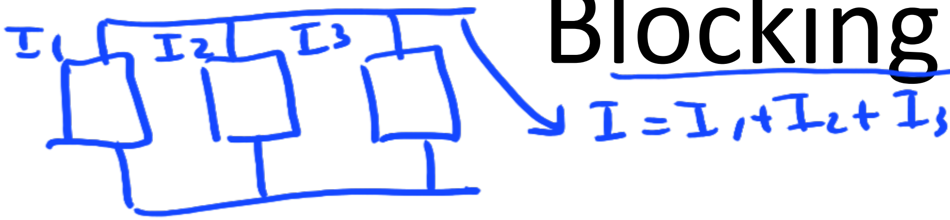
Without bypass diodes, a partially shaded module constricts the current delivered to the load (b). With bypass diodes, current is diverted around the shaded module.

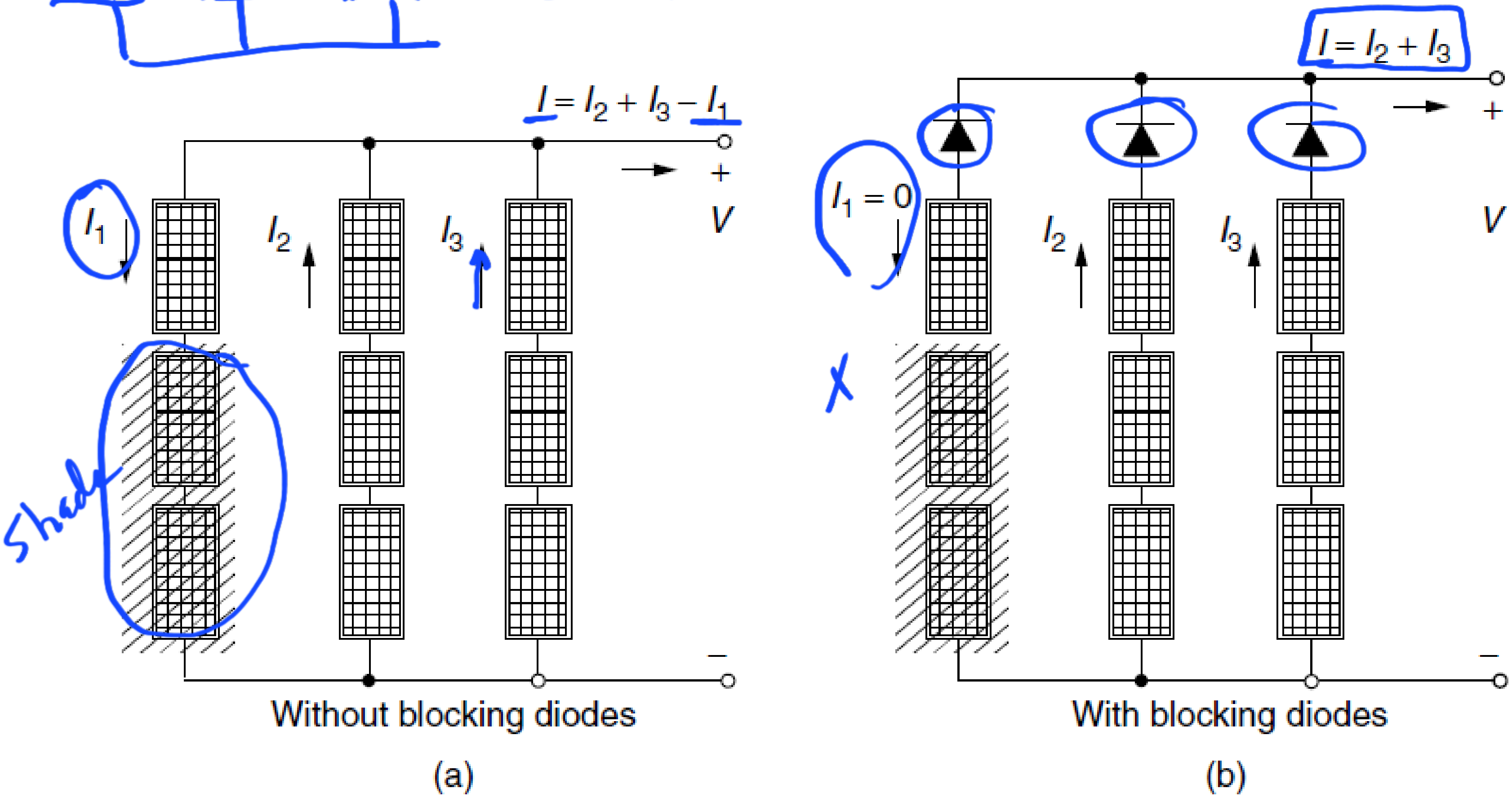
- Figure 8.43 (previous slide) helps explain how the bypass diodes do their job. Imagine five modules, wired in series, connected to a battery that forces the modules to operate at 65 V.
- In full sun the modules deliver 3.3 A at 65 V. When any of the cells are shaded, they cease to produce voltage and instead begin to act like resistors (6.6 per cell in this example) that cause voltage to drop as the other modules continue to try to push current through the string.
- Without a bypass diode to divert the current, the shaded module loses voltage and the other modules try to compensate by increasing voltage, but the net effect is that current in the whole string drops.
- If, however, bypass diodes are provided, as shown in Fig. 8.43c, then current will go around the shaded module and the charging current bounces back to nearly the same level that it was before shading occurred.

Blocking Diodes

- When strings of modules are wired in parallel, a problem may arise when one of the strings is not performing well.
- Instead of supplying current to the array, a malfunctioning or shaded string can withdraw current from the rest of the array.
- By placing *blocking diodes* (also called *isolation diodes*) at the top of each string as shown in Fig. next slide, the reverse current drawn by a shaded string can be prevented

Blocking Diodes





Blocking diodes prevent reverse current from flowing down malfunctioning or shaded strings.

Few more Notes

- The current of a PV device is directly proportional to surface area and solar irradiance.
- In other words, for a given device, doubling the surface area exposed to solar radiation will double the current output.
- Likewise, doubling solar irradiance on the device surface will double current.

- The maximum power point is located on the knee of the I-V curve and is the highest efficiency operating point for a PV device for the given conditions of solar irradiance and cell temperature.
- Due to the shape of the curve, maximum power voltage is typically about 70% to 80% of the value of the open-circuit voltage, while maximum power current is typically about 90% of the value of the short circuit current.

$$V_{mpp} \approx (0.7-0.8)\,V_{oc}$$
$$I_{mpp} \approx 0.9\,I_{sc}$$

- Maximum power voltage and current can be measured only while the PV device is connected to a load that operates the device at maximum power.

- Most commercial crystalline silicon PV cells have fill factors exceeding 70%, while the fill factor for many thin-film materials is somewhat less.
- For a higher fill factor cell, the current decreases much less with increasing voltage up to the maximum power point, and decreases much more with increasing voltage beyond maximum power.

- A decrease in fill factor over time indicates problems with PV devices, including degradation of the cells or, more commonly, increased resistance of the wiring or connections in the system.

Efficiency

- *Efficiency is the ratio of power* output to power input.
- The efficiency of PV devices compares the solar power input to the electrical power output.
- Solar irradiance is multiplied by the area of the PV device to determine watts of solar power, which can then be directly compared to watts of electrical power.
- PV cell efficiencies vary considerably among different PV technologies, and for the same material and technology, efficiencies vary widely between laboratory samples and commercial devices.

- Efficiency is expressed as a percentage and is calculated with the following formula:

$$\eta = \frac{P_{mp}}{E \times A}$$

@ max power point

- *Pm - maximum power (in W)*
- *E = solar irradiance (in W/m^2)*
- *A = area (in m^2)* ← of the Module (cell)

Example

- For example, what is the efficiency of a PV module with a surface area of 1.2 m^2 and a maximum power output of 160 W when exposed to 1000 W/m^2 solar irradiance?

$$\eta = \frac{P_{mp}}{E \times A}$$

$$\eta = \frac{160}{1000 \times 1.2}$$

$$\eta = \frac{160}{1200}$$

$$\eta = \mathbf{0.133} \text{ or } \mathbf{13.3\%}$$

- Cells with higher efficiencies require less surface area to produce each watt of power, which saves some costs for raw materials, mounting structures, and other equipment.
- However, higher efficiency modules are generally no less expensive than less efficient ones, because the price for modules is generally based on the maximum power rating and not on the size.
- For modules, efficiencies are often based on the entire module laminate area including the frame, and spacing between individual cells in the module.
- For individual cells, there is none of this extra area to affect the efficiency.
- This is one reason why module efficiencies are lower than their associated best cell efficiencies.

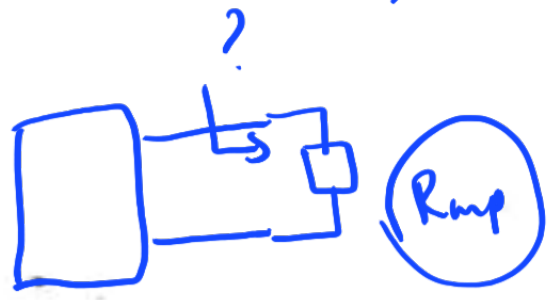
Operating point

- The operating point on an I-V curve is determined by the electrical load of the system.
- For example, if a battery is connected to a PV module, the battery voltage sets the operating voltage of the module. It also establishes the operating current that flows between the device and battery.
- If an incandescent lamp or DC motor is connected to a PV device, the effective resistance of the lamp filament or motor determines the operating point.
- Short-circuit current is associated with zero load resistance and open-circuit voltage is associated with infinite load resistance.
- Every point in between the two states has a specific load resistance that increases from left to right along the I-V curve.

Operating point

- PV cells operate most efficiently at their maximum power points. However, the maximum power point is constantly changing due to changes in solar irradiance and cell temperature.
- Consequently, some systems use maximum power point tracking (MPPT) to dynamically match the electrical loads to PV output in order to maximize the performance.
- This function is included in most interactive inverters and some battery charge controllers.
- The electrical load resistance required to operate a PV device at any point can be calculated using Ohm's law.

- For the maximum power point, the formula is:



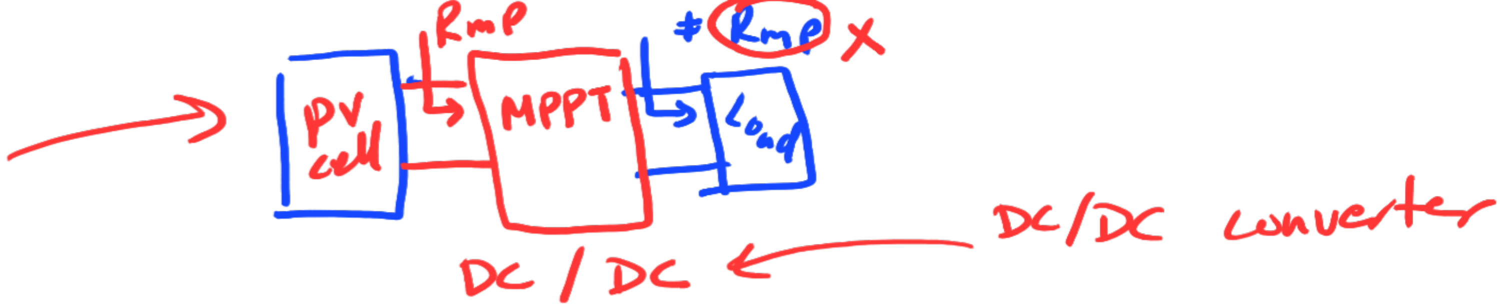
$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$

where

R_{mp} = resistance at maximum power point (in Ω)

V_{mp} = maximum power voltage (in V)

I_{mp} = maximum power current (in A)



- For example, a module has maximum power voltage of 15 V and maximum power current of 3 A.
- What resistance is required to operate the module at the maximum power point, and what is its maximum power?

$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$

$$R_{mp} = \frac{15}{3}$$

$$R_{mp} = \mathbf{5\ \Omega}$$

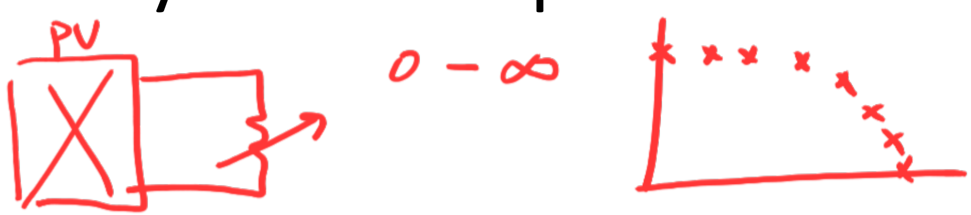
$$P_{mp} = V_{mp} \times I_{mp}$$

$$P_{mp} = 15 \times 3$$

$$P_{mp} = \mathbf{45\ W}$$

I-V Curve Measurement

- A variable resistive load, such as a rheostat or adjustable resistor, can be used to load a PV device over nearly its entire I-V curve.
- When combined with meters measuring voltage and current, this method can be used to generate the I-V curves of small PV devices or individual modules which can be then used to identify the key I-V curve parameters



Automated I-V Curve Measurement

- Automatic Measurement of I-V curve can be done using an electronic load
- This electronic load can be implemented using commercially available electronic loads
- Many other techniques can be used to implement the electronic load using capacitive charging, MOSFET , DC-Dc converter

Junction Box

- A junction box on the back of a module provides a protected location for electrical connections and bypass diodes.

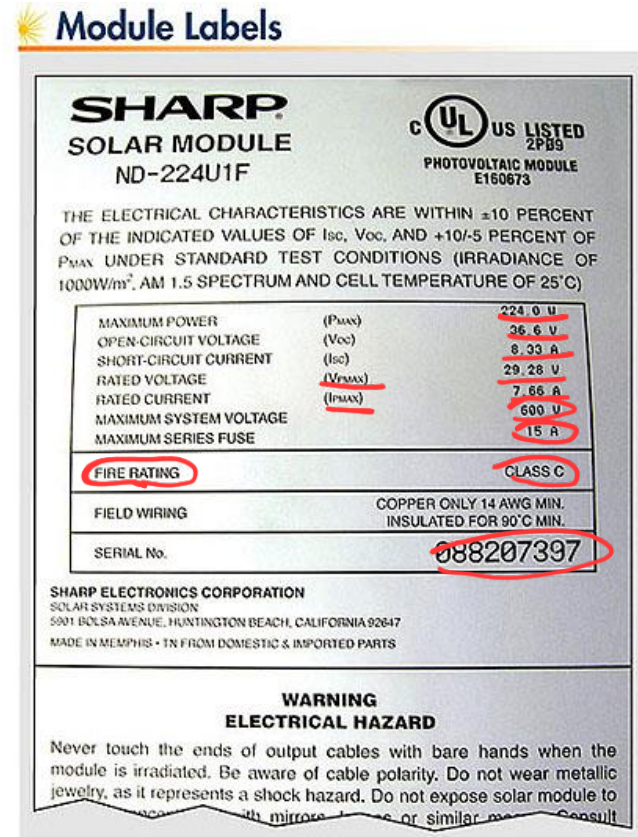
Reliability

tests

- Reliability of modules is assured through series Design qualification tests which include thermal cycling, humidity and freezing, impact and shock, immersion, cyclic pressure, twisting, vibration and other mechanical tests, and excessive and reverse current electrical tests.
- Design qualification has important implications for product warranties offered by manufacturers.
- As a result, most major module manufacturers offer warranties of 20 years or more, guaranteeing module peak power output of at least 80% of initial nameplate ratings.
- This equates to a degradation rate of no more than 1% per year.
- These exceptionally long warranty periods are not typical among other electrical equipment and appliance warranties, but are offered to assure buyers of the long term performance of PV systems.

Module Label

- Module labels must include performance ratings for the module and may include other information used to design a PV system.



https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/NDR250A5_NDR245A5_Flyer_0414_en.pdf

https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/1901_NDAH330H_Poly_Datasheet_EN.pdf

https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/1902_NU-AH360_370_Mono_Datasheet_EN_v1.pdf

Example Data Sheet

ND-R250A5 | 250W
ND-R245A5 | 245W
Polycrystalline silicon photovoltaic modules

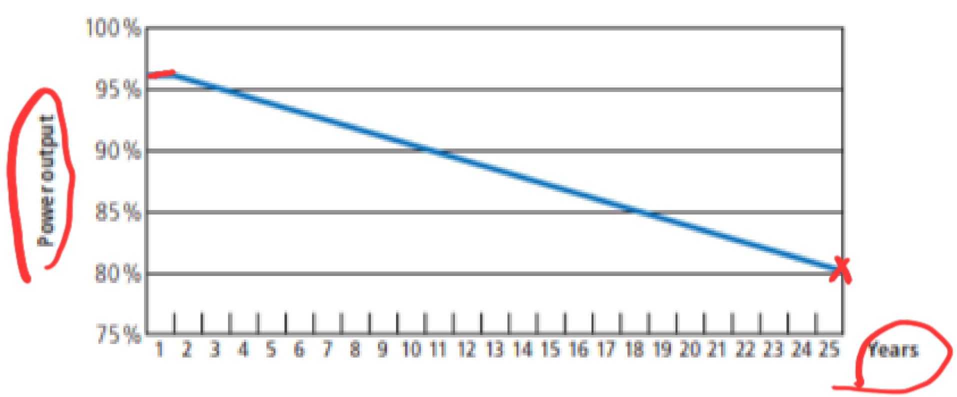
Product features

- High-performance photovoltaic modules made of polycrystalline (156.5 mm)² silicon solar cells with module efficiencies of up to 15.2%.
- 3 busbar technology for enhancing the power output.
- Anti-reflex coating to increase light absorption.
- Production controlled positive power tolerance from 0 to +5%. Only modules will be delivered that have the specified power or more for high energy yield.
- Improved temperature coefficient to reduce power losses at higher temperatures.
- High power performance even at lower irradiations.

Quality from Sharp

Continual checks guarantee a consistently high level of quality. Every module undergoes visual, mechanical, and electrical inspection. This is recognisable by means of the original Sharp label, the serial number, and the Sharp guarantee:

- 10-year product guarantee
- 25-year linear performance guarantee
  - Minimum 96% of the specified minimum power output during the first year
  - Maximum 0.667% annual reduction of the power output for the following 24 years



https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/NDR250A5_NDR245A5_Flyer_0414_en.pdf

ELECTRICAL DATA (AT STC)

		ND-R250A5	ND-R245A5	
Maximum power	P_{max}	250	245	W_p
Open-circuit voltage	V_{oc}	37.6	37.3	V
Short-circuit current	I_{sc}	8.68	8.62	A
Voltage at point of maximum power	V_{mpp}	30.9	30.7	V
Current at point of maximum power	I_{mpp}	8.10	7.99	A
Module efficiency	η_m	15.2	14.9	%

STC = Standard Test Conditions: irradiance 1,000 W/m², AM 1.5, cell temperature 25 °C.
Rated electrical characteristics are within ±10% of the indicated values of I_{sc}, V_{oc} and 0 to +5% of P_{max} (power measurement tolerance ±3%).

ELECTRICAL DATA (AT NOCT)

		ND-R250A5	ND-R245A5	
Maximum power	P_{max}	180.2	176.6	W_p
Open-circuit voltage	V_{oc}	36.7	36.4	V
Short-circuit current	I_{sc}	7.0	6.96	A
Voltage at point of maximum power	V_{mpp}	27.7	27.5	V
Nominal Operating Cell Temperature	NOCT	47.5	47.5	°C

NOCT: Module operating temperature at 800 W/m² irradiance, air temperature of 20 °C, wind speed of 1 m/s.

NOCT: Module operating temperature at 800 W/m² irradiance, air temperature of 20 °C, wind speed of 1 m/s.

LIMIT VALUES

Maximum system voltage	1,000 V DC
Over-current protection	15 A
Temperature range	−40 to +90 °C
Maximum mechanical load	2,400 N/m²

MECHANICAL DATA

Length	1,652 mm (+/−3.0 mm)
Width	994 mm (+/−2.0 mm)
Depth	46 mm (+/−0.8 mm)
Weight	19 kg

TEMPERATURE COEFFICIENT

P_{max}	−0.440 % / °C
V_{oc}	−0.329 % / °C
I_{sc}	+0.038 % / °C

GENERAL DATA

Cells	polycrystalline, 156.5 mm × 156.5 mm, 60 cells in series
Front glass	low iron tempered glass, 3 mm
Frame	anodized aluminium alloy, silver
Connection box	PPE/PPO resin, IP65 rating, 58 × 125 × 15 mm, 3 bypass diodes
Cable	4 mm², length 1,000 mm
Connector	SMK (MC4 compatible), Type CCT9901-2361F/2451F (Catalogue no. P51-7H/R51-7), IP67 rating To extend the module connection leads, only use SMK connector from the same series or MultiContactAG MC4 connector (PV-KST04/PV-KBT04)

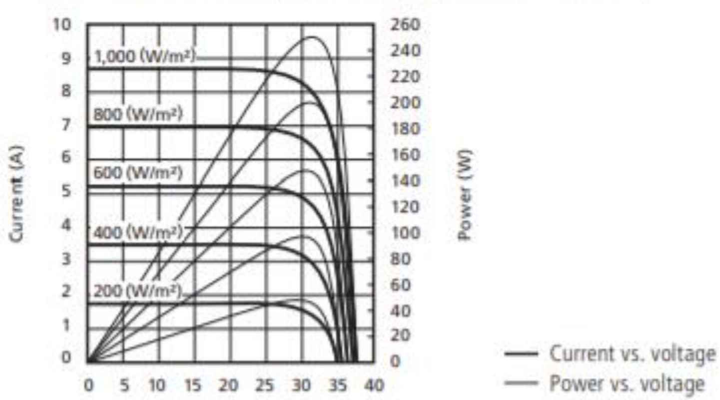
PACKING DATA

Modules per palette	30 pcs
Palette size (length × width × height)	1,670 × 1,010 × 1,840 (mm)
Palette weight	626 kg

2 modules are packed in one carton.

CHARACTERISTIC CURVES ND-R250A5

Characteristic curves: current/power vs. voltage (cell temperature: 25 °C)



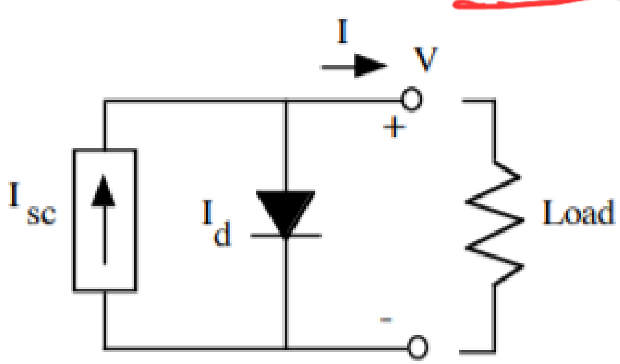
Degradation-and-failure-modes

- https://www.pveducation.org/pvcdrom/modules/degradation-and-failure-modes (FOR SELF STUDY)

Problems and Solutions

- Problems

For the simple equivalent circuit of a 0.017 m^2 photovoltaic cell shown below, the reverse saturation current is $I_0 = 4 \times 10^{-11}$ A and at an insolation of 1-sun the short-circuit current is $I_{SC} = 6.4$ A. At 25°C, find the following:



a. The open-circuit voltage.

b. The load current and output power when the output voltage is $V = 0.55$ V.

c. The efficiency of the cell at $V = 0.55$V.

a. Open circuit voltage from (5.11) is

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{6.4}{4x10^{-11}} + 1\right) = 0.663V$$

b. When the output voltage is 0.57 V, the load current will be

$$I_L = I_{SC} - I_d = I_{SC} - I_0\left(e^{38.9V} - 1\right)$$

$$= 6.4 - 4x10^{-11}\left(e^{38.9x0.57} - 1\right) = 6.23A$$

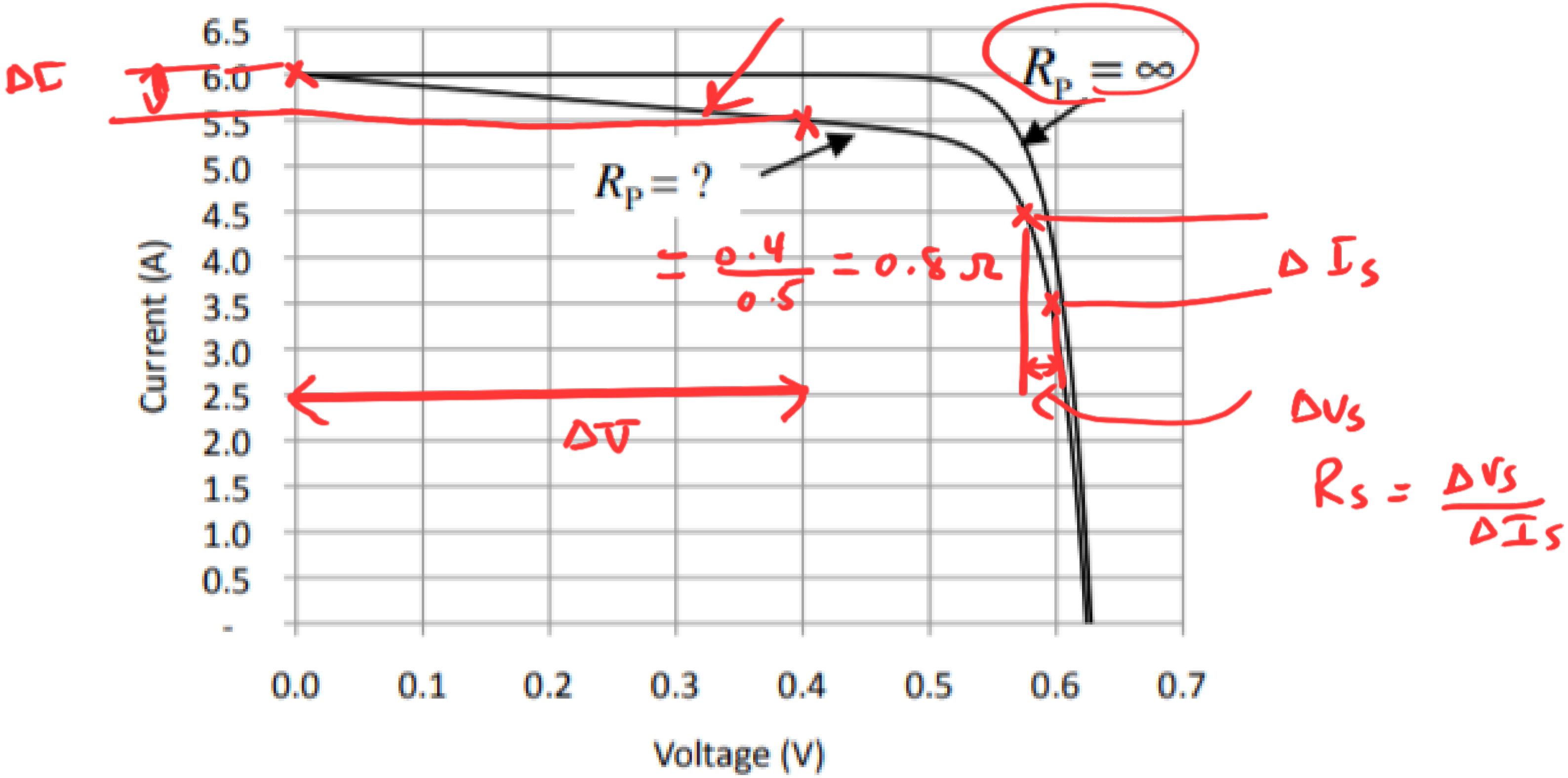
$$P = IV = 6.23A \cdot 0.57V = 3.55W$$

c. Cell efficiency

$$\eta = \frac{output}{input} = \frac{3.55W}{0.017m^2 x 1000W/m^2} = 0.209 = 20.9\%$$

The following figure shows two I-V curves. Both have zero series resistance. One is for a PV cell with an equivalent circuit having an infinite parallel

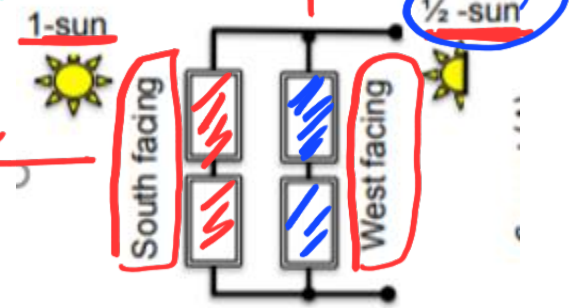
resistance. For the other, what is the parallel resistance in its equivalent circuit?



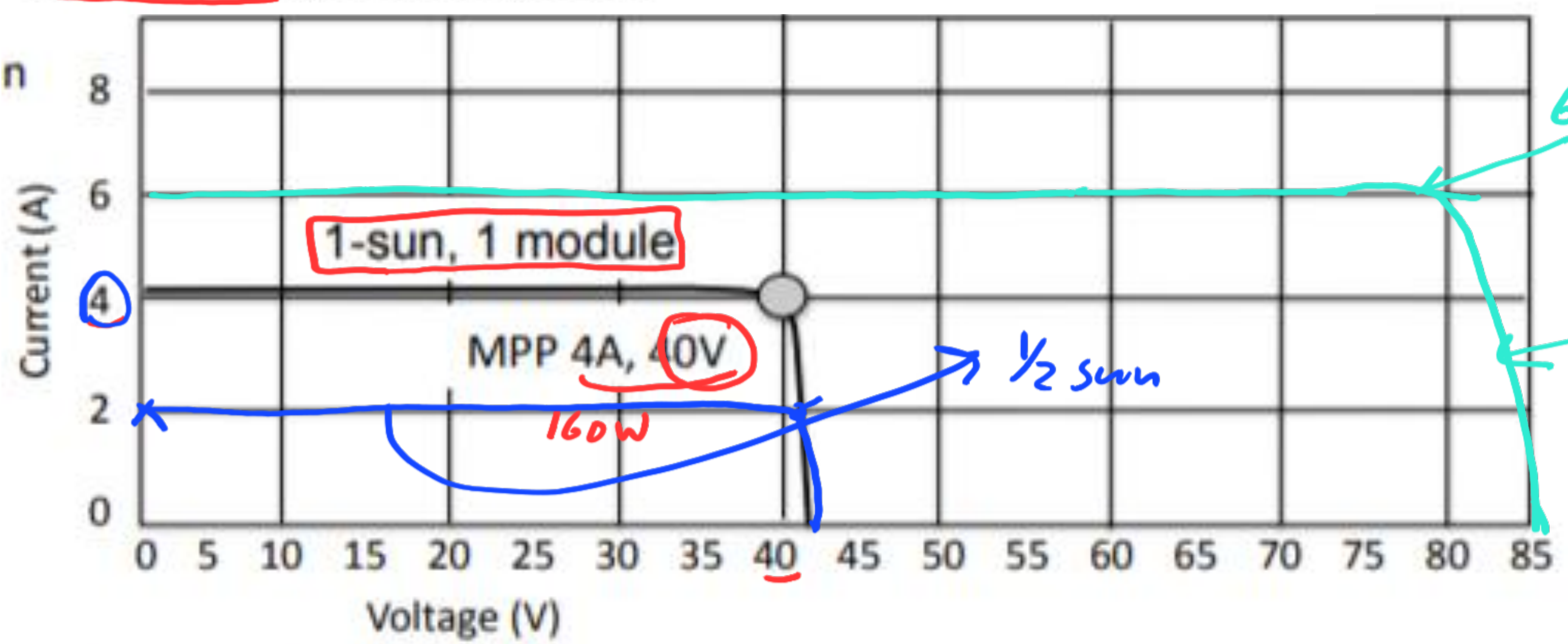
The slope of the drop off in current can be estimated from the point where V = 0.4V and ΔI = 6.0 – 5.5 = 0.5 A:

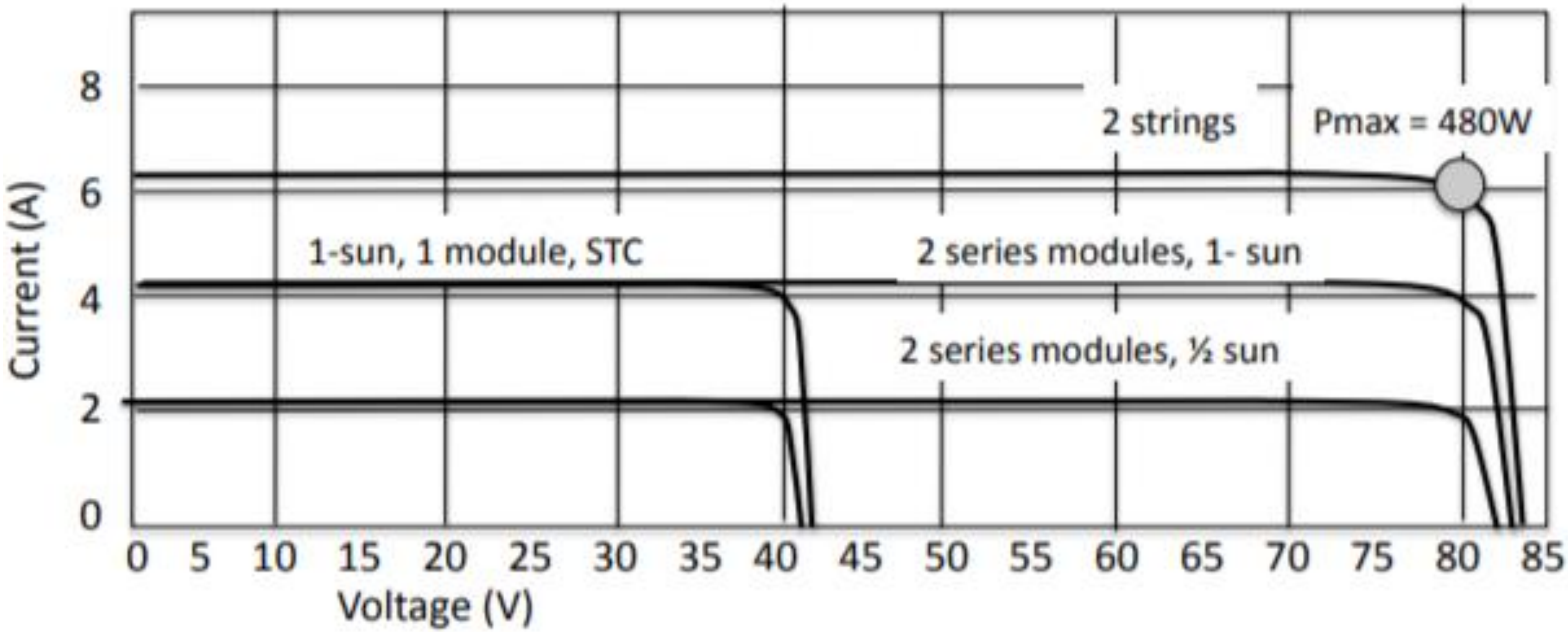
$$R_p = \frac{\Delta V}{\Delta I} = \frac{0.4}{0.5} = 0.8\Omega$$

A 4-module array has two south-facing modules in series exposed to 1000 W/m² of insolation, and two west-facing modules exposed to 500 W/m². The 1-sun *I-V* curve for a single module with its maximum power point at 4A, 40V is shown below.



Draw the I-V curve for the 4-module array under these conditions. What is the output power (W) at the array's MPP?





Current (A)
8
6
4
2
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
Voltage (V)
2 strings
Pmax = 480W
1-sun, 1 module, STC
2 series modules, 1- sun
2 series modules, ½ sun

SOLN: 480 W

A 200-W c-Si PV module has NOCT = 45°C and a temperature coefficient for rated power of -0.5%/°C.

At 1-sun of irradiation while the ambient is 25°C, estimate the cell temperature and output power.

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^{\circ}}{0.8}\right)\cdot S = 25 + \left(\frac{45 - 20}{0.8}\right)\cdot 1 = 56.25^{\circ} C$$

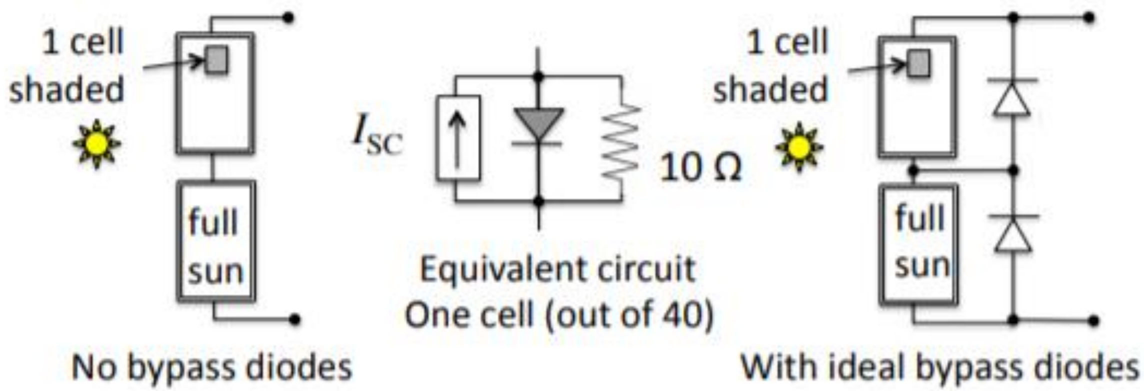
$$P_{max} = 200\text{W}\left[1\text{-}0.5\%/^{\circ}\text{C}(56.25\text{-}25)^{\circ}\text{C}\right] = 168.8\ \text{W} \quad \text{... a drop of } 15.6\%$$

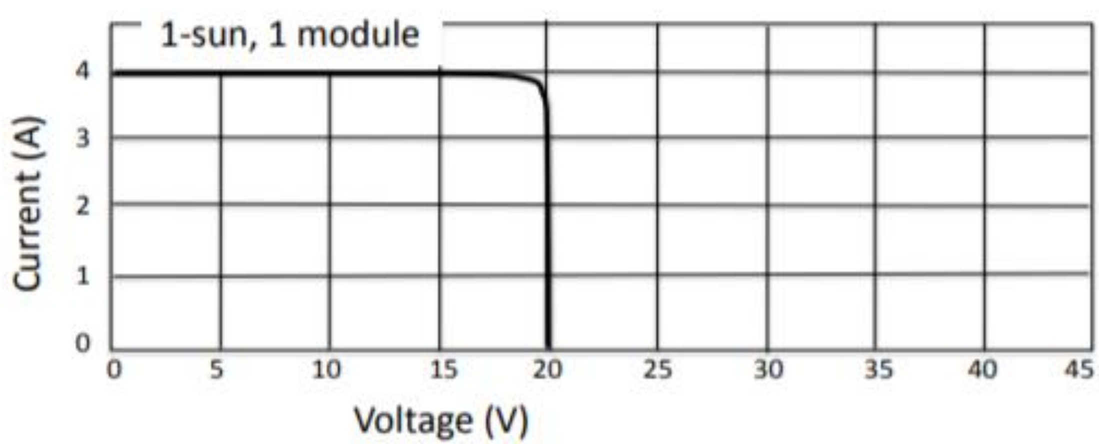
End of L13

24/4/2021

The 1-sun *I-V* curve for a 40-cell PV module in full sun is shown below along with an equivalent circuit for a single cell (including its 10Ω parallel resistance).

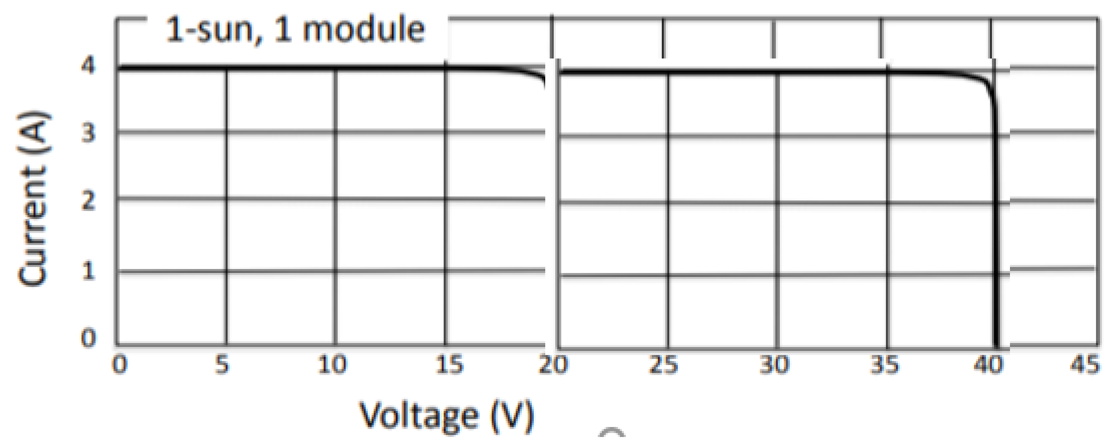
An array with two such modules in series has one fully shaded cell in one of the modules. Consider the potential impact of bypass diodes around each of the modules.





a. Sketch the 1-sun *I-V* curve for the series combination of modules with one cell shaded but no bypass diodes. Find the power output at the maximum power point. Compare it to the output when there is no shading.

b. Sketch the 1-sun *I-V* curve when the bypass diodes are included. Estimate the maximum power output now (close is good enough).



MPP without diodes is at 2A x 20V = 40W could guess, which is fine or prove it by

$$I = 4 - 0.1V \quad \text{so } P = VI = 4V - 0.1V^2$$

$$dP/dV = 4 - 0.1 \times 2V = 0$$

$$\text{So } V = 4/0.2 = 20V, \quad I = 2A, \quad P_{max} = 2 \times 20 = 40W$$

Without diodes, the output went from 160 W down to 40 W when 1 cell is shaded !

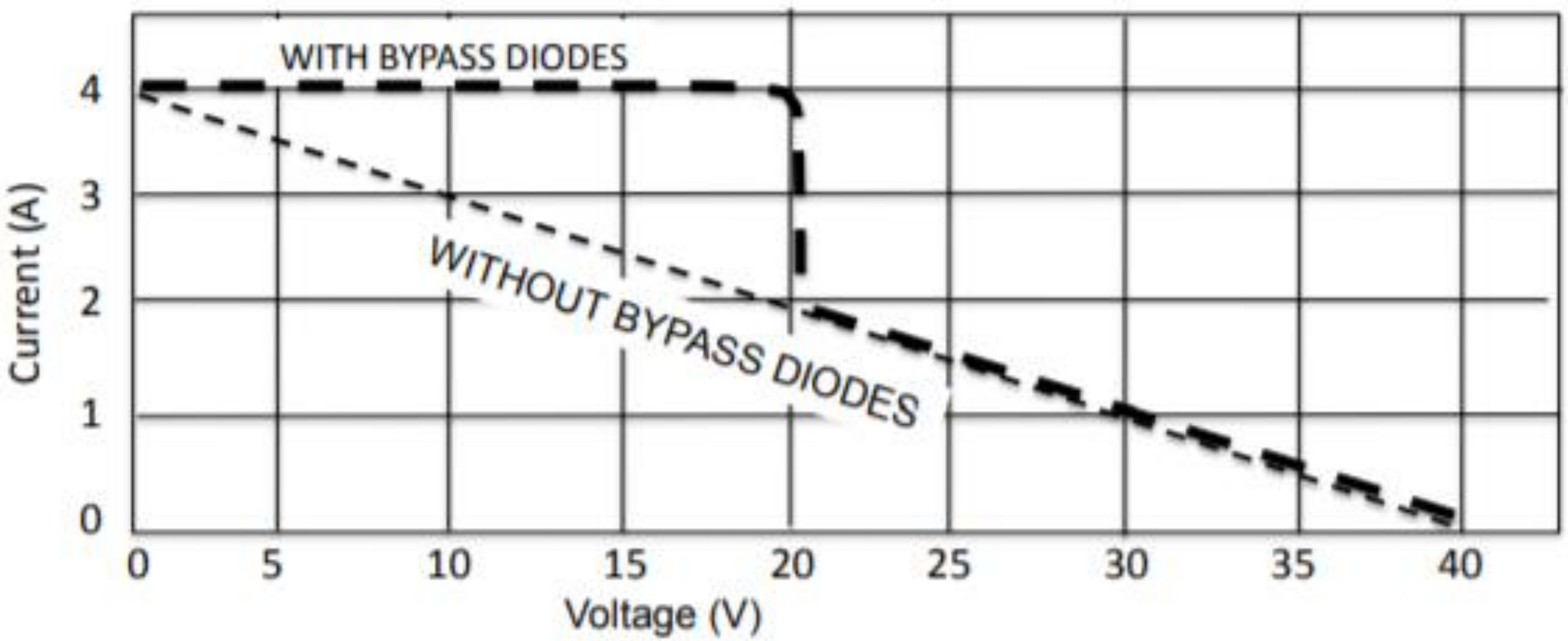
MPP without diodes is at 2A x 20V = 40W could guess, which is fine or prove it by

$$I = 4 - 0.1V \quad \text{so } P = VI = 4V - 0.1V^2$$

$$dP/dV = 4 - 0.1 \times 2V = 0$$

$$\text{So } V = 4/0.2 = 20V, \quad I = 2A, \quad P_{max} = 2 \times 20 = 40W$$

Without diodes, the output went from 160 W down to 40 W when 1 cell is shaded !



b. MPP with diodes is at about 4A x 20V = 80 W. Still lost half of the 160 W output when there is no shading.

ENEE 5307

L14 - 26/4/2021

PV Inverters

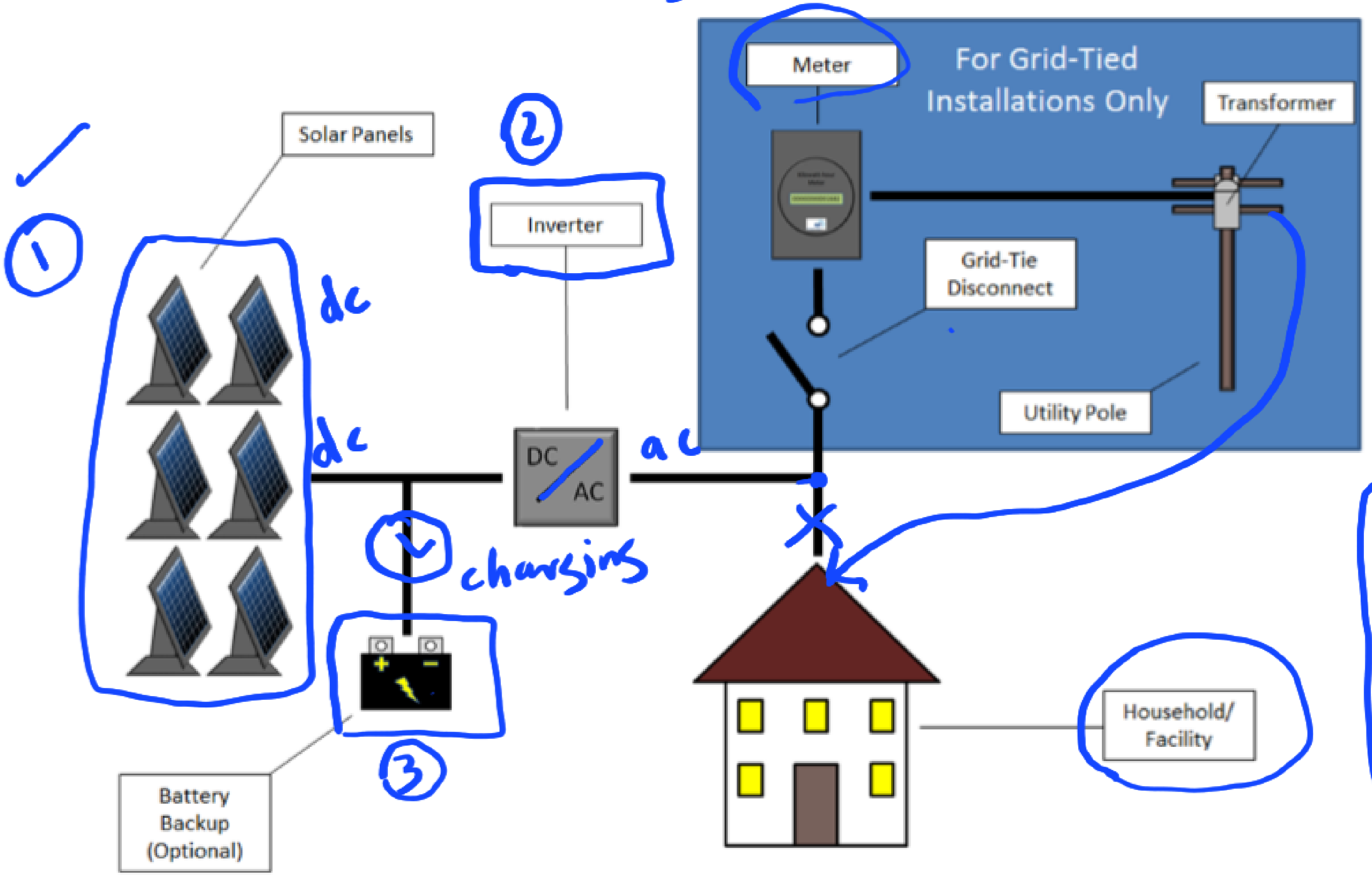
S2021

Start @ 12 $\underline{50}$

The Photovoltaic System

→ On-Grid (Batteries are optional)

→ off-Grid (Batteries are a must)

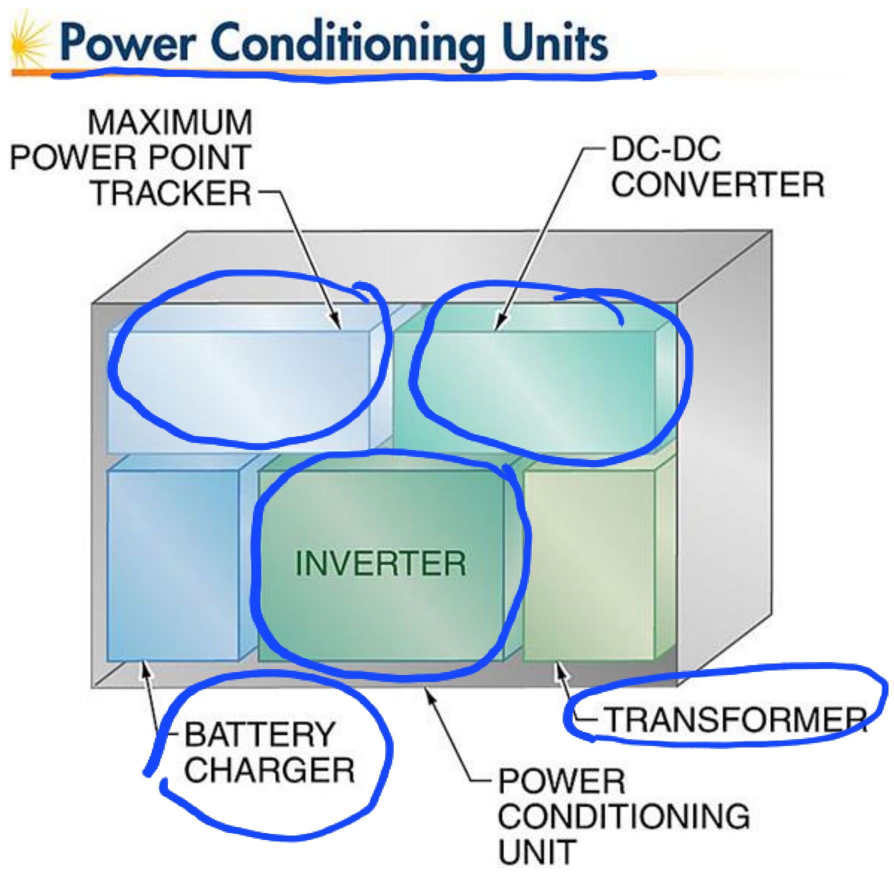


combined together

4) Maximum Power point trackers (MPPT)

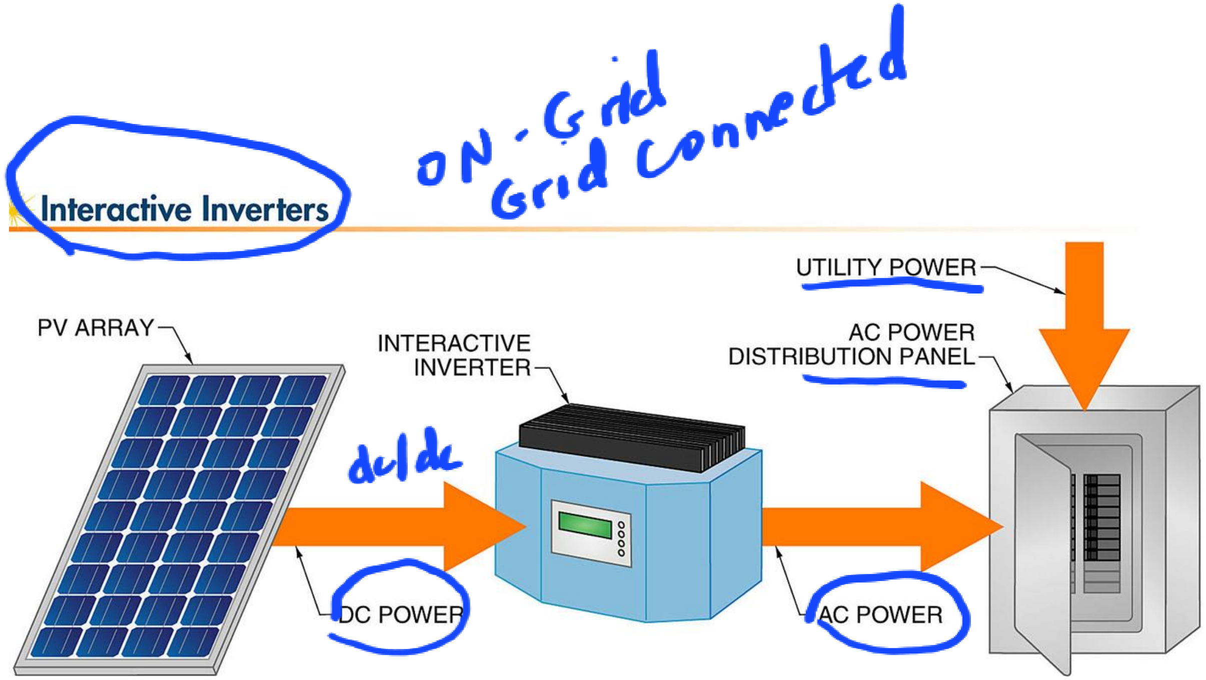
5) charge controller

•**Power conditioning units (PCU)** are inverters that also perform other power control and conversion functions.



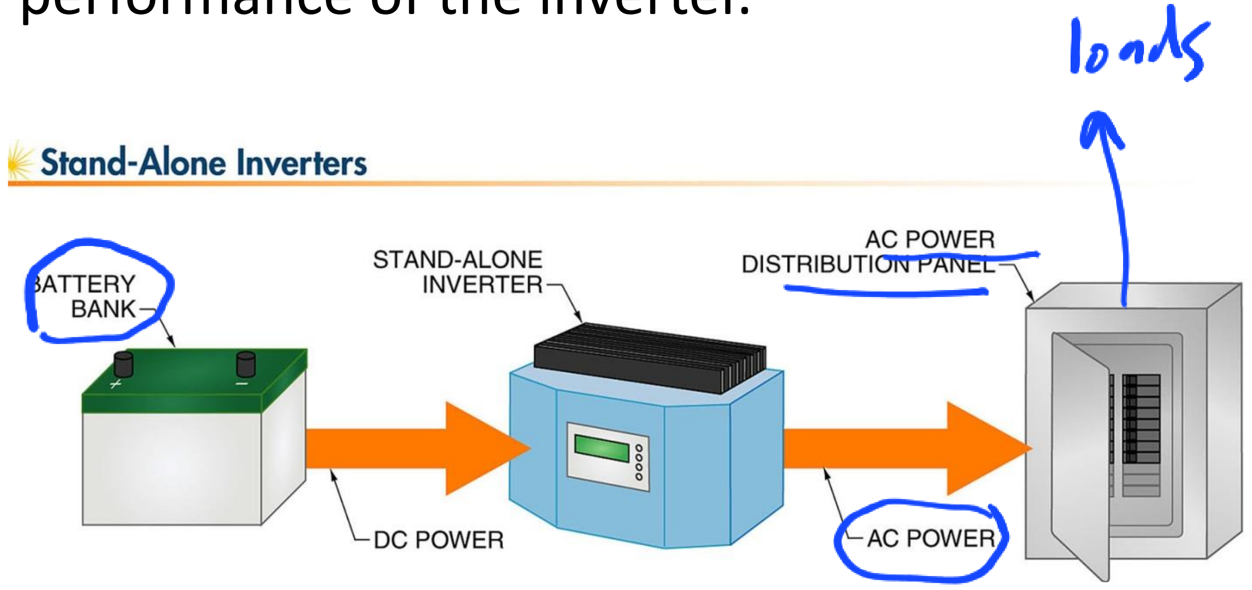
- An *inverter* is a device that converts DC power to AC power.
- Inverters are available in many different configurations and ratings.

- **Interactive inverters** are connected to the PV array and supply AC power that is synchronized with the utility grid.
- Sometimes called grid-connected or grid-tie inverters, these inverters interface between the PV array and the utility grid



Stand-alone inverters are connected to the battery bank and supply AC power to a distribution panel that is independent of the utility grid.

- PV arrays charge the batteries but do not directly influence the operation of the inverter.
- For stand-alone inverters, it is the electrical load connected to the AC output, rather than the DC power source, that affects the performance of the inverter.



- **AC module inverters** are small interactive inverters that are supplied by a single PV module.
- However, while the DC portion of the system is minimized, it is still accessible and may be subject to some requirements.

Enphase Energy

PV Inverters - Basic Facts for Planning PV Systems

- The inverter is the heart of every PV plant
- It converts direct current of the PV modules into grid-compliant alternating current and feeds this into the public grid.
- At the same time, it controls and monitors the entire plant.
- This way, it ensures on the one hand that the PV modules always operate at their radiation- and temperature-dependent maximum power.
- On the other, it continually monitors the power grid and is responsible for the adherence to various safety criteria.

The Right Inverter for Every Plant

- A large number of PV inverters is available on the market – but the devices are classified on the basis of **three important characteristics: 1.Power, 2. DC-related design, 3. and circuit topology**.
- **1.Power**
  The available power output starts at two kilowatts and extends into the megawatt range. Typical outputs are
- 5 kW for private home rooftop plants,
- 10 – 20 kW for commercial plants (e.g., factory or barn roofs)
- 500 – 800 kW for use in PV power stations.

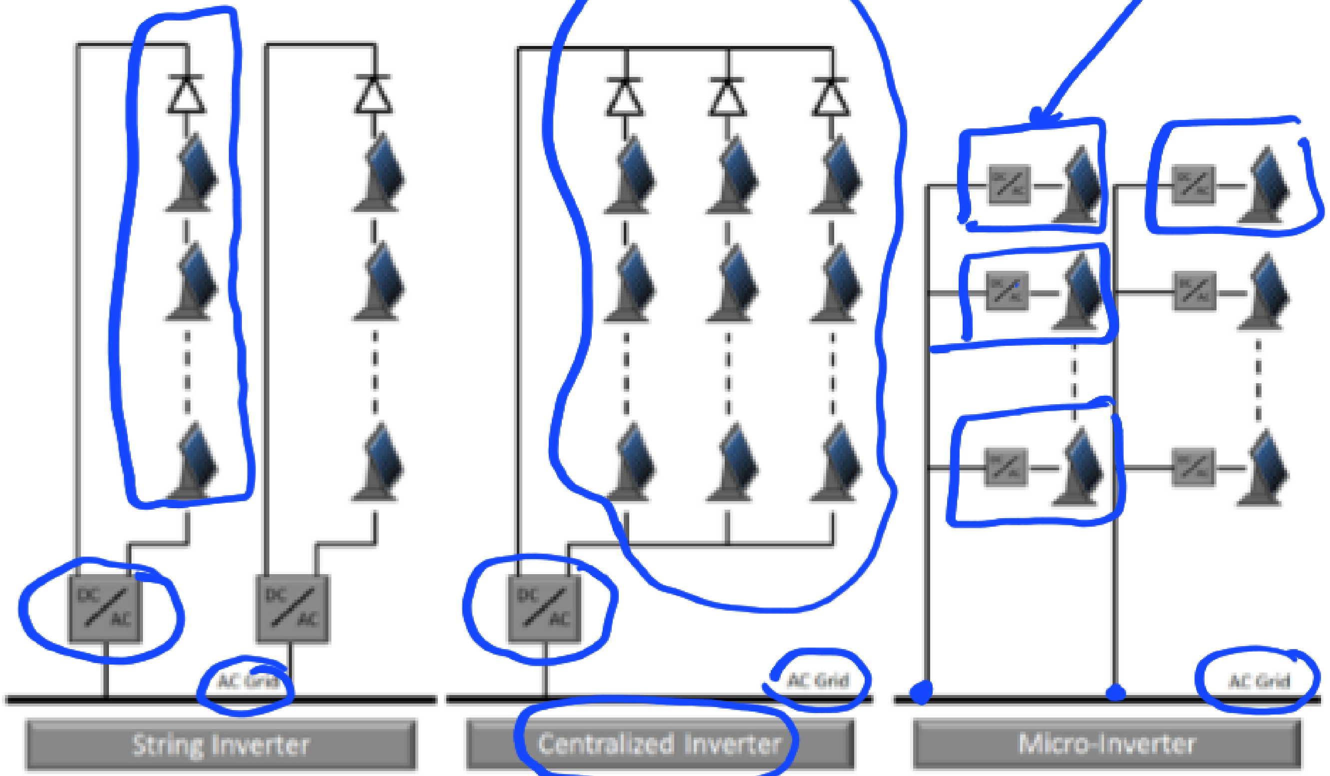
The Right Inverter for Every Plant: Module wiring.

- **2. The DC-related design concerns the wiring of the PV modules to the inverter.**
- In this connection, distinctions are made between string, multistring and central inverters,
- whereby the term "string" refers to a string of modules connected in series.
- Multistring inverters have two or more string inputs, each with its own MPP tracker (Maximum Power Point, see below). These make a particularly sensible choice when the PV array consists of differently oriented subareas or is partially shaded.
- Central inverters only have one MPP tracker despite a relatively higher power output. They are especially well-suited for large-scale plants with a homogeneous generator.

↓ PV modules

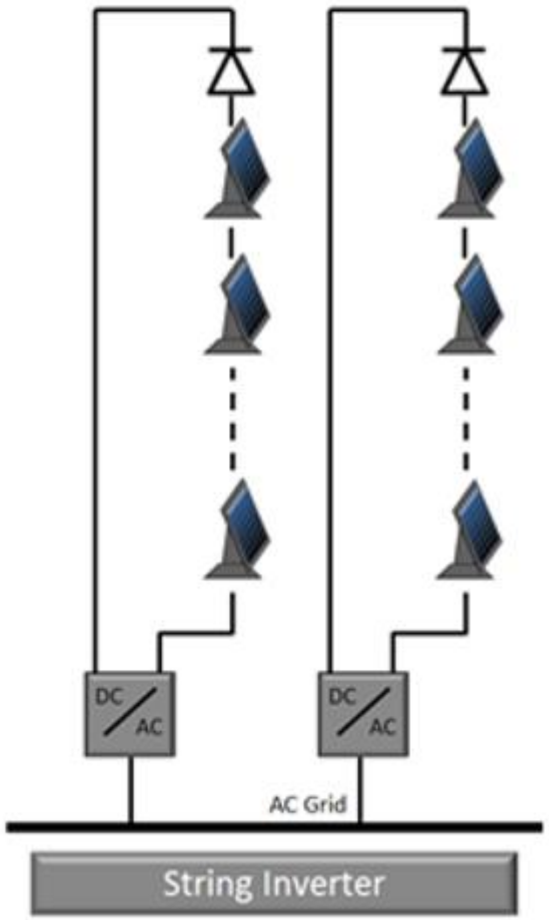
The Right Inverter for Every Plant: Module wiring.

- String Inverter
- Multistring inverters
- Central inverters
- Micro-Inverter



String Inverters

- As their name suggests, string inverters are designed to manage a single string of PV panels; therefore, each string of panels requires its own inverter.
- This is by far the most popular configuration for PV installations, due in part to the long lifetimes of the string inverters as well as the increased efficiency compared to centralized configurations.
- In a string configuration, each inverter is responsible for maximum power point tracking (MPPT) on a single string rather than the whole installation, allowing each string to operate at maximum efficiency

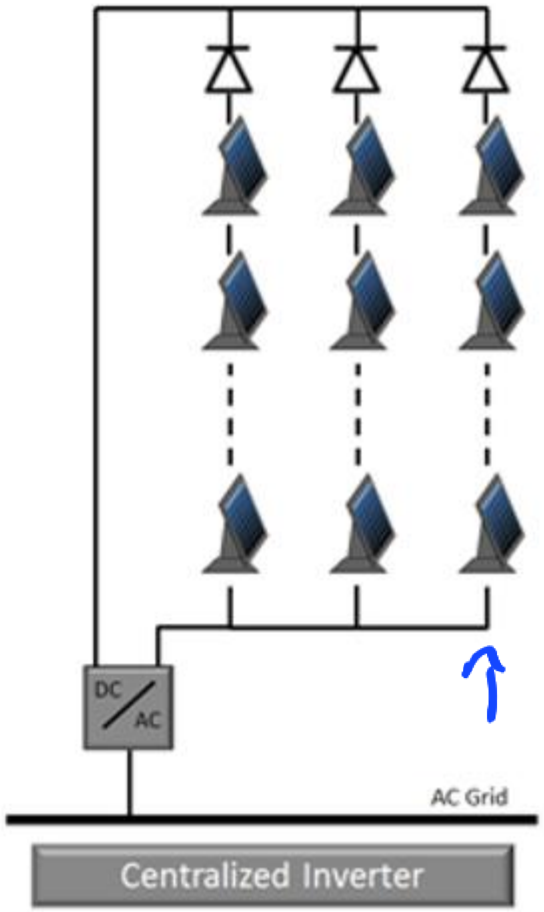


String Inverters

- This configuration does not have parallel connections of strings; instead smaller inverters for each string are used.
- Each string has its own MPPT, which means that all strings are completely independent from each other.
- So it is easy to build PV-systems even under constraints like different orientation of parts of the roof, different shading conditions or even various types or number of PV-modules.
- Of course, the modules of each string should be matched and operated under the same conditions because of the series connection within the string.
- A disadvantage of string-inverters in comparison to central inverters is the higher price per kW because of the rather low power level (1..5 kW) per unit.
- String inverters are build as single-phase inverters due to the low power level.

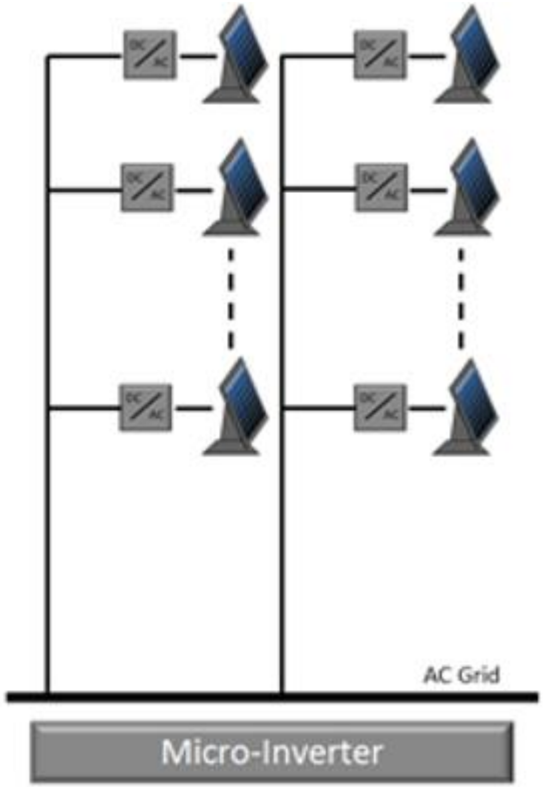
Centralized Inverters

- They are intended to manage multiple strings in an installation.
- This means that an entire distributed energy resource (DER) will require only one inverter.
- Centralized inverters are very popular for larger installations due to their increased lifetimes as well as the simplicity arising from having only one inverter.



Micro-Inverters

- Micro-inverters are intended to manage a single solar panel.
- Thus, each panel in the installation will require its own inverter.
- Many claim that with an inverter managing the MPPT of each panel individually, the installation as a whole will see a drastic increase in efficiency.
- For reasons of complexity, inconclusive data, and lack of smart capabilities, PPL generally recommends against the use of micro-inverters.



3. The Right Inverter for Every Plant: Circuit topology

- With regard to circuit topology, distinctions are made between one- and three-phase inverters, → inverter
- and between devices with and without transformers.
- One-phase inverters are usually used in small plants,
- in large PV plants either a network consisting of several one-phase inverters or three-phase inverters have to be used on account of the unbalanced load of 4.6 kVA.
- However, transformers serve the purpose of galvanic isolation (required in some countries) and make it possible to ground the PV module (necessary for some types of modules).
- Whenever possible, however, inverters without transformers are used.
- They are a little smaller and lighter than transformer devices and operate with a higher efficiency.

Tasks of the PV inverter

- The tasks of a PV inverter are as varied as they are demanding:

➢ **1. Low-loss conversion**
One of the most important characteristics of an inverter is its conversion efficiency.

➢ This value indicates what proportion of the energy “inserted” as direct current comes back out in the form of alternating current.

➢ Modern devices can operated with an efficiency of around 98 percent.

➢ 2. **Power optimization**
The inverter must find and continually observe the optimal operating point on the power characteristics curve, in order to “bring out” maximum power from the PV modules in every situation.

➢ The optimal operating point is called the "maximum power point" (MPP), and MPP tracking is extremely important for the energy output of a PV plant.

Tasks of the PV inverter:
3.Monitoring and securing

- On the one hand, the inverter monitors the energy yield of the PV plant and signals any problems.

output

- On the other, it also monitors the power grid that it is connected to. Thus, in the event of a problem in the power grid, it must immediately disconnect the plant from the grid for reasons of safety or to help support the grid – depending on the requirements of the local grid operator.
- In addition, in most cases the inverter has a device that can safely interrupt the current from the PV modules. (dc-disconnect)
- If the cutout device is integrated directly in the inverter, installation and wiring efforts are reduced considerably.

Tasks of the PV inverter: 4. Communication

- Communication interfaces on the inverter allow control and monitoring of all parameters, operational data, and yields.
- Data can be retrieved and parameters can be set for the inverter via a network connection, industrial fieldbus such as RS485, or wireless via Bluetooth®.
- In most cases, data is retrieved through a data logger, which collects and prepares the data from several inverters and, if desired, transmits them to a free online data portal (e.g. Sunny Portal from SMA).

• Inverter interfaces include on-board screens, remote data monitors, and computerized data acquisition and processing software.

Tasks of the PV inverter:
5.Temperature management

- The temperature in the inverter housing also influences conversion efficiency. If it rises too much, the inverter has to reduce its power.
- Under some circumstances the available module power cannot be fully used.
- On the one hand, the installation location affects the temperature – a constantly cool environment is ideal. On the other hand, it directly depends on the inverter operation: even an efficiency of 98 percent means a power loss of two percent –in form of heat. If the plant power is 10 kW, the maximum thermal capacity is still 200 W. Therefore, an efficient and reliable cooling system for the enclosure is very important –.
- The optimum thermal layout of the components allows them to dissipate their heat directly to the environment, while the whole encasing acts as a heat sink at the same time.
- This allows the inverters to work at maximum rated capacity even at ambient temperatures of up to 50° C.

Tasks of the PV inverter:
6.Protection

- A weather-proof enclosure, ideally built in line with protective rating IP65, allows the inverter to be installed in any desired place outdoors.
- The advantage: the nearer to the modules the inverter can be installed, the lower the expenditure for the comparatively expensive DC wiring.

- Inverter enclosures may include protective devices such as circuit breakers.

Grid side

PV module side

Planning PV plants

- Professional planning and plant design takes the conditions at the set-up location into account in terms of module selection and wiring: roof pitch, any shade and, of course, alignment. In Palestine, maximum yield is achieved when the modules are aligned to the south at an angle of around 32 deg.
- Next, the selection of a suitable inverter in terms of performance and technology is absolutely essential.
- The rated capacity of the PV array may be up to ten percent above the rated of the inverter.
- If an inverter is greatly undersized, this can have a negative effect on plant yield, since the inverter can no longer process part of the module power supplied during periods of high radiation.
- It is also important that the maximum DC voltage never exceeds the permissible inverter input voltage – otherwise damage to the inverter may be the result.

Planning PV plants

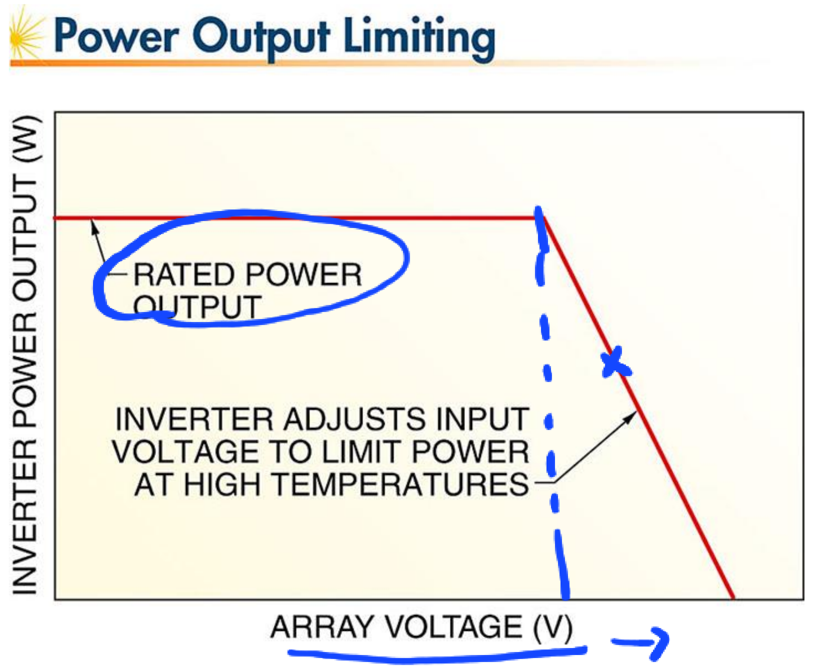
- Basically, almost every PV plant is unique and has to be designed customized for the specific location and requirements involved.
- For installers to make planning a plant easier, manufacturers, like SMA, provide professional planning tools.
- The free software **Sunny Design** allows solar specialists to design a tailor-made grid-tied PV plant for their customers.
- The program accesses a database containing all the current PV plants and high-resolution weather data, verifies the technical components, works out cable lengths and cross-sections and delivers data for an economic evaluation of the plant.

PVSYST ← for design

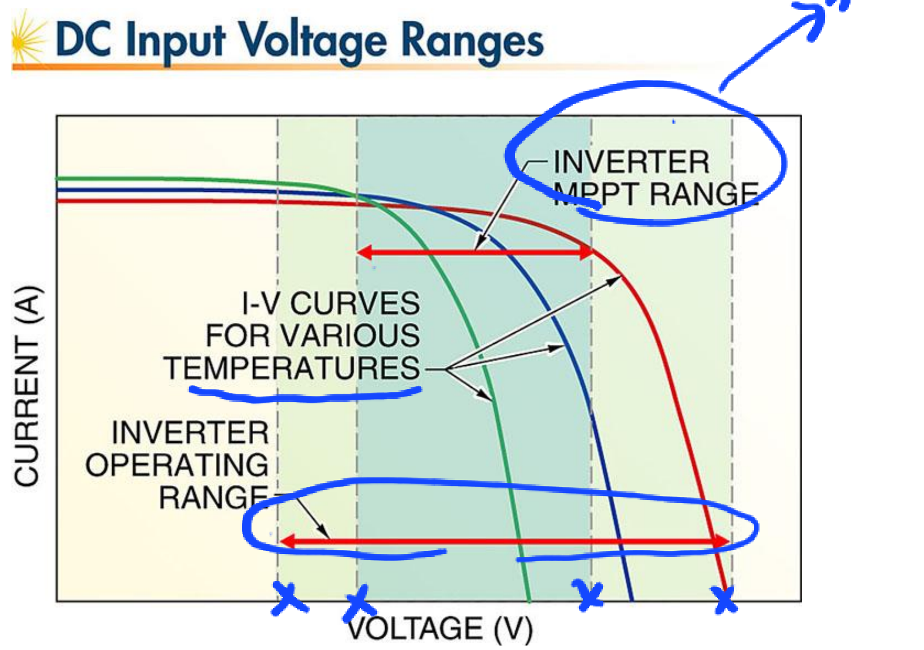
Inverter Nameplates

- Inverter nameplates include much of the needed information for sizing and operating the inverter.

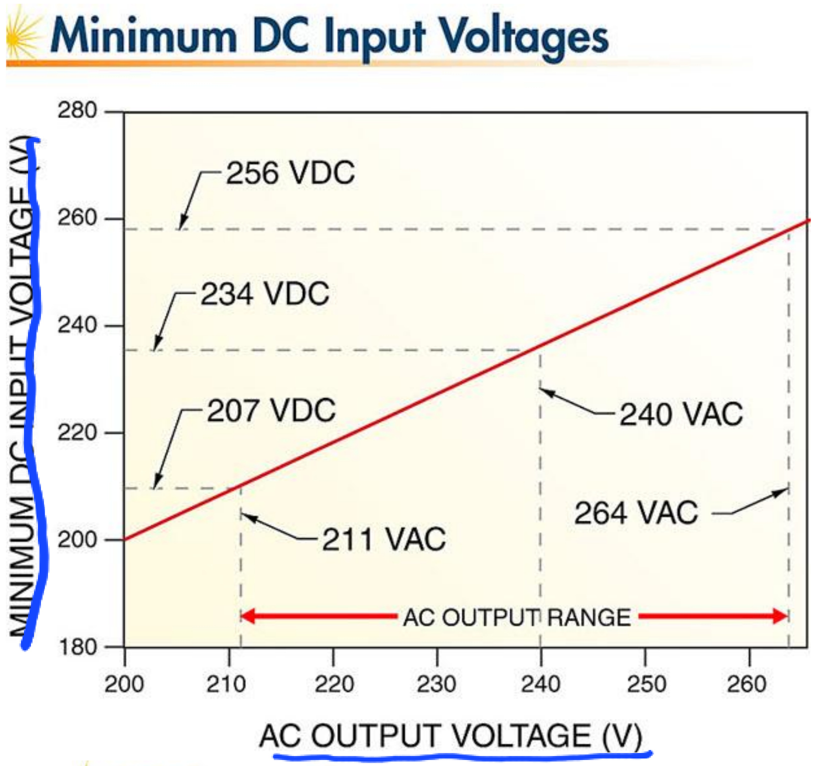
• At high temperatures, an interactive inverter may limit current input by raising the input voltage, which also lowers power input and output.



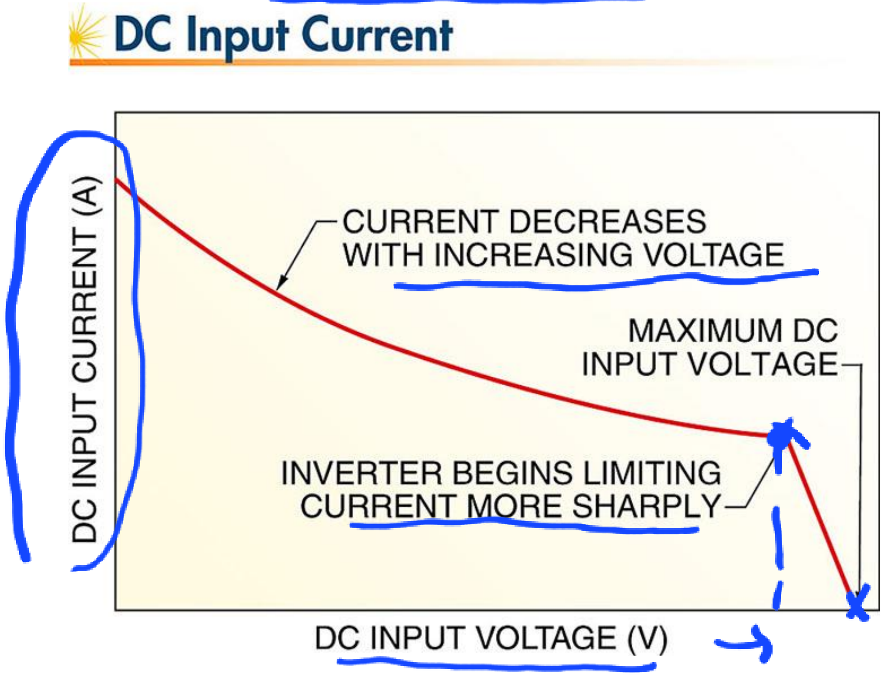
• Most inverters operate from a relatively wide range of input voltages, but the range for MPPT operation is smaller.



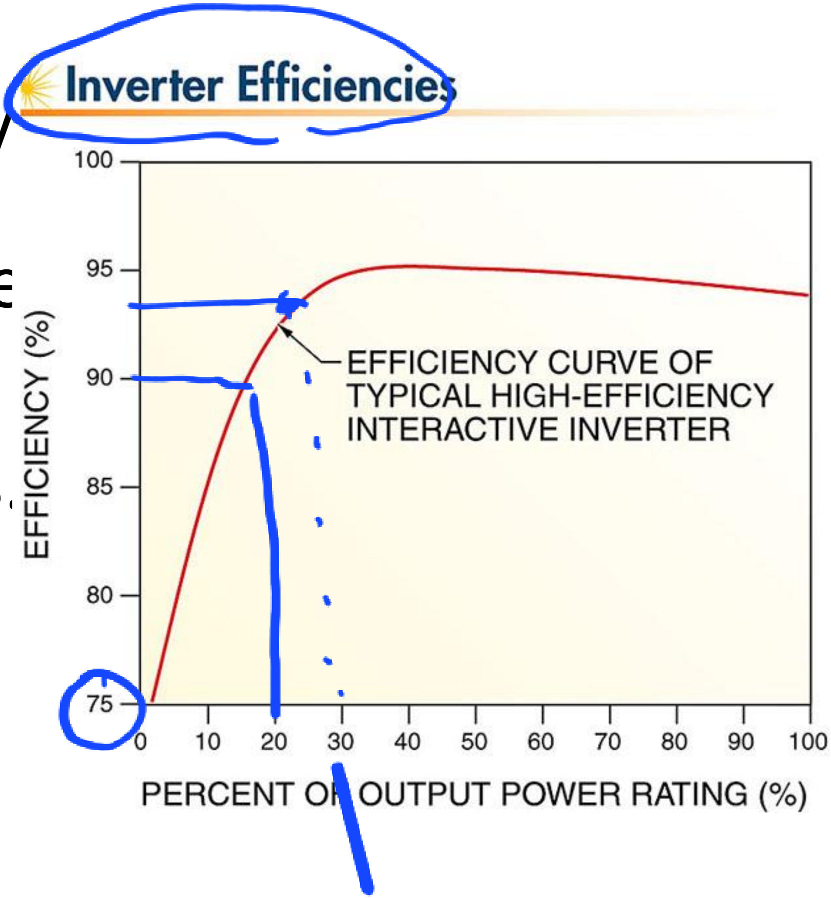
•In order to output AC voltage within the specified range, the DC input voltage must meet certain minimum values.



•Inverters may limit maximum DC input current with increasing DC input voltage.



- Most sine wave inverters maintain high efficiency over a wide operating-power range.
- Another important design issue that is driving the development of new topologies is the ability to exhibit a high efficiency also at partial loads, i.e. during the periods with reduced irradiation levels.
- Actually a weighted efficiency called 'European efficiency' has been defined that takes into consideration the periods for different irradiation levels across Europe.
- Today there are many PV inverter manufacturers in the market, such as SMA, Sunways, Conergy, Ingeteam, Danfoss Solar, Refu, etc., offering a wide range of transformerless PV inverters with very high European efficiency (>97 %) and maximum efficiency of up to 98 %.

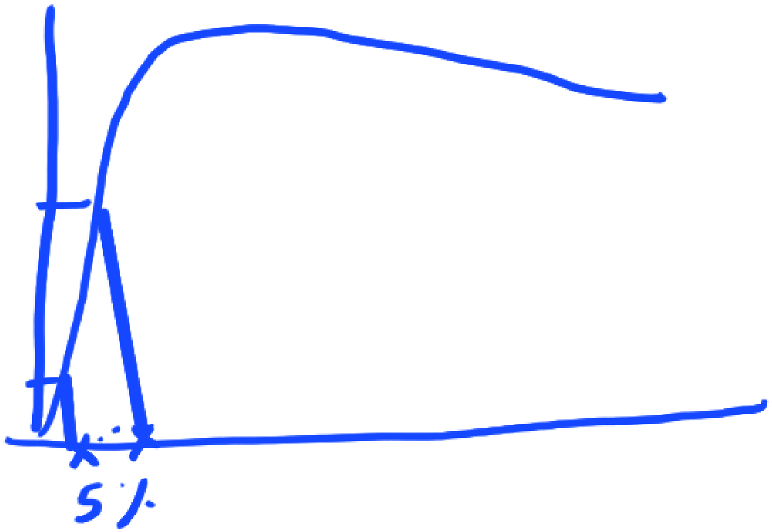


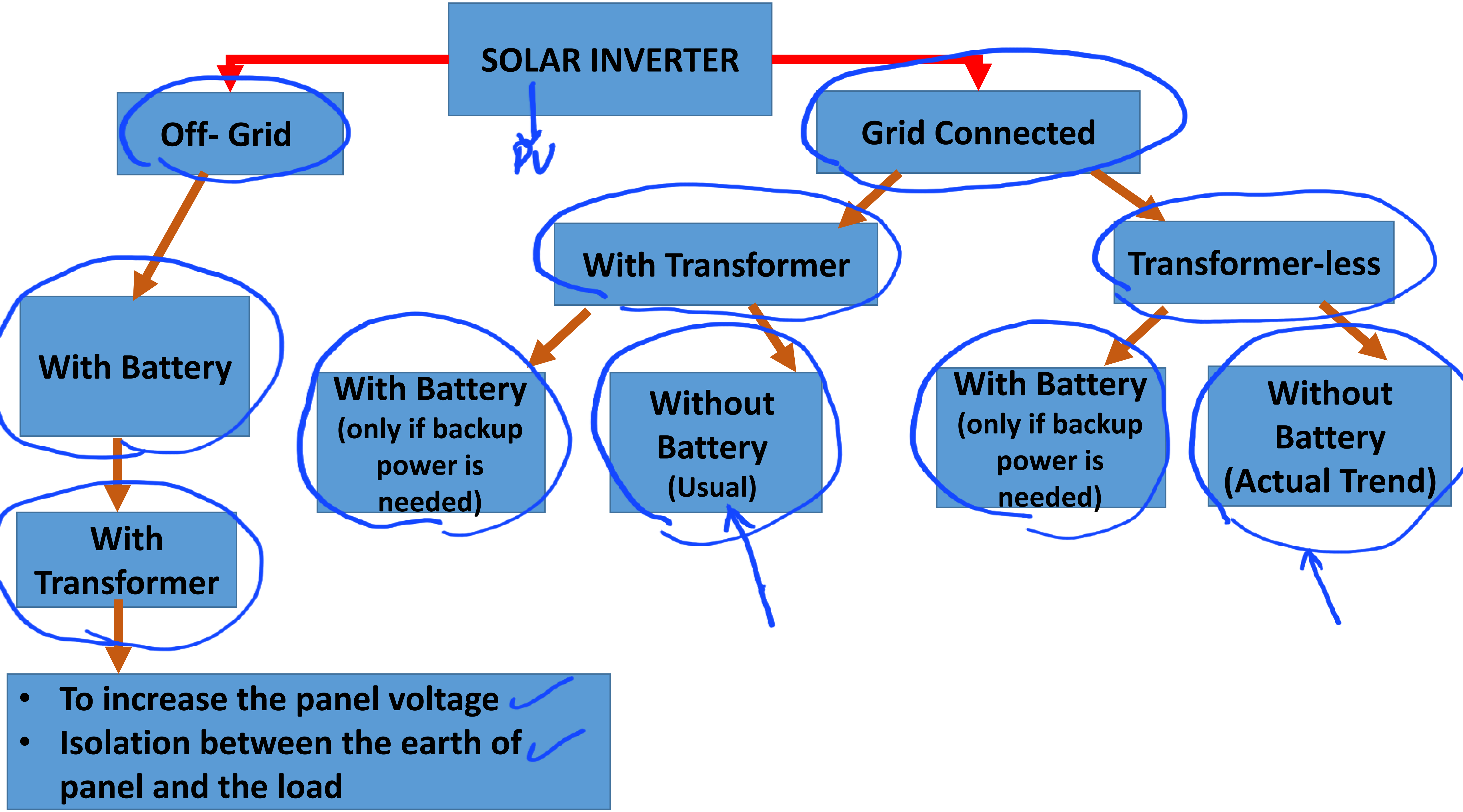
Efficiency of Grid Inverters

- **Euro Efficiency** = 0.03 x Eff5% + 0.06 x Eff10% + 0.13 x Eff20% + 0.1 x Eff30% + 0.48 x Eff50% + 0.2 x Eff100%.
- Now for climates of higher insolations like US south-west regions, the California Energy Commission (CEC) has proposed another weighting, which is now specified for some inverters used in the US.

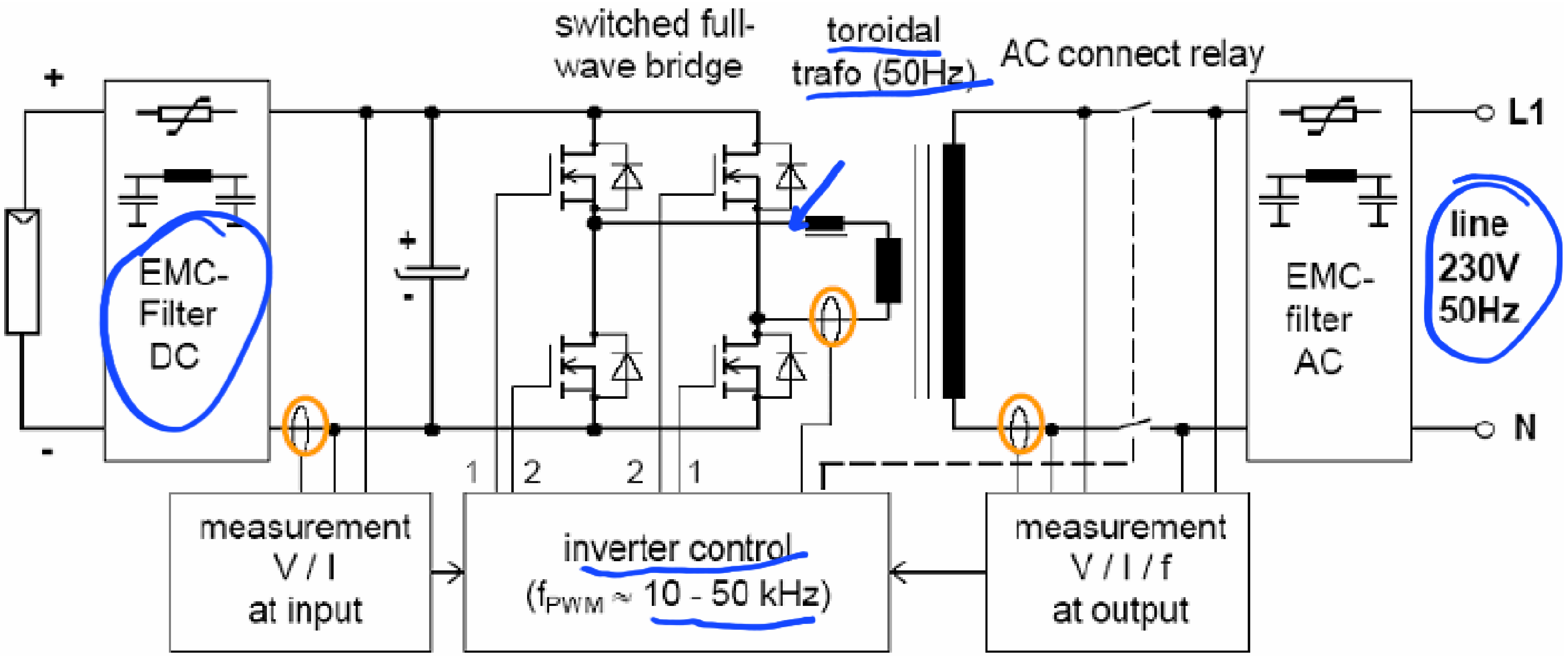
CEC Efficiency = 0.04 x Eff10% + 0.05 x Eff20% + 0.12 x Eff30% + 0.21 x Eff50% + 0.53 x Eff75%. + 0.05 x Eff100%

- **90 % of the market is grid-connected**
- **10 % of the market is off-grid**




SOLAR INVERTER
PV
Off- Grid
Grid Connected
With Battery
With Transformer
Transformer-less
With Battery (only if backup power is needed)
Without Battery (Usual)
With Battery (only if backup power is needed)
Without Battery (Actual Trend)
With Transformer
• To increase the panel voltage
• Isolation between the earth of panel and the load

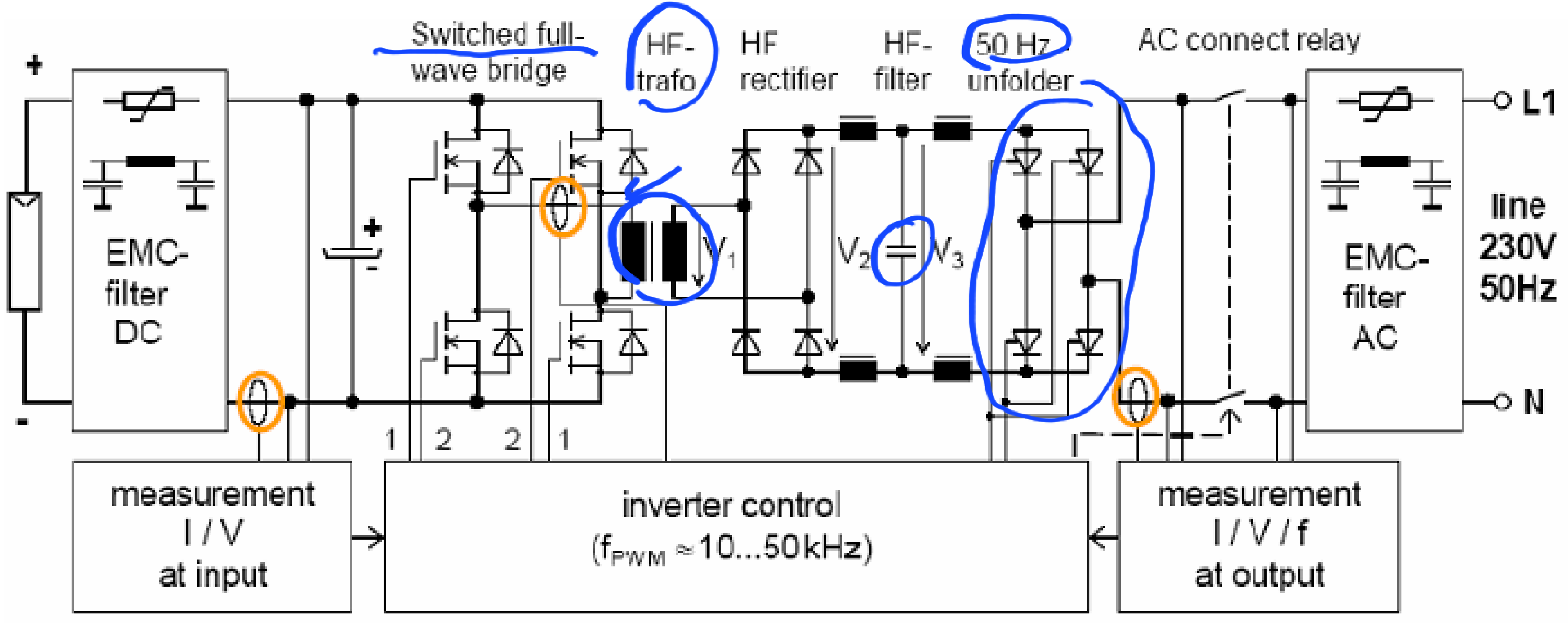
Grid Connected with LF transformer



Source : Evolution of Inverters for Grid Connected PV-Systems from 1989 to2000, H. Haeberlin

- **Advantages: very reliable, cost effective, No DC current injection, efficiency up to 96 %**
- **Disadvantages: weight, size** → 50 Hz transfo

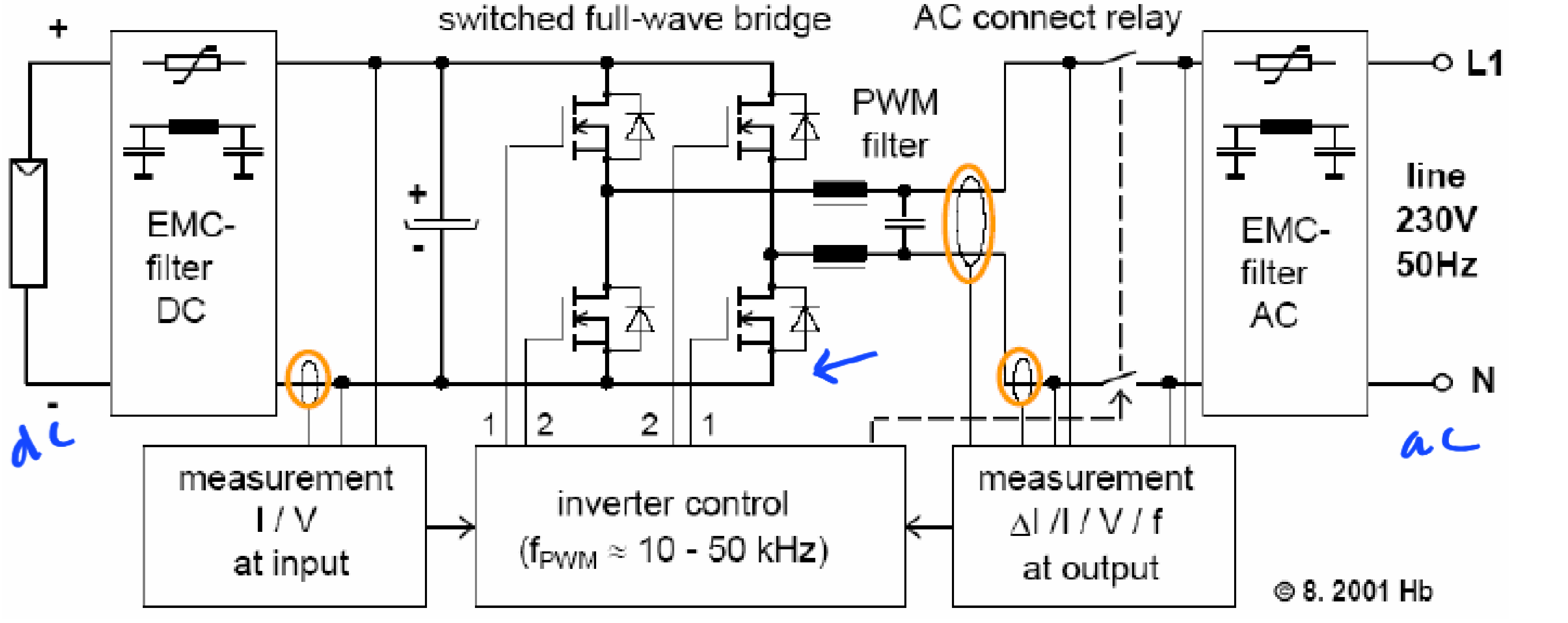
Grid Connected: Inverter with HF transformer (16…100 kHz)



Source : Evolution of Inverters for Grid Connected PV-Systems from 1989 to2000, H. Haeberlin

- **Advantages: low weight, small size**
- **Disadvantages: high number of components (reliability), DC current injection is possible, efficiency over 95 % difficult to achieve**

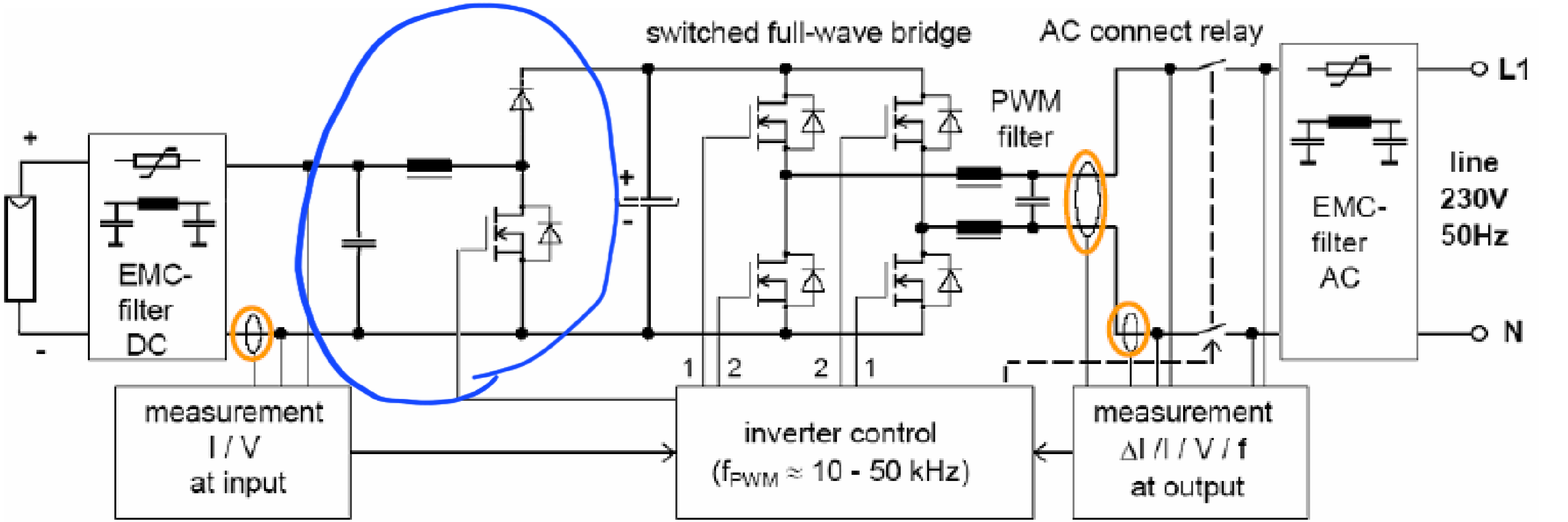
Grid Connected: Transformerless Inverter without DC Chopper



Source : Evolution of Inverters for Grid Connected PV-Systems from 1989 to2000, H. Haeberlin

- **Advantages: very high efficiency, low weight, small size**
- **Disadvantages: small input voltage range, no galvanic isolation, DC injection < 5 mA difficult to achieve, leakage current due to the AC component in PV module to earth**

Grid Connected: Transformerless Inverter with DC Chopper

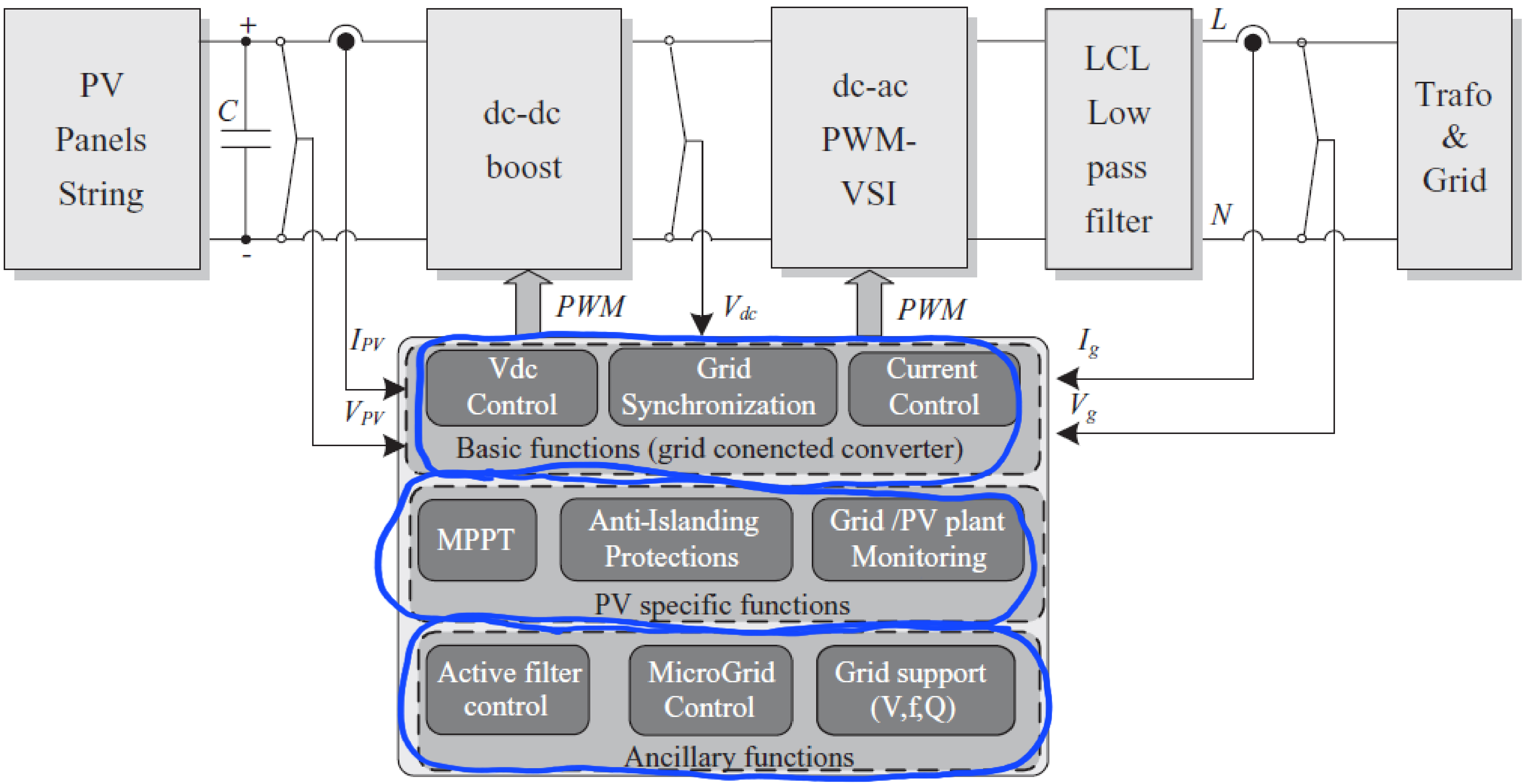


- **Advantages: very high efficiency, low weight, small size, wide input voltage range**
- **Disadvantages: no galvanic isolation, DC injection < 5 mA difficult, leakage current due to the AC-component in PV module to earth**

Control Structures

- Due to the very large variety of **transformer-less PV inverter topologies**, the control structures are also very different.
- In the following a generic, topology invariant control structure will be presented for a typical transformer-less topology with boost stage
- As can be seen, three different classes of control functions can be defined:

1) **Basic functions – common for all grid-connected inverters**
2) **PV specific functions – common for all PV inverters**
3) **Ancillary functions**


PV
Panels
String
+
C
-
dc-dc
boost
dc-ac
PWM-
VSI
LCL
Low
pass
filter
L
N
Trafo
&
Grid
PWM
V_{dc}
PWM
I_{PV}
V_{PV}
I_g
V_g
Vdc
Control
Grid
Synchronization
Current
Control
Basic functions (grid conencted converter)
MPPT
Anti-Islanding
Protections
Grid /PV plant
Monitoring
PV specific functions
Active filter
control
MicroGrid
Control
Grid support
(V,f,Q)
Ancillary functions

Basic functions – common for all grid-connected inverters

- **Grid current control**

==> ◦ THD limits imposed by standards

==> ◦ Stability in the case of large grid impedance variations

==> ◦ Ride-through grid voltage disturbances

- **DC voltage control**

==> ◦ Adaptation to grid voltage variations

==> ◦ Ride-through grid voltage disturbances

- **Grid synchronization**

==> ◦ Operation at the unity power factor as required by standards

==> ◦ Ride-through grid voltage disturbances

PV specific functions – common for all PV inverters

- Maximum power point tracking (MPPT)

==> ◦ Very high MPPT efficiency during steady state (typically >99 %)

==> ◦ Fast tracking during rapid irradiation changes (dynamical MPPT efficiency)

==> ◦ Stable operation at very low irradiation levels

- Anti-islanding (AI), as required by standards (VDE 0126, IEEE 1574, etc.)
- Grid monitoring

==> ◦ Synchronization

==> ◦ Fast voltage/frequency detection for passive AI

- Plant monitoring

==> ◦ Diagnostic of PV panel array

==> ◦ Partial shading detection

Ancillary functions

- **Grid support**

==> ◦ Local voltage control

==> ◦ Q compensation

==> ◦ Harmonic compensation

==> ◦ Fault ride-through

Future Trends

- PV inverter structures are evolving at a high pace. A high number of new patented transformer-less topologies based on either H-bridge or NPC appeared on the market with very high efficiency, up to 98 %.
- The obvious trend is more silicon for lower losses, as the number of switches has increased.
- The PV inverter market is driven by efficiency rather than cost, mainly due to the still very high price for PV energy.
- To increase even more the efficiency could be quite difficult using the current technology, but new research shows a real good potential in replacing the silicon switches by silicon-carbide ones.
- an efficiency increase of roughly 1 % was demonstrated on an HERIC topology by simply replacing the IGBT with a SiC MosFet.
- It is thus expected that in a few years the SiC MosFets will become commercially available, along with the SiC diodes, which are currently used today in very high efficiency boost converters.

→ new topologies

→ new device technologies

Future Trends

- Another trend in the design of PV inverters will be influenced by the grid requirements.
- At the moment, in many countries it is required that eventual islanding should be quickly detected and the inverter should be disconnected from the grid immediately in order to avoid any personal safety issues, especially for residential PV systems.
- However, as the PV weight in the grid integration is expected to grow very fast, it is possible that grid requirements will change and will require fault ride-through capability in order to stabilize the power system.
- Just like the case for wind power systems, this requirement has been introduced after a long period when its share in the power generation became important.
- This will most probably apply for large PV plants connected to distribution systems.

Future Trends

- Finally, integration of power components is an important factor as it is known from the electric drives sector that this will reduce the costs in the long term.
- The problem with PV inverters is that there are so many topologies and it is actually very difficult to find standard modules for implementation.
- A good example is SMA, which managed to produce customized power modules for the H5 topology.
- Semikron and Vincotech (previously a Tyco division) are now offering power modules for NPC topologies,
- Mitsubishi is offering intelligent power modules (IPM) with one or two boost converters plus an H-bridge inverter specially designed for PV applications,
- and this trend is expected to continue also with other major device manufacturers as the PV inverter market is growing very fast.

Disconnection Time for Voltage & Frequency Variation

Table 3.2 Disconnection time for voltage variations

IEEE 1547		IEC 61727		VDE 0126-1-1	
Voltage range (%)	Disconnection time (sec.)	Voltage range (%)	Disconnection time (sec.)	Voltage range (%)	Disconnection time (sec.)
$V < 50$	0.16	$V < 50$	0.10	$110 \le V < 85$	0.2
$50 \le V < 88$	2.00	$50 \le V < 85$	2.00		
$110 < V < 120$	1.00	$110 < V < 135$	2.00		
$V > 120$	0.16	$V > 135$	0.05		

Table 3.3 Disconnection time for frequency variations

IEEE 1547		IEC 61727		VDE 0126-1-1	
Frequency range (Hz)	Disconnection time (sec.)	Frequency range (Hz)	Disconnection time (sec.)	Frequency range (Hz)	Disconnection time (sec.)
$59.3 < f < 60.5^a$	0.16	$f_n - 1 < f < f_n + 1$	0.2	$47.5 < f < 50.2$	0.2

Reconnection after Trip and DC current Injection

Table 3.4 Conditions for reconnection after trip

IEEE 1547	IEC 61727	VDE 0126-1-1
$88 < V < 110$ (%) AND $59.3 < f < 60.5$ (Hz)	$85 < V < 110$ (%) AND $f_n - 1 < f < f_n + 1$ (Hz) AND Minimum delay of 3 min.	

Table 3.5 DC current injection limitation

IEEE 1574	IEC 61727	VDE 0126-1-1
$I_{DC} < 0.5$ (%) of the rated RMS current	$I_{DC} < 1$ (%) of the rated RMS current	$I_{DC} < 1$ A Maximum trip time 0.2 sec.

THD and harmonics levels

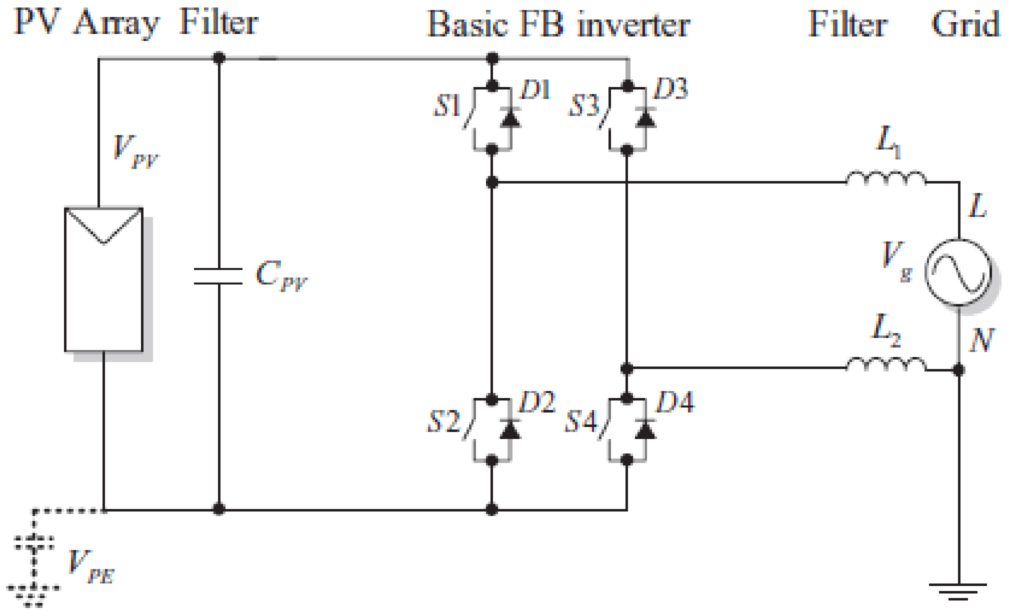
Table 3.6 Maximum current harmonics

IEEE 1547 and IEC 61727						
Individual harmonic order (odd)[a]	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	Total harmonic distortion THD (%)
(%)	4.0	2.0	1.5	0.6	0.3	5.0

[a]Even harmonics are limited to 25 % of the odd harmonic limits above.

Table 3.7 Current harmonic limits set by IEC 61000-3-2 (class A)

Odd harmonics		Even harmonics	
Order h	Current (A)	Order h	Current (A)
3	2.30	2	1.08
5	1.14	4	0.43
7	0.77	6	0.30
9	0.40	$8 \leq h \leq 40$	$0.23 \times 8/h$
11	0.33		
13	0.21		
$13 \leq h \leq 39$	$0.15 \times 15/h$		


PV Array
Filter
Basic FB inverter
Filter
Grid
V_{PV}
C_{PV}
S1
D1
S3
D3
S2
D2
S4
D4
L_1
L_2
L
N
V_g
V_{PE}

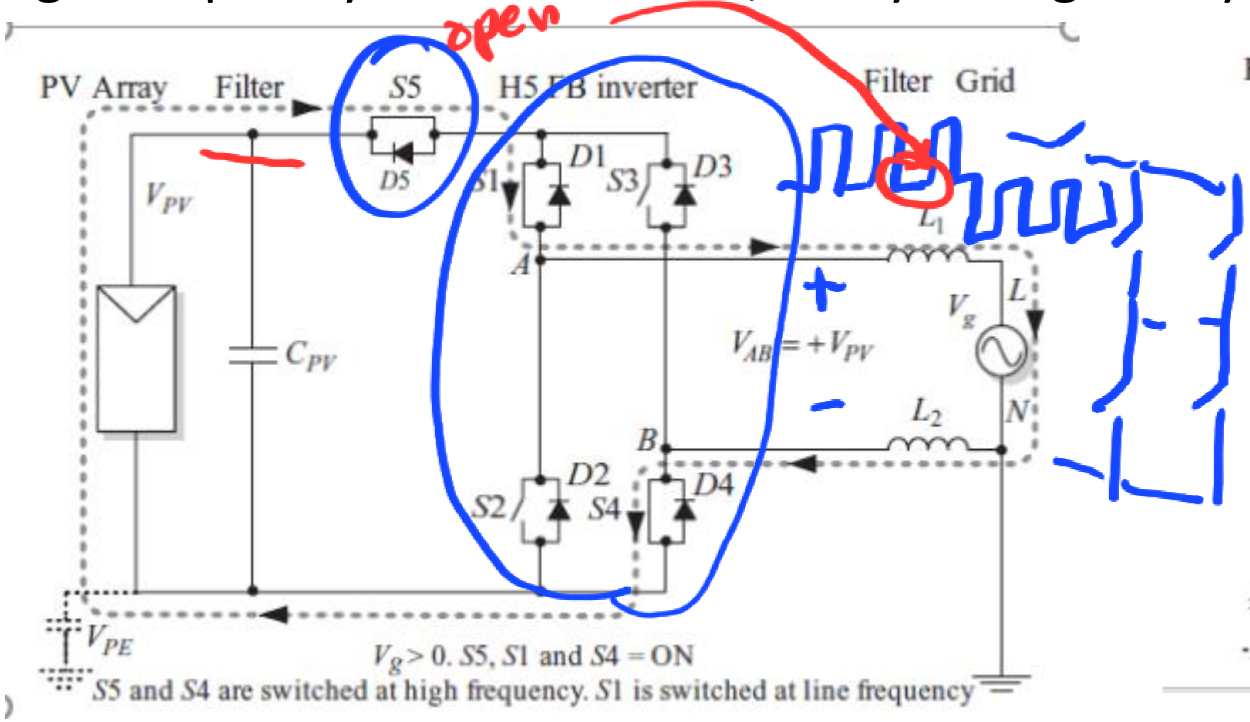
H5 Inverter (SMA)

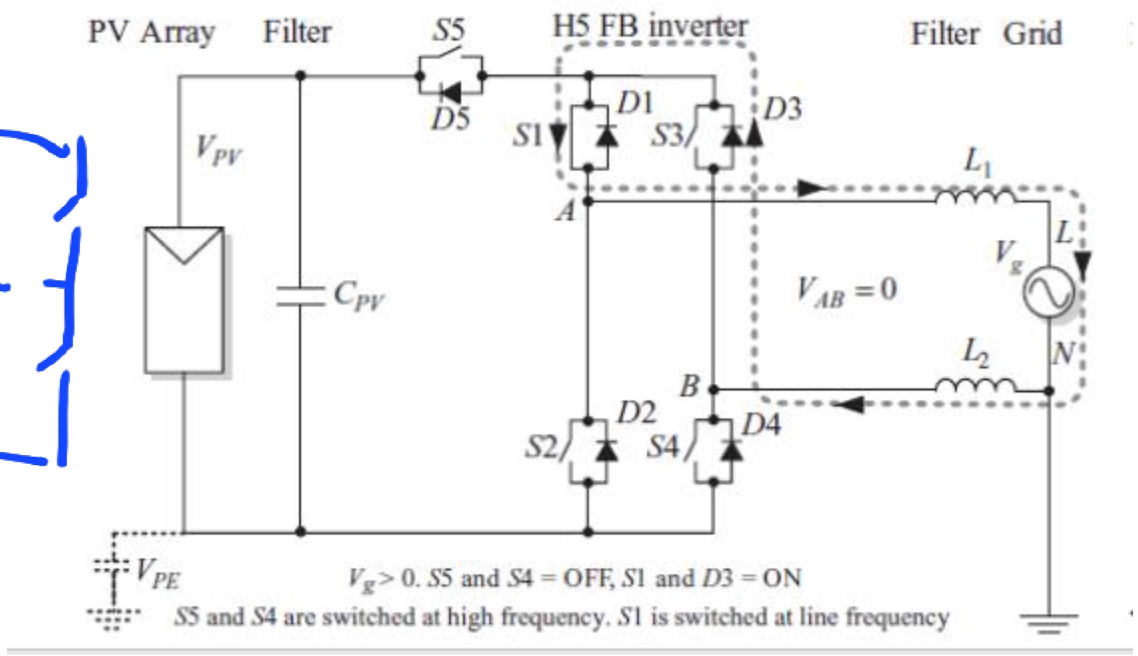
مطلوب تغير

- In 2005 SMA patented a new inverter topology called H5 .
- it is a classical H-bridge with an extra fifth switch in the positive bus of the DC link which provides two vital functions:

1) Prevents the reactive power exchange between *L*1(2) and *CPV* during the zero voltage state, thus increasing efficiency to about 98%

2) Isolates the PV module from the grid during the zero voltage state, thus eliminating the high-frequency content of *VPE*, and yielding a very low leakage current and EMI.



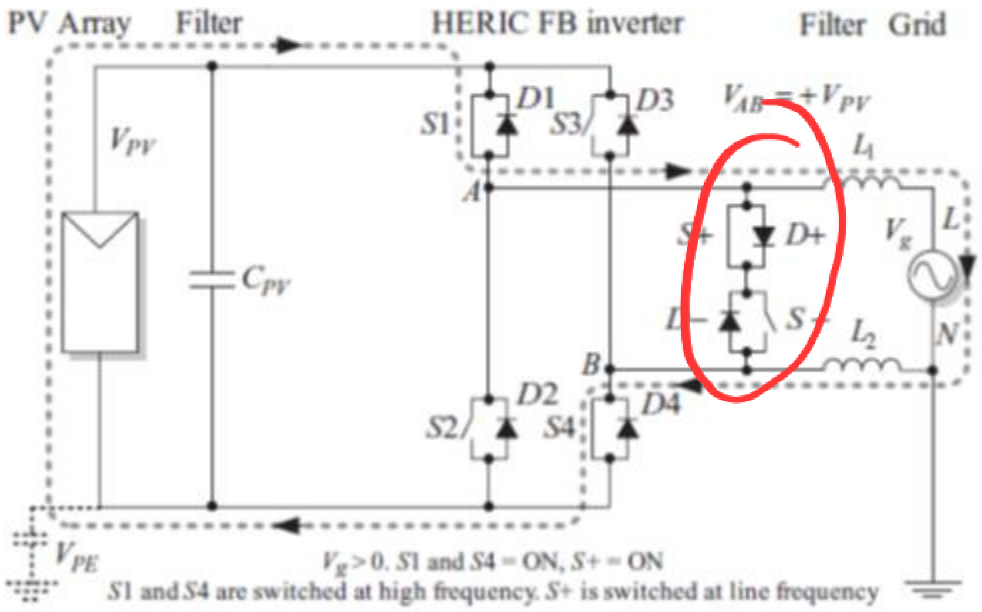


HERIC Inverter (Sunways)

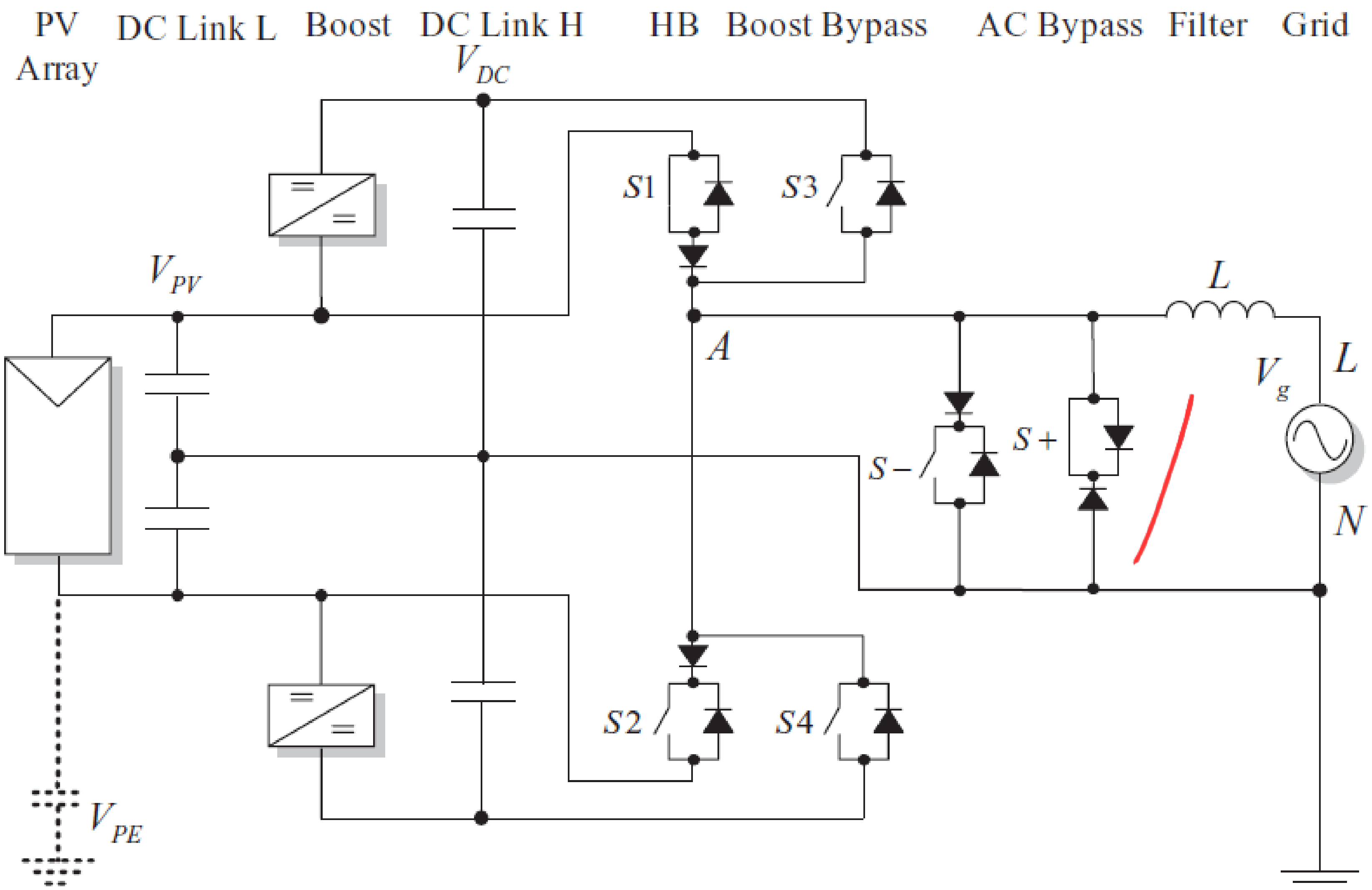
- In 2006, Sunways patented a new topology also derived from the classical H-bridge called HERIC (highly efficient and reliable inverter concept) by adding a bypass leg in the AC side using two back-to-back IGBTs
- The AC bypass provides the same two vital functions as the fifth switch in case of the H5 topology:

1) Prevents the reactive power exchange between *L*1(2) and *CPV* during the zero voltage state, thus increasing efficiency to ~97%

2) Isolates the PV module from the grid during the zero voltage state, thus eliminating the high-frequency content of *VPE* , yielding very low leakage current and EMI.

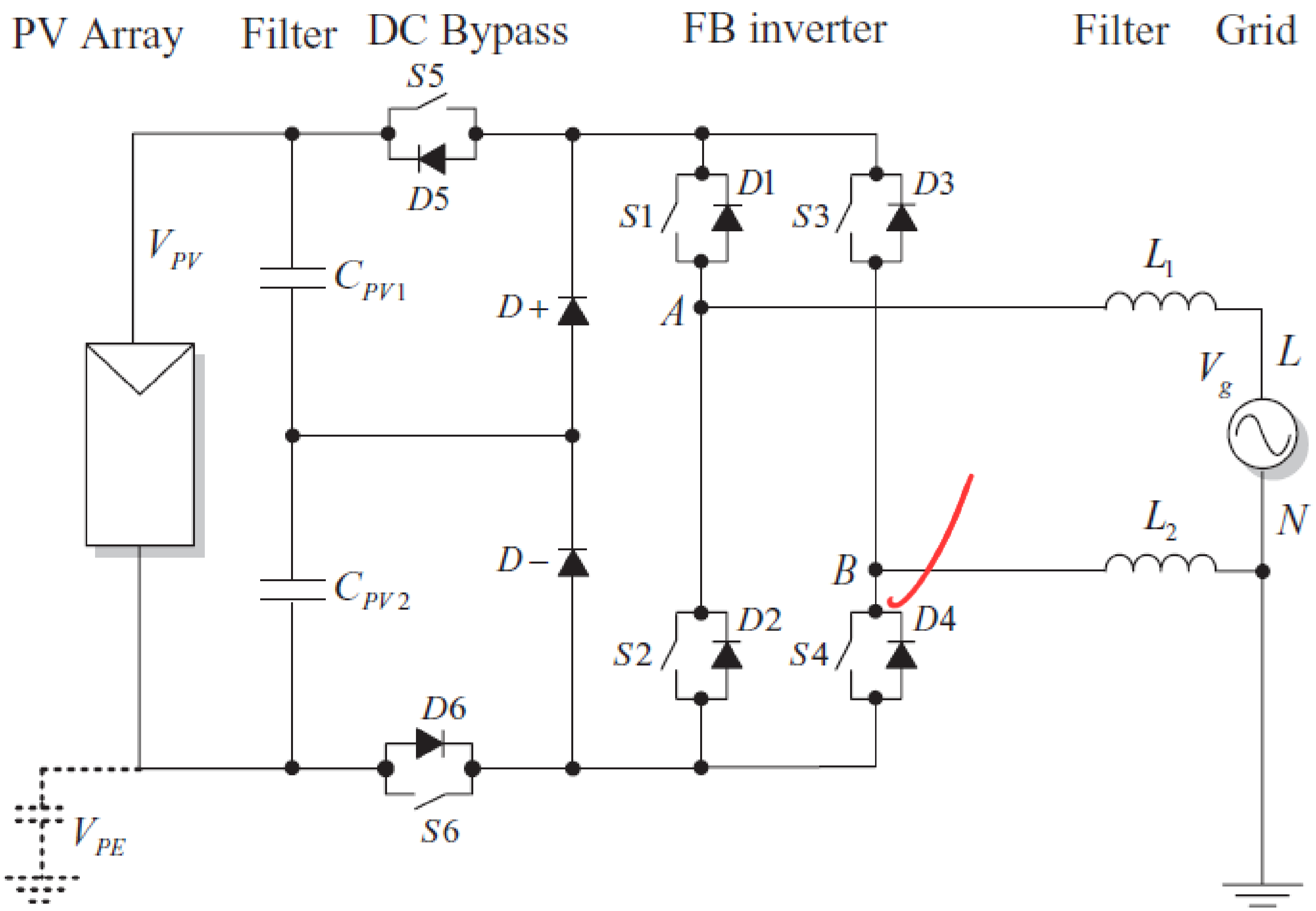


REFU Inverter



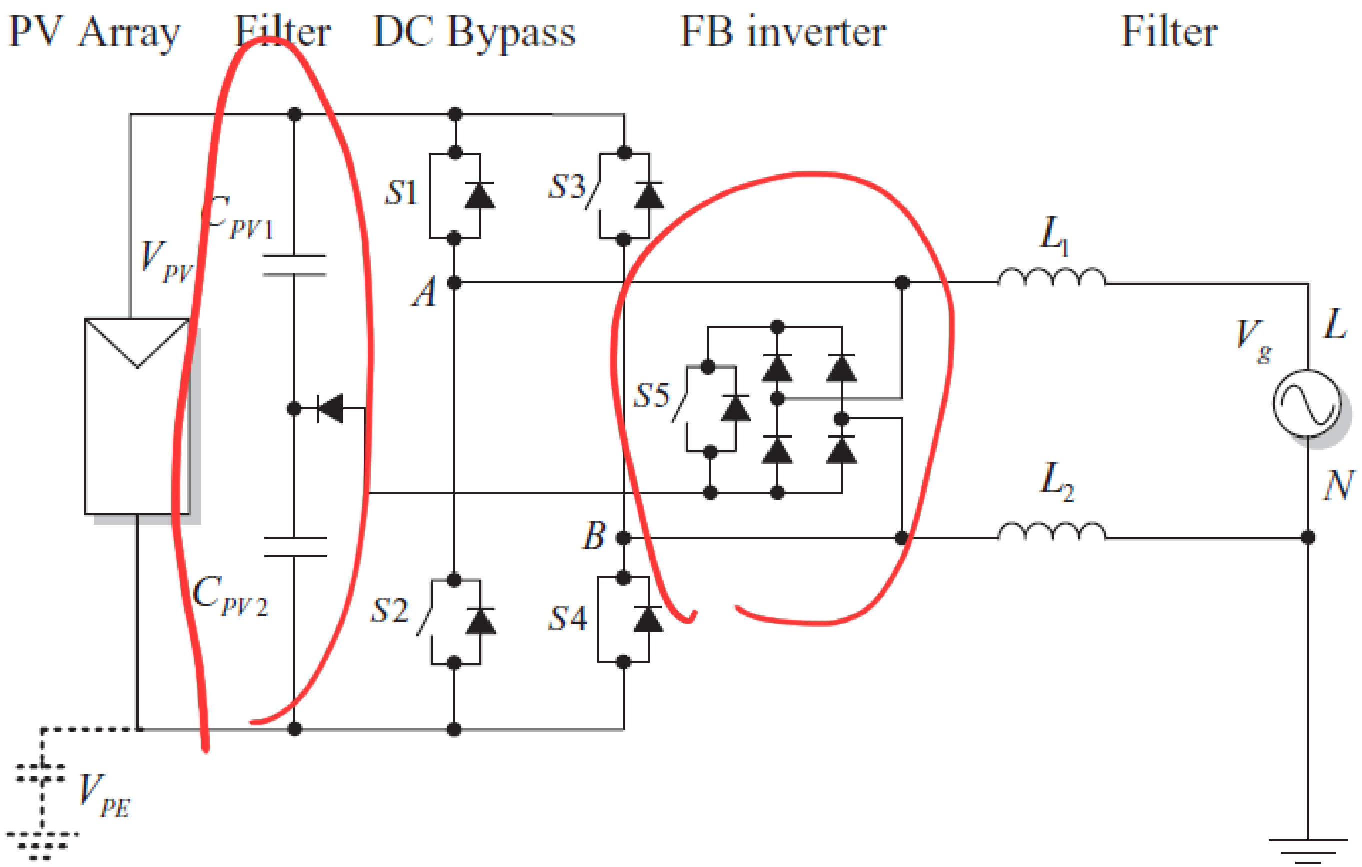
Full-Bridge Inverter with DC Bypass – FB-DCBP (Ingeteam)

- *The FB-DCBP topology is very suitable for use in transformer-less PV applications due to high efficiency and low leakage current and EMI.*
- *This topology is currently commercialized by Ingeteam in the Ingecon Sun TL series (2.5/3.3/6 kW) with reported European efficiency of 95.1%and maximum efficiency of 96.5%(Photon International, August 2007).*



Full-Bridge Zero Voltage Rectifier – FB-ZVR

- *The FB-ZVR inherits the advantages of the HERIC in terms of high efficiency and low leakage.*
- *Due to the high switching frequency of S5, the efficiency is lower than at HERIC, but it provides the advantage that can work at any power factor*

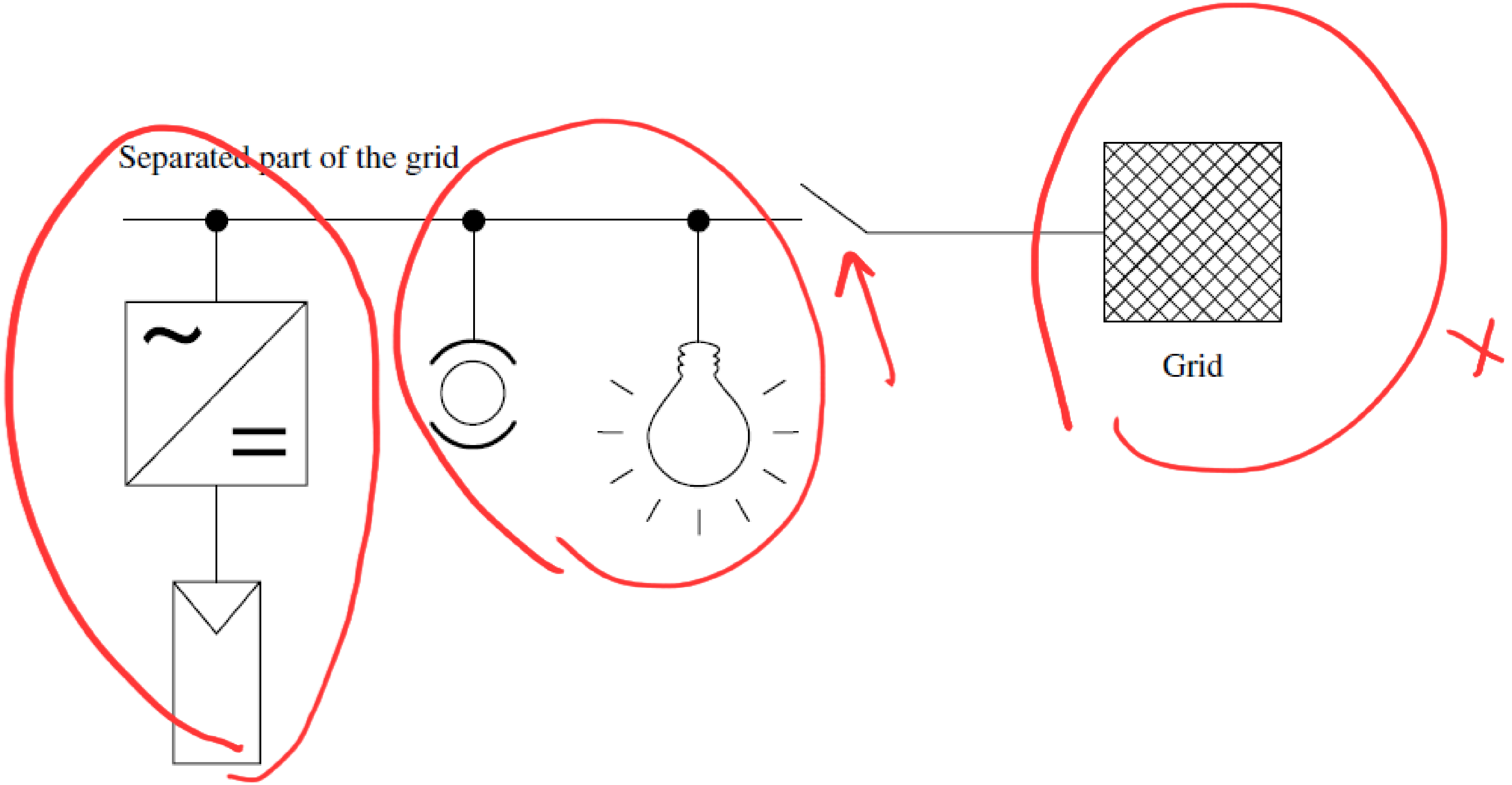


Safety Aspects with Grid-connected Inverters

- An important issue for grid-connected systems is associated with islanding protection.
- Islanding may occur, if a part of the local grid is switched off, for example, for maintenance reasons and if the injected power is equal to the actual load in the separated part of the grid. This situation is shown in the following figure (next slide)
- The situation described above becomes very unlikely since not only the effective power but the reactive power as well must be equal between production and consumption.

Safety Aspects with Grid-connected Inverters

- After switch-off, the separated part of the grid may continue operation, if the injected power by the PV system equals the actual load



Safety Aspects with Grid-connected Inverters

- As a first measure, frequency and voltage monitoring will identify by far most situations in grids turned off since the smallest deviations in production or in consumption will lead to changes in frequency or voltage or in both of them.
- The experience with big wind farms has shown that limitation of voltage or frequency may lead to undesired results, however.
- In case of heavy loads on the grid, both the voltage and the frequency may fall below the set point. In this situation, cut-off of power sources takes place when they would be needed urgently to support the grid.
- As a further method to identify islanding conditions, monitoring of the grid's impedance is being performed by injecting power peaks, which do not correspond with the fundamental frequency (50 or 60 Hz), by the inverter into the grid and by monitoring this influence on the grids voltage shape. This method is currently accepted by German safety code.

→ End of Inverter Topic

→ We will do inverter choice and calculation in the design

L15
محاضرة تعويض
27/4/2021

L11-
PV System Sizing and Design

+ L16 part 1
Project Task 2
Details
28/4/2021

Introduction

- **For electrical systems that use PV arrays as their only source of electricity, system sizing is critical.**
- **The size of the array, battery bank, and other major components necessary to adequately meet the load requirements must be carefully calculated.**
- **Sizing procedures are an important part of planning any PV system, but are especially stringent for stand-alone systems.**
- **Worksheets can be used to organize information and guide system-sizing calculations for most simple systems,**
- **More complex or hybrid systems may require computer models or simulation software.**

Sizing Grid Connected PV Systems

- These systems require relatively simple calculations and allow the widest variance in component sizing.
- These systems operate in parallel with utility service, sizing is not critical because failure of the PV system to produce energy does not affect operation of electrical loads, the PCU draws power from the grid .
- Excess Energy is sent into the grid

PCU: Power Conditioning Unit includes an MPPT and a DC-AC inverter

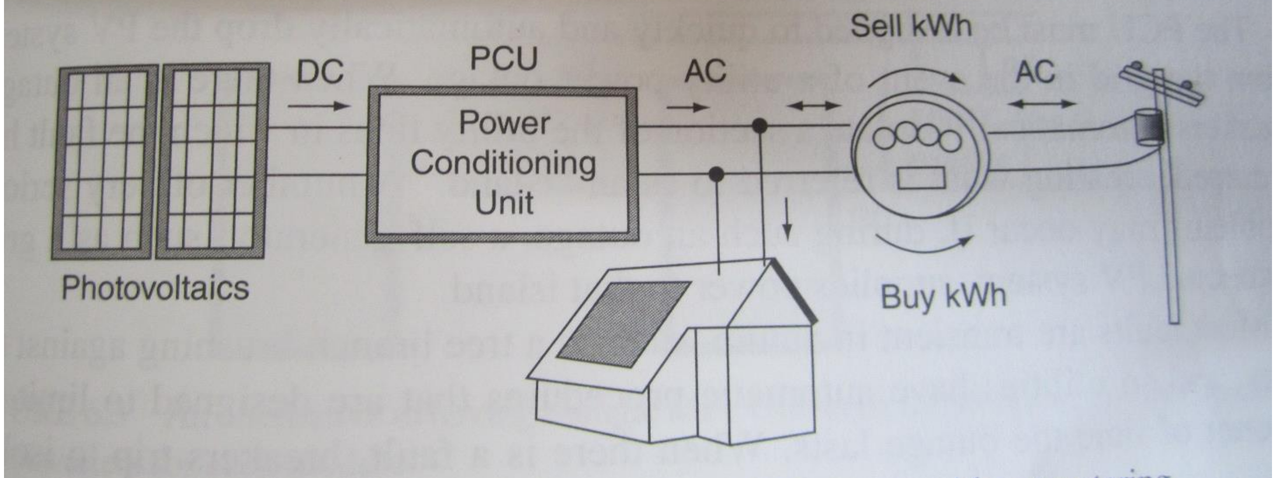


FIGURE 6.1 Simplified grid-connected PV system with net metering.

Sizing Grid Connected PV Systems

- Additional energy can be imported from the utility at any time.
- **Sizing interactive systems begins with the specifications of a PV module chosen for the system.**
- Module ratings at Standard Test Conditions (STC) are used to calculate the total expected array DC power output per peak sun hour

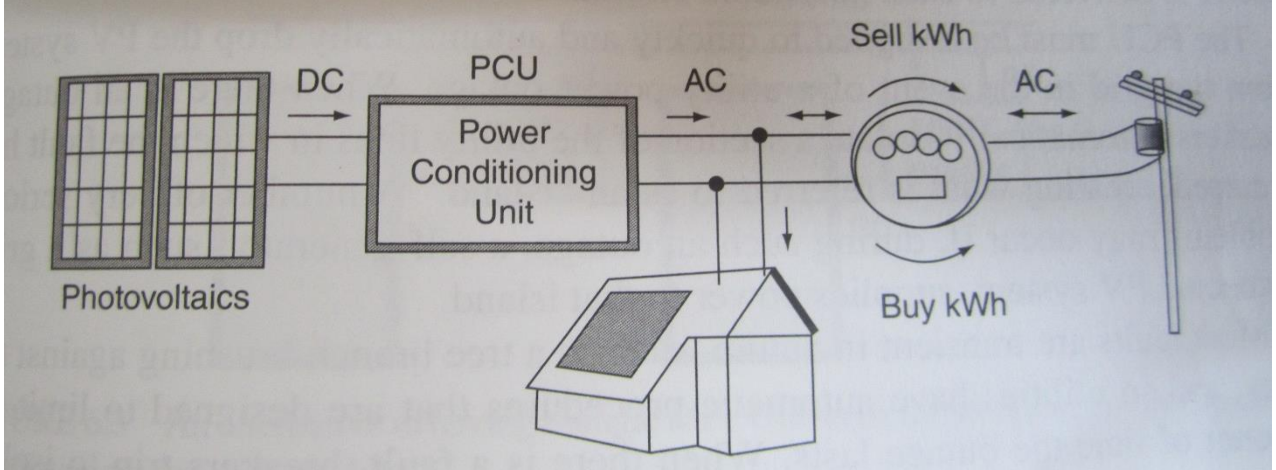


FIGURE 6.1 Simplified grid-connected PV system with net metering.

Sizing Interactive PV Systems (Grid Tied)

- This Power at STC is then de-rated for various losses and inefficiencies in the system, which includes the following:
  1) Guaranteed module output that is less than 100%
  2) Array operating temperature
  3) Array wiring and mismatch losses
  4) Inverter power conversion efficiency
  5) Inverter MPPT efficiency
- The result is **a final AC power output** that is substantially lower but realistically accounts for expected real-world conditions

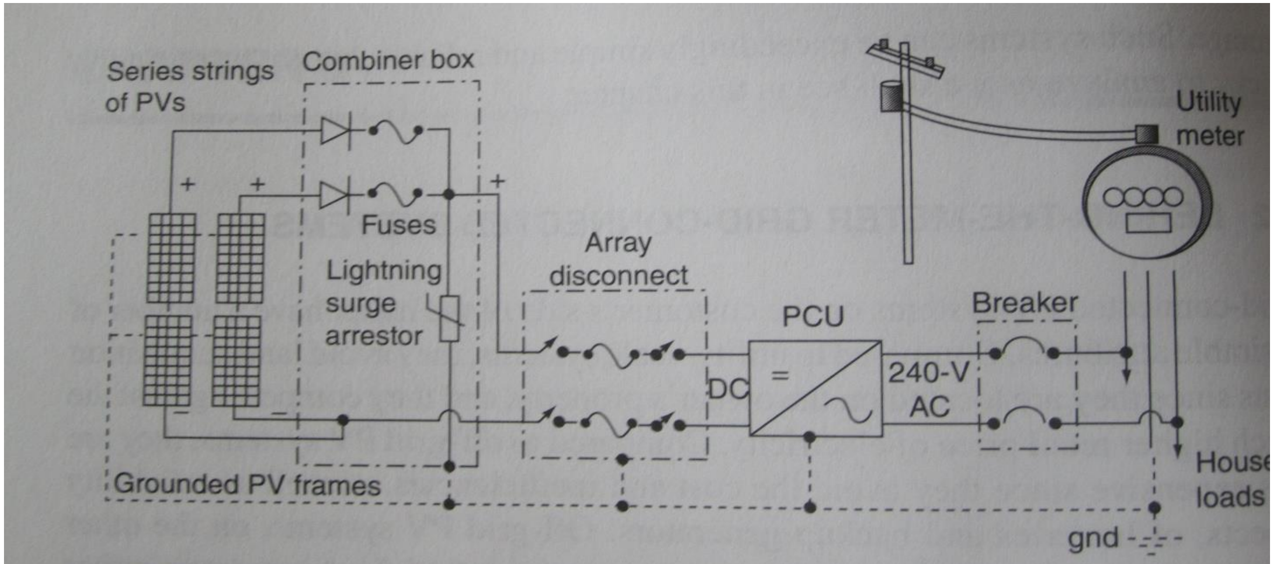
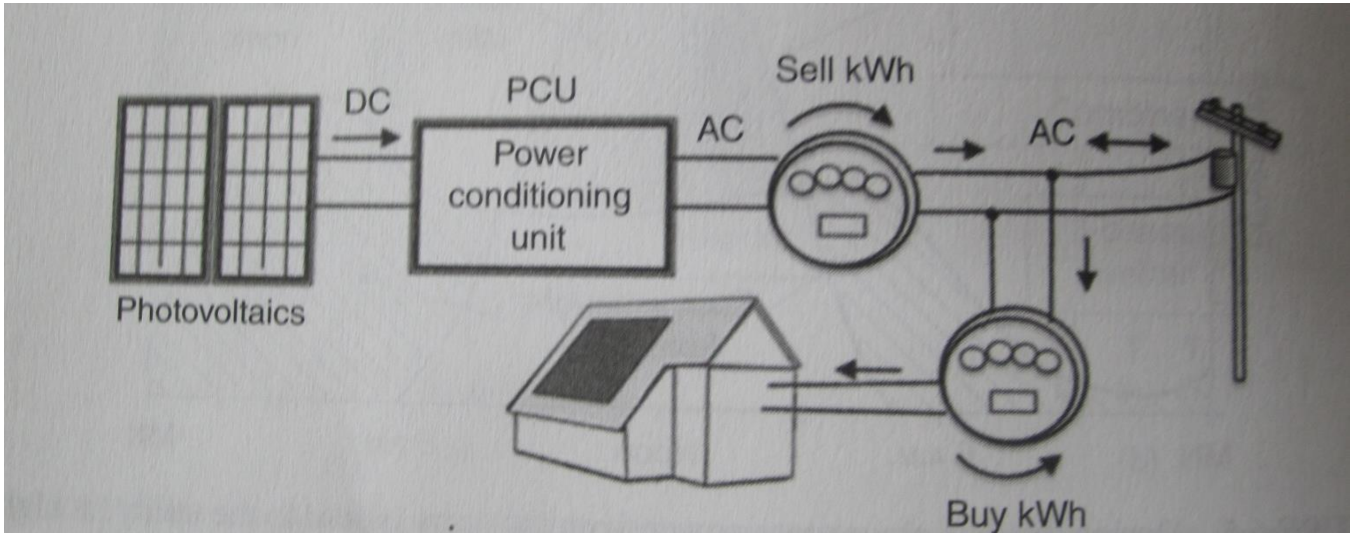


FIGURE 6.2 Principal components in a grid-connected PV system using a single inve and a single utility meter.

Item	Range	PVWATTS Default
PV module nameplate DC rating	0.80–1.05	0.95
Inverter and Transformer	0.88–0.98	0.92
Module mismatch	0.97–0.995	0.98
Diodes and connections	0.99–0.997	1.00
DC wiring	0.97–0.99	0.98
AC wiring	0.98–0.993	0.99
Soiling	0.30–0.995	0.95
System availability	0.00–0.995	0.98
Shading	0.00–0.995	1.00
Sun tracking	0.95–1.00	1.00
Age	0.70–1.00	1.00
Total derate factor without NOCT		0.770



- **A Two-meter system allows a feed-in tariff to provide separate rates for power generated by PV and power used by customers**

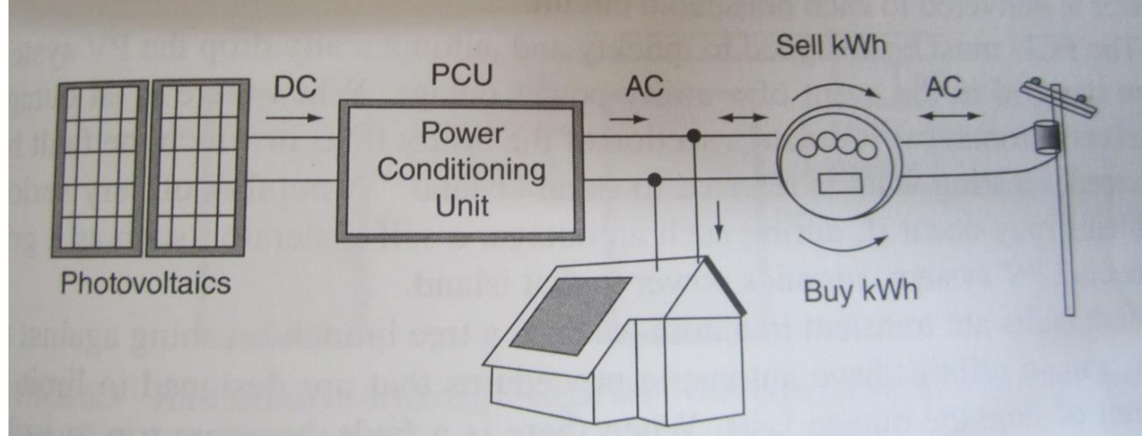


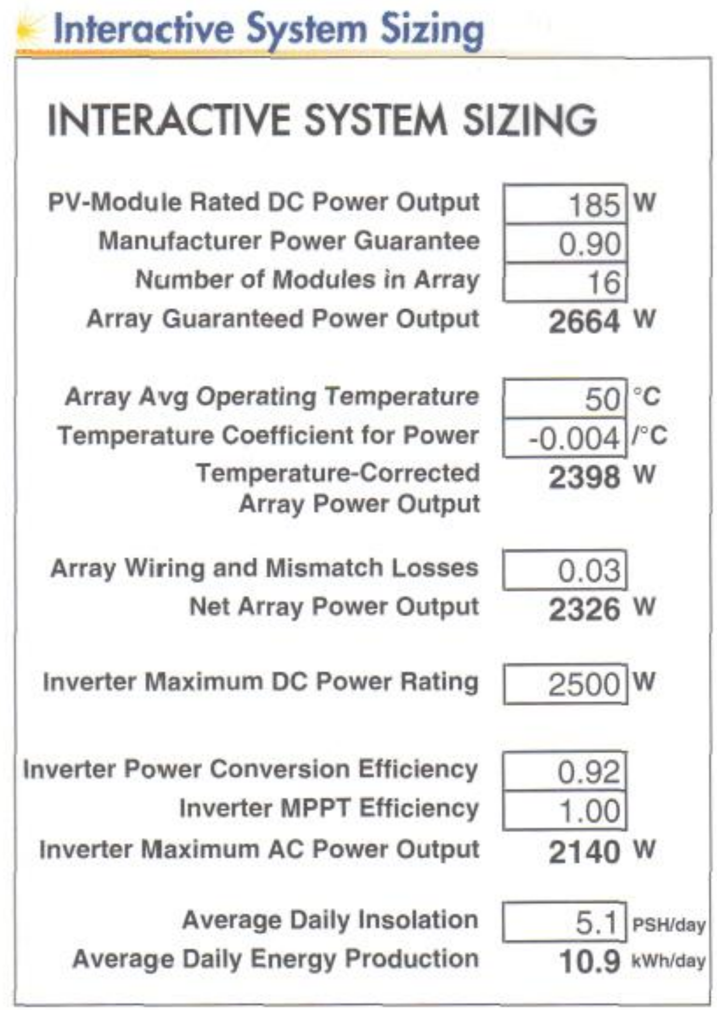
FIGURE 6.1 Simplified grid-connected PV system with net metering.

System Sizing

- A grid connected system is built with the following details:
- Module Wp=185 W,
- Total used 16 modules, 80% power guarantee after 20 years,
- Average operating Temp 50 deg, Temp derating for power =-0.004/C,
- Wiring and mismatch losses 3%,
- Inverter efficiency assumed 92%,
- MPPT 100%,
- PSH=5.1/day
- Determine the expected energy production per day?

System Sizing

- To determine the expected energy production per day, the final AC power output is multiplied by the insolation for the month or year.
- For example, if the calculated AC power output is 2140 W per peak sun hour and the average annual insolation is 5.1 peak sun hours (kWh/m2/day),
- Then the average energy production is expected to be 10.9 kWh/day. (2140 W x 5.1 h/day =10914 wh)
- If the final system power output is not within the desired range, such as above a minimum size requirement for an incentive program, different module and/or inverter choices can be made.
- Also, various system configurations can be compared with their associated system costs for a value-based analysis.



- **The size of an interactive system is primarily limited by the space available for an array and the owner's budget.**
- **However, financial incentive requirements, net metering limits, and existing electrical infrastructure may also influence system size decisions.**

A Grid connected PV System is to be designed using twenty 250- W modules. The array delivers power to a 5500 W inverter. The key specification parameters of the inverter and modules is given in the table below:

Inverter Specification			**PV Module Specification**	
Max. AC Power	5500 W		Rated Power Pdc	250 W
Input voltage range at MPP	250-700 V		Open circuit voltage Voc	37.38 V
Maximum Input Voltage	1000 V		Short Circuit Current Isc	8.72 A
Maximum Input Current	50 A		Voltage at MPP	30.64 V
Efficiency	97%		Current at MPP	8.16 A
Guarantee	10 years		Power guarantee after 20 years	80%

A. What are the possible arrangement/connection of modules in series /parallel?
   For example one possible arrangement is (5S,4P):
   (5S, 4P) means the system consists of four strings in parallel (P) , each consists of 5 series connected modules (S).

B. Which one of the combinations in part A are recommended? Explain why?

C. If the cost of PV system is 0.85 $/W for the panels, inverter cost 2300 $, wires and circuit breakers 500 $, one time installation cost 500 $, annual maintenance 100$/year. Assume the cost of electricity is 0.2 $/ kWh, what would be the pay-back period (years) of the system (assume life time of project 20 years and psh=6). Is the investment in this project recommended?

A. What are the possible arrangement/connection of modules in series /parallel?

For example one possible arrangement is (5S,4P):

(5S, 4P) means the system consists of four strings in parallel (P) , each consists of 5 series connected modules (S).

Module	
Pdc	250
Voc	37.38
Isc	8.72
Vmp	30.64
Imp	8.16
Pow_guar	0.8
Inverter	
Pmax	5500
Vmp	250-700
Vmax	1000
Imax	50
eff	0.97

		250-700	1000	50	50	
Ns	Np	Vmp	Vmax	Imp	Imax	ok?
20	1	612.8	747.6	8.16	8.72	√√
10	2	306.4	373.8	16.32	17.44	√
5	4	153.2	186.9	32.64	34.88	x
4	5	122.56	149.52	40.8	43.6	x
2	10	61.28	74.76	81.6	87.2	x
1	20	30.64	37.38	163.2	174.4	x

Choice (20S, 1P) or (10S, 2P) are valid choice

Total Cost				
Panels	20	250	0.85	4250
Inverter	2		2300	4600
maintainance	20		100	2000
installaion	1		500	500
wires	1		500	500

Sum = 11850 $

Production	
psh	6
Life_derating	0.9
Inv_derating	0.97
Power_rated (W)	5000
Power _derated (W)	4365
Energy_year (kW)	9559.35
Energy revenu/year ($)	1911.87
PayBack Period (year)= total cost/revenue per year	=11850/1911 =6.19812

Example 2

- Choosing The right Inverter
- Give 14 panels of 300W rating from sharp and Inverters from Fronius IG3000, IG4000 and IG5000
- Choose the right inverter and show best module connection (number of strings)

NU-AC300B

NU-AC Series

300 W Black

The Design Solution

Limit values

Maximum system voltage	1,000 VDC
Over-current protection	15 A
Temperature range	-40 to 85 °C

Electrical data (STC)

		NU-AC300B	
Maximum power	P_{max}	300	W_p
Open-circuit voltage	V_{oc}	40.03	V
Short-circuit current	I_{sc}	9.71	A
Voltage at point of maximum power			V
Current at point of maximum power			A
Module efficiency			%

STC = Standard Test Conditions: irradiance 1,000 W/m², AM 1.5, c
Rated electrical characteristics are within ±10% of the indicated
Reduction of efficiency from an irradiance change of 1,000 W/m²

Temperature coefficient

P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

Electrical data (NMOT)

		NU-AC300B	
Maximum power	P_{max}	224.13	W_p
Open-circuit voltage	V_{oc}	37.94	V
Short-circuit current	I_{sc}	7.87	A
Voltage at point of maximum power	V_{mpp}	30.50	V
Current at point of maximum power	I_{mpp}	7.35	A

NMOT = Nominal Module Operating Temperature: 45 °C, irradiance 800 W/m², air temperature of 20 °C, wind speed of 1 m/s.

FRONIUS IG 2000 / 3000 / 2500-LV

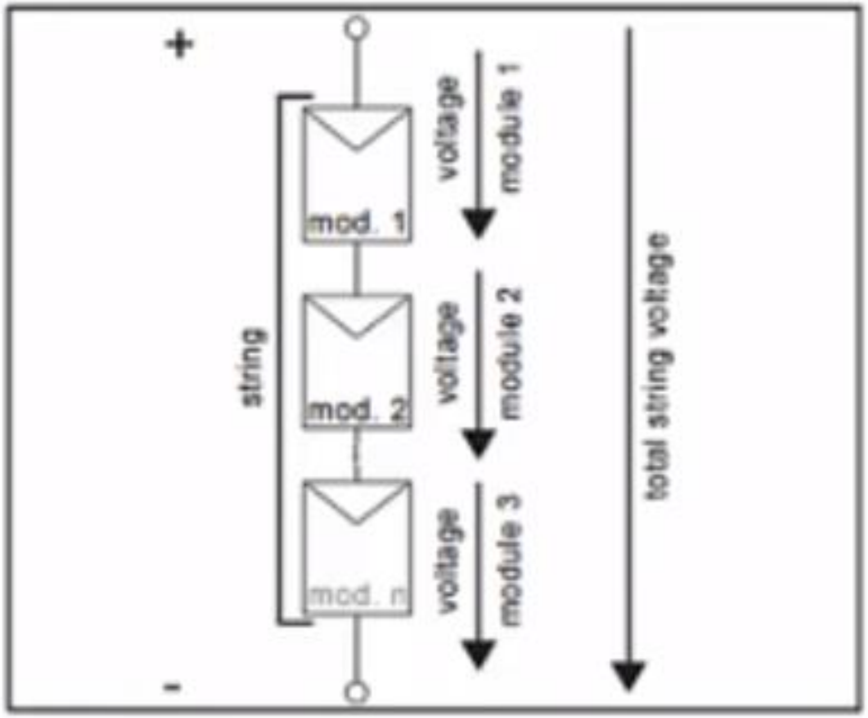
Input data	IG 2000	IG 3000	IG 2500-LV
Recommended PV power	1500-2500 Wp	2000-3300 Wp	1800-3000 Wp
MPP-voltage range		150 - 400 V	
Max. input voltage (at 1000 W/m² / 14 °F in no-load operation)		500 V	
Nominal input voltage		270 V	
Nominal input current	7.2 A	10.0 A	8.6 A
Maximum usable input current	13.6 A	18 A	16.9 A
Max. array short circuit current	25 A	25 A	25 A

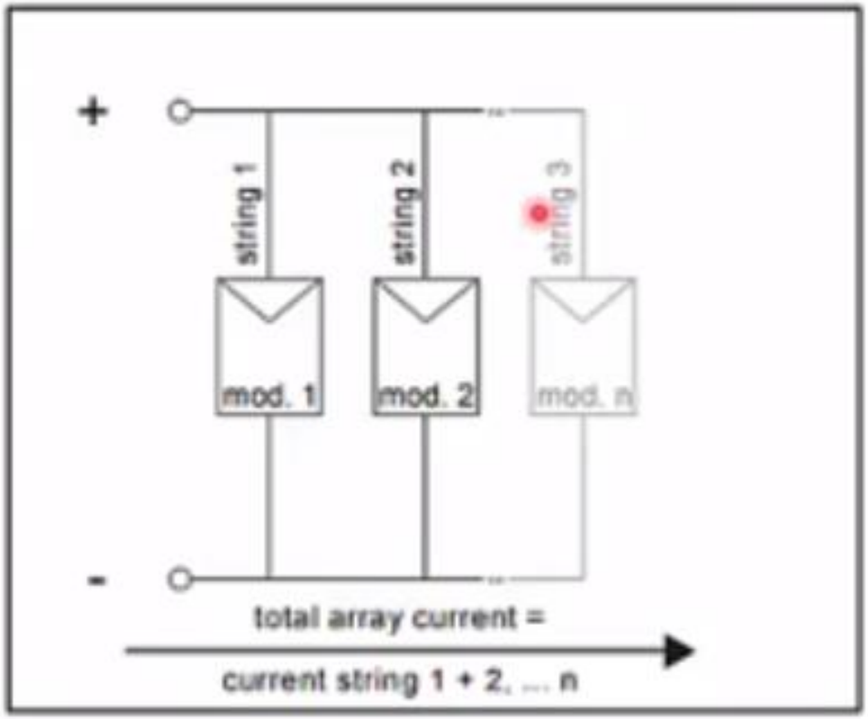
FRONIUS IG 4000 / 5100 / 4500-LV

Input data	IG 4000	IG 5100	IG 4500-LV
Recommended PV power	3000-5400 Wp	4000-6300 Wp	3600-5500 Wp
MPP-voltage range		150 - 400 V	
Max. input voltage (at 1000 W/m² / 14 °F in no-load operation)		500 V	
Nominal input voltage		270 V	
Nominal input current	16.3 A	20.8 A	18.3 A
Maximum usable input current	26.1 A	33.2 A	29.3 A
Maximum array short circuit	40 A	40 A	40

General data	IG 2000	IG 3000	IG 2500-LV
Maximum efficiency	95.2 %	95.2 %	94.4 %
Consumption in standby (night)		< 0.15 W	
Consumption during operation		7 W	
Cooling		controlled forced ventilation	
Protection type		NEMA 3R	
Size l x w x h		18.5 x 16.33 x 8.71 in. (470 x 418 x 223 mm)	
Weight		26 lb. / 11.8 kg	
Admissible ambient temperature		-4 to +122 °F (-20 to 50 °C)	

General data	IG 4000	IG 5100	IG 4500-LV
Maximum efficiency	95.2 %	95.2 %	94.4 %
Consumption in standby (night)		< 0.15 W	
Consumption during operation		15 W	
Cooling		controlled forced ventilation	
Protection type		NEMA 3R	
Size l x w x h		28.34 x 16.46 x 8.78 in. (720 x 418 x 223 mm)	
Weight		41.8 lb. / 19 kg	
Admissible ambient temperature		-4 to +122 °F (-20 to 50 °C)	


+
-
mod. 1
mod. 2
mod. n
string
voltage module 1
voltage module 2
voltage module 3
total string voltage


+
-
string 1
string 2
string 3
mod. 1
mod. 2
mod. n
total array current =
current string 1 + 2, ... n

Calculation For an array of 14 modules

1. Power of one string =14 modules

   Pdc_array=14*300*0.95*0.95

   = 3790 W

2. Voltage of Array

   Vsystem= 14*Vmpp

   = 14*32.68

   =457.5 V

3. Current of Array

   Isystem= 1*Isc

   = 1*9.71

   =9.71 A

4. First Guess of Inverter: (14S, 1P)

One String:

Pmax	**3790 W**
I max	**9.71 A**
Vmpp	**457.5**
V(oc_string)	**560.4**

Inverter Type	Pmax		Max usable DC input current (A)		Max DC input voltage (V)		MPP voltage (V)	
IG 3000	2500-3300	3790 W	18	9.71 A	500	560.4	150-400	457.5
IG 4000	3000-5400	3790 W	26.1	9.71 A	500	560.4	150-400	457.5
IG 5000	4000-6300	3790 W	33.2	9.71 A	500	560.4	150-400	457.5

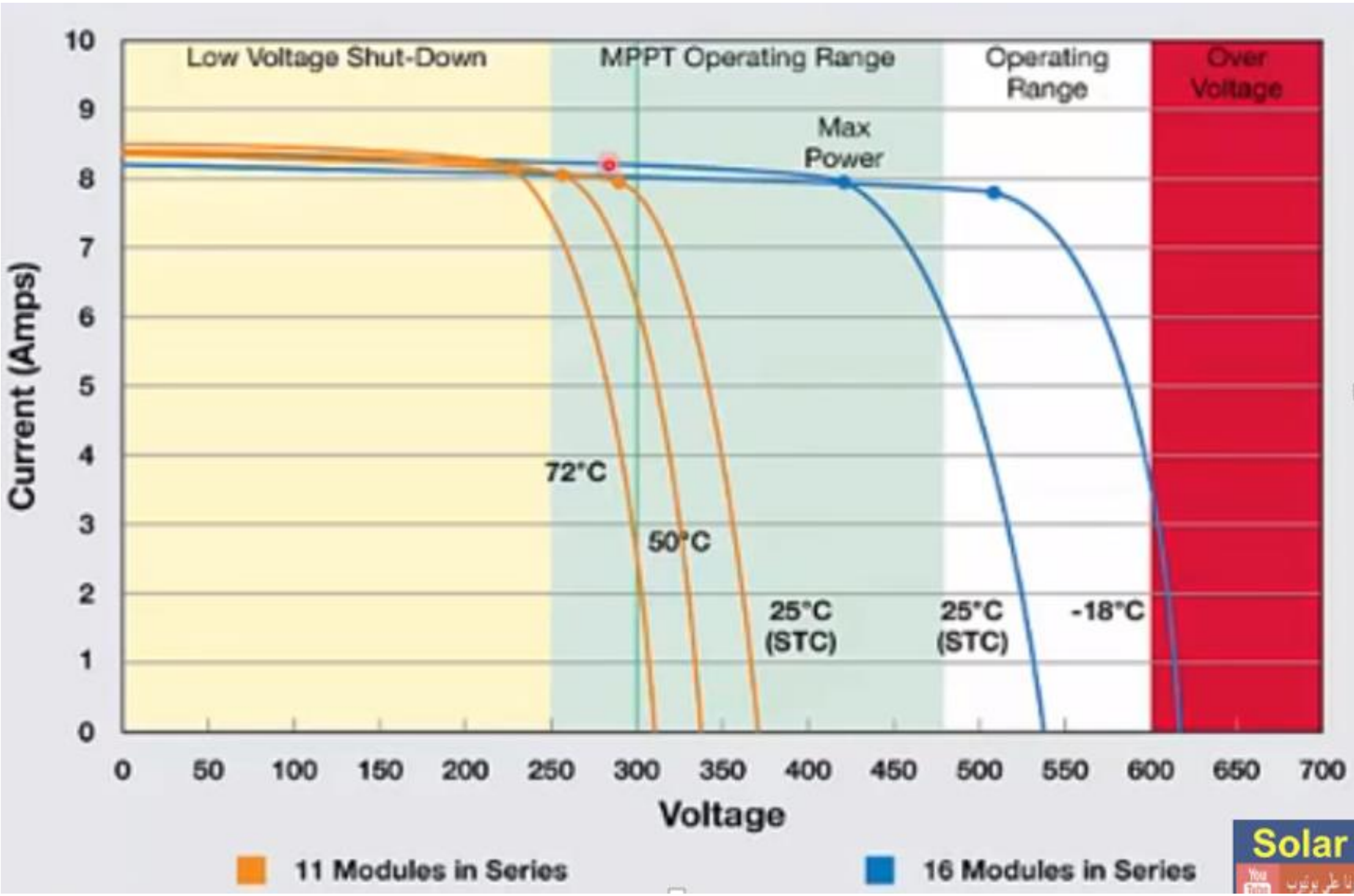
For Two Strings: 7//7 (or 7S, 2P)

Pmax	3790 W
I max	19.42 A
Vmpp	213.8
V(oc_string)	280.2

Inverter Type	Pmax		Max usable DC input current (A)		Max DC input voltage (V)		MPP voltage (V)	
IG 3000	2500-3300	3790 W	18	19.42	500	280.2	150-400	213.8
IG 4000	3000-5400	3790 W	26.1	19.42	500	280.2	150-400	213.8
IG 5000	4000-6300	3790 W	33.2	19.42	500	280.2	150-400	213.8

Choice : IG 4000

Coldest Day Calculation



5. Coldest Day Calculation: assume -10 deg C

Temperature coefficient	
P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

- Temperature Difference ΔT:

ΔT = -10-25= -35 degrees

Temperature Coeff for voltage =-0.273%/C

Voltage % Rise = ΔT* Temperature Coeff

=-35 C* -0.273%/C=9.55%

Vmax(oc)= **280.2 (1+0.0955)=307V √**

For one string =614 V X

5. Hottest Day Calculation: assume +50 deg C

Temperature coefficient	
P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

- Temperature Difference ΔT:

ΔT = 50-25= 25 degrees

Temperature Coeff for voltage =-0.273%/C

Voltage % Rise = ΔT* Temperature Coeff

=25 C* -0.273%/C=-6.83%

Vmin(oc)= **280.2 (1-0.0683)= 261 √** **(one string =522 V X)**

Isc(max)=19.42(1+25*0.00037)=19.42*1.00925=19.6 A √

Conclusions

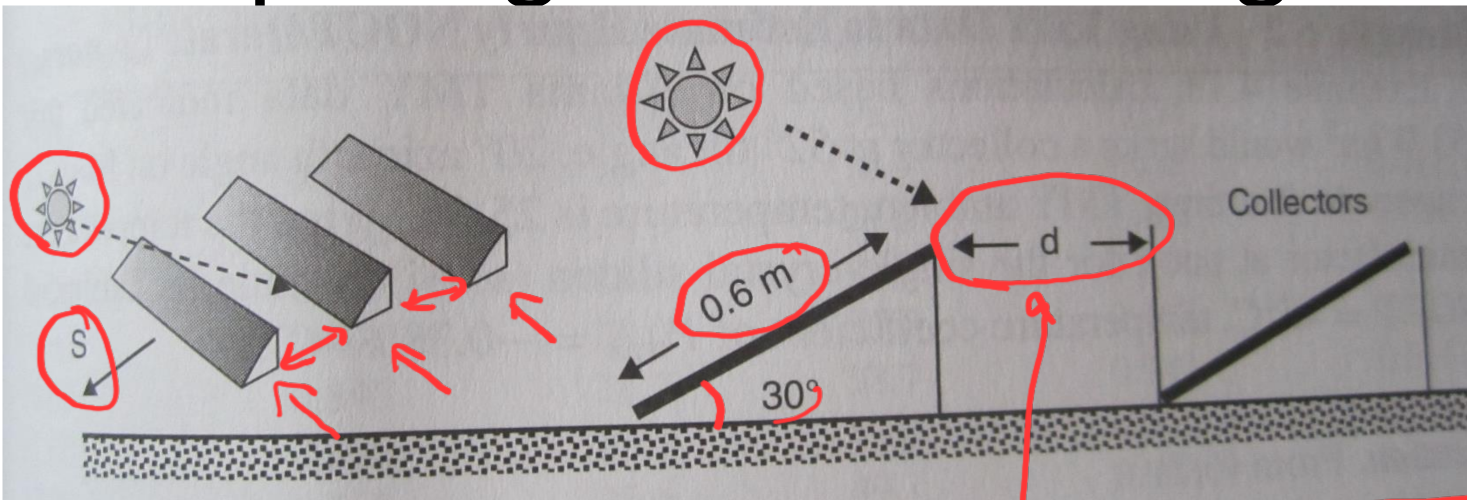
- One String choice is not possible (14S, 1P)
- Two string choice is better (7S,2P)
- Inverter IG 4000 is the best choice, note that

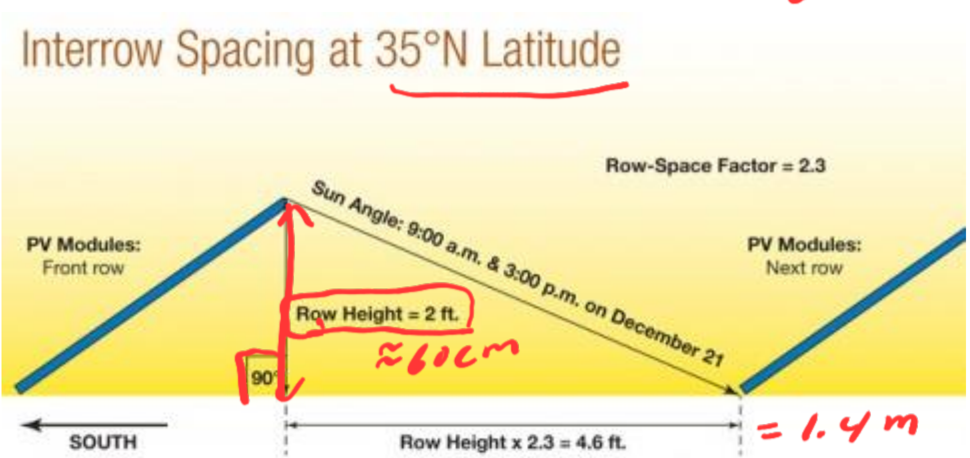
IG 4000	**3000-5400**	**3790 W**	**26.1**	**19.42**	**500**	**280.2**	**150-400**	**213.8**

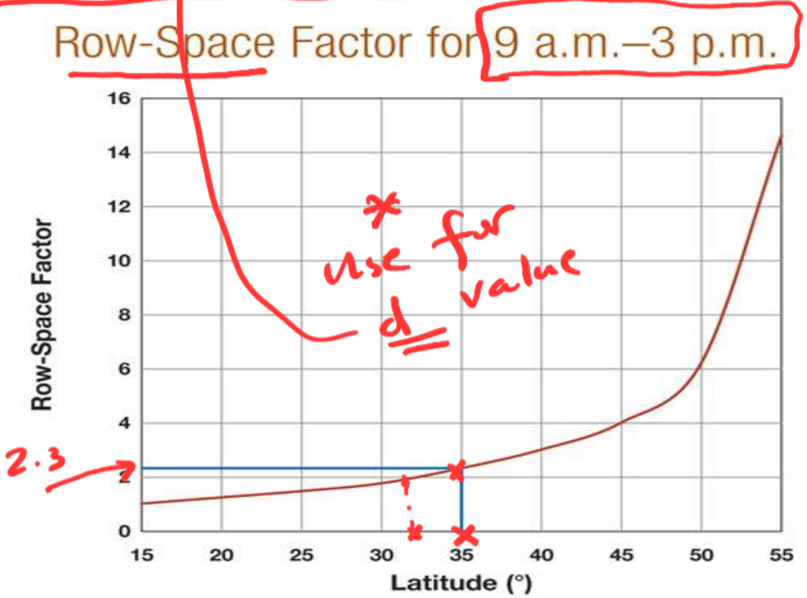
- Must pay attention to the voltage which might be reduced due to shading or aging of PV modules
- Other possibilities like (2S,7P) cannot be used since voltage will not be enough

End of L15
27/4/2021

Spacing due to shading







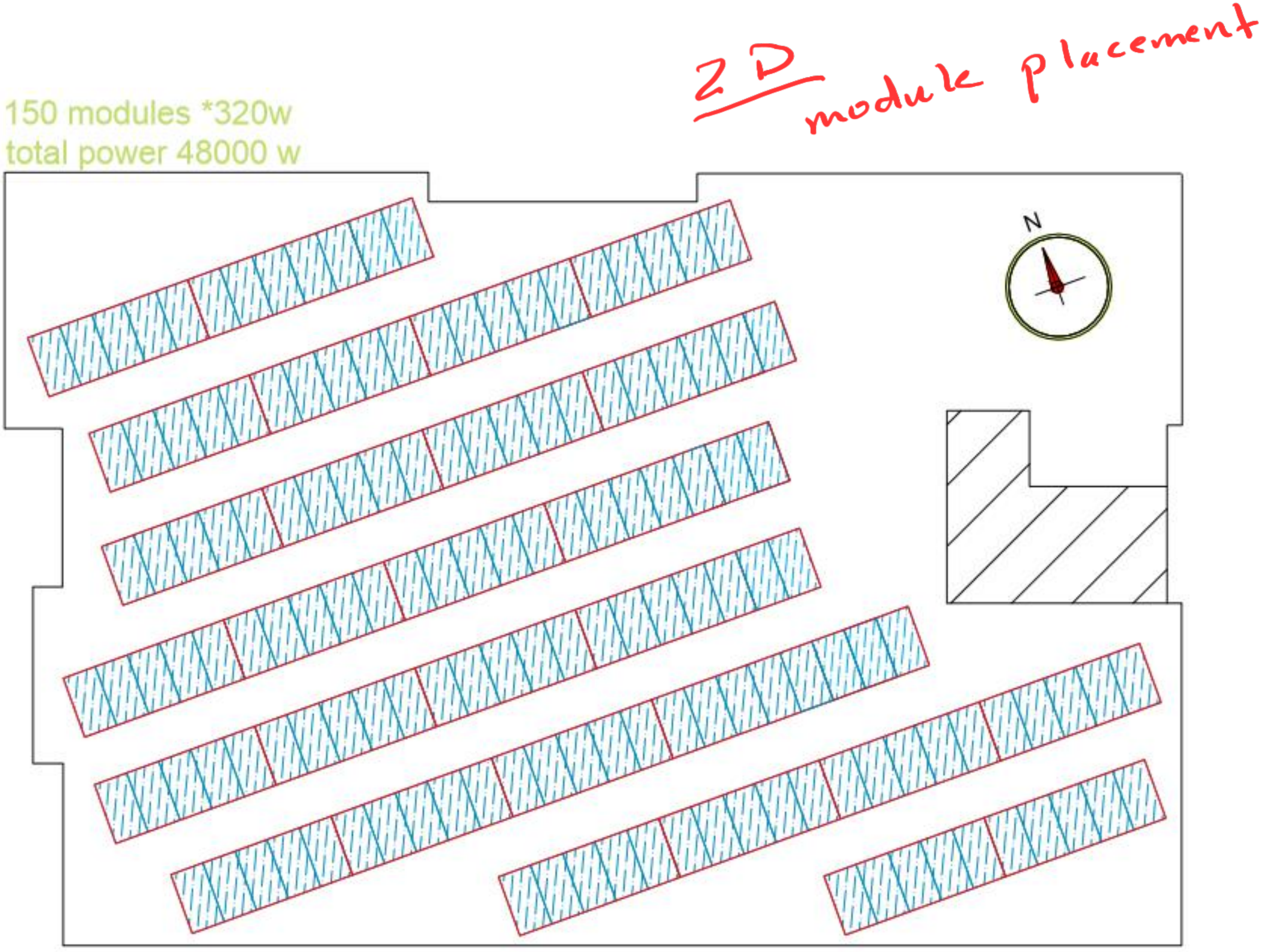
Multiply the row-space factor by the module height to get the necessary distance between rows of modules.

- https://www.youtube.com/watch?v=5DpXIfz38R4

Example PV System Design- مبنى مصنع الادوية في جامعة بير زيت

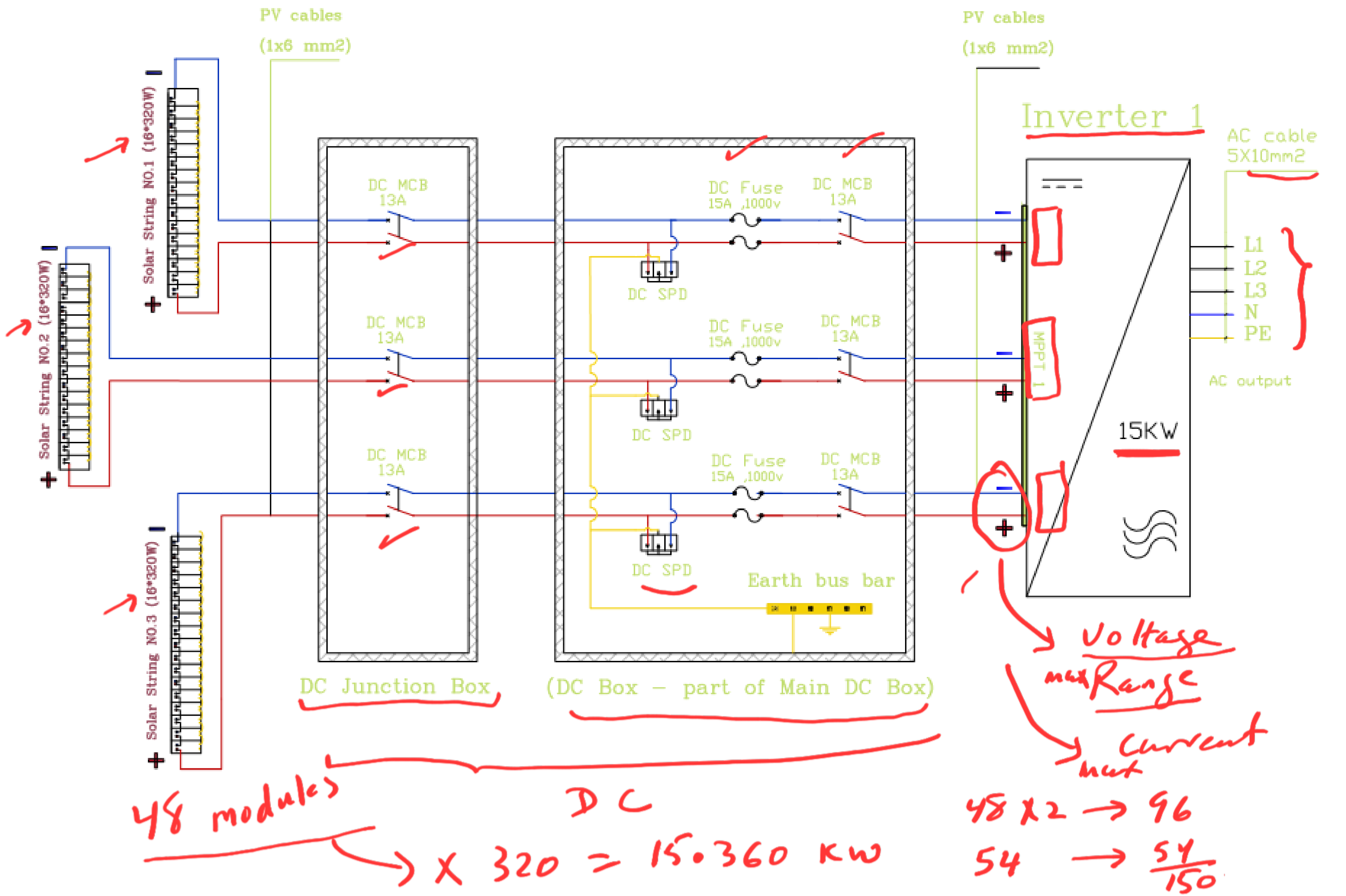
Meteorological Information	
Daily horizontal irradiation	5.66kWh/m2/day
Ambient Air Temperature (Min)	0 C
Ambient Air Temperature (Max)	42 C
Orientation	
Place of Installation	BirZeit-Palestine
Total Area	700 m2
Orientation	South
Fixed system	inclination=22 deg
Module-Inverter Details	
Module Type	Polycrystalline
Module capacity	320Wp
Module Efficiency	16.49 %
Total Installed Module capacity	48 kWp
Number of modules	150
Inverters Capacity	48-kW
Inverter Efficiency	98%
Number of inverters	3
Grid connection	
JEDCO	Net metering

Table 1: Summary of the basic design parameters for the 48-KW grid-connected solar PV system



2D module placement
150 modules *320w
total power 48000 w
N

3D module placement


PV cables
(1x6 mm2)
Solar String NO.1 (16*320W)
Solar String NO.2 (16*320W)
Solar String NO.3 (16*320W)
DC MCB
13A
DC Fuse
15A ,1000v
DC SPD
Earth bus bar
DC Junction Box
(DC Box - part of Main DC Box)
Inverter 1
MPPT 1
15KW
AC cable
5X10mm2
L1
L2
L3
N
PE
AC output
Voltage
max Range
max current
48 modules
DC
X 320 = 15.360 KW
48 X 2 → 96
54 → 54/150

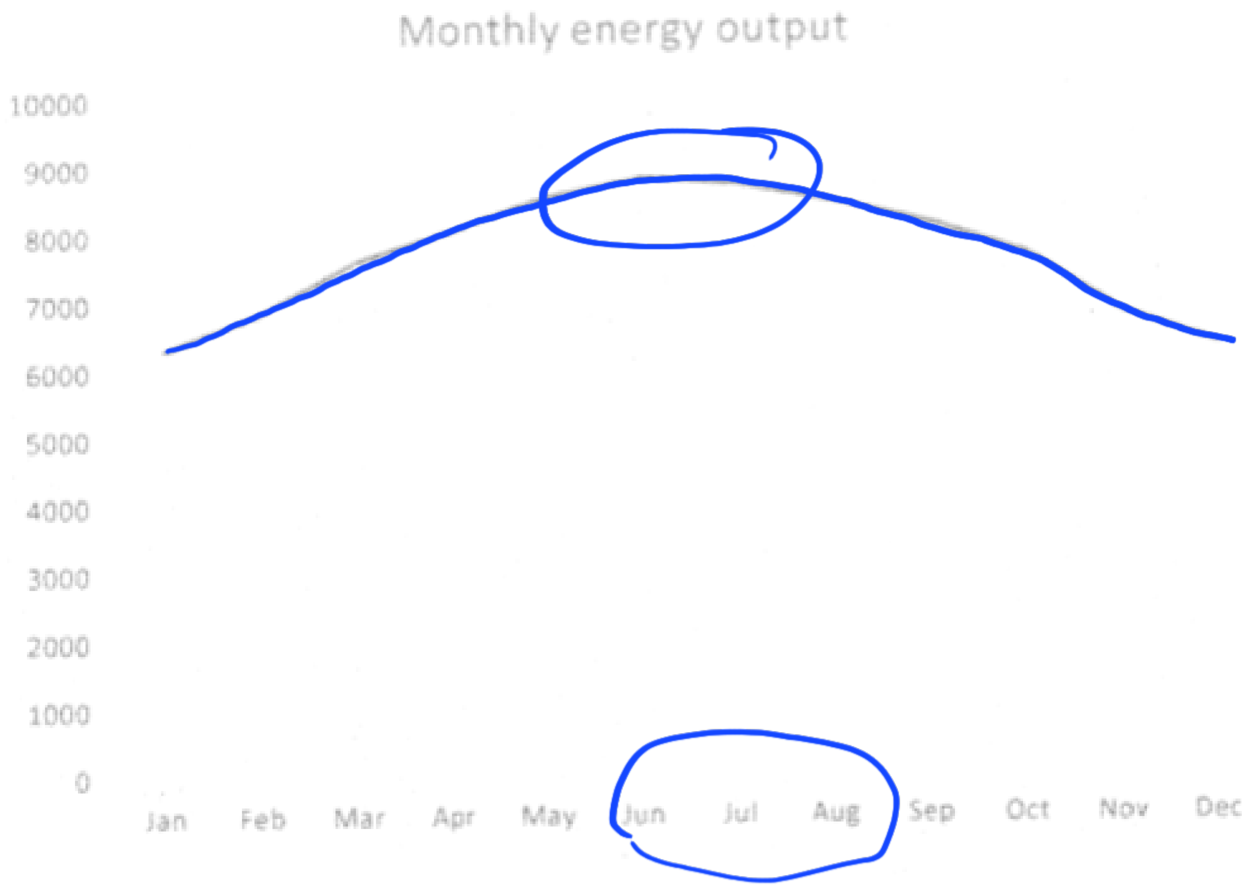
- Estimated losses due to temperature and low irradiance: 10.9% (using local ambient temperature)
- Estimated loss due to angular reflectance effects: 2.1%
- Other losses (cables, inverter etc.): 9.0%
- Combined PV system losses: 22%

Month	Ed	Em	Hd	Hm
Jan	143.0	4433.6	3.8	118.4
Feb	168.1	4707.0	4.3	125.7
Mar	220.9	6847.8	5.9	182.9
Apr	243.0	7289.6	6.5	194.7
May	273.3	8472.7	7.3	226.3
Jun	290.9	8727.3	7.8	233.1
Jul	288.3	8936.9	7.7	238.7
Aug	281.2	8716.4	7.5	232.8
Sep	260.2	7806.2	7.0	208.5
Oct	222.8	6905.8	6.0	184.5
Nov	178.6	5357.7	4.8	143.1
Dec	147.5	4572.9	3.9	122.1
Average	226.5	6897.8	6.05	184.2
Total for Year		82773.85	KWh	

Best summer yeild

psh
6.05 kwh/day

- Ed: Average daily electricity production from the given system (kWh).
- Em: Average monthly electricity production from the given system (kWh).
- Hd: Average daily sum of global irradiation per square meter received by the modules of the given System (kWh/m2).
- Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)



Monthly energy output from fixed-angle PV system

The economic analysis of the 48-KW grid-connected solar PV system was carried out to assess the cost and intended benefits of the project. Simulating the net present value and simple payback period as well as estimating the greenhouse gas saving potential of renewable energy projects over their entire operational life. The NPV and simple payback period will help determine how feasible the project will be. The total investment cost comprises the following components; module, inverter, cables, mounting structures, engineering and project management, labor and miscellaneous costs. The PV modules and inverter cost alone makes up about 60% of the total investment cost. The total investment cost for the 48-KW project is estimated at US$ 61733(1286.5 US$/1KW).

Solar PV system energy production	82773KW/year
Solar PV system cost	61733 US $
Operating and Maintenance Cost	0.02 US $/KW/Day
Total for Maintenance Cost	1752 US $/ 5Year
Project Life	25 year
KW Price (Tariff)	0.180 US$/KW
Total cost for energy production	14899 US $/Year
Payback period (Maximum)	4.14 Years

Economic Analysis Table

Analyses of the simulation results show that, the project when implemented will supply about 82773 kw/year electricity annually, which is about ...% of BirZeit annual electricity consumption.

The project also stands the chance of saving about 32398 tons of CO_2 which would have been emitted by a crude oil fired thermal power plant generating the same amount of electricity. Therefore, the other non-financial benefits like the greenhouse gas emissions savings can, in the long run, help mitigate the adverse effects of the climate change problem plaguing the entire earth.

تأجيل Project-part 1 ← لاسبوع من التاريخ السابق

Project part2-Design task1

- Design a grid-connected system with maximum possible Capacity. to be used on top of a building located in Jerico and oriented south with available space area (40 mX40 m) –see sketch
- Calculate the usable area taking into account no shading from 9am-3 pm. Consider the proper orientation and tilt of the panels for maximum summer months energy yield (June, July and August) (provide a sketch for the placement)
- Use modules rated at 350 Wp or more, assume cost is 0.3$/Watt (make sure modules are available in Pvsyst and do not forget to check the guaranteed power and life time of the modules.

Project part2-Design task1

- **Available inverters-guaranteed for 10 years (https://www.europe-solarstore.com/solar-inverters/sma/sunny-tripower.html)**

Technical data	Sunny Tripower 3.0	Sunny Tripower 4.0	Sunny Tripower 5.0	Sunny Tripower 6.0
Input (DC)				
Max. PV array power	6000 Wp	8000 Wp	9000 Wp	9000 Wp
Max. input voltage	850 V	850 V	850 V	850 V
MPP voltage range	140 V to 800 V	175 V to 800 V	215 V to 800 V	260 V to 800 V
Rated input voltage	580 V			
Min. input voltage / initial input voltage	125 V / 150 V			
Max. input current input A / input B	12 A / 12 A			
Max. DC short-circuit current input A/input B	18 A / 18 A			
Number of independent MPP inputs / strings per MPP input	2/A: 1; B: 1			
Output (AC)				
Rated power (at 230 V, 50 Hz)	3000 W	4000 W	5000 W	6000 W
Max. apparent power AC	3000 VA	4000 VA	5000 VA	6000 VA
Nominal AC voltage	3/N/PE; 220 V / 380 V 3/N/PE; 230 V / 400 V 3/N/PE; 240 V / 415 V			
AC voltage range	180 V to 280 V			
AC grid frequency / range	50 Hz / 45 Hz to 55 Hz 60 Hz / 55 Hz to 65 Hz			
Rated grid frequency / rated grid voltage	50 Hz / 230 V			
Max. output current	3 x 4.5 A	3 x 5.8 A	3 x 7.6 A	3 x 9.1 A
Power factor at rated power / Displacement power factor, adjustable	1 / 0.8 overexcited to 0.8 underexcited			
Feed-in phases / connection phases	3 / 3			
Efficiency				
Max. efficiency / European efficiency	98.2% / 96.5%	98.2% / 97.1%	98.2% / 97.4%	98.2% / 97.6%

do not use

Use these inverters

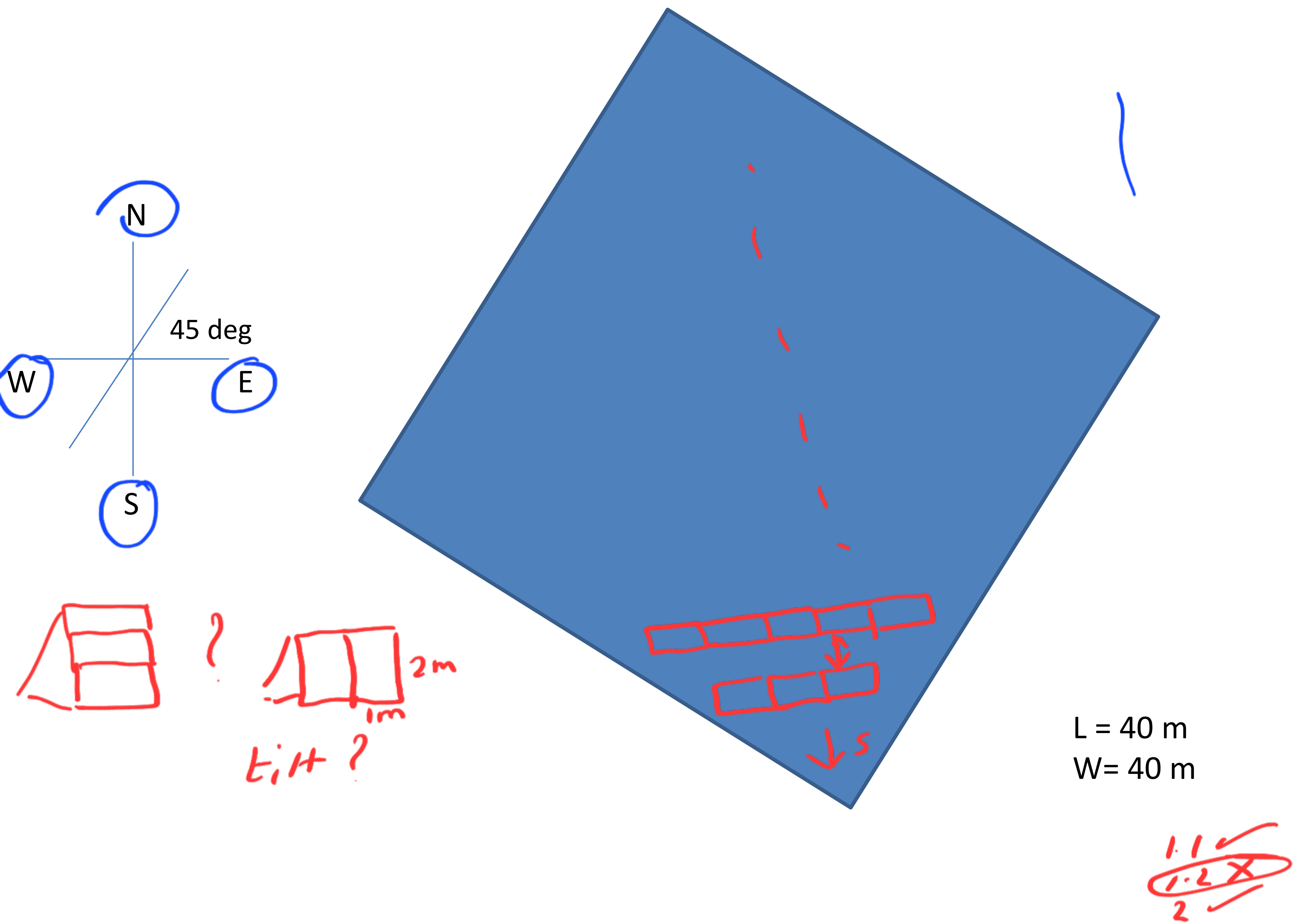
Technical Data	Sunny Tripower 15000TL	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)			
Max. DC power (at cos φ = 1) / DC rated power	15330 W / 15330 W	20440 W / 20440 W	25550 W / 25550 W
Max. input voltage	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	240 V to 800 V / 600 V	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A	33 A / 33 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3	2 / A:3; B:3
Output (AC)			
Rated power (at 230 V, 50 Hz)	15000 W	20000 W	25000 W **
Max. AC apparent power	15000 VA	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	
AC voltage range	180 V to 280 V	180 V to 280 V	
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	
Rated power frequency / rated grid voltage	50 Hz / 230 V	50 Hz / 230 V	
Max. output current / Rated output current	29 A / 21.7 A	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited	1 / 0 overexcited to 0 underexcited	
THD	≤ 3%	≤ 3%	
Feed-in phases / connection phases	3 / 3	3 / 3	
Efficiency			
Max. efficiency / European Efficiency	98.4% / 98.0%	98.4% / 98.0%	98.3% / 98.1%

Take the prices of inverters and any other information related to the inverters from the link provided in previous page

- Balance of system (BOS) components, wiring, installation, monitoring cost (0.2 $ per watt dc)
- Calculate the payback period of the system if the Utility would buy the electricity at 0.16$/kWh
- After you finish the design, verify it using PVSYST
- Sketch the placement of the panels and the connection diagram of the panels (Sketches must be done using any software tool or online applications)
- ~~Extra~~ task : 1.2

Assume we want to provide storage for 2 days autonomy of 10% of the project capacity, calculate Battery bank. Assume ambient temperature extremes are -5 to + 45 degrees .

task to be done after finishing Battery topic


N
45 deg
W
E
S
2m
1m
tilt ?
S
L = 40 m
W= 40 m
1.1
1.2 X
2

Project part2-Design task2

- You are employed as a PV design Engineer and your company wants to invest in the PV power generation sector by implementing a 2 Mega Watt DC project. The project will be connected to local electricity grid.

1. Assume the location will be in any rural area in Palestine with cost of Land 10 thousand Jordanian Dinars per donum . سعر الدونم الواحد)
2. Provide a complete design proposal for the project, it is better to have more than one option to propose to your company's CEO. Of course you need to provide cost of project and payback period.
3. You must show number and ratings of panels, inverters and all system components. (provide specs for the used components)

Project part2-Design task2

4. Use Pvsyst to help in your design and to show different alternatives. (generate reports from PVSYST)

5. Consider placement of the PV panels with shading free from 9am to 3 pm and calculate total land area needed.

6. You can divide your system into arrays and make it a modular system, then provide a sketch (2D and 3D) for at least one array.

Project Rules and deadlines:

-Groups consist of 4 students

-Must provide a report, a power point presentation showing summary of **work and record a 5-10 minute video with all group members participating in the video**

-Each group should provide details of who did what in the project?

Deadlines: 31-5-2021

L11-part 2

to be covered after Batteries

PV System Sizing and Design (Standalone Systems)

Batteries

Sizing Standalone Systems

- Stand-alone PV systems are designed to power **specific on-site loads**, so the size of these systems is directly **proportional to the load** requirements.
- If the system is too small, there will be losses in load availability and system reliability.
- If the system is too large, excess energy will be unutilized and wasted.
- Therefore, sizing of stand-alone systems requires a fine balance between energy supply and demand.
- Because of this necessary balance, sizing stand-alone systems requires more analysis and calculations than are required for interactive systems.
- Most of these calculations build upon one another as the analyses proceed.
- Moreover, sizing stand-alone systems is an iterative process.
- That is, if the final calculations indicate that the components are improperly sized, the starting values must be changed and the calculation process repeated until the system output matches the load requirements

Sizing Standalone Systems

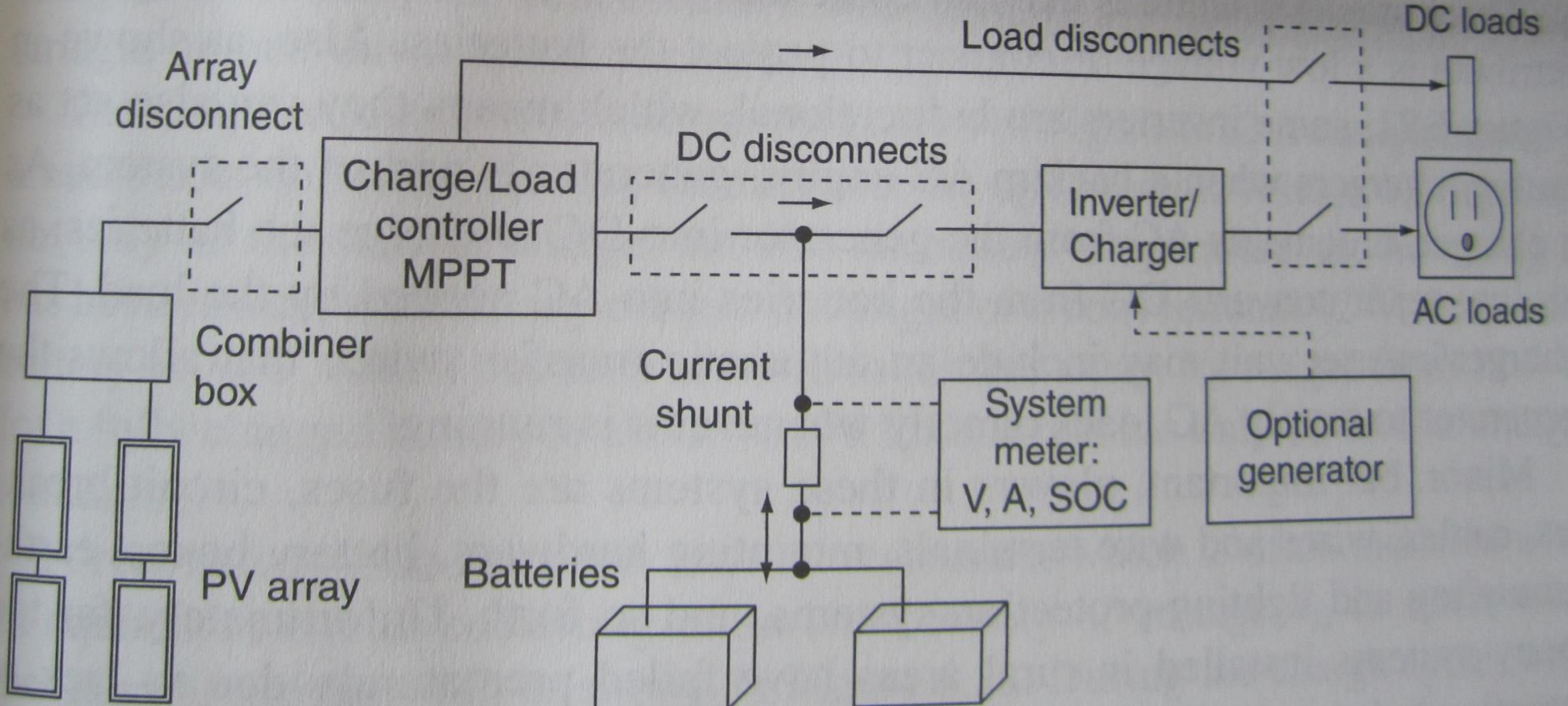


FIGURE 6.21 A "one-line" diagram of the important components in a stand-alone PV system.

Sizing Calculations –Standalone system

- Sizing PV systems for stand-alone operation involves four sets of calculations.

➔ **First, a load analysis** determines the electrical load requirements.

➔ Then, **monthly load requirements** are compared to the local insolation data to determine the critical design month.

➔ Next, the battery bank is sized to be able to independently supply the loads for a certain length of time, such as if cloudy weather educes array output.

➔ Finally, the PV array is sized to fully charge the battery bank under the critical conditions

Load Analysis

- Analyzing the electrical loads is the first and most important step in PV-system sizing.
- The energy consumption dictates the amount of electricity that must be produced.
- All existing and potential future loads must be considered. Underestimating loads will result in a system that is too small and cannot operate the loads with the desired reliability.
- However, overestimating the load will result in a system that is larger and more expensive than necessary.
- Comprehensive yet conservative load estimates will ensure that the system is adequately sized.

Load Analysis

- A load analysis tabulates the various kinds of loads and their power and electrical-energy requirements.

Load Analysis

LOAD ANALYSIS

Month:

AC LOADS

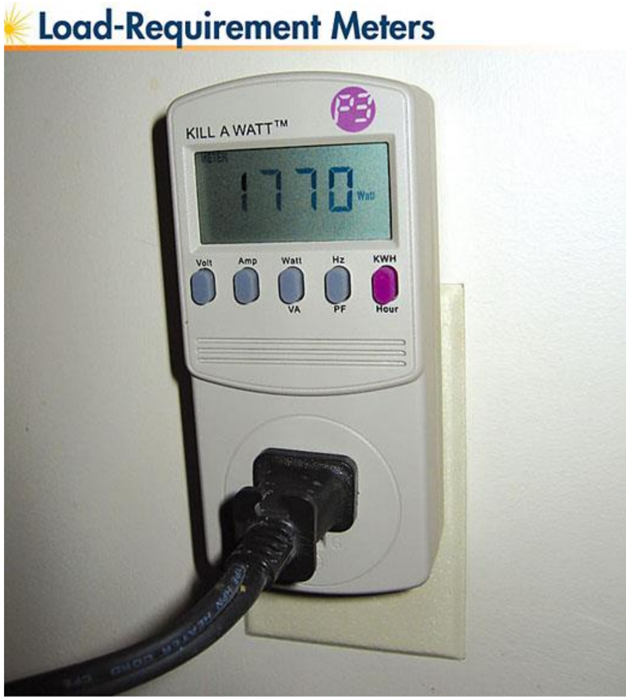
Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)

DC LOADS

Total AC Power		W
Total DC Power		W
Total Daily AC Energy Consumption		Wh/day
Total Daily DC Energy Consumption		Wh/day
Weighted Operating Time		hr/day
Inverter Efficiency		
Average Daily DC Energy Consumption		Wh/day

Power Demand

- Peak-power information is usually found on appliance nameplates or in manufacturer's literature.
- When this information is not available, peak power demand can be estimated by multiplying the maximum current by the operating voltage, though this is less accurate for reactive loads.
- Measurements, meter readings, or electric bills may also be used to help establish existing load requirements.

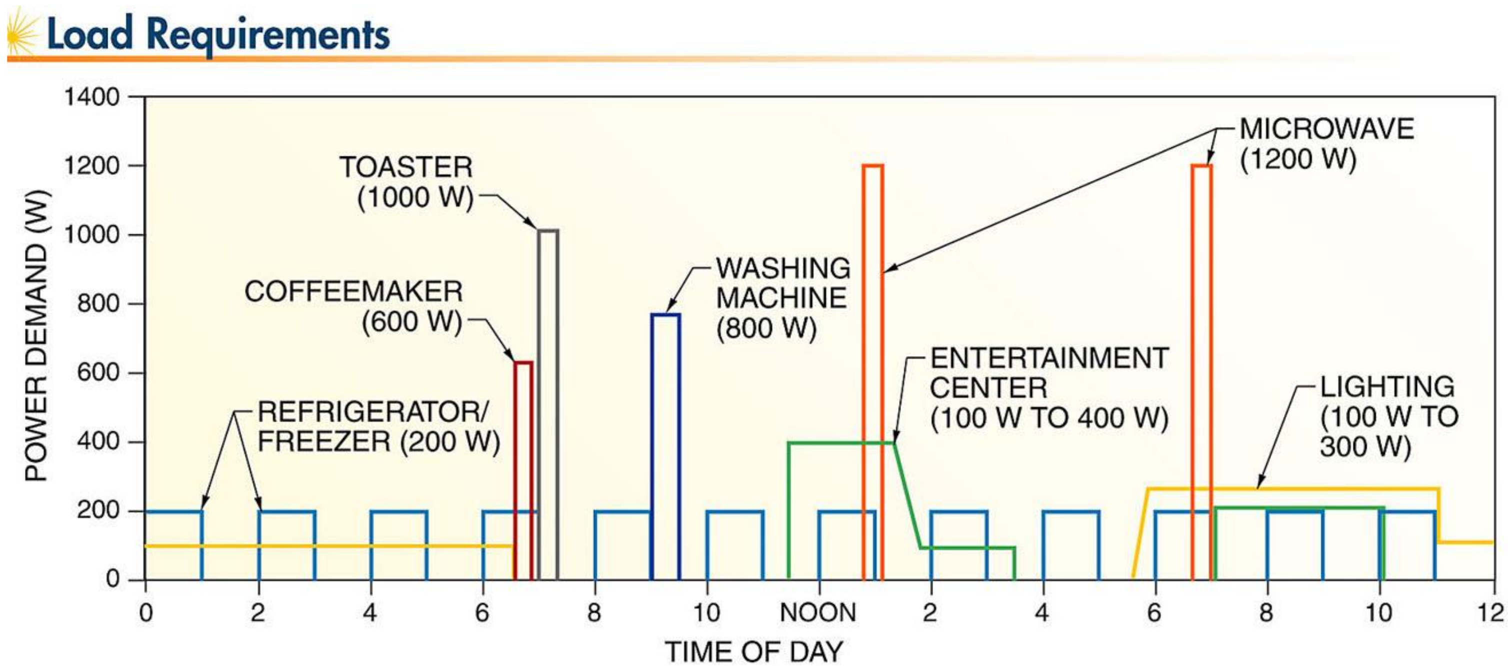


Power Demand & Energy Consumption

- The peak power demands are then summed.
- **The total power demand is considered when determining the required inverter AC-power output rating.**
- **While it is not likely that every load would be ON at the same time, it is recommended to size the inverter with extra capacity.**
- Electrical energy consumption is based on the power demand over time.
- **Loads rarely operate continuously, so each load's operating time must be determined. This is the total number of hours per day that the load is operating.**

Power Demand & Energy Consumption

- Load requirements include the power demand and electrical-energy consumption for all the expected loads in the system



Operating time

- The battery-bank discharge rate will change as various loads turn ON and OFF during the day.
- In this case, a weighted average operating time (t_{op}) is calculated using the following formula:

$$t_{op} = \frac{(E_1 \times t_1) + (E_2 \times t_2) + \ldots + (E_n \times t_n)}{E_1 + E_2 + \ldots + E_n}$$

- E_1 = DC energy required for load 1 (in Wh/day)
- t_1 = operating time for load 1 (in hr/day)

Operating Time

- **For example, one DC load uses 2400 Wh/day and operates for 4 hr and another DC load uses 1000 Wh/day and operates for 7 hr.**
- What is the weighted average operating time?

$$t_{op} = \frac{(E_1.t_1) + (E_1.t_1)}{E_1 + E_2}$$

$$t_{op} = \frac{(2400x4) + (1000x7)}{2400 + 1000}$$

$$t_{op} = 4.9hr / day$$

- The two loads have a combined effect of a single 694 W load operating for 4.9 hr/day [(2400 Wh + 1000 Wh) / 4.9 hr = 694 W].
- **If the system includes both AC and DC loads, the AC load energy requirement must be first be converted to equivalent DC energy. This is done by dividing each AC energy consumption amount by the inverter efficiency.**

Inverter Selection

- If the system includes AC loads, an inverter must be selected.
- Several factors must be considered when selecting the inverter.
- **First, the inverter must have a maximum continuous power output rating at least as great as the largest single AC load.**
- A slightly oversized inverter is usually recommended to account for potential future load additions.
- **The inverter must also be able to supply surge currents to motor loads, such as pumps or compressors, while powering other system loads.**

Example

$$E_{SDC} = \frac{E_{AC}}{\eta_{inv}} + E_{DC}$$

where

E_{SDC} = required daily system DC electrical energy (in Wh/day)

E_{AC} = AC energy consumed by loads (in Wh/day)

η_{inv} = inverter efficiency

E_{DC} = DC energy consumed by loads (in Wh/day)

For example, if a load analysis determines that a system requires 800 Wh/day for the AC loads and 200 Wh/day for the DC loads and the inverter efficiency is 90%, what is the daily DC electrical energy required by the system?

$$E_{SDC} = \frac{E_{AC}}{\eta_{inv}} + E_{DC}$$

$$E_{SDC} = \frac{800}{0.90} + 200$$

$$E_{SDC} = 889 + 200$$

$$E_{SDC} = \mathbf{1089\ Wh/day}$$

Critical Design Analysis

- A stand-alone system must produce enough electricity to meet load requirements during any month.
- **Therefore, systems are sized for the worst-case scenario of high load and low insolation.**
- A critical design analysis compares these two factors throughout a year, and the data for the worst case is used to size the array.
- **The *critical design ratio* is the ratio of electrical energy demand to average insolation during a period.**
- The load data comes from the load analysis, which is usually performed for each month.
- The insolation data is available from the solar radiation data sets. (or can be estimated for any given location based on previous lectures).
- The ratio is calculated for each month.

Critical Design Month

- **The *critical design month* is the month with the highest critical design ratio.**
- This is the worst-case scenario, and the associated load and insolation data are used to size the rest of the system.
- If the loads are constant over the entire year, the critical design month is the **month with the lowest insolation** on the array surface.
- For most locations in the Northern Hemisphere, this is a winter month, either December or January.
- However, when the load requirements vary from month to month, the critical design month must take into account both the loads and the available insolation.
- Because of these two factors, the critical design month may turn out to be any month of the year.

Critical Design Month

- Sizing for the critical design month typically results in excess energy at other times of the year.
- If this excess is significant, the system designer may want to consider adding diversion loads or changing to a different system configuration, such as a hybrid system, that better matches the available electrical energy to the loads.

Array Orientation

- Since array orientation has a significant effect on receivable solar radiation, array orientation must also be accounted for in a critical design analysis.
- If the mounting surface restricts the array to only one possible orientation, then the analysis is conducted to determine the critical design factors for that orientation.
- However, if multiple orientations are possible, separate analyses are performed for each orientation. A critical design month can be identified for each of the array orientations, since the receivable solar radiation will be different for each.
- Of the resulting critical design months, the one with the smallest design ratio is the best choice.

Array Sizing

- The orientations most commonly used in a critical design analysis are tilt angles equal to the latitude, latitude +15°, and latitude-15°, each at an azimuth of due south.
- **The greater array tilt angle maximizes the received solar energy in winter months, and the smaller array tilt angle maximizes the received solar energy in summer months.**
- For azimuth angles other than due south, the insolation data must be adjusted to obtain the most accurate results.
- **Computer models are available to predict average monthly insolation for alternate orientations**.

- A critical design analysis compares the load requirements and insolation for each month to determine the critical design month.

Critical Design Analysis

CRITICAL DESIGN ANALYSIS

Month	Average Daily DC Energy Consumption (Wh/day)	Array Orientation 1		Array Orientation 2		Array Orientation 3	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							

Critical Design Month

Optimal Orientation

Average Daily DC Energy Consumption Wh/day

Insolation PSH/day

DC-System Voltage

- The DC-system voltage is established by the battery-bank voltage in battery-based systems.
- This voltage dictates the operating voltage and ratings for all other connected components, including DC loads, charge controllers, inverters, and (for battery-based systems) the array.
- DC voltage in battery-based systems is critically important.
- The DC voltage for battery- based PV systems is usually an integer multiple of 12 V, usually 12 V, 24 V, or 48 V.

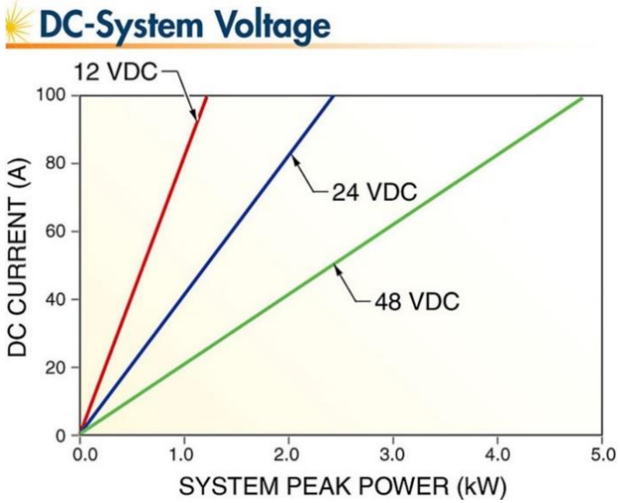
DC-System Voltage

- The selection of the battery-bank voltage affects system currents
- **For example, a 1200 W system operating at 12 V draws 100A(1200W/12 V= 100 A).**
- The same 1200 W system draws only 50 A at 24 V, or 25 A at 48 V.
- Lower current reduces the required sizes of conductors, overcurrent protection devices, disconnects, charge controllers, and other equipment.
- Also, since voltage drop and power losses are smaller at lower currents, higher-voltage systems are generally more efficient.

DC-System Voltage

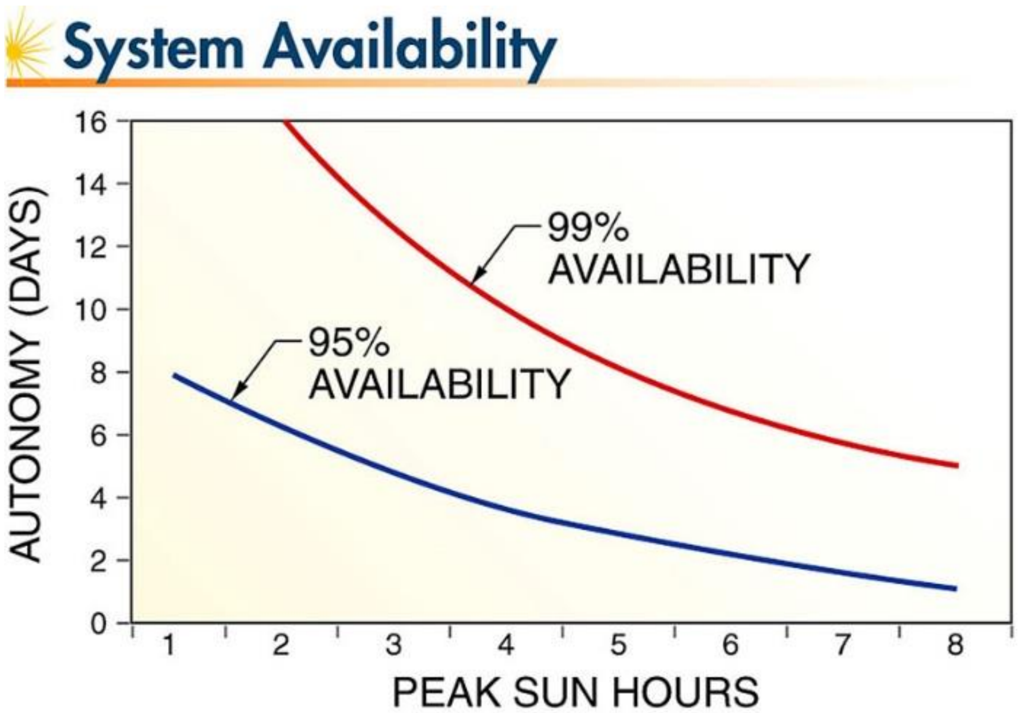
•DC-system voltage is chosen in proportion with the array size and to keep the operating current below 100 A.

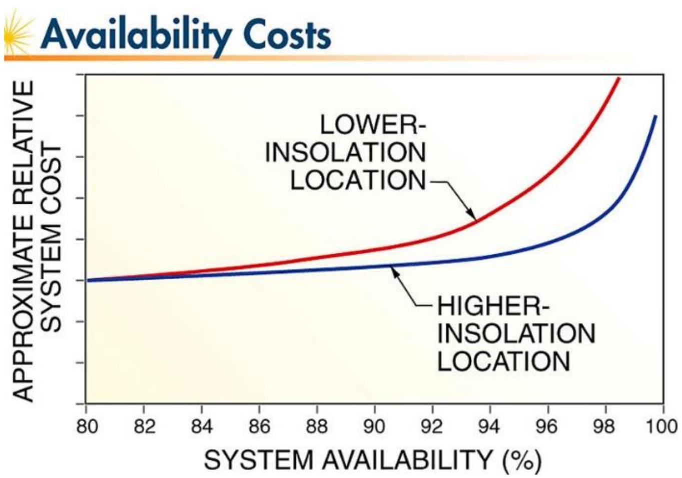
- As a rule of thumb, stand-alone systems up to 1 kW use a minimum 12V battery-bank voltage, which limits DC currents to less than 84 A.
- Similarly, battery voltages of at least 24 V are used for systems up to 2 kW,
- and at least 48 V for systems up to 5 kW.
- Very large standalone systems may use battery voltages of 120 V,
- though battery banks over 48 V involve additional code requirements and safety measures.



Availability

- **System availability is approximated from the local insolation and the autonomy period.**





- **Increasing system availability significantly increases the cost of the system.**

Battery Bank Sizing

- Batteries for stand-alone PV systems are sized to store enough energy to meet system loads for the desired length of autonomy without any further charge or energy contributions from the PV array.
- Greater autonomy requires larger and costlier battery banks, but reduces the average daily depth of discharge, which prolongs battery life.

- The required battery-bank capacity is determined from the electrical-energy requirements to operate the loads during the critical design month for the length of the autonomy period and at the desired battery-system voltage.
- Battery Capacity ***Bout*** is calculated:

$$B_{out} = \frac{E_{crit} \times t_a}{V_{SDC}}$$

- where
- B_{out} = required battery-bank output (in Ah)
- E_{crit} = daily electrical-energy consumption during critical design month (in Wh/day)
- t_a = autonomy (in days)
- V_{SDC} - nominal DC-system voltage (in V)

The average discharge rate

- The average discharge rate is determined from the total operating time over the period of autonomy, taking the allowable depth of discharge into account.

$$r_d = \frac{t_{op} \times t_a}{DOD_a}$$

- where
- *rd -* average discharge rate (in hr)
- *top =* weighted average operating time (in hr/day)
- *ta =* autonomy (in days)
- *DODa =* allowable depth of discharge

- The required capacity is calculated using the following formula:

$$B_{rated} = \frac{B_{out}}{DOD_a \times C_{T,rd}}$$

- where
- *Brated =* battery-bank rated capacity (in Ah)
- *Bout* = battery-bank required output (in Ah)
- *DODa =* allowable depth of discharge
- *$C_{T,rd}$ =* temperature and discharge-rate derating factor

Array Current

- The required PV array current is calculated using the following formula:

$$I_{array} = \frac{E_{crit}}{(\eta_{batt})(V_{SDC})(t_{PSH})}$$

- where

I_{array} required array maximum-power current (in A)

E_{crit} daily electrical-energy consumption during critical design month (in Wh/day)

η_{batt} battery-system charging efficiency

V_{SDC} nominal DC system voltage (in V)

t_{PSH} peak sun hours for critical design month (in hr/day)

For example, consider a nominal 24 V system in a location with 4.9 peak sun hours that must supply 1580 Wh per day. The battery-system charging efficiency is estimated at 0.90. What is the required array current?

$$I_{array} = \frac{E_{crit}}{\eta_{batt} \times V_{SDC} \times t_{PSH}}$$

$$I_{array} = \frac{1580}{0.90 \times 24 \times 4.9}$$

$$I_{array} = \frac{1580}{105.8}$$

$$I_{array} = \mathbf{14.9\ A}$$

Array Sizing

ARRAY SIZING

Average Daily DC Energy Consumption for Critical Design Month		Wh/day
DC System Voltage		VDC
Critical Design Month Insolation		PSH/day
Battery Charging Efficiency		
Required Array Maximum-Power Current		A
Soiling Factor		
Rated Array Maximum-Power Current		A
Temperature Coefficient for Voltage		/°C
Maximum Expected Module Temperature		°C
Rating Reference Temperature		°C
Rated Array Maximum-Power Voltage		VDC
Module Rated Maximum-Power Current		A
Module Rated Maximum-Power Voltage		VDC
Module Rated Maximum Power		W
Number of Modules in Series		
Number of Module Strings in Parallel		
Total Number of Modules		
Actual Array Rated Power		W

Figure 9-18. *The array sizing worksheet uses insolation data and load requirements to size the array.*

Array Rated Output and Soiling Factor

- *Soiling* is the accumulation of dust and dirt on an array surface that shades the array and reduces electrical output. The magnitude of this effect is difficult to accurately determine, but estimates will account for most of this effect.
- A derating factor of 0.95 is used for light soiling conditions with frequent rainfall and/or a higher tilt angle, and a derating factor of 0.90 or less is used for heavy soiling conditions with long periods between rainfalls or cleanings.
- The rated array maximum-power current is calculated using the following formula:
- Cs – soiling factor

$$I_{rated} = \frac{I_{array}}{C_S}$$

Temperature Effect

- High temperature reduces voltage output. A temperature coefficient of -0.004/°C is applied to voltage, indicating that voltage falls by about 0.4% for every degree above the reference or rating temperature, which is usually 25°C (77°F).
- In addition, the array voltage must be higher than the nominal battery-bank voltage in order to charge the batteries.
- An array with a 12 V maximum-power voltage will not charge a nominal 12V battery because the actual voltage of a nearly charged battery is about 14.5 V.
- The array voltage must be at least 14.5 V to charge a nominal 12 V battery.
- **Therefore, the rated array maximum-power voltage is multiplied by 1.2 to ensure that the array voltage is sufficient to charge the battery bank.**

- The rated array maximum-power voltage is calculated using the following formula:

$$V_{rated} = 1.2 \times \{V_{SDC} - [V_{SDC} \times C_{\%V} \times (T_{max} - T_{ref})]\}$$

V_{rated} = rated array maximum-power voltage (in V)

V_{SDC} = nominal DC-system voltage (in V)

$C_{\%V}$ = temperature coefficient for voltage (in /°C)

T_{max} = maximum expected module temperature (in °C)

T_{ref} = reference (or rating) temperature (in °C)

- For example, consider an array for a nominal 24 V DC system that must output 18 A.
- The soiling conditions are expected to be light and the maximum module temperature is estimated at 50°C.
- What are the minimum rated maximum power current and voltage parameters?

$$I_{rated} = \frac{I_{array}}{C_S}$$

$$I_{rated} = \frac{18}{0.95}$$

$$I_{rated} = \mathbf{18.95\ A}$$

$$V_{rated} = 1.2 \times \{V_{SDC} - [V_{SDC} \times C_{\%V} \times (T_{max} - T_{ref})]\}$$

$$V_{rated} = 1.2 \times \{24 - [24 \times -0.004 \times (50 - 25)]\}$$

$$V_{rated} = 1.2 \times [24 - (24 \times -0.004 \times 25)]$$

$$V_{rated} = 1.2 \times (24 + 2.4)$$

$$V_{rated} = \mathbf{31.7\ V}$$

Module Selection

- For each module, three parameters are needed for sizing:

  the maximum power, the maximum-power operating current, and the maximum-power operating voltage.

- As with batteries, modules should be chosen to result in an array that is as close as possible to the desired array ratings, but slightly higher.
- The number of parallel strings of modules required is determined by dividing the rated array current output by the selected module maximum-power current output and rounding up to the next whole number.

Design Example (Standalone System)

- A home is being constructed near Albuquerque, NM and needs standalone power, this home power consumption is detailed in the next slide
- Design a suitable PV system

LOAD ANALYSIS Month: August

AC LOADS

Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)
Refrigerator/Freezer	1	200	10	2000
Microwave	1	1200	0.5	600
Toaster	1	1000	0.05	50
Coffeemaker	1	600	0.25	150
Washing Machine	1	800	0.29	232
Entertainment Center	1	200	3	600
Computer System	1	100	2	200
Plug Loads	1	200	1	200
Water Pump	1	800	0.33	264
Ceiling Fans	2	50	24	2400
Fluorescent Lighting	4	15	6	360
Fluorescent Lighting	4	32	4	512

DC LOADS

Total AC Power	5388	W
Total DC Power	0	W
Total Daily AC Energy Consumption	7568	Wh/day
Total Daily DC Energy Consumption	0	Wh/day
Weighted Operating Time	**11.2**	hr/day
Inverter Efficiency	0.90	
Average Daily DC Energy Consumption	**8409**	Wh/day

For the month of August, the load analysis yields a total AC-power demand of about 5.4 kW and a daily energy consumption of 7568 Wh/day.

If all loads operate at the same time, the inverter must have a continuous power output rating of at least 5.4 kW. Although it is unlikely that all loads will be operating simultaneously, a 5.5 kW inverter is selected to allow for future load additions.

Since the efficiency of the inverter is 90%, the total average daily DC energy required is **8409 Wh/day.** This number will be used in the critical design analysis, along with energy requirements for every other month, to determine the critical design month. The weighted operating time for the critical design month will be used in the battery-sizing calculations.

Critical Design Analysis

CRITICAL DESIGN ANALYSIS

Month	Average Daily DC Energy Consumption (Wh/day)	Array Orientation 1 Latitude – 15		Array Orientation 2 Latitude		Array Orientation 3 Latitude + 15	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
January	6532	4.6	1420	5.3	1232	5.8	1126
February	6436	5.4	1192	6.0	1073	6.2	1038
March	6254	6.3	993	6.5	962	6.5	962
April	6197	7.3	849	7.2	861	6.6	939
May	6160	7.7	800	7.2	856	6.3	978
June	7568	7.8	970	7.1	1066	6.1	1241
July	8300	7.4	1122	6.9	1203	6.0	**1383**
August	8409	7.2	1168	6.9	1219	6.3	1335
September	7834	6.6	1187	6.8	1152	6.5	1205
October	6160	5.9	1044	6.5	948	6.6	933
November	6327	4.8	1318	5.5	1150	5.9	1072
December	**6578**	4.3	**1530**	**5.0**	**1316**	5.5	1196

- **Critical Design Month: December**
- **Orientation: Latitude**
- **Average Daily DC Energy Consumption: 6578**
- **Insolation: 5.0 PSH/day**

- The critical design ratio is calculated for each month.
- For each orientation, the highest ratio of load requirement to insolation corresponds to the critical design month. For two of the orientations, the month is December.
- For the latitude + 15° orientation, the month is July.
- Of the three possible critical design months, the month of December at the latitude orientation produces the lowest ratio.
- This indicates the optimal orientation.
- For this designated critical design month, the load requirement value is used for battery-bank sizing and the insolation value is used for array sizing.

Battery Bank

- A 48 V system is used
- Autonomy is set for 3 days
- A small engine generator should be aslo available

$$B_{out} = \frac{(E_{crit})(t_a)}{(V_{SDC})} = \frac{(6578)(3)}{(48)} = 411Ah$$

$$B_{rated} = \frac{B_{out}}{(DOD_a)(C_{T,rd})} = \frac{411}{(0.8)(0.9)} = 571Ah$$

$$r_d = \frac{(t_{op})(t_a)}{DOD_a} = \frac{(11.2)(3)}{0.8} = 42\text{ h}$$

- Flooded lead acid batteries with 295 Ah capacity are used , so 4 in series are required to provide 48V bus, and two strings in parallel to provide required capacity

BATTERY-BANK SIZING

Average Daily DC Energy Consumption for Critical Design Month	6578	Wh/day
DC System Voltage	48	VDC
Autonomy	3	days
Required Battery-Bank Output	411	Ah
Allowable Depth-of-Discharge	0.80	
Weighted Operating Time	11.2	hrs
Discharge Rate	42	hrs
Minimum Expected Operating Temperature	0	°C
Temperature/Discharge Rate Derating Factor	0.90	
Battery-Bank Rated Capacity	571	Ah
Selected Battery Nominal Voltage	12	VDC
Selected Battery Rated Capacity	295	Ah
Number of Batteries in Series	4	
Number of Battery Strings in Parallel	2	
Total Number of Batteries	8	
Actual Battery-Bank Rated Capacity	590	Ah

In this application, the load fraction is estimated at 0.75. The average daily depth of discharge is 17%. From the manufacturer's data, this battery has an expected life of 4000 cycles at 20% average daily depth of discharge. Correspondingly, at least 10 years of service should be expected in this application.

Array Sizing

$$I_{\text{array\_rated}} = \frac{E_{crit}}{(\eta_{batt})(V_{SDC})(t_{PSH})(Cs)} = \frac{6578}{(0.85)(48)(5)(0.95)} = 33.9A$$

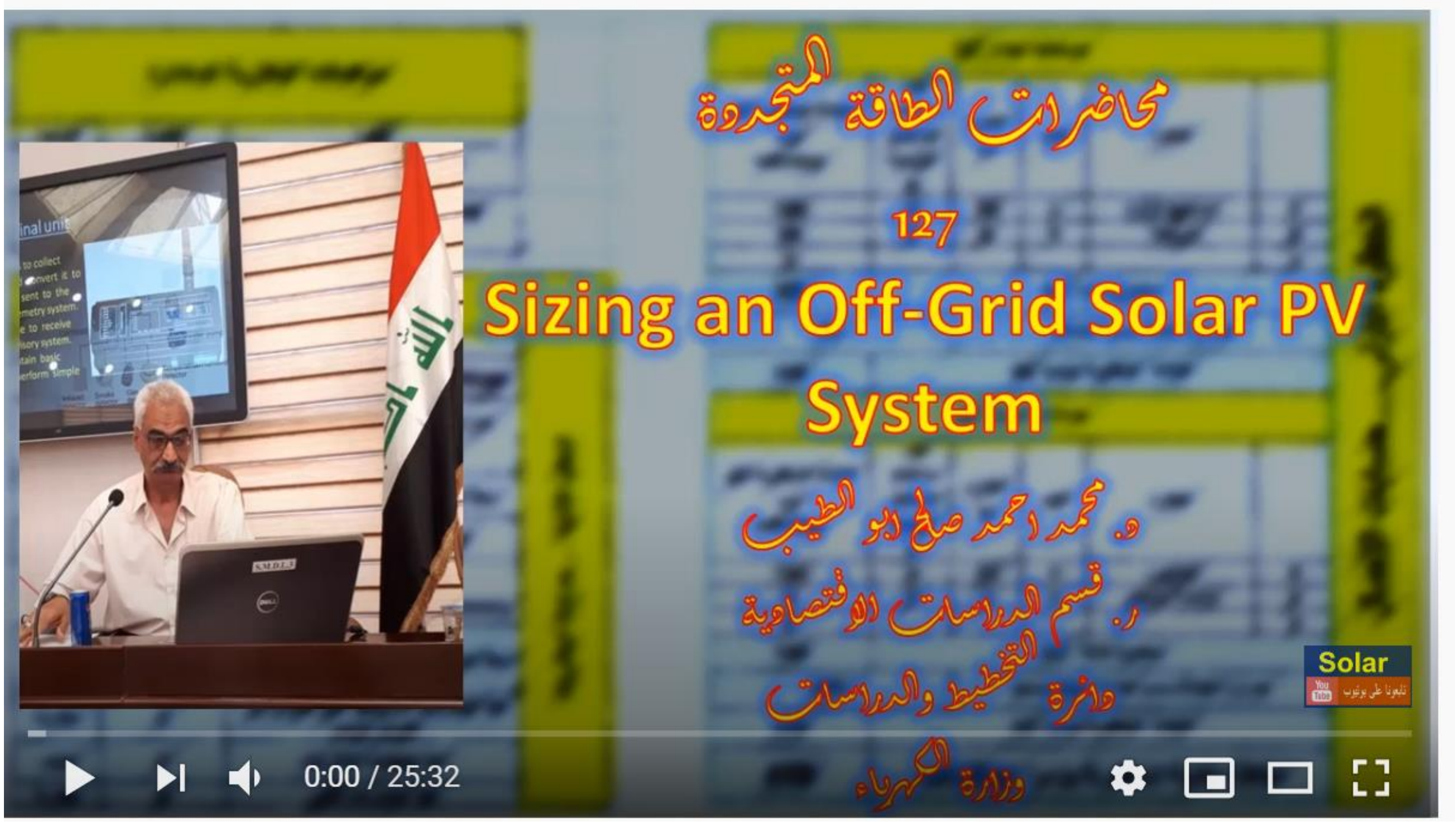
$$V_{\text{array\_rated}} = 1.2x\{(V_{SDC}) - [(V_{SDC}).(C_{\%V}).(T_{\max} - T_{ref})]\}$$
$$= 1.2x\{(48) - [(48).(-0.004\%/V).(50-25)]\}$$
$$= 63.4\ \text{V}$$

- A 185 Wp module with
- Imax=5.11 A, Vmax=36.2 V is chosen
- Ns=63.4/36.2=1.74 ➔ Ns=2
- Np=33.9/5.1=6.65 Np=7
- Total modules Nt=Ns*NP=14
- Total rated power= 14*185=2590 W

ARRAY SIZING

Average Daily DC Energy Consumption for Critical Design Month	6578	Wh/day
DC System Voltage	48	VDC
Critical Design Month Insolation	5.0	PSH/day
Battery Charging Efficiency	0.85	
Required Array Maximum-Power Current	32.2	A
Soiling Factor	0.95	
Rated Array Maximum-Power Current	33.9	A
Temperature Coefficient for Voltage	−0.004	/°C
Maximum Expected Module Temperature	50	°C
Rating Reference Temperature	25	°C
Rated Array Maximum-Power Voltage	63.4	VDC
Module Rated Maximum-Power Current	5.11	A
Module Rated Maximum-Power Voltage	36.2	VDC
Module Rated Maximum Power	185	W
Number of Modules in Series	2	
Number of Module Strings in Parallel	7	
Total Number of Modules	14	
Actual Array Rated Power	2590	W

https://www.youtube.com/watch?v=Cm6ks0Rp-z8



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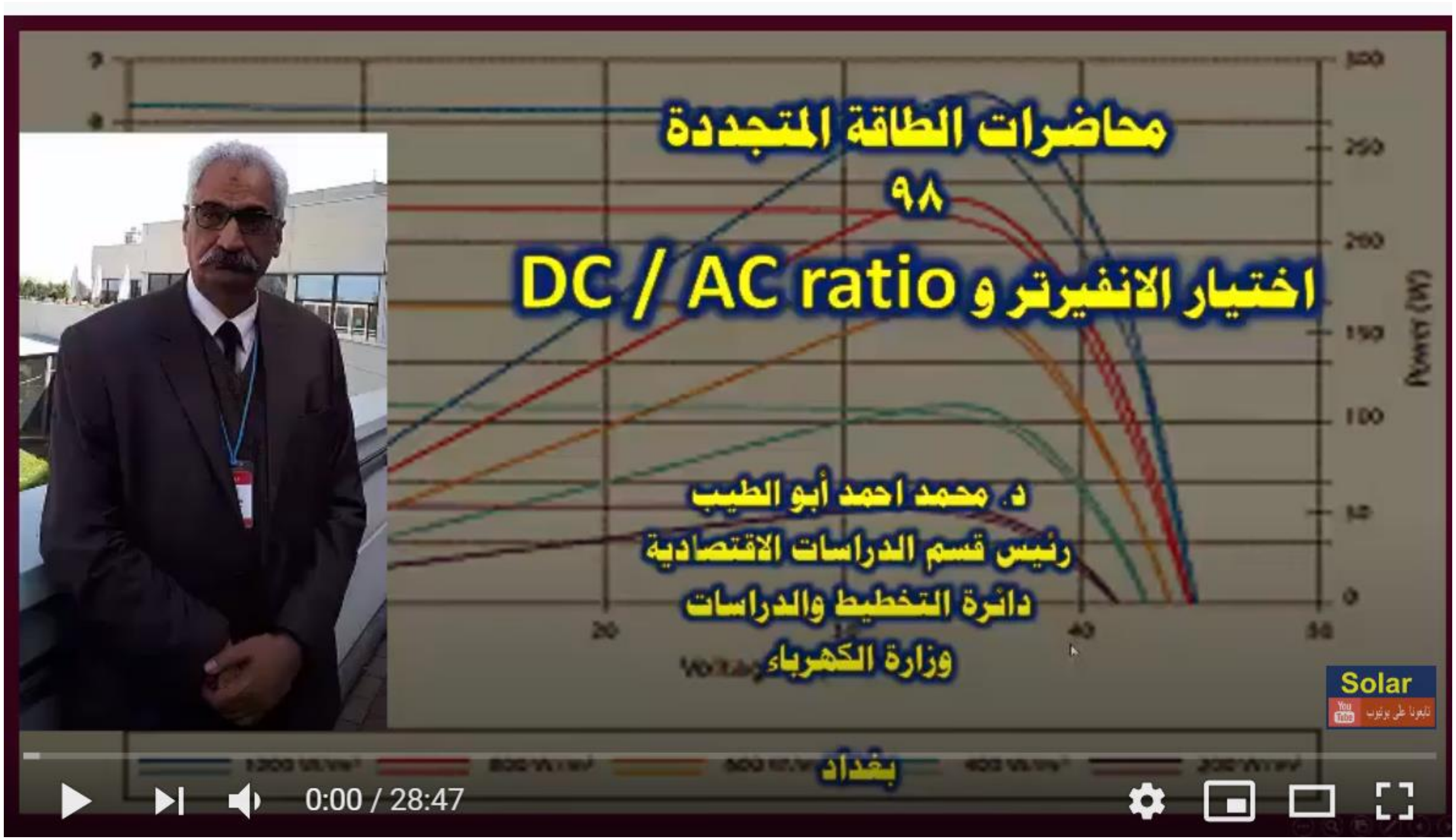
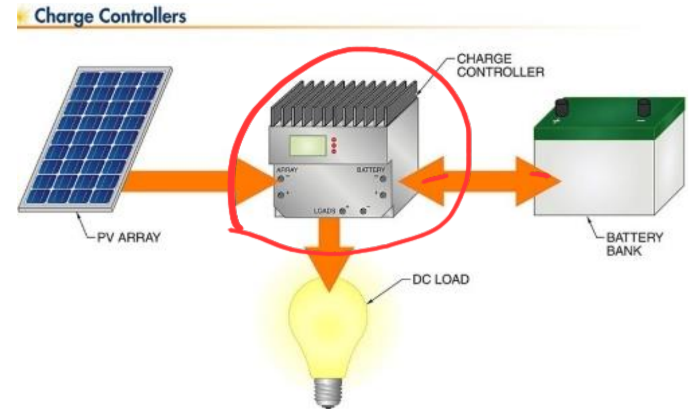


Maximum Power Point Trackers (MPPTs) and Charge Controllers



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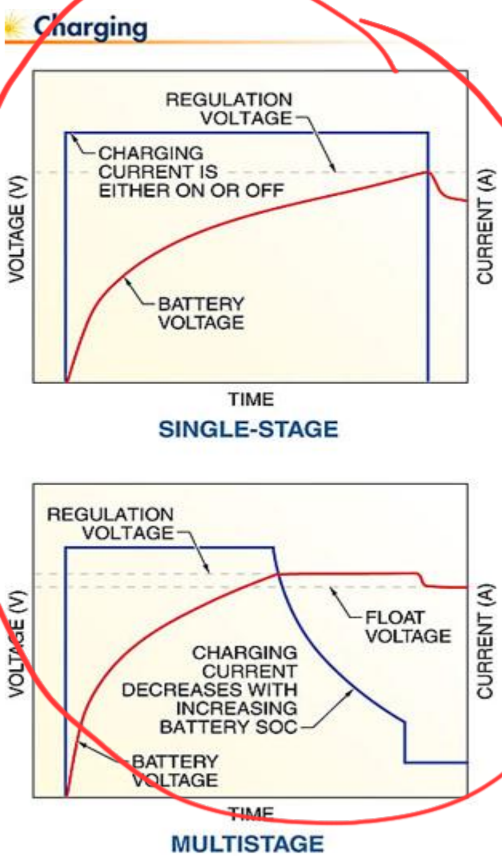
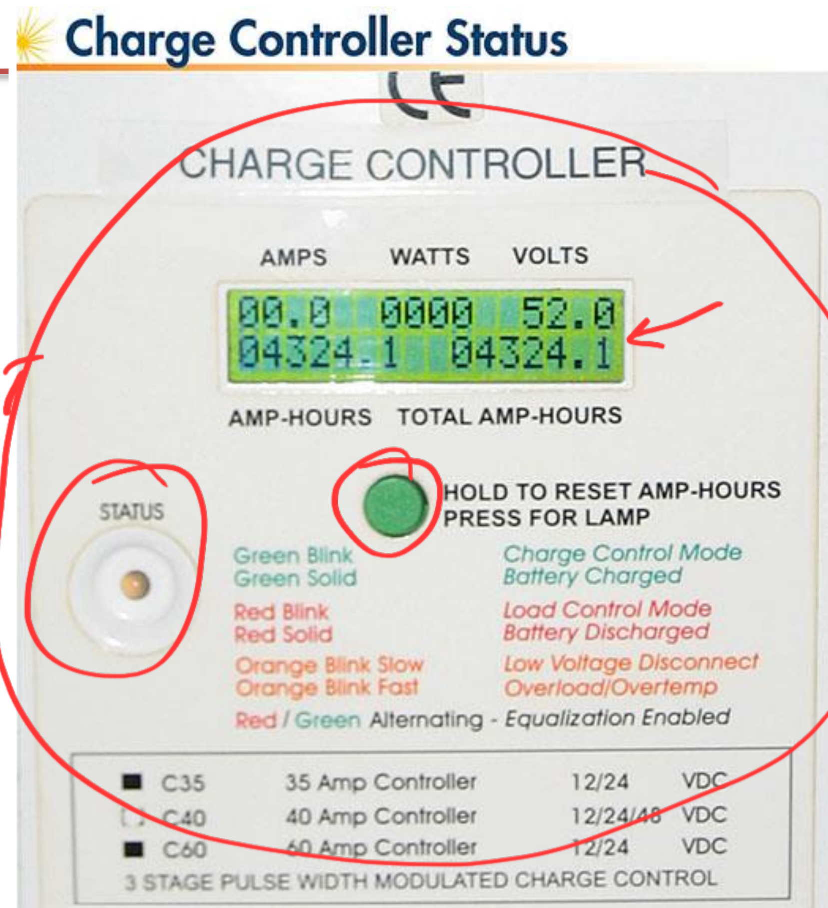
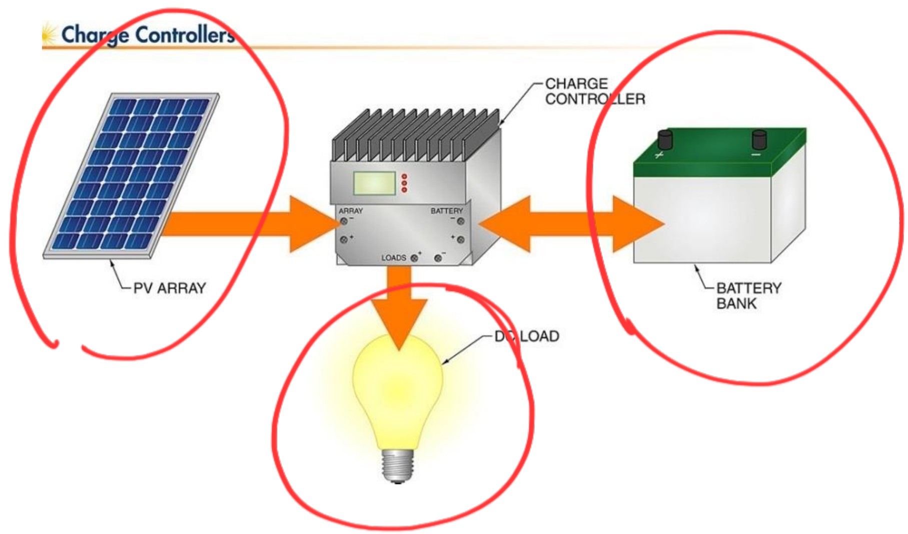




Charge Controller Function

- In applications where batteries are used , it is critical to prevent overcharging or deep-discharging of batteries to preserve their life and ensure good performance
- This is achieved using what is called charge controllers
- Charge controllers manage interactions and energy flows between a PV array, battery bank, and electrical load.

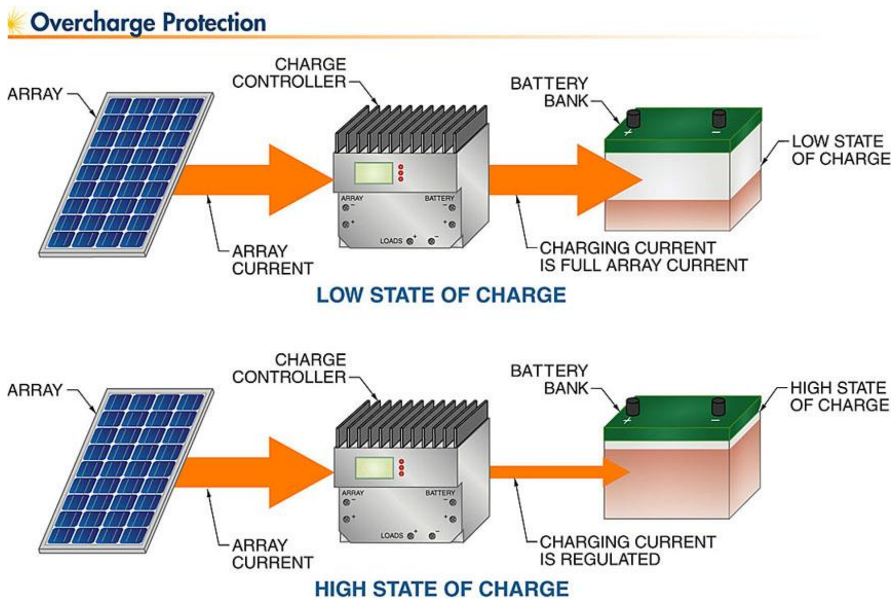


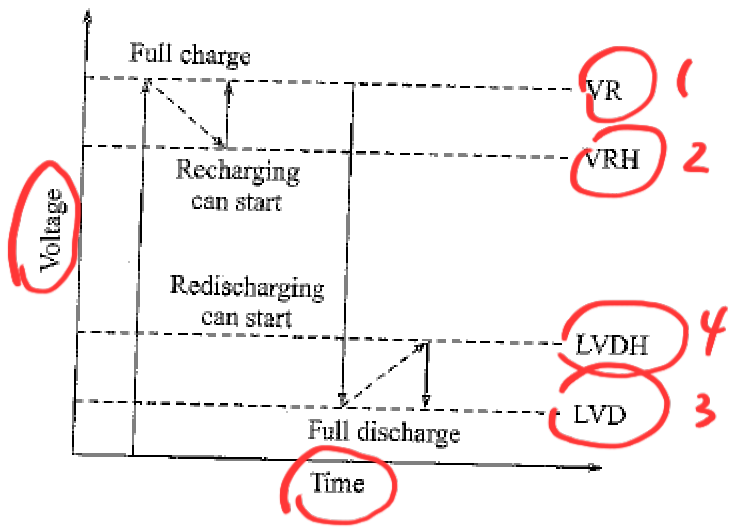
Set Points

- Charge controllers regulate the charging and discharging of a battery
- Charge controllers senses the voltage of the battery (or State Off Charge “SOC”) and decides either to disconnect it from the source (PV array) to prevent from overcharging
- It also prevent deep discharging by disconnecting the load
- The charge control algorithm has set points (threshold values) depending upon which it takes the decisions

Commonly used Set points

- **Voltage Regulation (VR) set-point:** It is the maximum voltage up to which a battery can be charged (without getting overcharged).
- If this threshold is reached, the controller either disconnects the battery from the source or starts regulating the current delivered to the battery

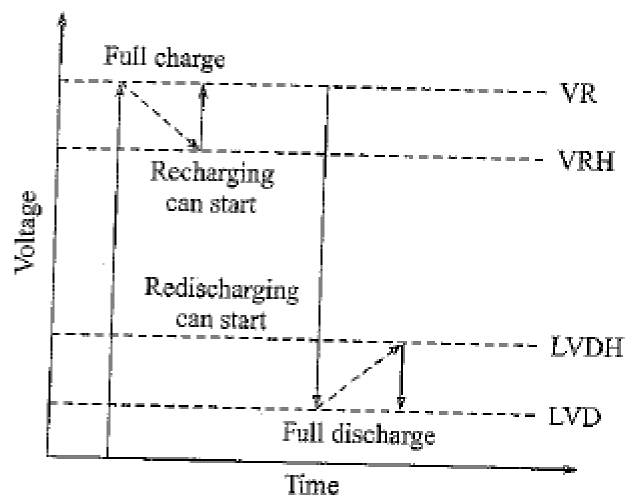




Charge controllers protect batteries from overcharge by terminating or limiting charging current

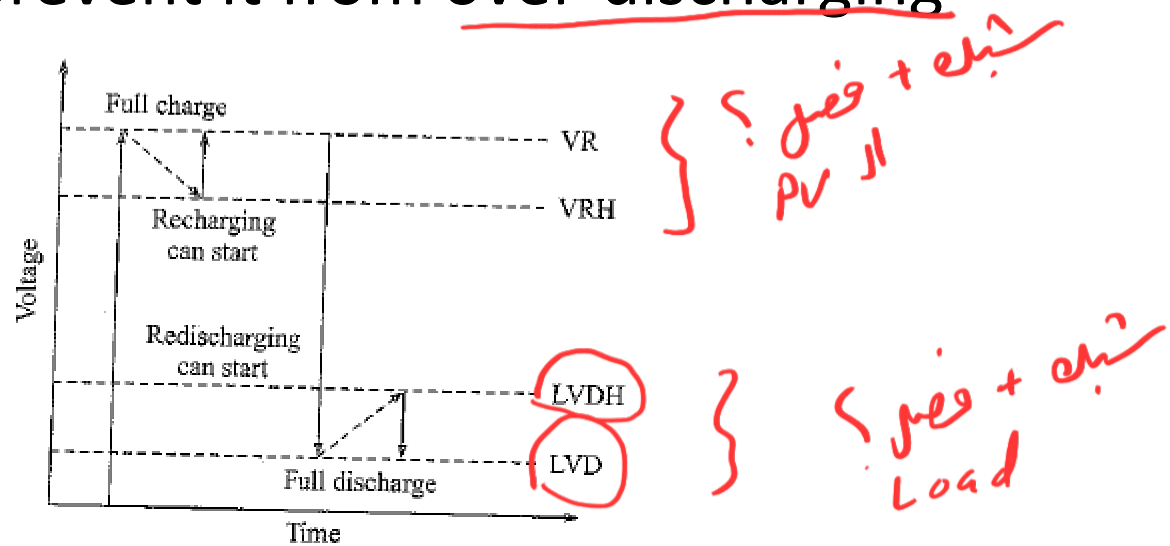
Commonly used Set points

- **Voltage Regulation Hysterisis (VRH):** It is the difference between VR and the voltage at which the controller reconnects the battery to the PV source and starts charging
- If VRH is too small , it will result in tighter regulation but the control will be oscillatory and may affect the battery life.
- At the same time , a large value of VRH may lead to slight overcharging every cycle
- VRH is important in determining how effectively the controller charges the battery
- In practice a trade-off is reached for VRH



Low Voltage Disconnect (LVD):

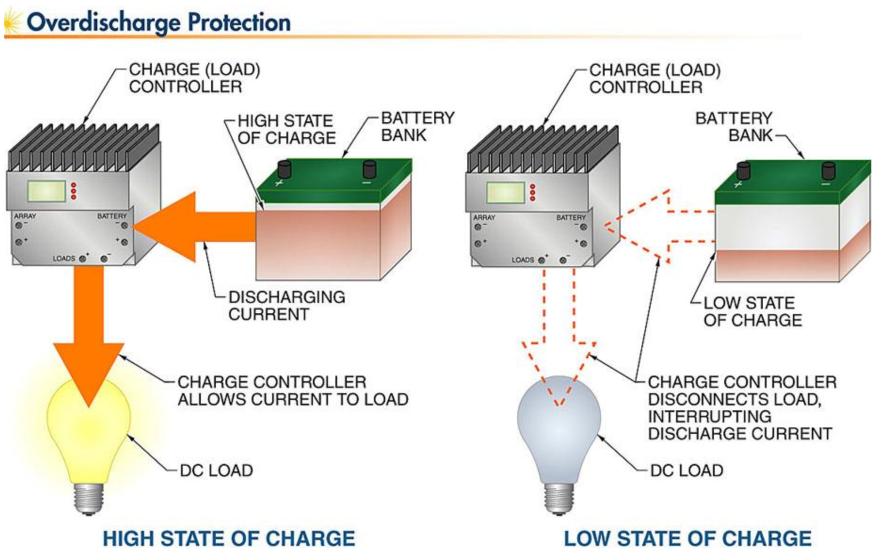
- **Low Voltage Disconnect (LVD):** It is the minimum voltage up to which the battery can be allowed to discharge, without getting deep discharged, it is also defined as the maximum Depth Of Discharge "DOD" of the battery
- The charge controller disconnects the load from the battery terminals as soon as the battery voltage touches LVD to prevent it from over-discharging



Load Disconnect

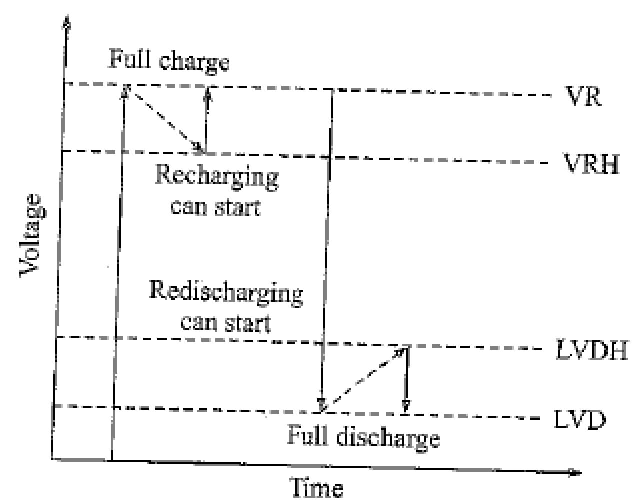
(protect from Overdischarge)

- Charge controllers protect batteries from over-discharge by disconnecting loads at low battery voltage.

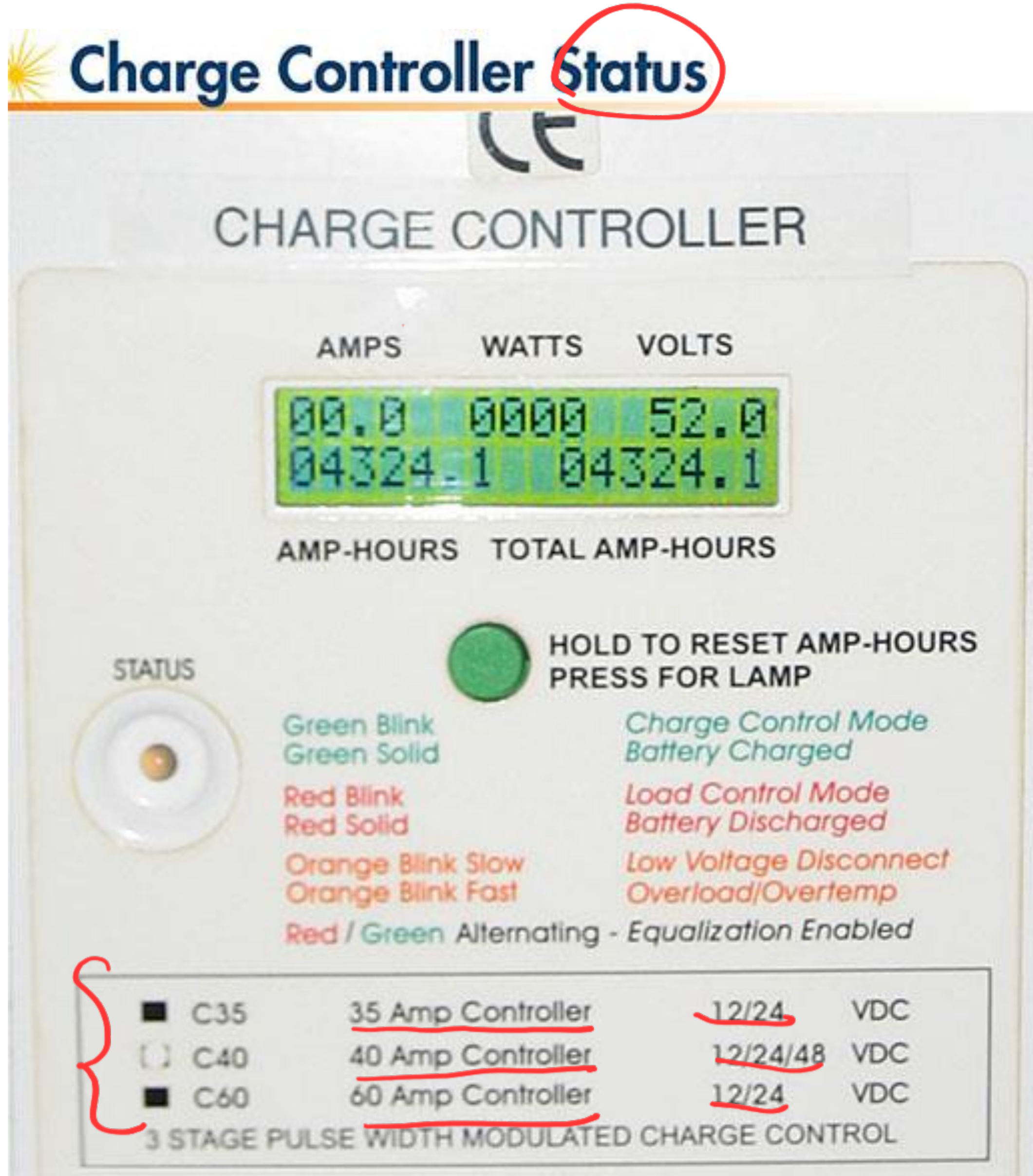


Low Voltage Disconnect Hysterisis

- **Low Voltage Disconnect Hysterisis (LVDH):** It is the difference between LVD value and the battery voltage at which load can be reconnected to the battery terminals
- If LVDH is too small the load will be switched on and off more frequently which can affect the battery and the load adversely



•Most commercial charge controllers include displays or LEDs to indicate battery voltage, state of charge, and/or present operating mode.

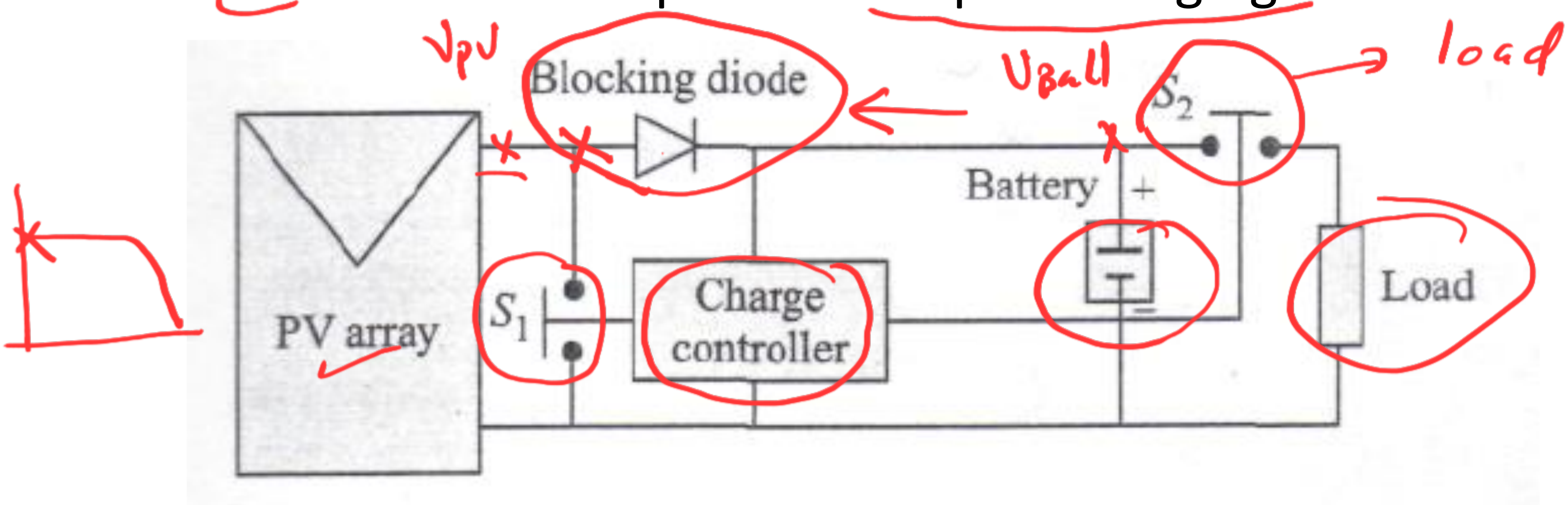


Types of Charge Controllers

- There are 4 types:
  - Shunt (Linear)
  - Series (Linear)
  - Switching (DC-DC converter)
  - MPPT

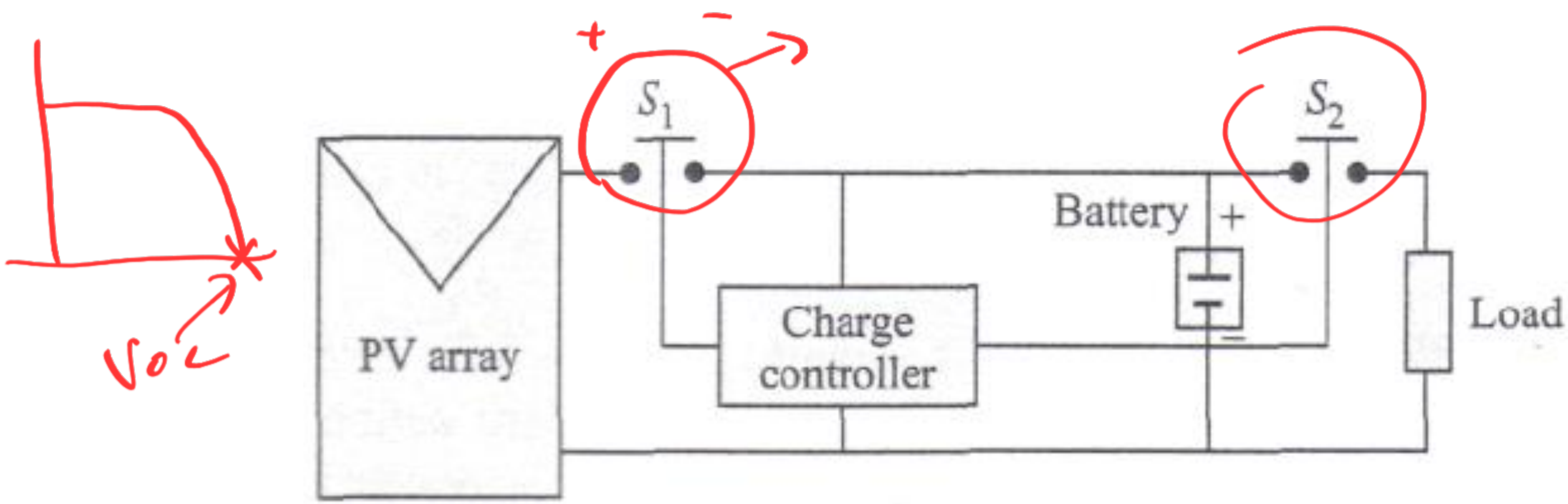
Shunt type

- Switch *S1* is connected in shunt with the PV panel, which is turned on when the battery voltage reaches its over voltage limit (VR).
- The PV array is short-circuited and it no more feeds the battery.
- The blocking diode prevents short circuiting of the battery and also prevents the battery to discharge through the PV array during the nights and low insolation periods.
- The switch *S2* allows the battery to discharge **through the** load.
- When the battery voltage reaches the threshold value (LVD), the switch *S2* is turned off to prevent deep discharging



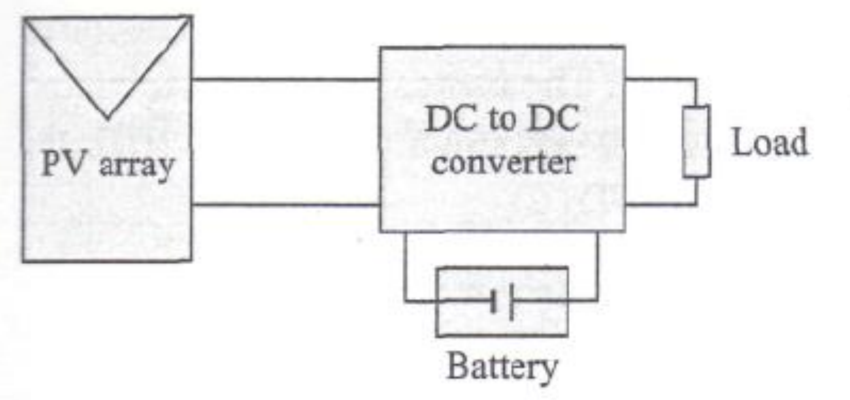
Series type charge controller

- The switch S1 is turned off to prevent the battery from getting overcharged. A major drawback of this method is the additional loss in the switch *S1 which* now carries the PV output current charging the battery.
- Depending on the application and type of battery used, different charge controller configurations are used which either completely disconnect the array from the battery or allow a regulated current to flow through the battery to maintain the battery voltage.



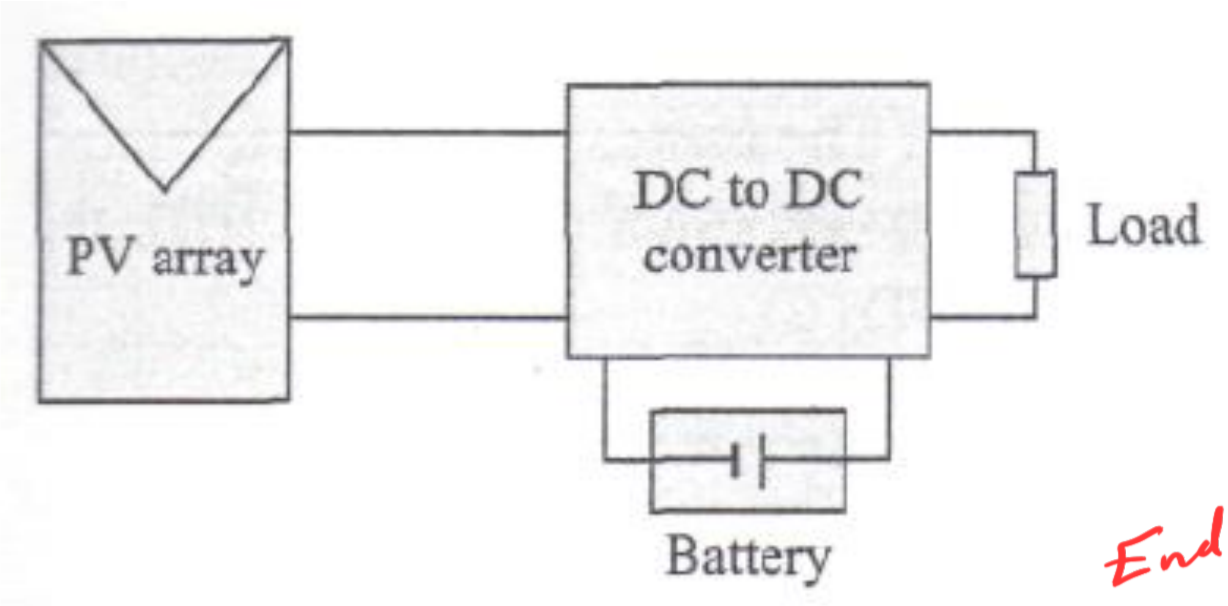
DC to DC converter type charge controller (Switching)

- The series and shunt type of charge controllers are not efficient
- if a DC to DC converter is used to interface the battery- and load combination with the PV array, it provides a smoother control and efficient and optimum use of the PV source.
- **A buck,** boost or buck-boost type DC to DC converter can be used to regulate the output of the PV array to feed the load. The DC to DC converter offers **the following advantages:**
- (a) There are no additional losses due to the conduction of switches such as *Sl* and S2.



DC to DC converter type charge controller

- (b) The regulation of battery charging current and battery voltage is superior.
- (c) The output voltage of the PV array and the battery voltage need not be identical now. So the PV" can be operated at the MPP



End of L16/P2
28/4/2021

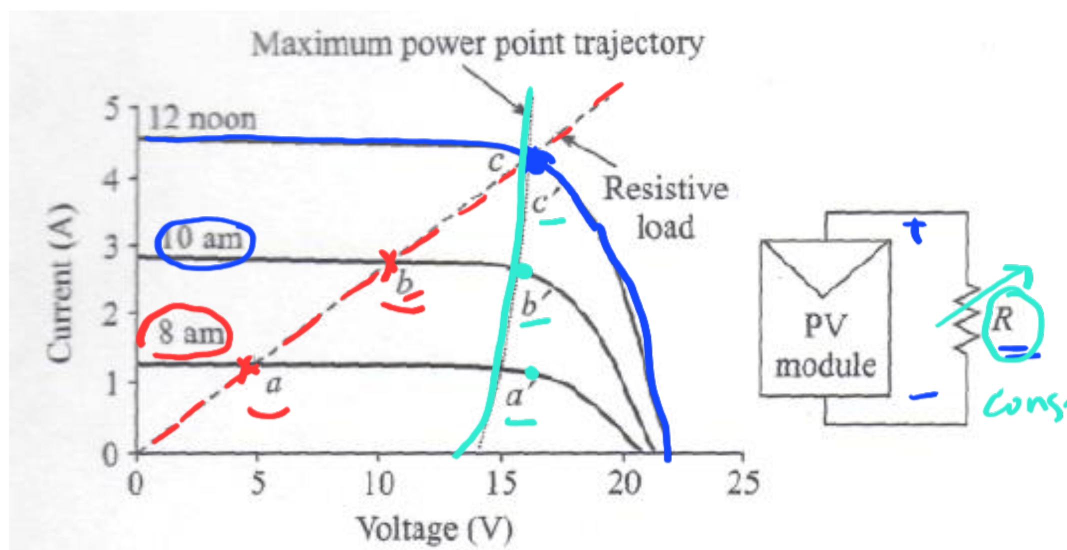
MPPT Charge controllers

L17 10/5/2021

- The battery charging methods described above pump whatever energy is coming out from the PV array into the battery.
- To charge battery in a more efficient manner, the PV array is operated at a point where the **PV output power is maximum**.
- The output power of the PV array changes with the change in voltage across it.
- To extract maximum power from the PV array, a DC to DC converter is used between the PV array and the battery.
- **The duty cycle of the DC to DC converter is controlled to impose optimum voltage across the PV array which corresponds to maximum power point (MPP).**

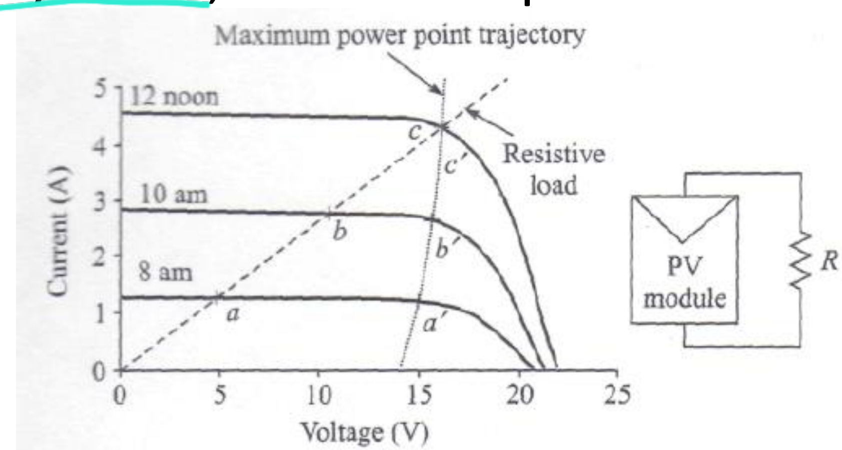
MAXIMUM POWER POINT TRACKING (MPPT)

- When a solar PV module is used in a system, its operating point is decided by the load to which it is connected.
- Also, since solar radiation falling on a PV module varies throughout the day, the operating point of module also changes throughout the day.
- As an example, the operating point of a PV module and a resistive load for 12 noon, 10 am and 8 am is schematically shown in Fig. denoted by *a, b* and c.



MAXIMUM POWER POINT TRACKING (MPPT)

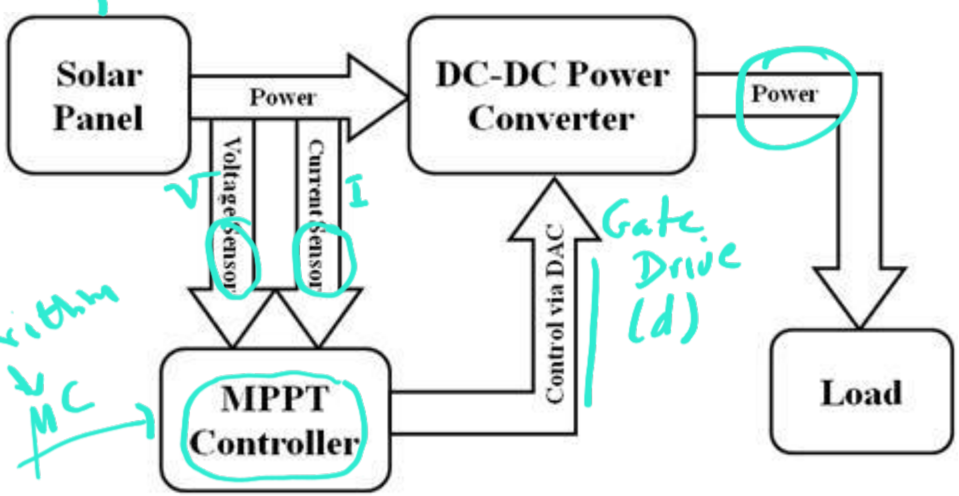
- Ideally, under all operating conditions, we would like to transfer maximum power from a PV module to the load.
- In Fig. the trajectory of a point at which the solar PV module will give maximum power is also shown.
- Thus, for maximum power transfer, instead of operating at points *a, b* and *c* the module should be operating at points *a ʻ b'* and *c'.*
- In order to ensure the operation of PV modules for maximum power transfer, a special method called Maximum Power Point Tracking (MPPT) is employed in PV systems, which is explained in the following paragraphs.



MPPT and Sun Tracking

- Here it should be noted that the MPPT is not the same as the mechanical tracking (also called sun-tracking, discussed earlier) of solar PV modules.
- In the case of sun-tracking. PV modules are rotated mechanically so that the radiation intercepted by a module is maximum (hence maximizing power generation) under a given condition, while in the case of MPPT, electronic circuitry is used to ensure that maximum amount of generated power is transferred to the load.

- The maximum power tracking mechanism makes use of an algorithm and an electronic circuitry.
- **The mechanism is based on the principle of impedance matching between load and PV module, which is necessary for maximum power transfer**.
- This impedance matching is done by using a DC to DC converter, the impedance is matched by changing the duty cycle *(d)*
- Figure shows a simple block diagram for MPPT.



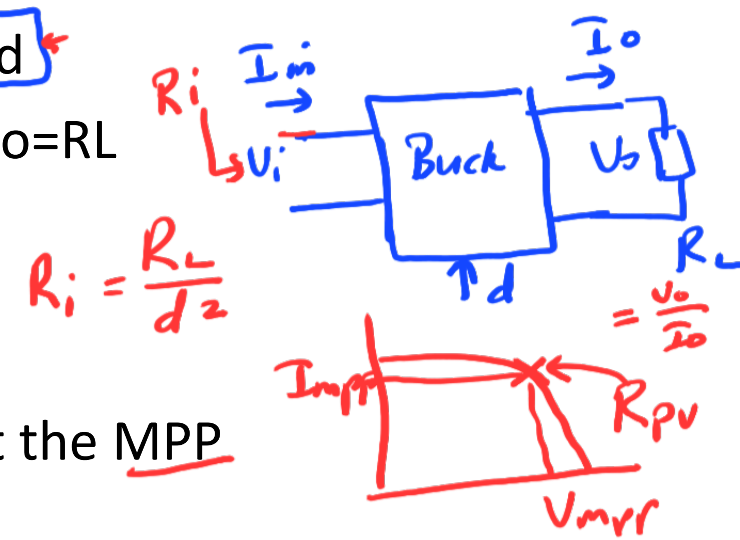
Impedance Matching

- The power from the solar module is calculated by measuring the voltage and current.
- This power is an input to the algorithm which then adjusts the duty cycle of the switch, resulting in the adjustment of the reflected load impedance according to the power output of PV module.
- For instance, the relation between the input voltage (Vi) and the output voltage *(Vo)* and impedance of load *(RL)* reflected at the input side (Ri) of a **buck type DC to DC converter** can be given as:

$$V_o = d\,V_i \quad \text{and} \quad Io = Iin/d$$

$$Ri = Vi/Ii = (Vo/d)/(dIo); \; Vo/Io = RL$$

$$R_i = \frac{R_L}{d^2}$$



d is duty cycle,

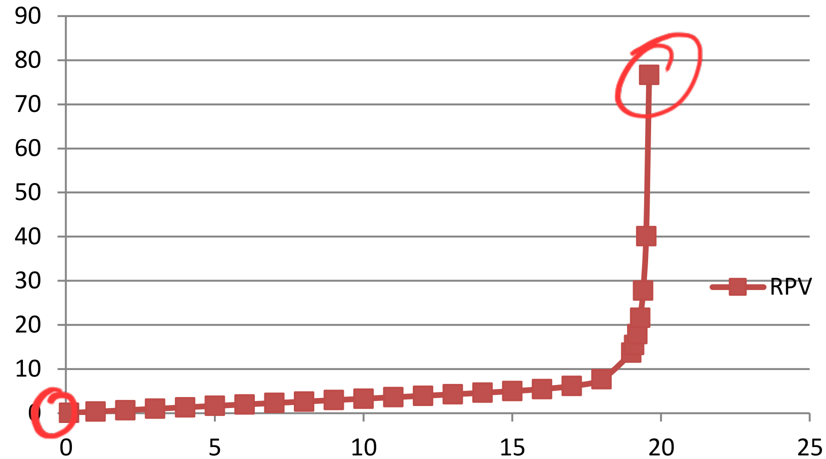
- By varying d , Ri is changed to match Rpv at the MPP

Input Impedance for DC-DC Converters

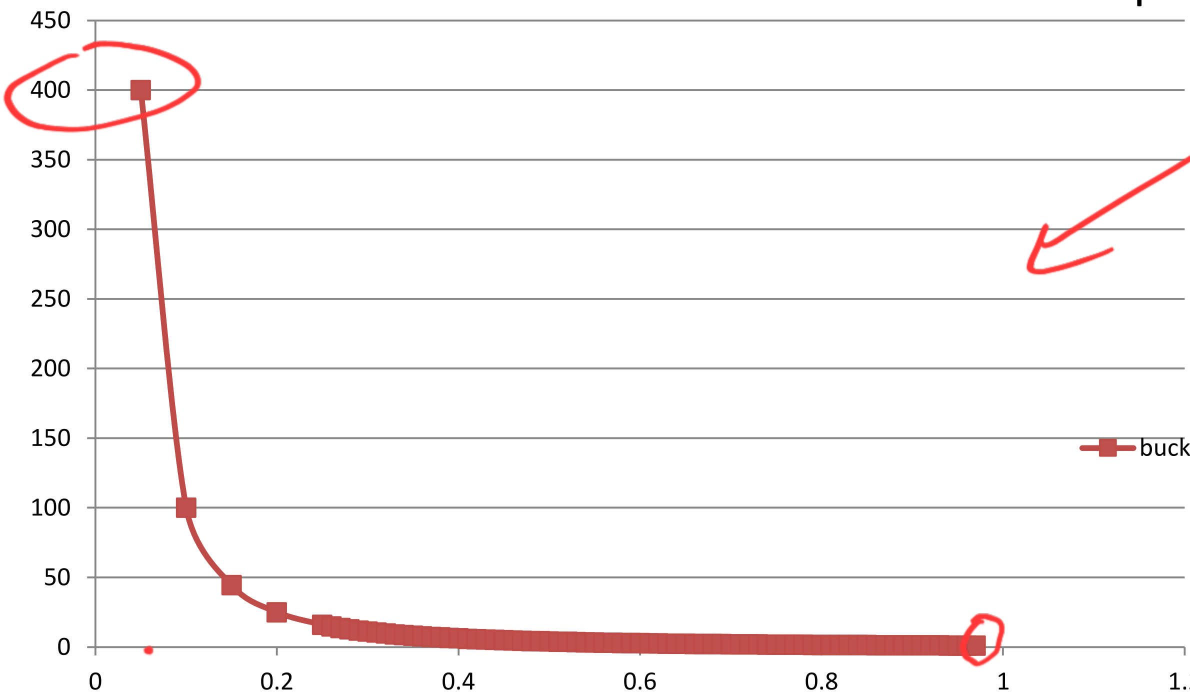
Converter Type	Input Impedance
Buck	$R_{in} = R_L \left[\frac{1}{d}\right]^2$
Boost	$R_{in} = R_L[1 - d]^2$
Buck-Boost	$R_{in} = R_L \left[\frac{1-d}{d}\right]^2$

عمليا → 0.05 – 0.95

- d can be varied from 0 to 1, input impedance also varies
- For Buck the reflected impedance is higher than load impedance, for the boost it is lower and for buck boost it can be lower or higher



Output Impedance for PV module



$$R_{in} = \frac{V_i}{I_i} = R_L \left(\frac{1}{d}\right)^2$$

For $R_L = 1$

Input Impedance for Buck

MPPT Mehods

- There are some conventional methods for MPPT.
- These methods include:

1. Constant Voltage method
2. Open Circuit Voltage method
3. Short Circuit Current method
4. **Perturb and Observe method***
5. **Incremental Conductance method***
6. Temperature method
7. Temperature Parametric method

Details of some MPPT algorithms are discussed

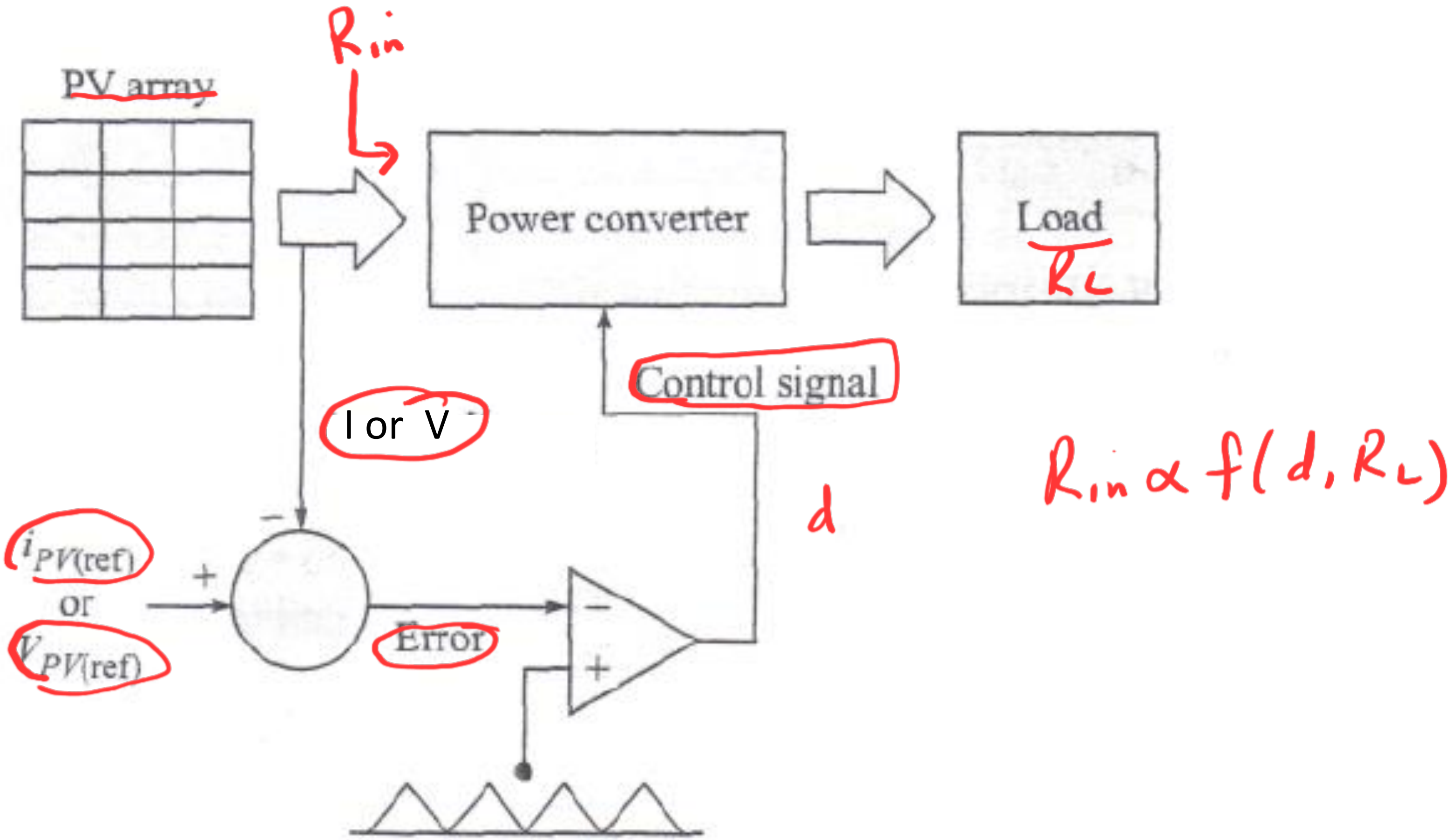
Constant Voltage Method

- This method simply uses single voltage to represent the Vmp.
- In some cases this value is programmed by an external resistor connected to a current source pin of the control IC.
- In this case, this resistor can be part of a network that includes a NTC thermistor so the value can be temperature compensated.
- For the various different irradiance variations, the method will collect about 80% of the available maximum power.
- The actual performance will be determined by the average level of irradiance.
- In the cases of low levels of irradiance the results can be better.

Open Circuit Voltage Method

- An improvement on this method uses Voc to calculate Vmp.
- Once the system obtains the Voc value, Vmp is calculated by,
- $$V_{mp} = kV_{oc}$$
- The k value is typically between to 0.7 to 0.8. It is necessary to update Voc occasionally to compensate for any temperature change.
- Sampling the Voc value can also help correct for temperature changes and to some degree changes in irradiance.
- Monitoring the input current can indicate when the Voc should be re-measured.
- The k value is a function of the logarithmic function of the irradiance, increasing in value as the irradiance increases.
- An improvement to the Voc method is to also take this into account

MPPT circuit for constant current/constant voltage method



** Incremental Conductance Method

$$\frac{dp}{dv} = 0, \text{ at MPP}$$

$$\frac{dp}{dv} > 0, \text{ at left of MPP}$$

$$\frac{dp}{dv} < 0, \text{ at right of MPP}$$

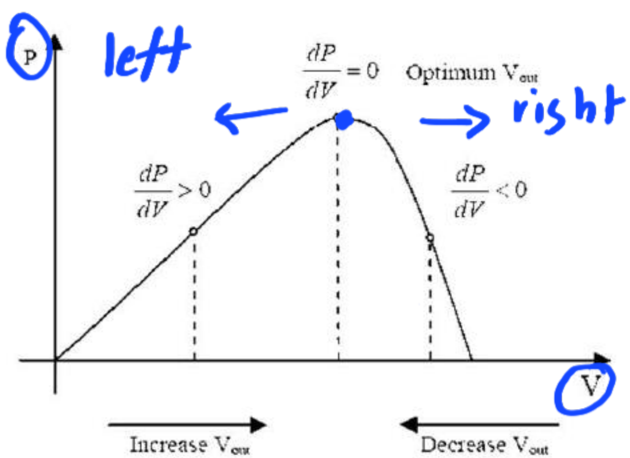
$P = I \cdot V$

$$\frac{dp}{dv} = \frac{d(IV)}{dv}$$

$$\frac{dI}{dV} = \frac{\Delta I}{\Delta V}$$

$$= I + V\frac{dI}{dV}$$

$$= I + V\frac{\Delta I}{\Delta V}$$



- The incremental conductance method based on the fact that, **the slope of the PV array power curve is zero at the MPP,** positive on the left of the MPP.

And negative on the right on the MPP.

This can be given by,

$$\frac{dP}{dV} = I + V\frac{dI}{dV} = 0$$

$$= I + V\frac{\Delta I}{\Delta V} = 0$$

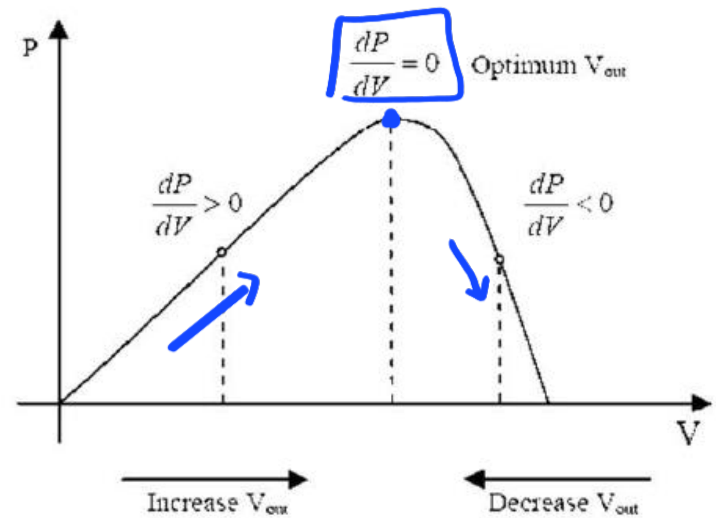
So that,

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \text{ at MPP} \quad (3.1)$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V}, \text{ at left of the MPP} \quad (3.2)$$

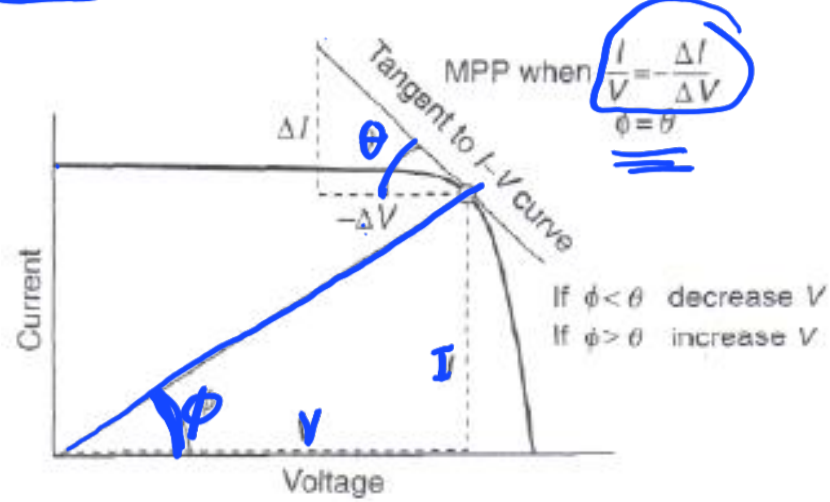
$$\frac{\Delta I}{\Delta V} < \frac{-I}{V}, \text{ at right of the MPP} \quad (3.3)$$

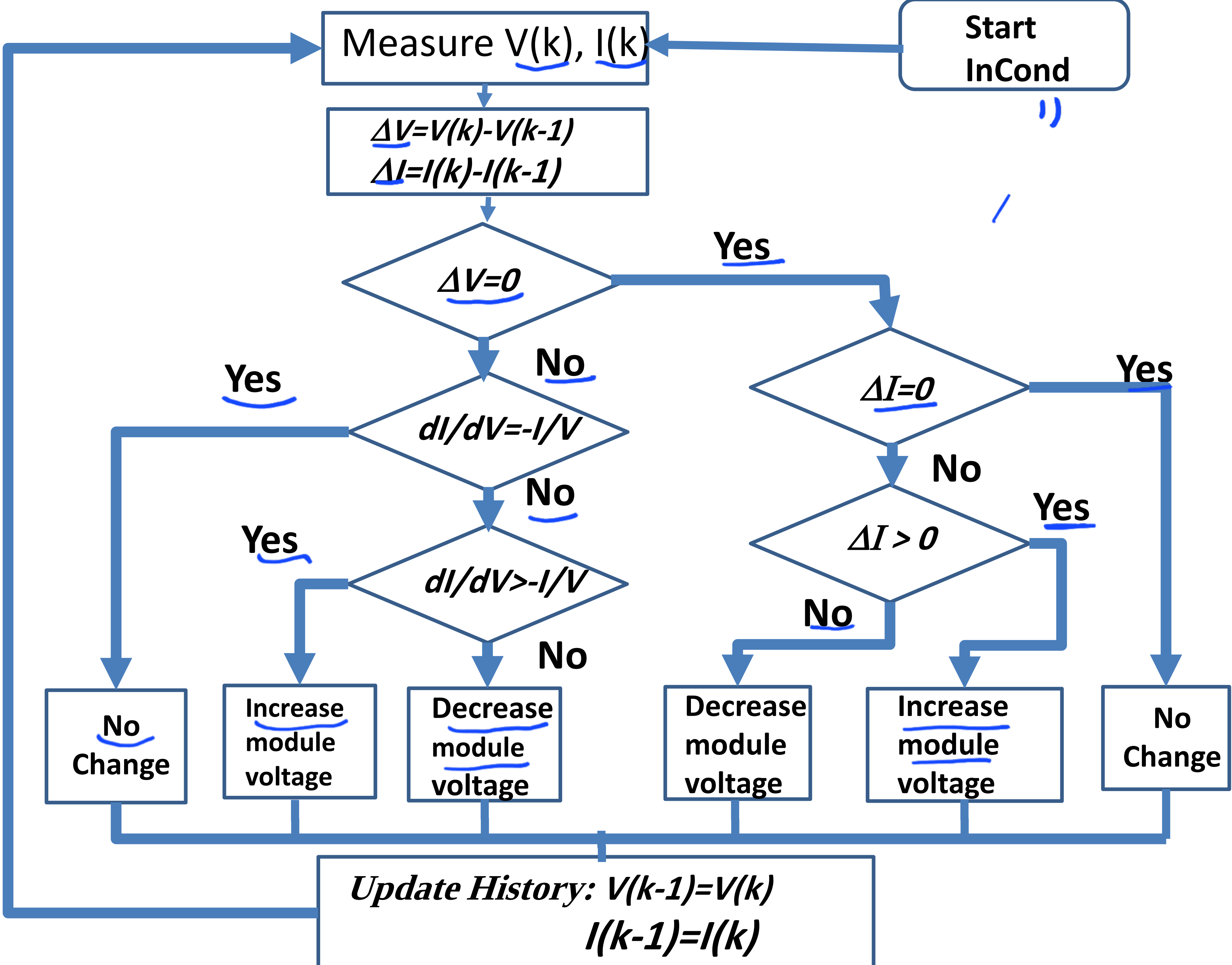
- **The ratio of I/V, called the instantaneous conductance, is based on measurements of PV current and voltage taken at fixed increments of time.**
- **The ratio ΔI /ΔV, called the incremental conductance, refers to changes that might have occurred in I and V during one of those time steps.**
- Figure shows one interpretation of these conductance's on a PV I-V curve.
- The instantaneous conductance is the slope of a line drawn from the origin to the operating point.
- The incremental conductance is the negative slope of the I-V curve at that same operating point.



$$\begin{cases} dP/dV < 0 & \text{right of MPP,} \\ dP/dV = 0 & \text{at MPP,} \\ dP/dV > 0 & \text{left of MPP.} \end{cases}$$

- **We could imagine, therefore, that the MPP can be found by incrementing the duty cycle of the converter until the ratio of the incremental changes ΔV and ΔI equals I/V; that is, until the angles ϕ and θ are equal.**
- Having located the MPP, the duty cycle of the converter remains fixed until subsequent I and V measurements indicate that a change is needed.
- That change may be the result of temperature or insolation shifts in the I-V curve, which move the MPP.
- For example, if insolation increases, the MPP will move somewhat to the right. At the next time step, the sensors will indicate an increase in current ΔI, but until the duty cycle changes, Δ V is still zero.
- That increase in insolation has moved the MPP to the right so the PV voltage needs to increase: that is. the dutv cvcle needs to increase.



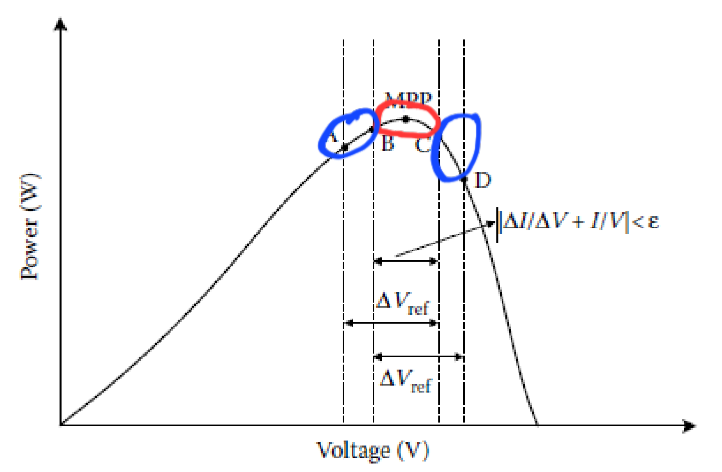


Start
InCond
Measure V(k), I(k)
ΔV=V(k)-V(k-1)
ΔI=I(k)-I(k-1)
ΔV=0
Yes
No
ΔI=0
Yes
No
dI/dV=-I/V
Yes
No
ΔI > 0
Yes
No
dI/dV>-I/V
Yes
No
No Change
Increase module voltage
Decrease module voltage
Decrease module voltage
Increase module voltage
No Change
Update History: V(k-1)=V(k)
I(k-1)=I(k)

Practical Implementation

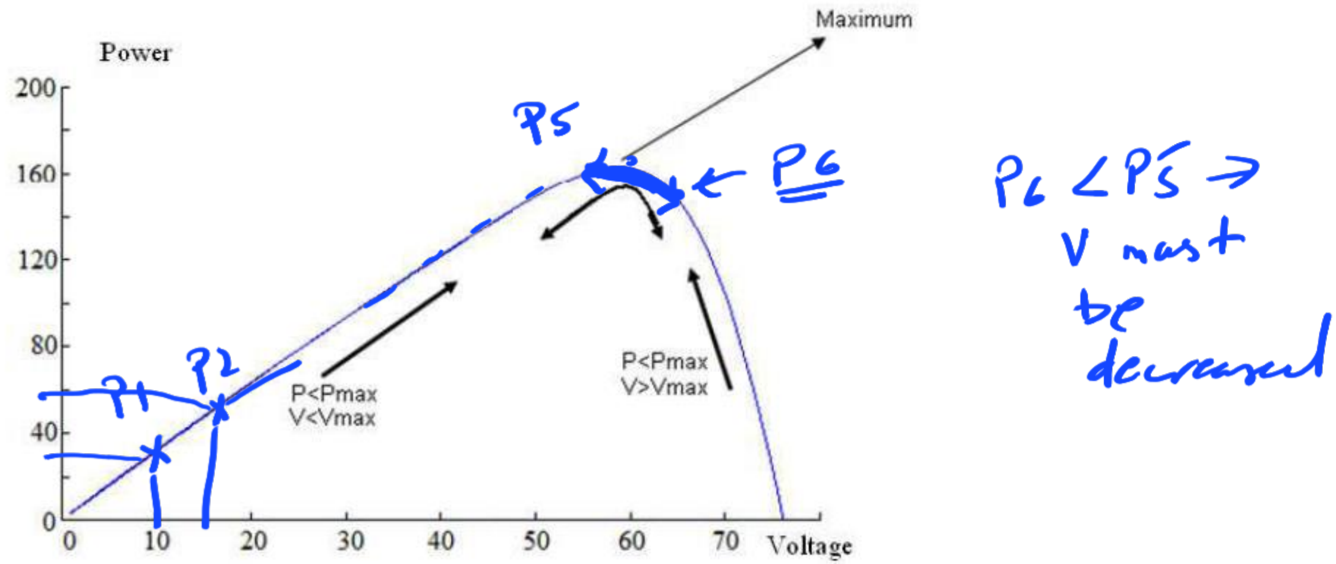
- Practically, due to the noise and errors, satisfying the condition of $\Delta I/\Delta V = -I/V$ may be very difficult .
- Therefore, this condition can be satisfied with good approximation by
- $|\Delta I/\Delta V + I/V| < \varepsilon$, where ε is a positive small value.
- Based on this algorithm, the operating point is either located in the BC interval or
- oscillating among the AB and CD intervals, Selecting the step size (ΔV_{ref}), shown in, is a trade-off between accurate steady tracking and dynamic response.
- If larger step sizes are used for quicker dynamic responses, the tracking accuracy decreases and the tracking point oscillates around the MPP.
- On the other hand, when small step sizes are selected, the tracking accuracy will increase. In the meantime, the time duration required to reach the MPP will increase

→ d ± Δd



Perturb and Observe (P&O) Method or “Hill Climbing method”

- **In this method the controller adjusts the voltage by a small amount from the array and measures power, if the power increases, further adjustments in the direction are tried until power no longer increases.**
- This is called P&O method. Due to ease of implementation it is one of the most commonly used MPPT method.
- The voltage to a cell is increased initially, if the output power increase, the voltage is continually increased until the output power starts decreasing.
- Once the output power starts decreasing, the voltage to the cell decreased until maximum power is reached. This process is continued until the MPPT is attained.
- This result is an oscillation of the output power around the MPP.

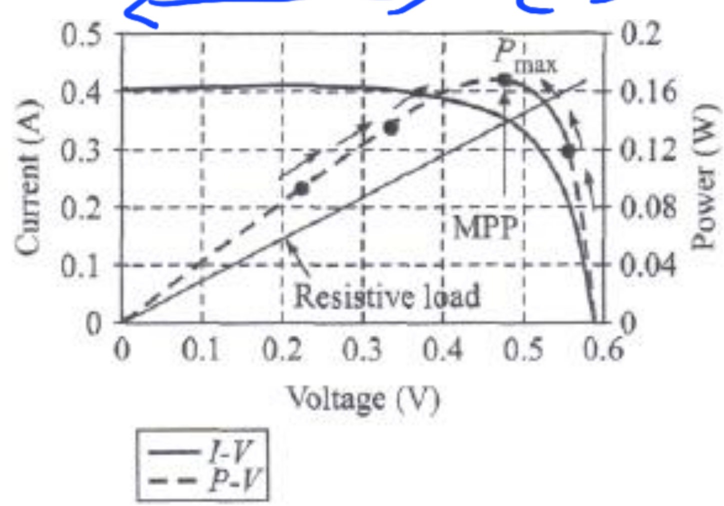


- In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, P is observed.
- If the P is positive, then it is supposed that it has moved the operating point closer to the MPP.
- Thus, further voltage perturbations in the same direction should move the operating point toward the MPP.
- If the P is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP.

Hill Climbing method (perturb and observe) Buck Converter

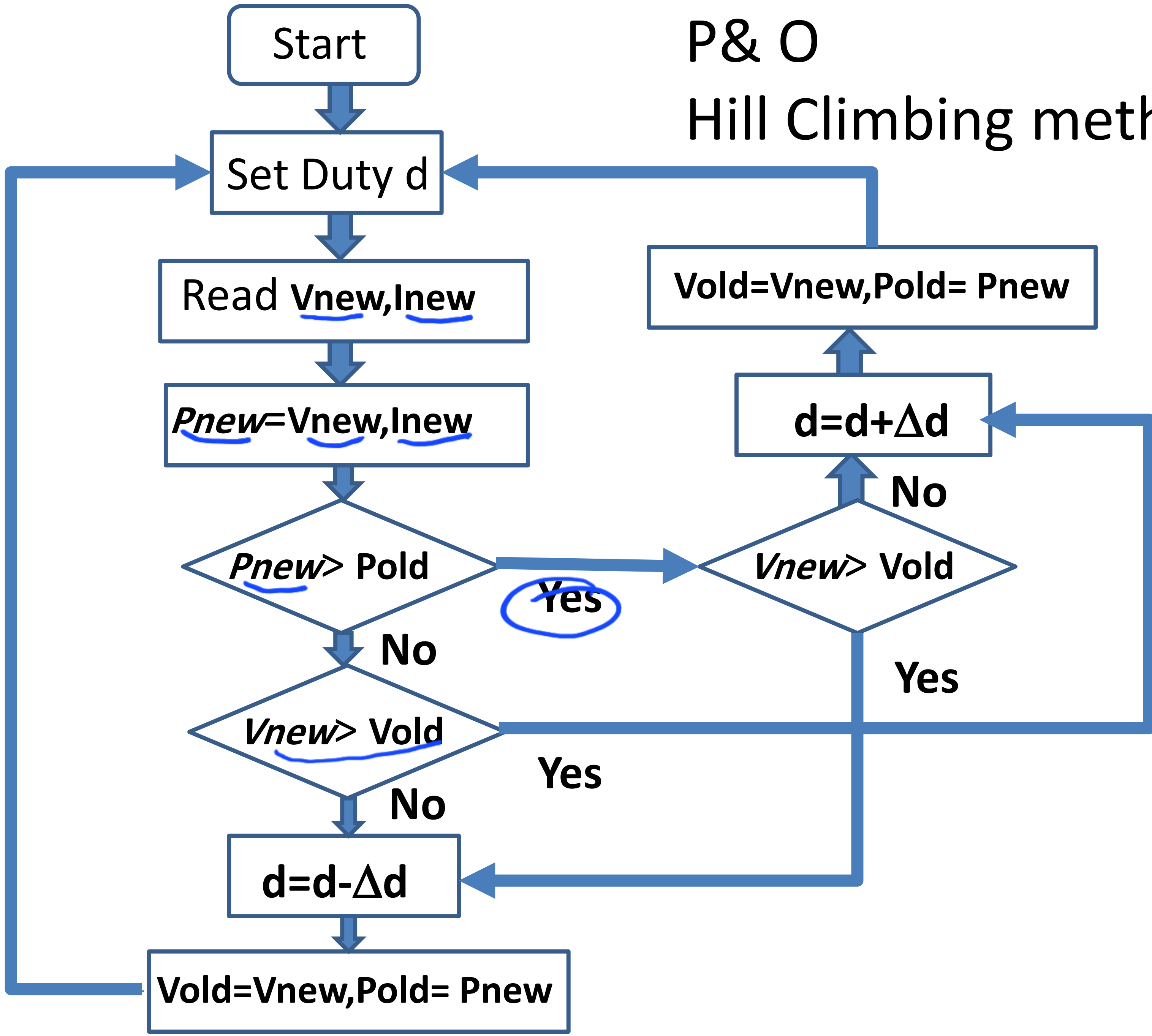
- The algorithm of this scheme is described below along with the help of mathematical expressions

$$
\left.
\begin{array}{l}
\text{In the voltage source region, } \dfrac{\partial P_{PV}}{\partial V_{PV}} > 0 \Rightarrow d = d + \Delta d \text{ (i.e., increment } d\text{)} \\[2ex]
\text{In the current source region, } \dfrac{\partial P_{PV}}{\partial V_{PV}} < 0 \Rightarrow d = d - \Delta d \text{ (i.e., decrement } d\text{)} \\[2ex]
\text{At MPP, } \dfrac{\partial P_{PV}}{\partial V_{PV}} = 0 \Rightarrow d = d \text{ or } \Delta d = 0 \text{ (i.e., retain } d\text{)}
\end{array}
\right\}
$$



- if the slope is positive (Pnew > Pold) the duty cycle is increased *($d = d + \Delta d$).*
- This means that the slope is positive and the module is operating in the constant current region.
- In case of the slope being negative (Pnew < *Pold)* then the duty cycle is reduced

  ($d = d - \Delta d$), as the operating region in this case is the constant voltage region.
- This algorithm can be implemented using a microcontroller.

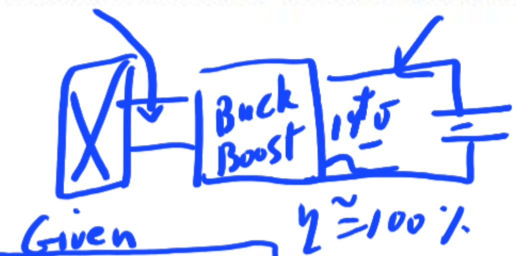


Start
P& O
Hill Climbing method
Set Duty d
Read Vnew,Inew
Vold=Vnew,Pold= Pnew
Pnew=Vnew,Inew
d=d+Δd
No
Pnew> Pold
Yes
Vnew> Vold
No
Yes
Vnew> Vold
Yes
No
d=d-Δd
Vold=Vnew,Pold= Pnew

5.13 Consider a single 87.5 W, First Solar CdTe module (Table 5.3) used to charge a 12-V battery.

a. What duty cycle should be provided to a maximum-power-point, buck-boost converter to deliver 14-V to the battery when the module is working at standard test conditions (STC)? How many amps will it deliver to the battery under those conditions?

b. Suppose ambient temperature is 25°C with 1-sun of insolation. Recalculate the amps delivered to the battery.



SOLN:

a. The First Solar module has an STC MPP of 1.78 A, 49.2 V. So the converter needs to drop the 49.2 V down to 14 V. From (5.36)

$$\frac{D}{1-D} = \frac{14V}{49.2V}$$

$$14 - 14D = 49.2D \quad .... \quad D = \frac{14}{14+49.2} = 0.2215$$

Since we assume power in equals power out,

$$49.2x1.78 = 14xI_B$$

$$I_B = \frac{49.2x1.78}{14} = 6.255A$$

SOLN:

b. First find cell temperature. From the table, NOCT = 45°C so from (5.23):

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20}{0.8}\right)S = 25 + \left(\frac{45 - 20}{0.8}\right)1 = 56.25^{o}$$

These cells have a - 0.25%/°C power degradation, so at 25°C:

Power loss = 0.25%/°C x (56.25-25)°C = 7.8125%

Power @ 25°C = 87.5 (1 - 0.078125) = 80.39 W

Again, with power in equal power out:

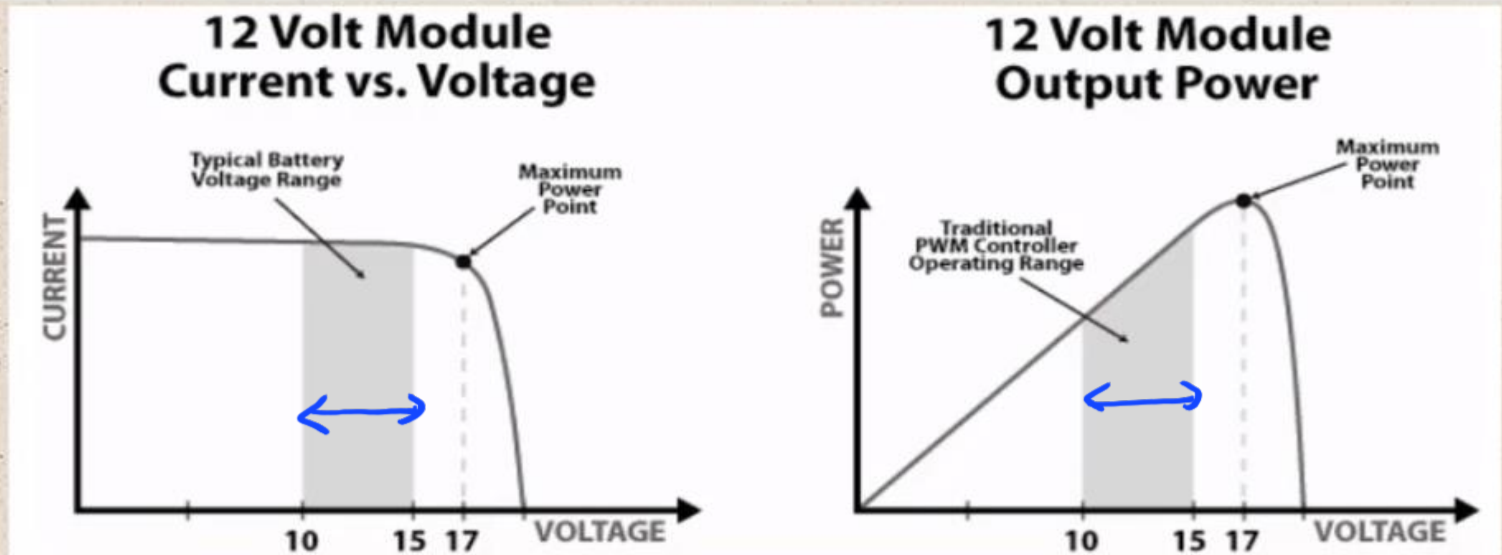
80.39 = 14V x I A   Charging current = 80.39/14 = 5.74 A

That's a loss of 8.2% due to temperature.

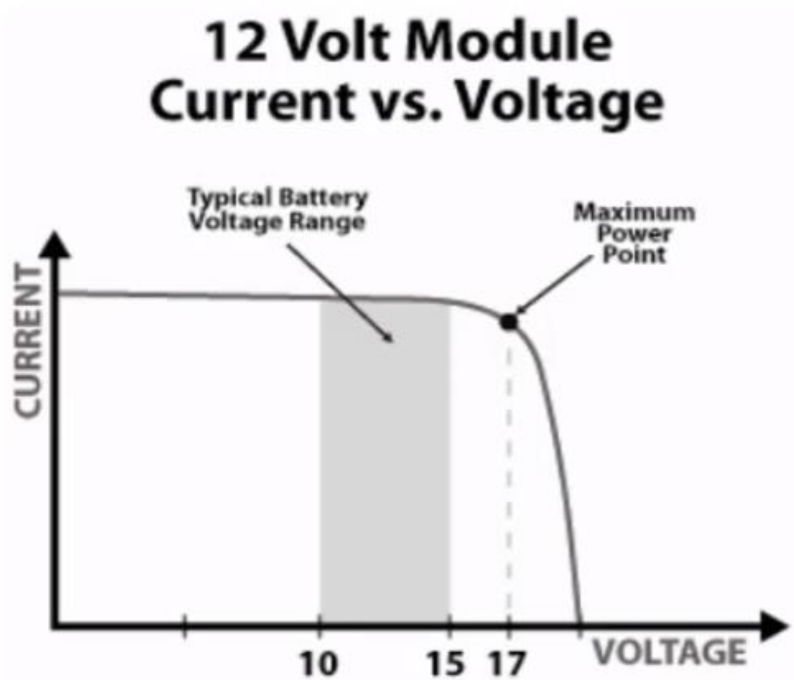
PWM Charging:

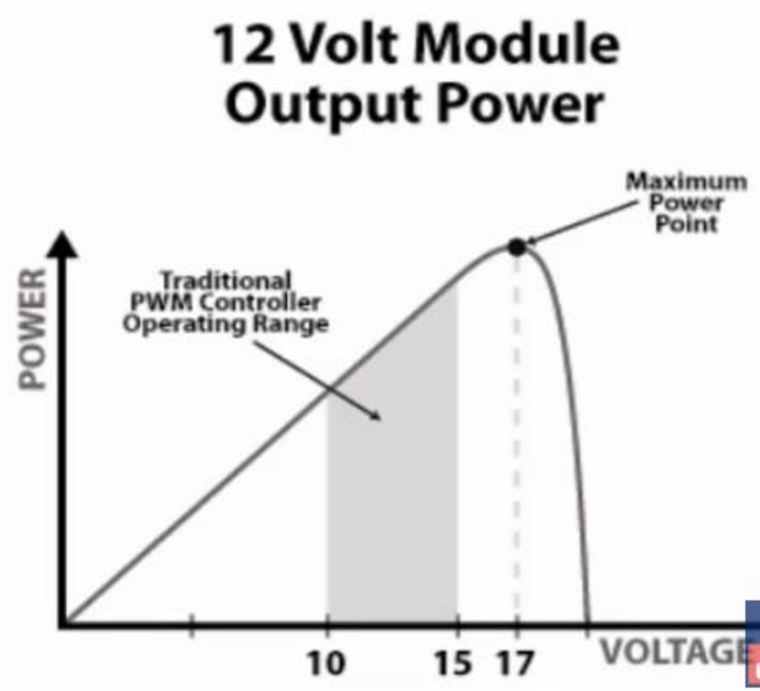
Traditional solar regulators featuring PWM (pulse width modulation) charging operate by connecting the solar array directly to the battery bank. When the array is connected directly to the battery bank, the array output voltage is 'pulled down' to the battery voltage. This occurs because the batteries are a very large load for the limited current sourcing capability of a solar array.

The V_{mp} (maximum power voltage) rating is the voltage where the product of the output current and output voltage (amps * volts) is greatest and output power (watts = amps * volts) is maximized. Module wattage ratings (i.e. 100W, 205W) are normally specified at the V_{mp}.



Using a nominal 12V system as an example, the battery voltage will normally be somewhere between 10 – 15 Vdc. However, 12V nominal solar modules commonly have a V_{mp} of about 17V. When the array (having V_{mp} of 17V) is connected to the batteries for charging, the batteries pull down the output voltage of the array. Thus, the array is not operating at its most efficient voltage of 17V, but rather at somewhere between 10 and 15V. The following graphs illustrate this phenomenon:



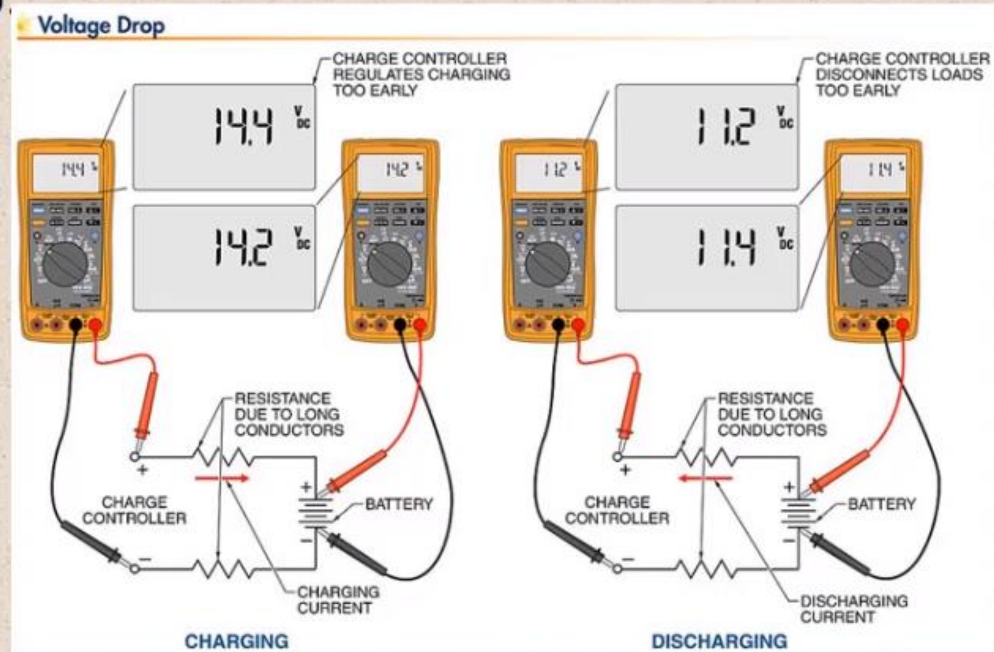


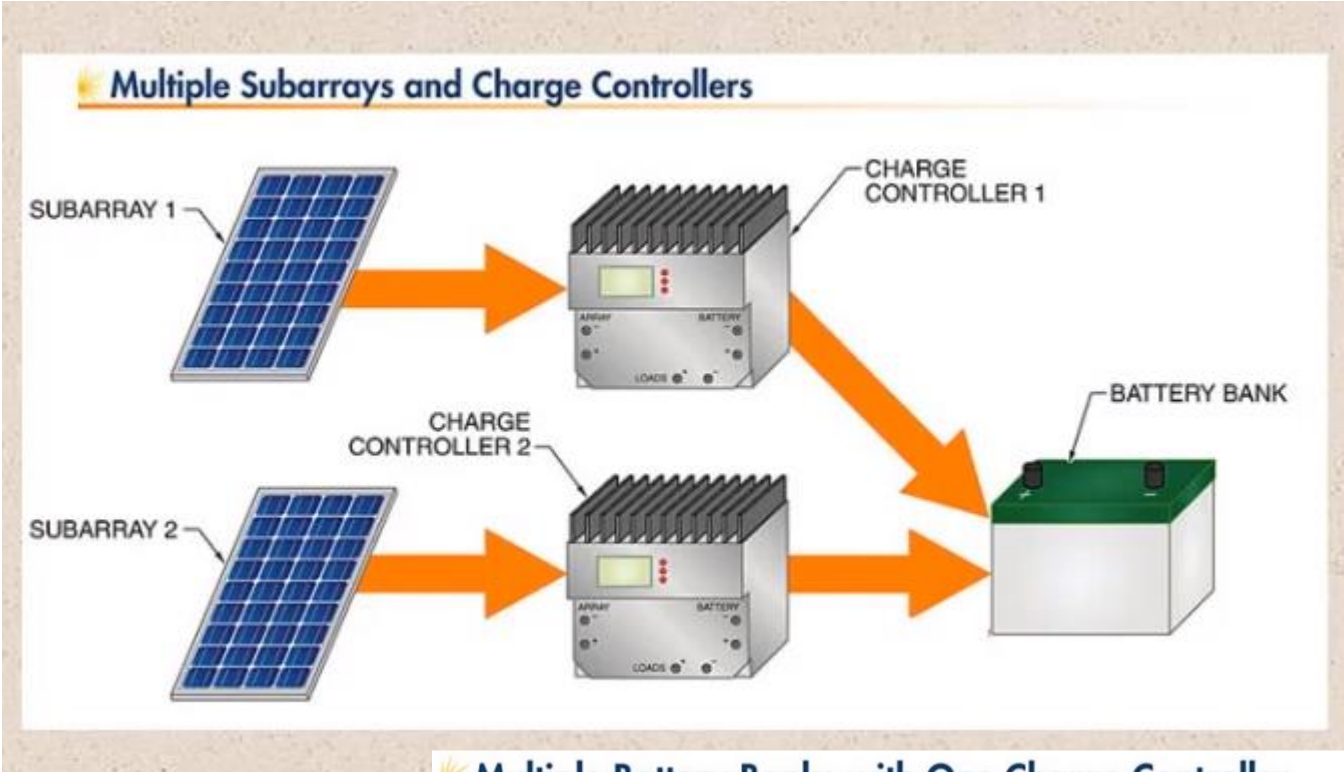
Set points?

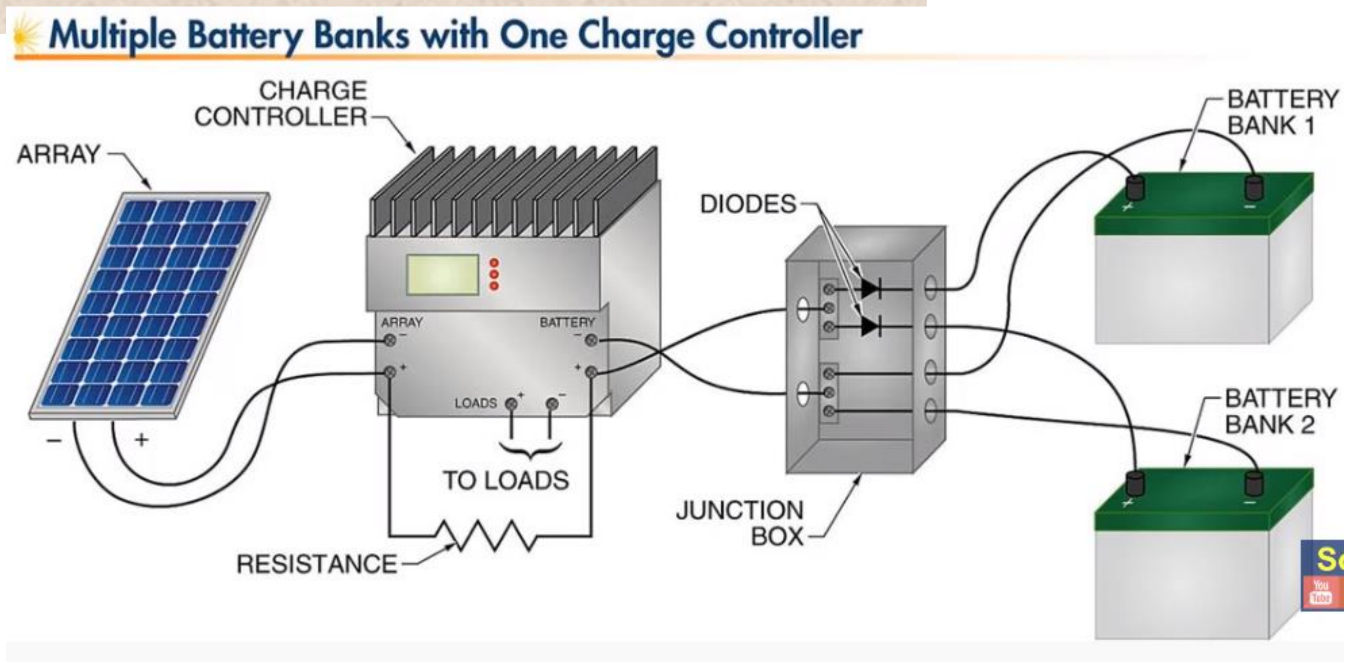
The voltages at which the controller changes the charge rate are called **set points**. When determining the ideal set points, there is some compromise between charging quickly before the sun goes down, and mildly overcharging the battery. The determination of set points depends on the anticipated patterns of usage, the type of battery, and to some extent, the experience and philosophy of the system designer or operator. Some controllers have adjustable set points, while others do not.

Cables and voltage drop

Installing charge controllers close to batteries also minimizes voltage drop. As charging current increases on the conductors between the charge controller and battery terminals, the voltage drop increases. Since many charge controllers sense battery voltage with the conductors used to deliver charging current, the measured voltage is slightly higher than the actual battery voltage. This prematurely activates charge regulation, causing the battery to be undercharged.




Multiple Subarrays and Charge Controllers
SUBARRAY 1
CHARGE
CONTROLLER 1
BATTERY BANK
CHARGE
CONTROLLER 2
SUBARRAY 2


Multiple Battery Banks with One Charge Controller
CHARGE
CONTROLLER
ARRAY
BATTERY
BANK 1
DIODES
ARRAY
BATTERY
LOADS
TO LOADS
RESISTANCE
JUNCTION
BOX
BATTERY
BANK 2

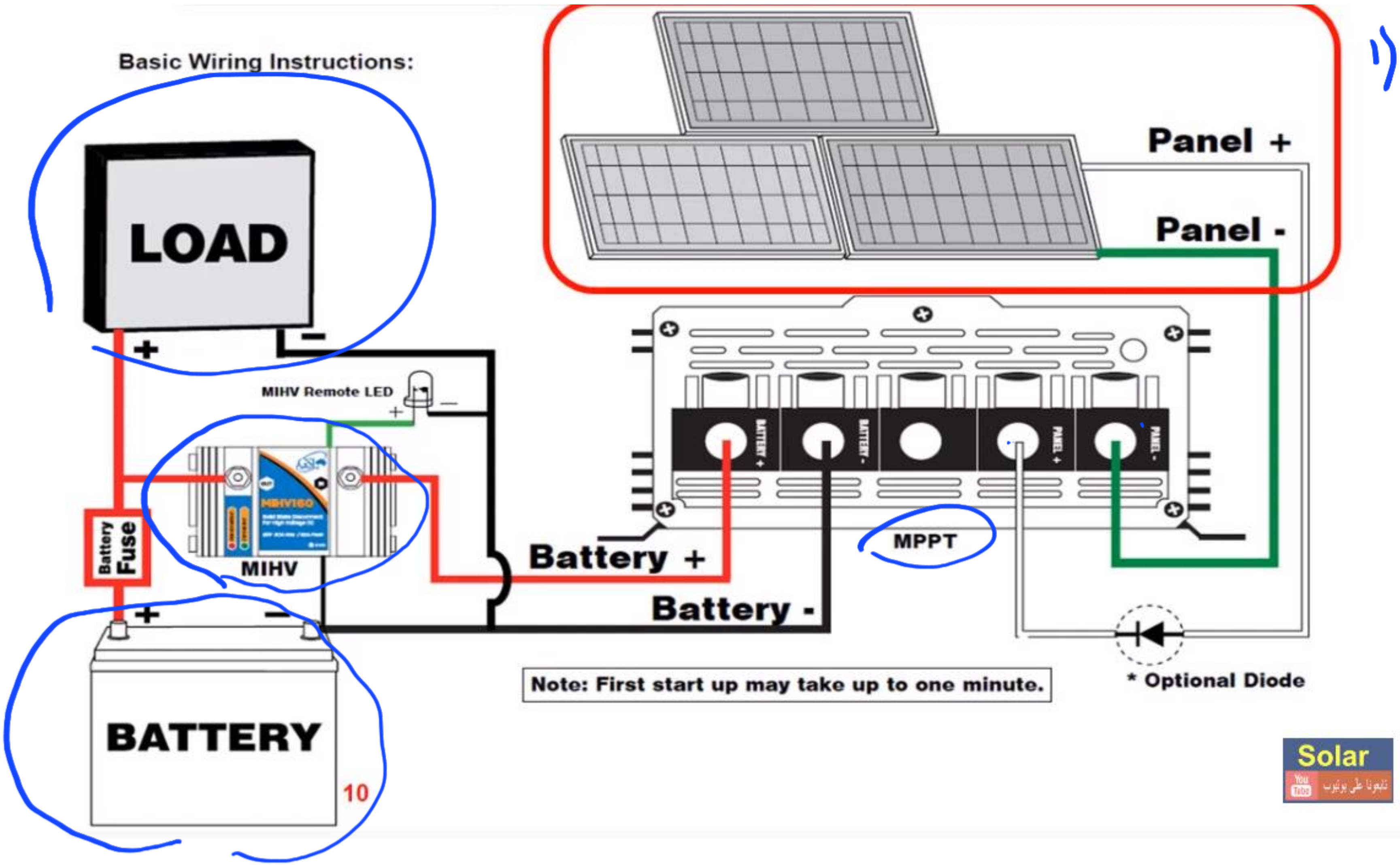
BlueSolar PWM-Pro	12/24-5	12/24-10	12/24-20	12/24-30
Battery Voltage	12/24V with automatic system voltage detection			
Rated charge current	5A	10A	20A	30A
Automatic load disconnect	Yes			
Maximum solar voltage	28V / 55V (1)			
Self-consumption	< 10mA			
Load output	Manual control + low voltage disconnect			
Protection	Battery reverse polarity (fuse)		Output short circuit	Over temperature
Battery temperature sensor	Optional (article SCC940100100)			
Temperature compensation	-30 mV / °C resp. -60 mV / °C (if temperature sensor installed)			
Remote panel	Optional (article SCC900300000)			
Grounding	Common positive			
Operating temp. range	-20 to +50°C			
Humidity (non-condensing)	Max 98%			

DEFAULT SETTINGS				
Absorption charge (2)	14.4V / 28,8V			
Float charge (2)	13.8V / 27,6V			
Equalization charge (2)	14,6V / 29,2V			
Low voltage load disconnect	11,1V / 22,2V			
Low voltage load reconnect	12,6V / 25,2V			
ENCLOSURE				
Terminal size	4mm²	4mm²	10mm²	10mm²
Protection category	IP30			
Weight	0,13kg	0,13kg	0,3kg	0,5kg
Dimensions (h x w x d)	138x70x37 mm 5.4x2.7x1.4 inch	138x70x37 mm 5.4x2.7x1.4 inch	160x82x48 mm 6.3x3.2x1.9 inch	200x100x57 mm 7.9x4.0x2.3 inch
STANDARDS				
Safety	IEC 62109-1			
Emission	EN 61000-6-1, EN 61000-6-3, ISO 7637-2			

1) For 12V use 36 cell Solar panels
For 24V use 72 cell Solar panels

Type of Charge controller

7. The latest generation of charge controllers incorporates a technology called **maximum power point tracking**, or **MPPT**. This function is designed to increase the efficiency of the PV array by converting the typically higher voltage (17-21 VDC in a 12 VDC nominal system) to the 14 VDC or so required to charge the battery. Stated simply, **the un-useable high-end voltage is converted to useable extra amps**. Remember the relationship between volts, amps, and watts: watts = amps x volts. An MPPT charge controller takes advantage of this relationship to deliver more useable power from the PV array to the batteries. The electronics


Basic Wiring Instructions:
LOAD
+
−
MIHV Remote LED
Battery Fuse
MIHV
BATTERY
10
Panel +
Panel -
Battery +
Battery -
MPPT
* Optional Diode
Note: First start up may take up to one minute.
Solar
تابعونا على يوتيوب

MPPT is most effective under these conditions:

Cold weather, cloudy or hazy days:

Normally, PV module works better at colder temperatures and MPPT is utilized to extract maximum power available from them.

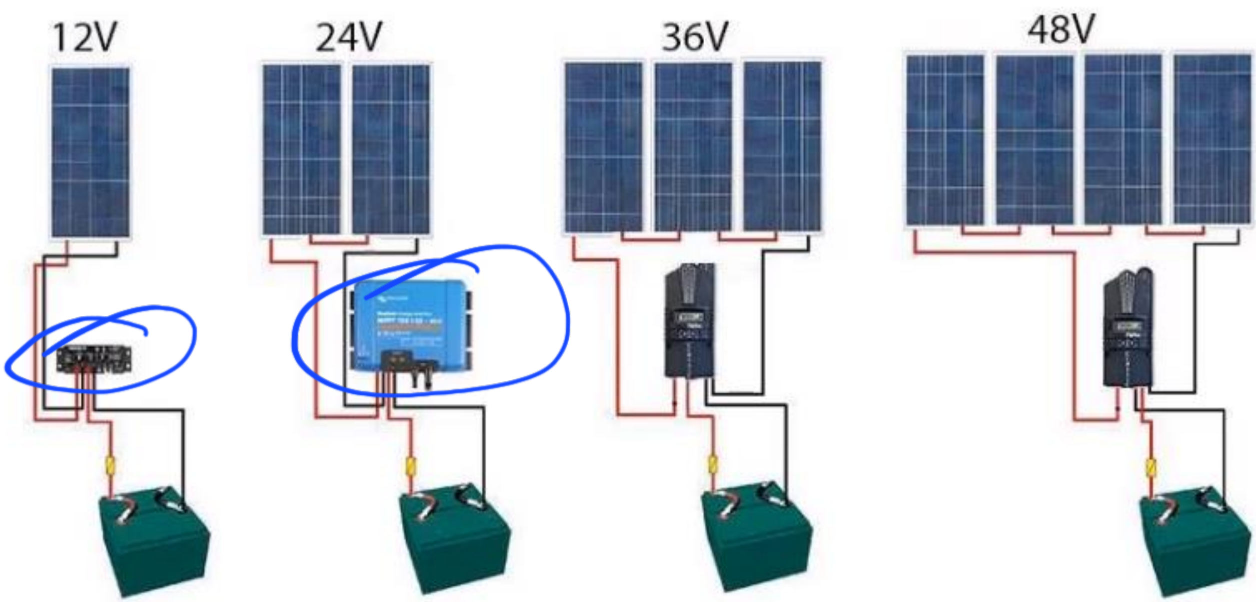
When battery is deeply discharged:

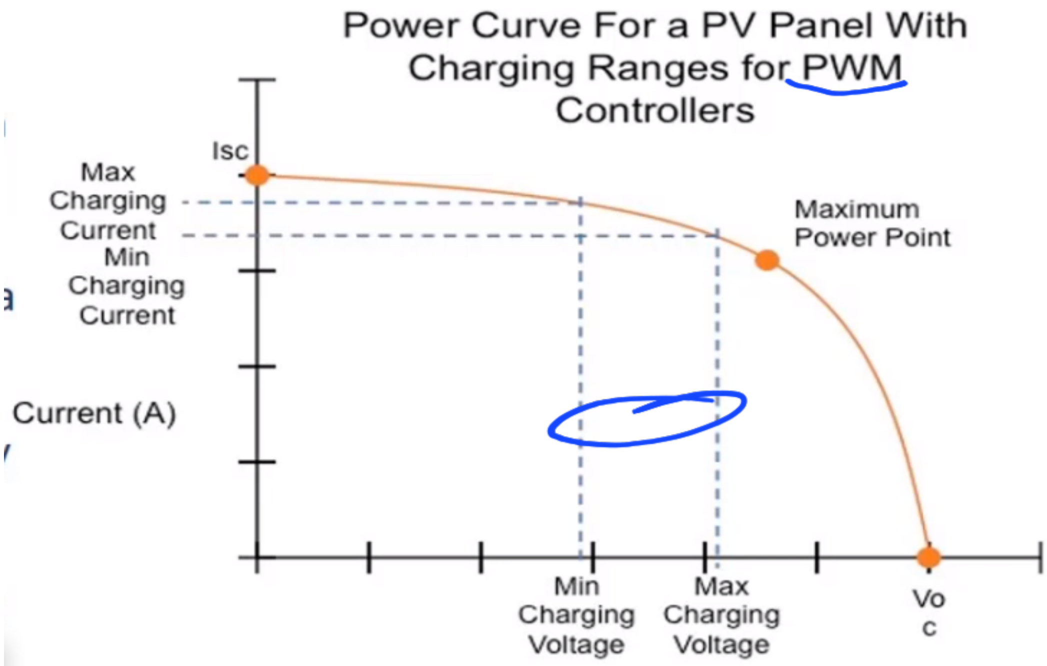
MPPT can extract more current and charge the battery if the state of charge in the battery is lowers.

Maximum Power Point Tracking Controllers

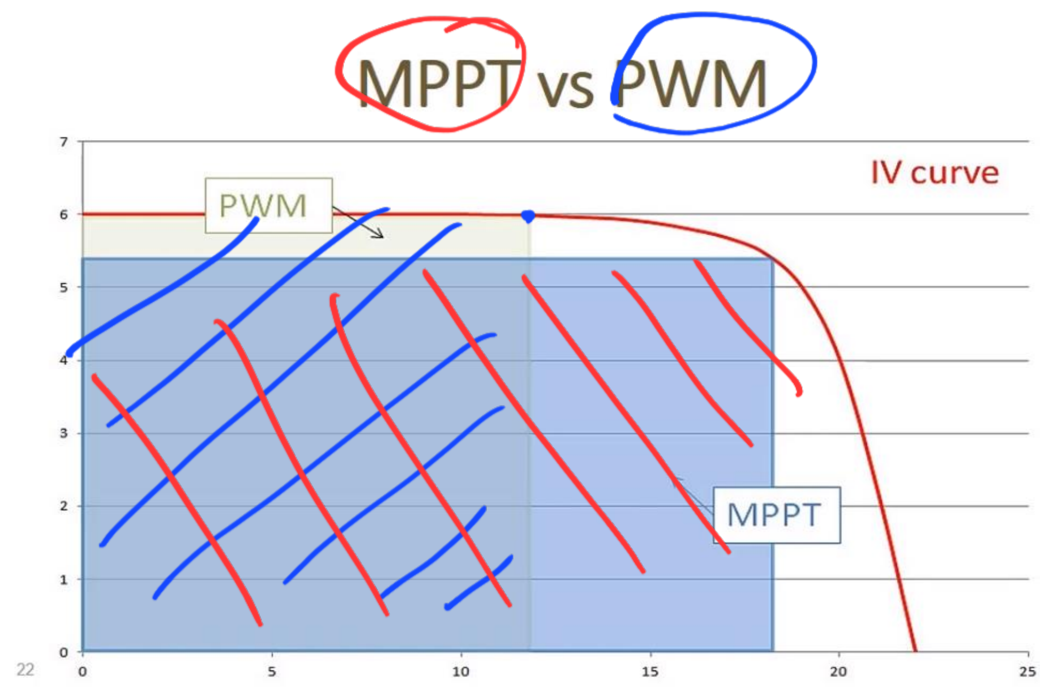
- A MPPT controller adjusts the voltage output to take advantage of the Vpp and charge the battery more

- *Peak Power Voltage* (Vpp) is the maximum power point that a PV system can deliver; varies with temperature and sunlight intensity





Only voltage control



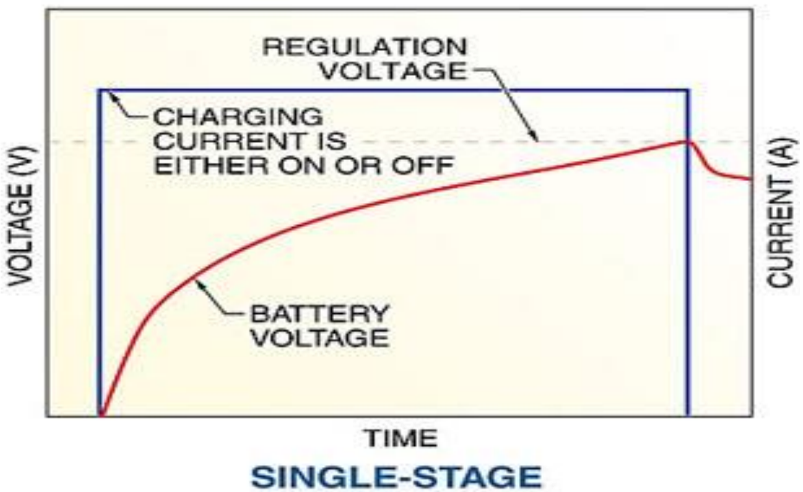
End of charge controllers
& MPPT Topic

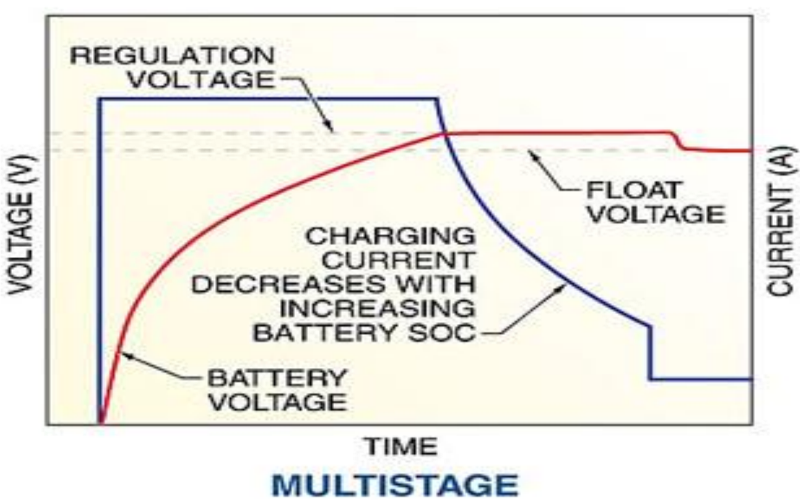
T8

L18 (L17 P2)

PV Batteries

Charging

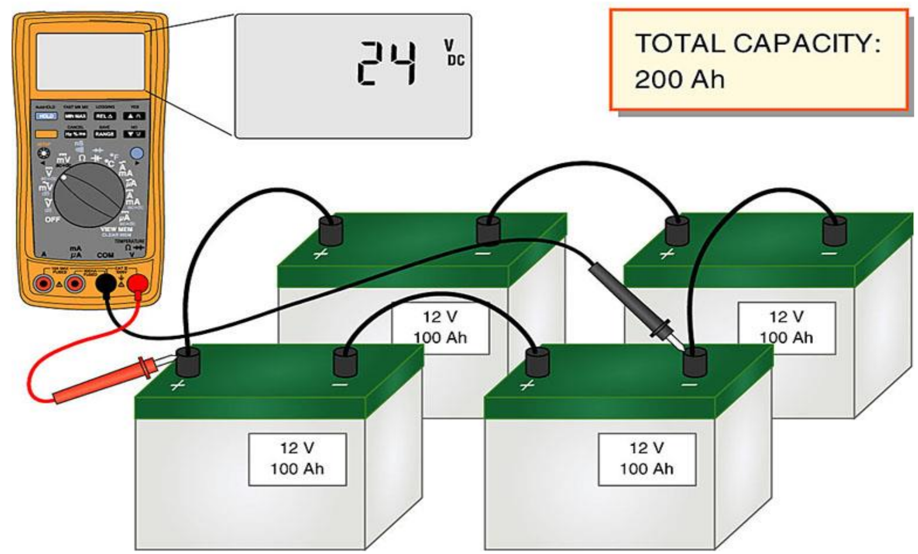




Batteries

East Penn Manufacturing Co., Inc.

Batteries in Series and Parallel

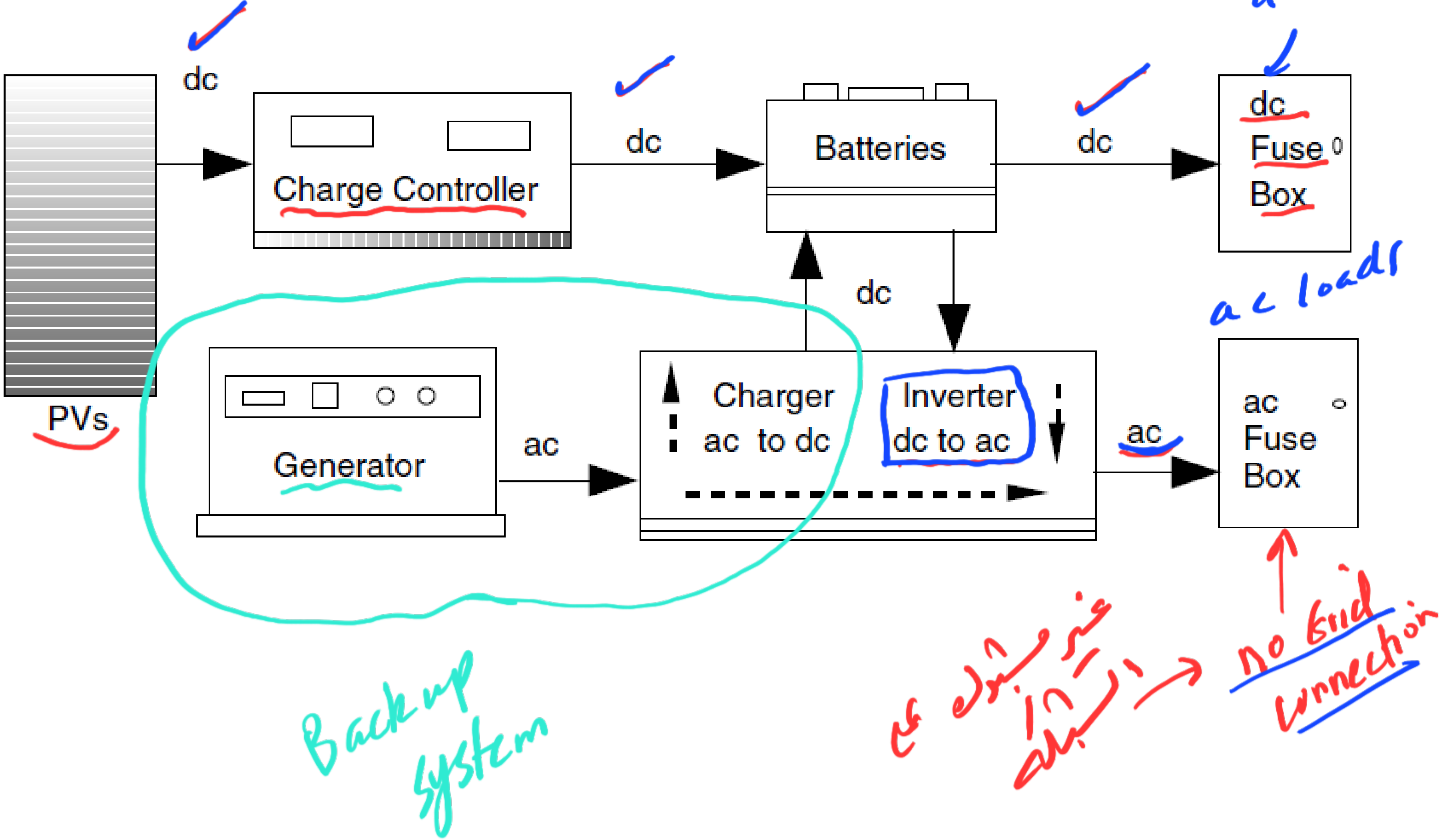


ENEE5307
2021

Outline

- Battery Principles
- Battery Types
- Battery Systems

Standalone PV System with Backup Generator



Batteries

- Stand-alone systems need a method to store energy gathered during good times to be able to use it during the bad.
- Lead-acid batteries are presently the most commonly used type in PV systems.
- In addition to energy storage, batteries provide several other important energy services for PV systems, :
- 1) the ability to provide surges of current that are much higher than the instantaneous current available from the array,
- 2) Controlling the output voltage of the array so that loads receive voltages that are within their own range of acceptability.

Batteries Classifications

1. Primary Batteries- cannot be recharged
2. Secondary batteries: can be recharged

- Batteries are divided into classes based on discharge and cycle characteristics.
- **Secondary batteries are often classified as**: traction; starting, lighting, and ignition (SLI); or stationary batteries.
- The differences in their design and materials result in different discharge and cycle characteristics

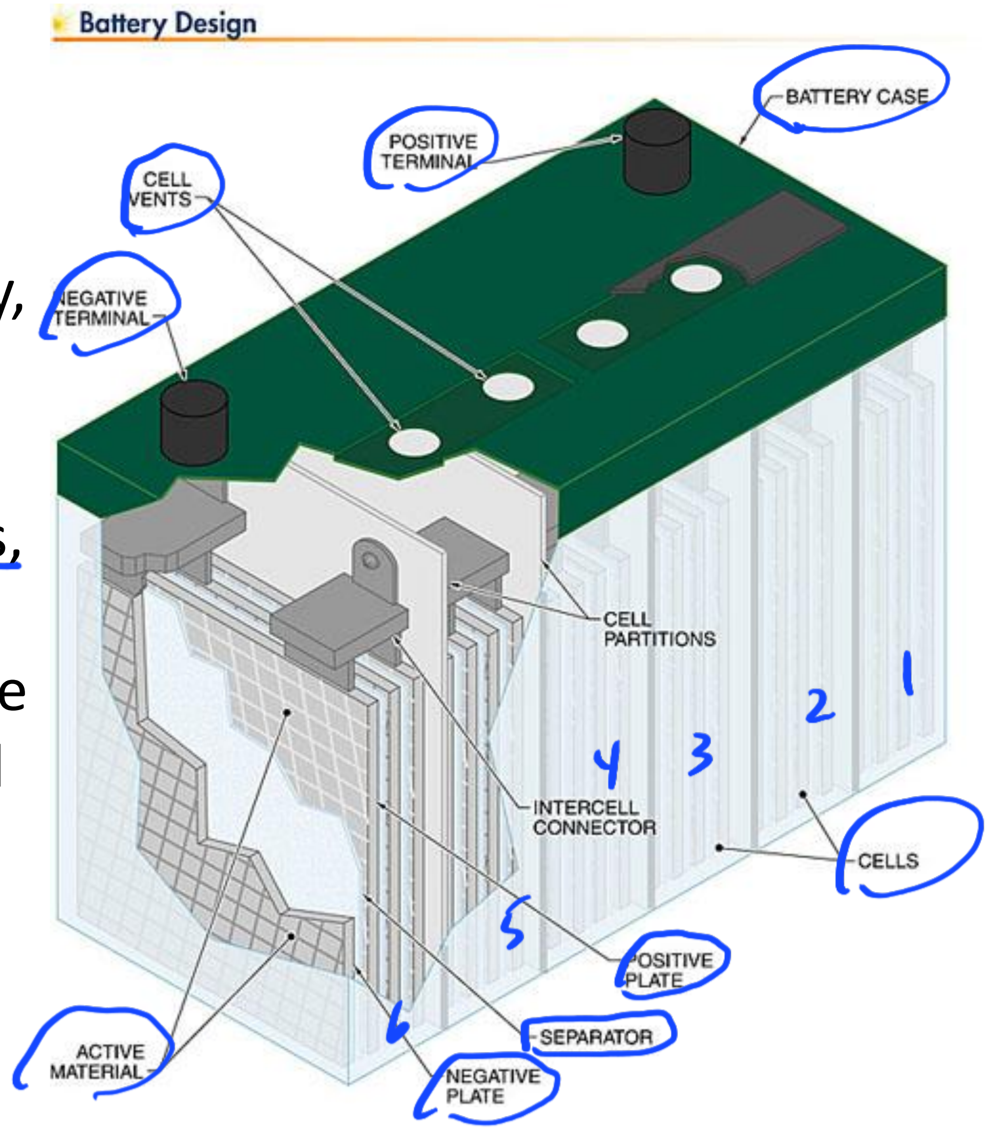
Battery Classifications

TRACTION BATTERIES

SLI BATTERIES

STATIONARY BATTERIES

- **Many components are common to various battery types**.
- **In each cell**, there can be a single pair or, more commonly, **several pairs of positive and negative plates.**
- When there are multiple pairs, all the positive plates are connected together and all the negative plates are connected together.
- ***Electrolyte*** is the conducting medium that allows the transfer of ions between battery cell plates.
- Electrolyte may be in a liquid or gelled form.



- **Thicker plates** tolerate deeper discharges over long periods while maintaining good adhesion of the active material to the grid, resulting in longer battery life.
- Thicker plates and larger cases mean that these batteries are big and heavy.
- A single 12-V deep-discharge battery can weigh several hundred pounds.
- They are designed to be discharged repeatedly by 80% of their capacity without harm, although such deep discharges result in a lower lifetime number of cycles

- **Thinner plates** allow more pairs per cell, maximizing surface area for delivering high currents.

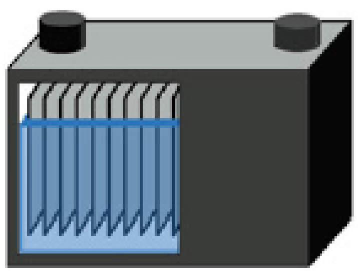


Figure 1: Starter battery

The starter battery has many thin plates in parallel to achieve low resistance with high surface area. The starter battery does not allow deep cycling.

Courtesy of Cadex

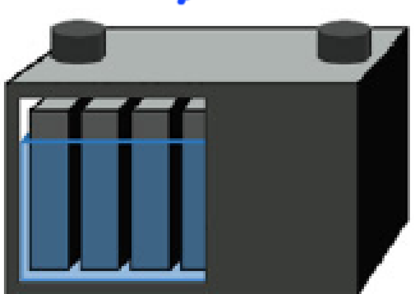


Figure 2: Deep-cycle battery

The deep-cycle battery has thick plates for improved cycling abilities. The deep-cycle battery generally allows about 300 cycles.

Courtesy of Cadex

Types of Batteries for PV Systems

- Lead-acid batteries are the most common type of batteries used in PV systems.
- Lead-acid batteries are generally inexpensive and widely available in many capacities from 10 Ah to over 1000 Ah.
- Their deep-cycle characteristics make them ideal for PV applications, **but they do not tolerate extreme temperatures well and may require frequent maintenance**
- The characteristics of lead-acid batteries vary between different designs.

Lead-Acid Battery Characteristics

	TYPE	COST	AVAILABILITY	DEEP-CYCLE PERFORMANCE	TEMPERATURE TOLERANCE	MAINTENANCE
Flooded electrolyte	Lead-antimony	low	very good	good	good	high
	Lead-calcium open-vent	low	very good	poor	poor	medium
	Lead-calcium sealed-vent	low	very good	poor	poor	low
	Lead-antimony/lead-calcium	low	limited	good	good	medium
Captive electrolyte	Lead-calcium sealed-vent	medium	limited	fair	poor	low
	Lead-antimony/lead-calcium	medium	limited	fair	poor	low

Liquid

Gel

Types of Batteries for PV Systems

- Competitors to conventional lead-acid batteries include:

(1) nickel–cadmium,

(2) nickel–metal hydride,

(3) lithium–ion,

(4) lithium–polymer,

(5) and nickel–zinc technologies.

- Of these, only nickel–cadmium "Nicads" are even barely competitive with lead-acid batteries, but this may change in the near future due to the surge of interest and development in new battery technologies for electric and hybrid vehicles.
- Table (next slide) summarizes typical values of some of the important characteristics of these battery technologies. **(research on Battery Types and new Technologies)**

TABLE 9.14 Rough Comparison of Battery Characteristics[a]

Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000	10–15	70	60	1000
Nickel–metal hydride	100%	50	1000–2000	8–10	70	65	1200

[a] Actual performance depends greatly on how they are used.

- Lead-acid batteries are listed in three categories:

1)conventional automobile batteries for engine starting, vehicle lighting, and engine ignition (SLI);

2)low-cost, deep-cycle batteries typically used in golf carts; and

3) longer-lifetime, true deep-cycle batteries.

- Two other battery types are shown, nickel–cadmium (or Nicads) and nickel–metal hydride batteries, which are beginning to be used in some hybrid-electric vehicles.

- As can be seen, lead-acid batteries are by far the least expensive option, they have the highest efficiencies, and the more expensive ones, when used properly, can last nearly as long as their competitors.

TABLE 9.14 Rough Comparison of Battery Characteristics[a]

Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000	10–15	70	60	1000
Nickel–metal hydride	100%	50	1000–2000	8–10	70	65	1200

[a] Actual performance depends greatly on how they are used.

Basics of Lead-Acid Batteries

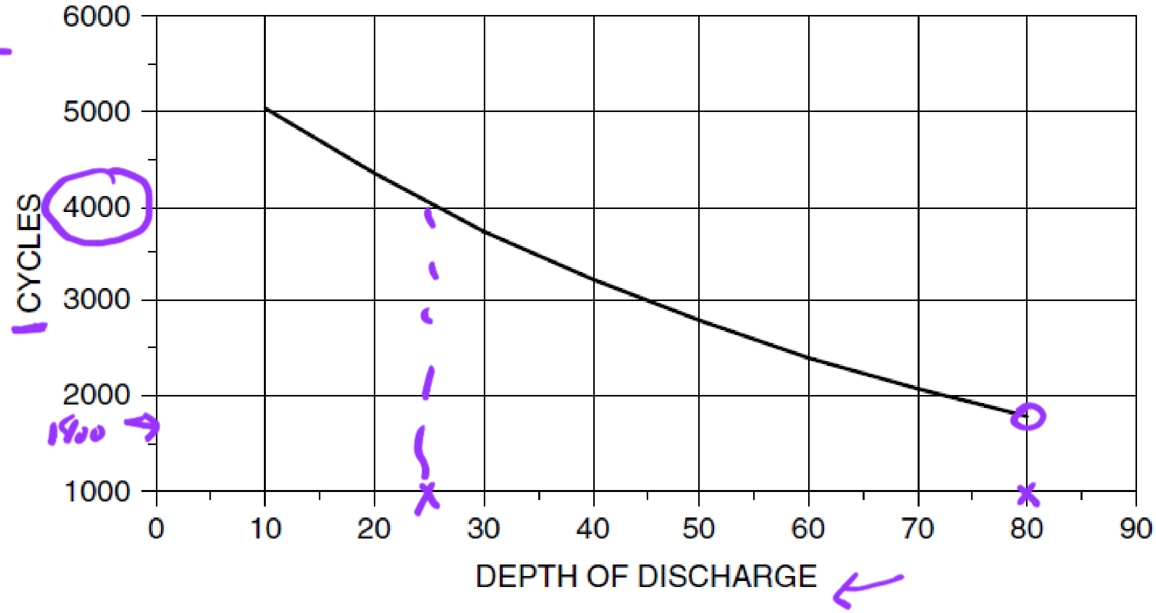
- Lead-acid batteries date back to the 1860s when inventor Raymond Gaston Plant´e fabricated the first practical cells
- Many advances since then have lead to a global market that now **exceeds $30 billion in annual retail sales**, with about three-fourths of that being starting, lighting, and ignition (SLI) automobile batteries.
- The largest Battery bank is found **in Chino, California**, is capable of **delivering 4 h of 10 MW power** (5000 A at 2000 V) into the grid.
- Automobile SLI batteries have been highly refined to perform their most important task, which is to start your engine.
- To do so, they have to provide short bursts of very high current (400–600 A!).
- Once the engine has started, its alternator quickly recharges the battery, which means that under normal circumstances the battery is almost always at or near full charge.

20% discharge only

Lead-Acid Batteries (حمض الرصاص)

- SLI batteries are not designed to withstand deep discharges, and in fact they will fail after only a few complete-discharge cycles.
- This makes them inappropriate for most PV systems, in which slow, but deep, discharges are the norm.
- If they must be used, as is sometimes the case in developing countries where they may be the only batteries available, daily discharges of less than about 20% can yield approximately 500 cycles, or a year or two of operation.
- In comparison with SLI batteries, deep discharge batteries have thicker plates, which are housed in bigger cases that provide greater space both above and beneath the plates.
- Greater space below allows more debris to accumulate without shorting out the plates, and greater space above lets there be more electrolyte in the cell to help keep water losses from exposing the plates

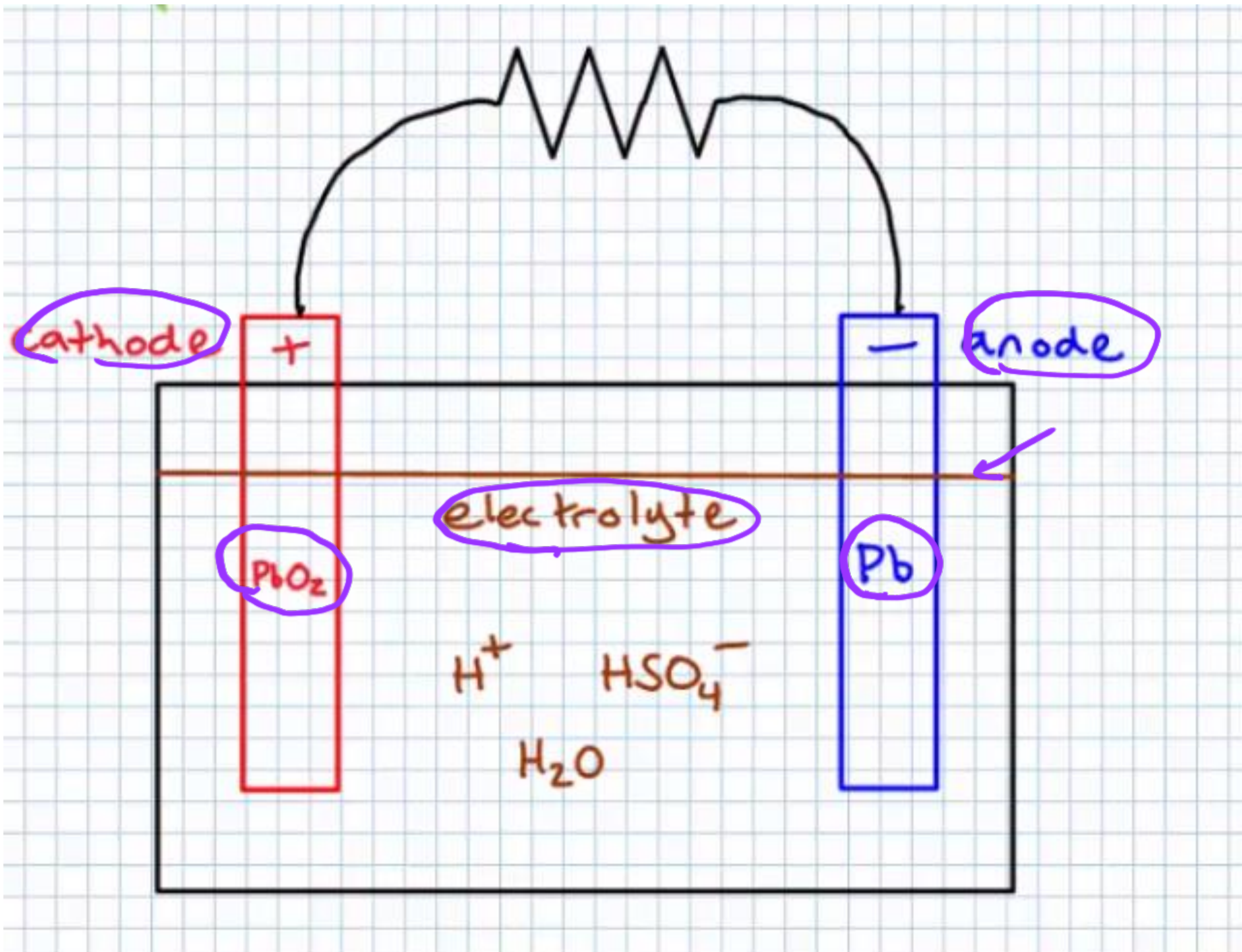
- Figure below suggests that a typical deep-cycle, lead-acid battery can be cycled about 4000 times when discharged by 25% of its rated capacity, which would give it a lifetime of over 10 years.
- At a daily discharge of 80%, about 1800 cycles could be expected, which suggests a lifetime of around 5 years.
- Other factors, including quality of battery, frequency of maintenance, charge rates, and final charging cut-off vo



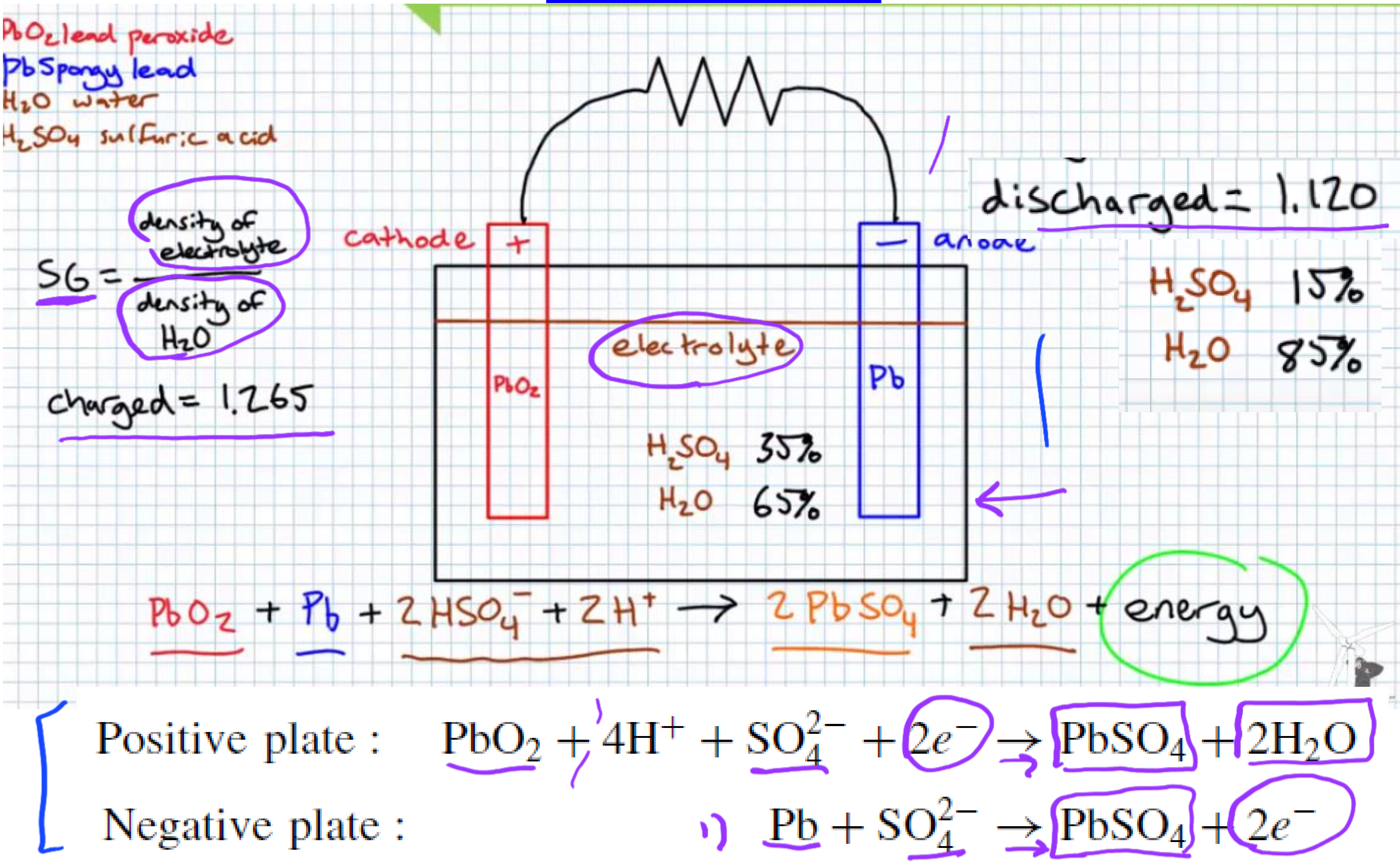
Impact of depth of discharge on the number of cycles a typical deep-cycle lead-acid battery might be able to provide. An automobile SLI battery delivers only around 500 cycles at 20% discharge.

Battery Chemistry (self Study)

- To understand some of the subtleties in sizing battery systems, we need a basic understanding of their chemistry.
- Very simply, an individual 2-V cell in a lead-acid battery consists of a positive electrode made of lead dioxide **(PbO2)** and an negative electrode made of a highly porous (مسامية عالية), metallic lead (Pb) structure, both of which are completely immersed (مغموره تماما) in an electrolyte consisting of a dilute solution of **sulfuric acid** (حمض الكبريتيك)and water.
- Thin lead plates are structurally very weak and would not hold up well to physical abuse unless **alloyed** with a strengthening material.
- Automobile SLI batteries use **calcium for strengthening**, but calcium does not tolerate discharges more than about 25 percent very well.
- Deep discharge batteries use **antimony Sb** (الاثمد من اشباه المعادن عدده الذري 51)instead, and so are often referred to as lead-antimony batteries.


cathode
+
anode
−
electrolyte
PbO2
Pb
H+
HSO4−
H2O

https://www.youtube.com/watch?v=ZRruGTRHqiw



Chemical Reactions (self study)

- The chemical reactions taking place while the battery **discharges** are as follows:

SO4 كبريتات او سلفات

$$\text{Positive plate :} \quad PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

$$\text{Negative plate :} \quad Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

- It is, by the way, simpler to refer to the terminals by their charge (positive or negative) rather than as the anode and cathode.
- Strictly speaking, the anode is the electrode at which oxidation occurs, which means that during discharge the anode is the negative terminal, but during charging the anode is the positive terminal.
- As can be seen from equation 2, during discharge the electrons are released at the negative electrode, which then flow through the load to the positive plate where they enter into the reaction given by equation 1 above

Chemical Reactions - Discharging

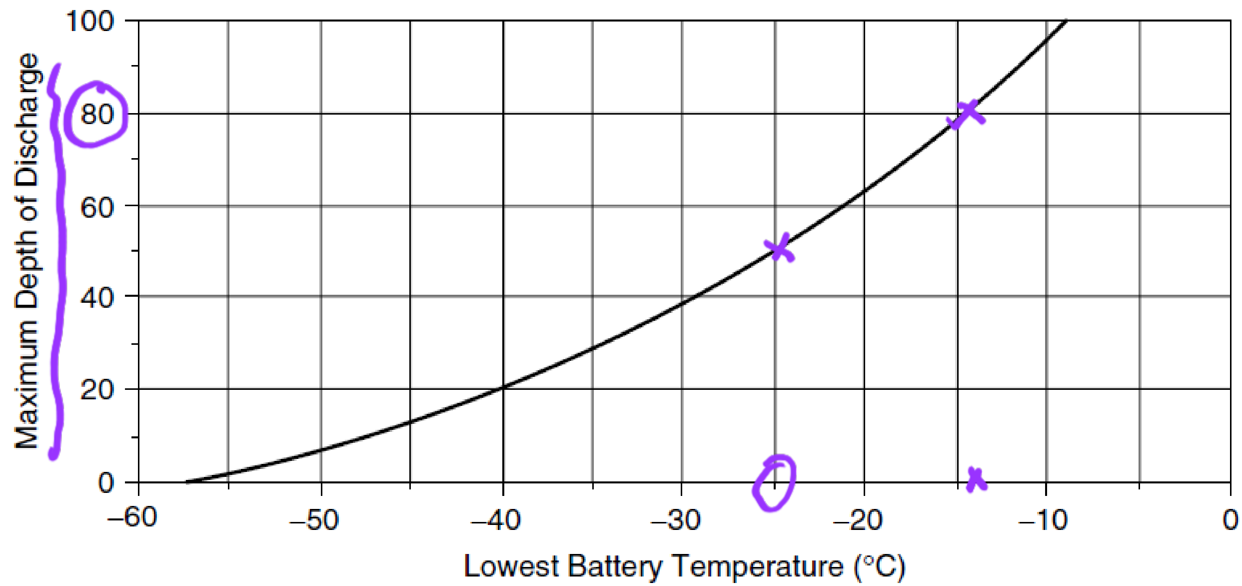
Positive plate : $PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$

Negative plate : $Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$

- The key feature of both reactions is that sulfate ions (SO_4^{2-}) that start out in the electrolyte when the battery is fully charged end up being deposited onto each of the two electrodes as lead sulfate ($PbSO_4$) during discharge.
- **This lead sulfate, which is an electrical insulator, blankets the electrodes, leaving less and less active area for the reactions to take place.**
- **As the battery approaches its fully discharged state, the cell voltage drops sharply while its internal resistance rises abruptly** , SG is reduced

- During discharge the specific gravity of the electrolyte drops as sulfate ions leave solution, providing an accurate indicator of the battery's state of charge (SOC)
- The battery is more vulnerable to freezing in its discharged state since the anti-freeze action of the sulfuric acid is diminished when there is less of it present.
- A fully discharged lead-acid battery will freeze at around −8◦C (17◦F), while a fully charged one won't freeze until the electrolyte drops below −57◦C (−71◦F).
- In very cold conditions, concern for freezing may limit the maximum allowable depth of discharge, as shown below.

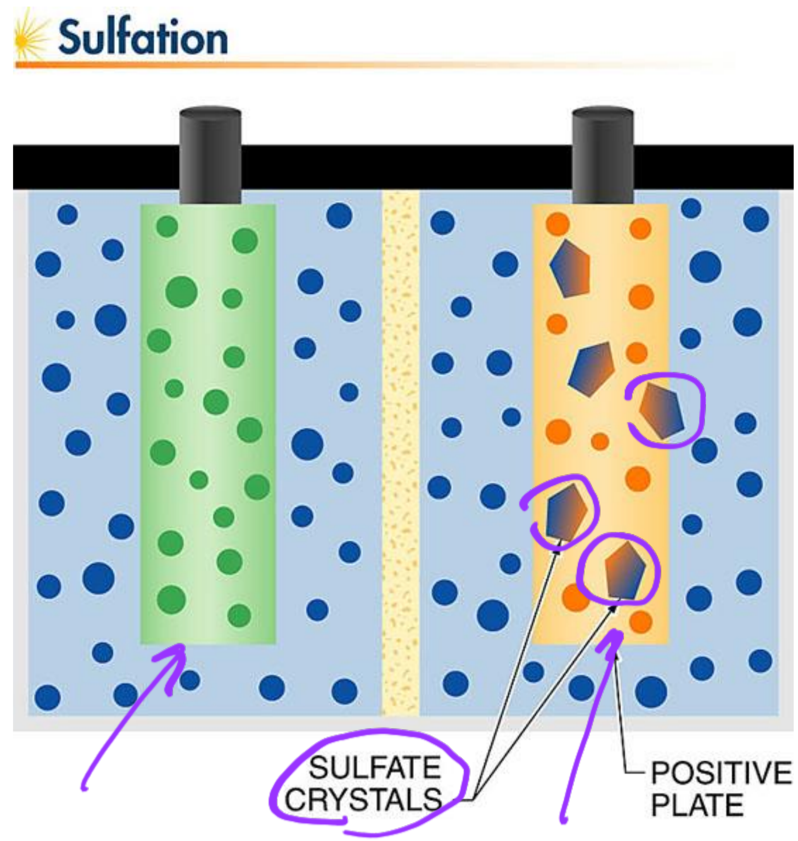
Concern for battery freezing may limit the allowable depth of discharge of a lead-acid battery.

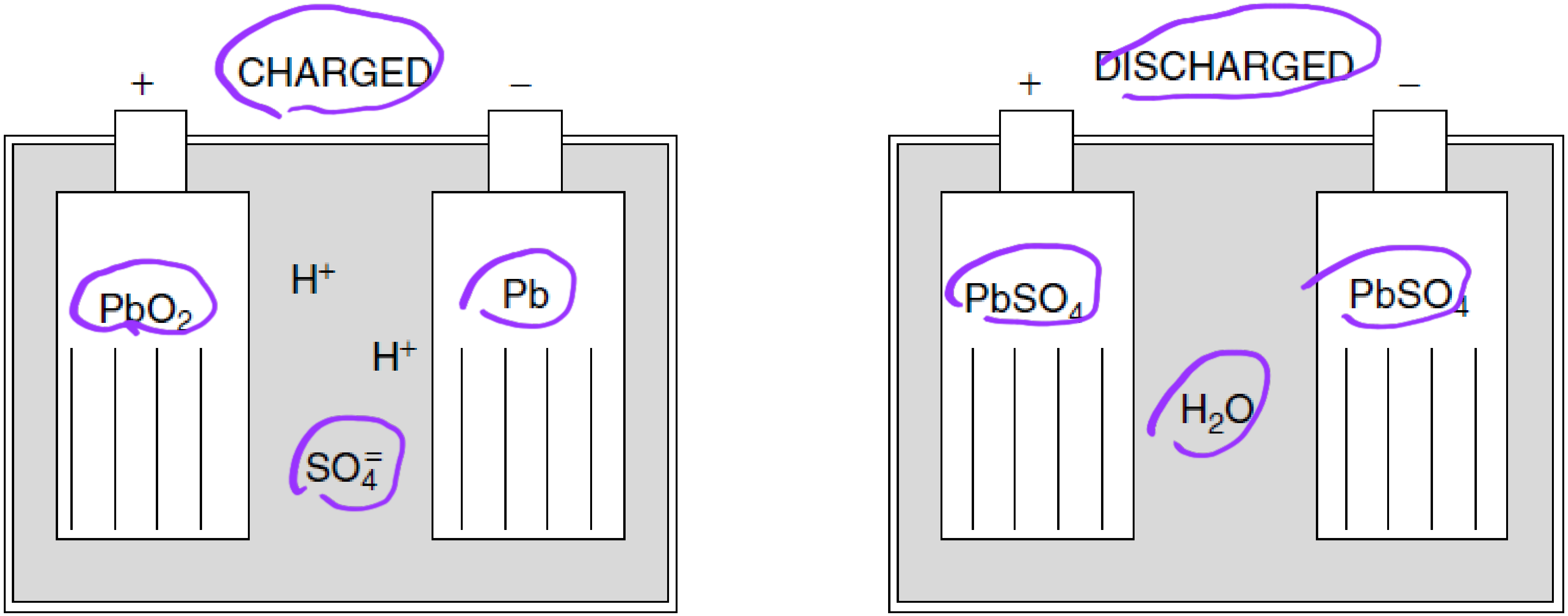


Chemical Reactions - Charging

- The opposite reactions occur during charging.
- Battery voltage and specific gravity rise, while freeze temperature and internal resistance drop.
- Sulfate is removed from the plates and reenters the electrolyte as sulfate ions
- Unfortunately, not all of the lead sulfate returns to solution, and each battery charge/discharge cycle leaves a little more sulfate permanently attached to the plates.
- **This sulfation is a primary cause of a battery's finite lifetime.**

- **Sulfation:** The amount of lead sulfate that permanently bonds to the electrodes depends on the length of time that it is allowed to exist, **which means that for good battery longevity it is important to keep batteries as fully charged as possible and to completely charge them on a regular basis.**
- Sulfation reduces the capacity of a lead-acid cell by locking away active material as crystals.





A lead-acid battery in its charged and discharged states.

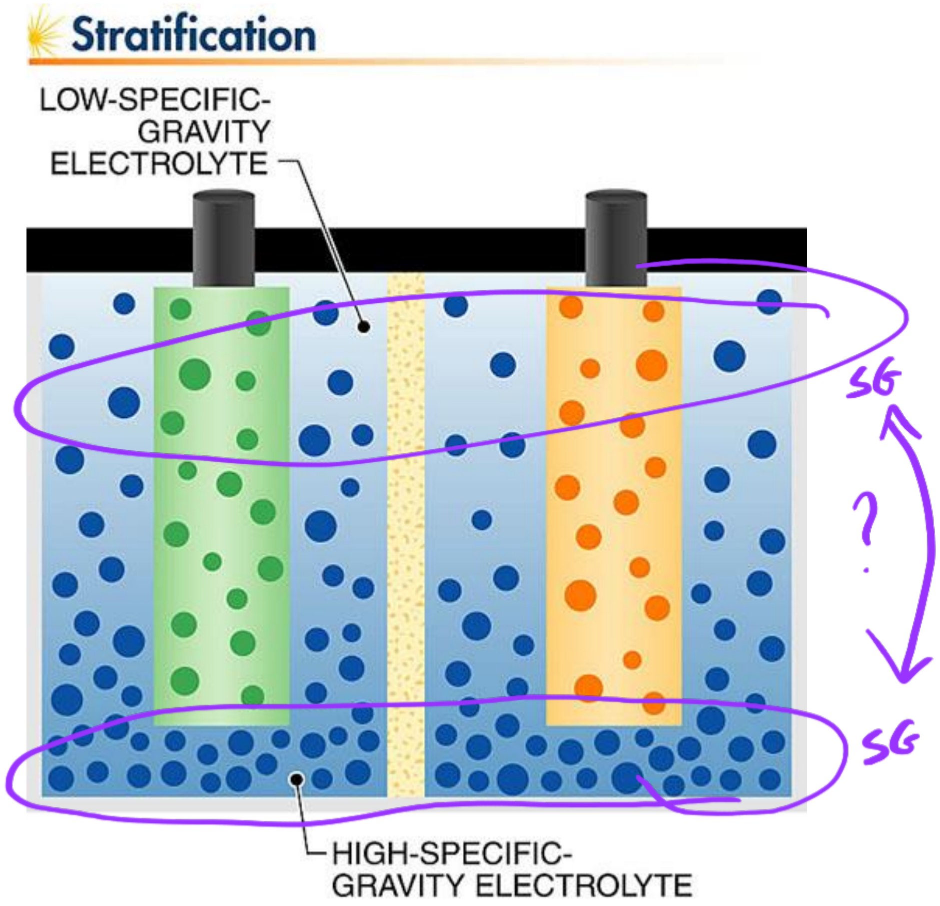
$$\text{Positive plate: } PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

$$\text{Negative plate: } Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

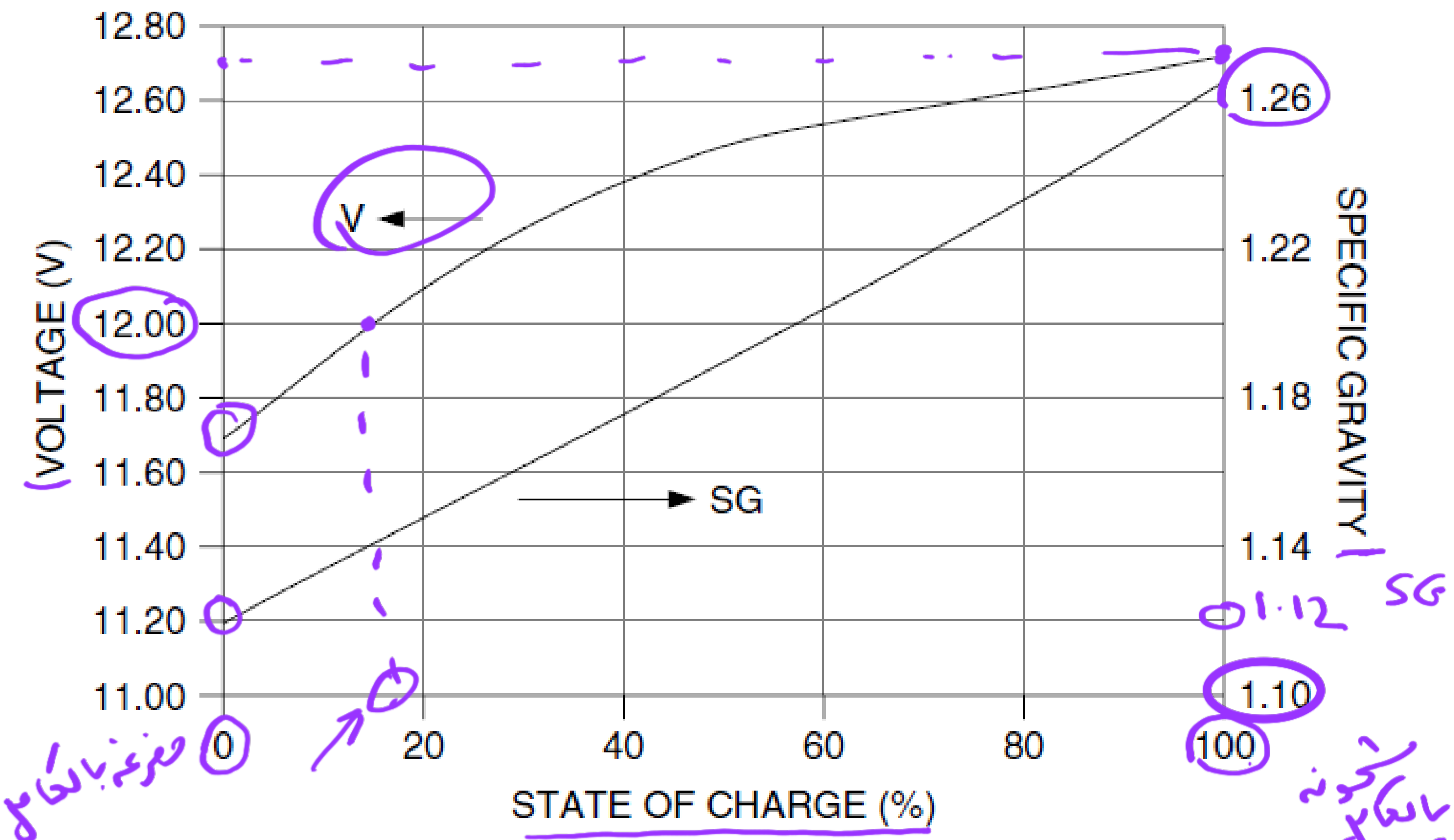
See movie

- As batteries cycle between their charged and partially discharged states, the voltage as measured at the terminals and the specific gravity of the electrolyte changes.
- While either may be used as an indication of the state of charge (SOC) of the battery, both are tricky to measure correctly.
- **To make an accurate voltage reading, the battery must be at rest**, **which means that at least several hours must elapse after any charging or discharging**.
- Specific gravity is also difficult to measure since **stratification of the electrolyte means that a sample taken from the liquid above the plates may not be an accurate average value.**
- **Stratification (ترسب)** results when the specific gravity of the electrolyte is higher at the bottom of a cell than at the top.

- During charging, electrolyte acid ions form on the plates and gradually descend to the bottom of the cell.
- Over time, the electrolyte can develop a greater acid concentration at the bottom of the cell than at the top.



Stratification is generally the result of low charge rates or undercharging, which does not produce the gassing needed to agitate the electrolyte



Bearing those complications in mind, Figure above shows voltage for a nominal lead-acid 12-V battery at rest along with the specific gravity for a well-mixed electrolyte, as a function of the state of charge.

It is interesting to note that a 12-V battery is only about 20% charged when its terminal voltage is 12 V.

Battery Storage CAPACITY

- *Capacity* is the measure of the electrical energy storage potential of a cell or battery.
- Several **physical factors** affect the capacity, including the quantity of active material; the number, design, and dimensions of the plates; and the electrolyte concentration.
- **Operational factors** affecting capacity include discharge rate, charging method, temperature, age, and condition of the cell or battery.
- Capacity is commonly expressed in ampere-hours (Ah), but can also be expressed in watt-hours (Wh). For example, a battery that delivers 5 A for 20 hr has delivered 100 Ah.
- If the battery averages 12 V during discharge, the capacity can also be expressed as 1200 Wh (100 Ah x 12V = 1200 Wh).

Battery Storage Capacity

- Energy storage in a battery is typically given in units of amp-hours (Ah) **at some nominal voltage and at some specified discharge rate.**
- A lead-acid battery, for example, has a nominal voltage of 2 V per cell (e.g., 6 cells for a 12-V battery), and manufacturers typically specify the amp-hour capacity at a discharge rate that would drain the battery down over a specified period of time at a temperature of 25◦C.
- For example, a fully charged 12-V battery that is specified to have a 10-h, 200-Ah capacity could deliver 20 A for 10 h, at which point the battery would be considered to be fully discharged

Extra Resources

- https://www.youtube.com/watch?v=sM2ss-EvAco

- https://www.youtube.com/watch?v=ZRruGTRHqiw
- Battery Charging Detailed
- https://www.youtube.com/watch?v=B9XLbuvq9As
- https://www.youtube.com/watch?v=A6mKd5__-abk

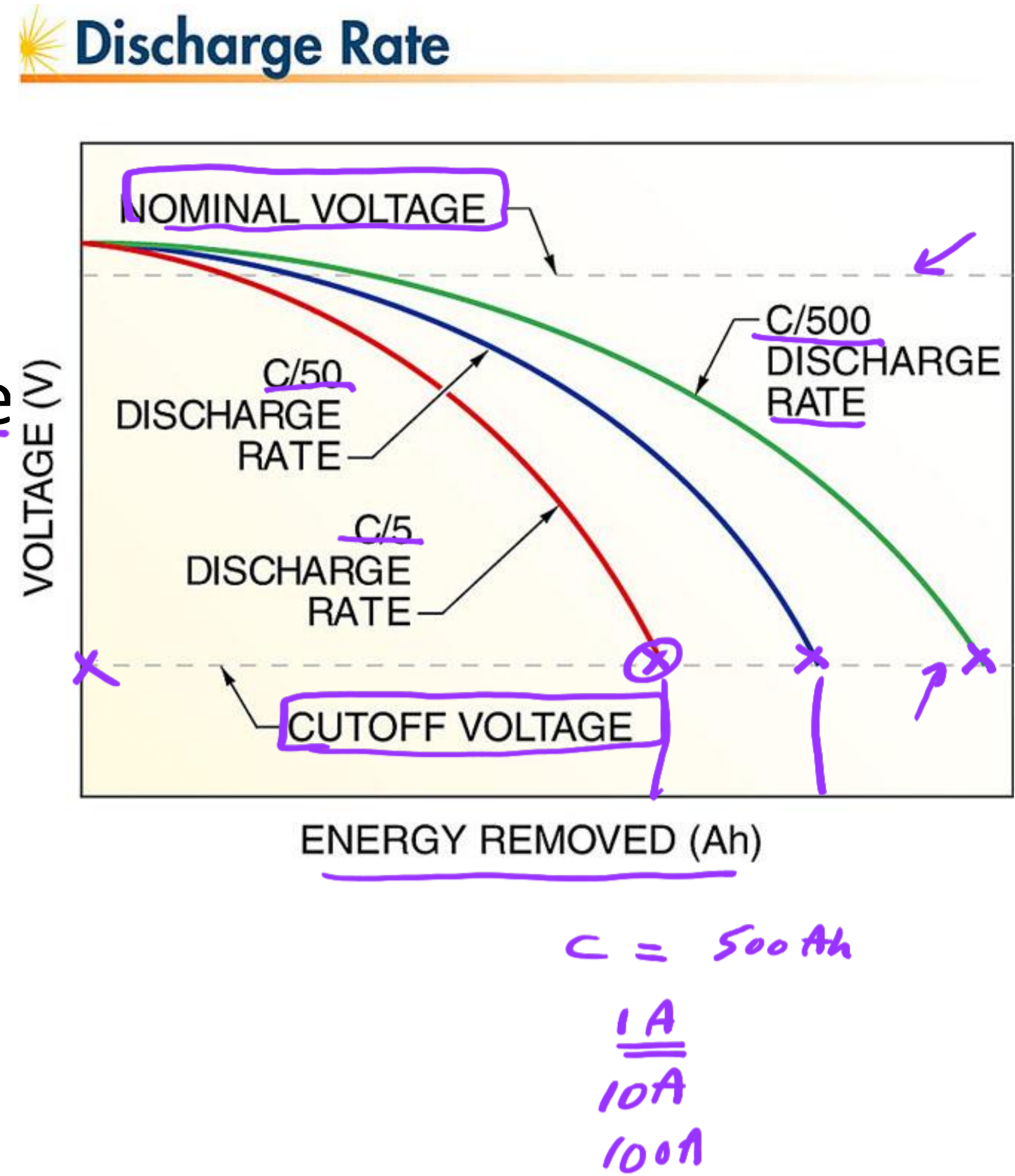
Battery Capacity and Discharge Rate

- Notice how tricky it would be to specify how much energy the battery delivered during its discharge.
- Energy is volts × amps × hours, but since voltage varies throughout the discharge period, we can't just say 12 V × 20 A × 10 h = 2400 Wh.
- To avoid that ambiguity, almost everything having to do with battery storage capacity is specified in amp-hours rather than watt-hours.

Battery Capacity and Discharge Rate

- A 200-Ah battery that is delivering 20 A is said to be discharging at a *C*/10 rate, where the *C* refers to Ah of capacity and the 10 is hours it would take to deplete (*C*/10 = 200 Ah/10 h = 20 A).
- That same 200-Ah battery won't be able to deliver 50 A for a full 4 h (*C*/4), however, and it will actually deliver 10 A for more than 20 h (*C*/20).
- In other words, the amp-hour capacity depends on the rate at which current is withdrawn. Rapid draw-down of a battery results in lower Ah capacity, while long discharge times result in higher Ah capacity

- Capacity is directly affected by the rate of discharge.
- Lower discharge rates are able to remove more energy from a battery before it reaches the cutoff voltage.
- Higher discharge rates remove less energy before the battery reaches the same voltage



Discharge Rate

- Deep-cycle batteries intended for photovoltaic systems are often specified in terms of their 20-h discharge rate ($C/20$), which is more or less of a standard, as well as in terms of the much longer $C/100$ rate that is more representative of how they are actually used.
- Table 9.15 provides some examples of such batteries, including their $C/20$ and $C/100$ rates as well as their voltage and weight.

TABLE 9.15 Example Deep-Cycle Lead-Acid Battery Characteristics

BATTERY	Voltage	Weight (lbs)	Ah @ $C/20$	Ah @ $C/100$
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

- **The amp-hour capacity of a battery is not only rate-dependent, but also depends on temperature.** Figure 9.42 captures both of these phenomena by comparing capacity under varying temperature and discharge rates to a reference condition of *C*/20 and 25◦C.
- **These curves are approximate for typical deep-cycle lead-acid batteries,** so specific data available from the battery manufacturer should be used whenever possible.
- As shown in Fig. 9.42, battery capacity decreases dramatically in colder conditions. At −30◦C (−22◦F), for example, a battery that is discharged at the *C*/20 rate will have only half of its rated capacity.

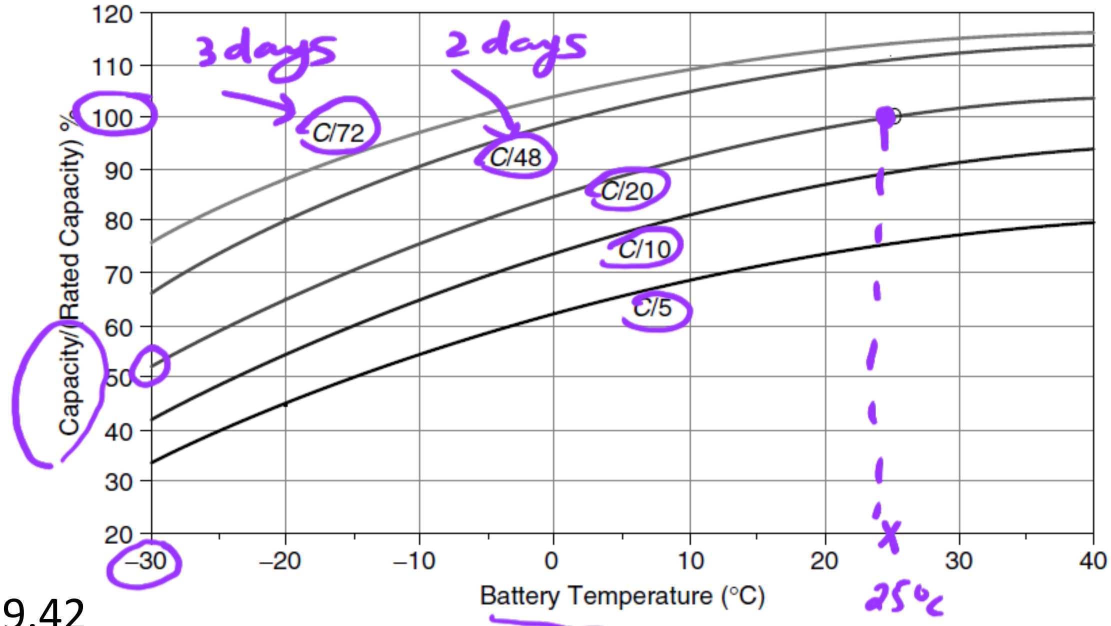
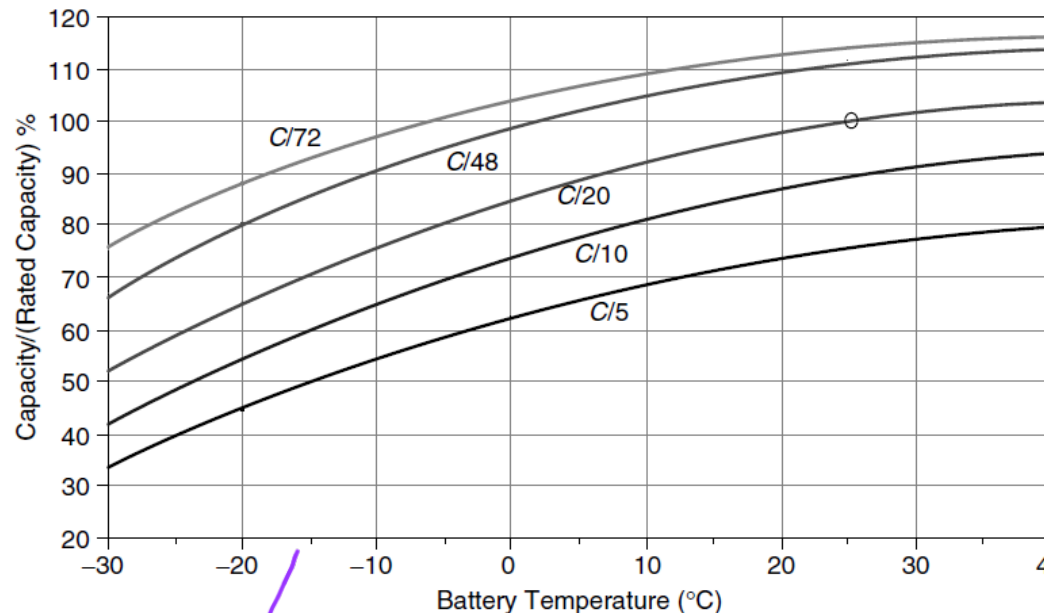


Fig. 9.42

- The combination of cold temperature effects on battery performance—decreased capacity, decreased output voltage, and increased vulnerability to freezing when discharged—mean that lead-acid batteries need to be well protected in cold climates.
- Also, the apparent improvement in battery capacity at high temperatures does not mean that heat is good for a battery.
- In fact, a rule-of-thumb estimate is that battery life is shortened by 50% for every 10◦C above the optimum 25◦C operating temperature.

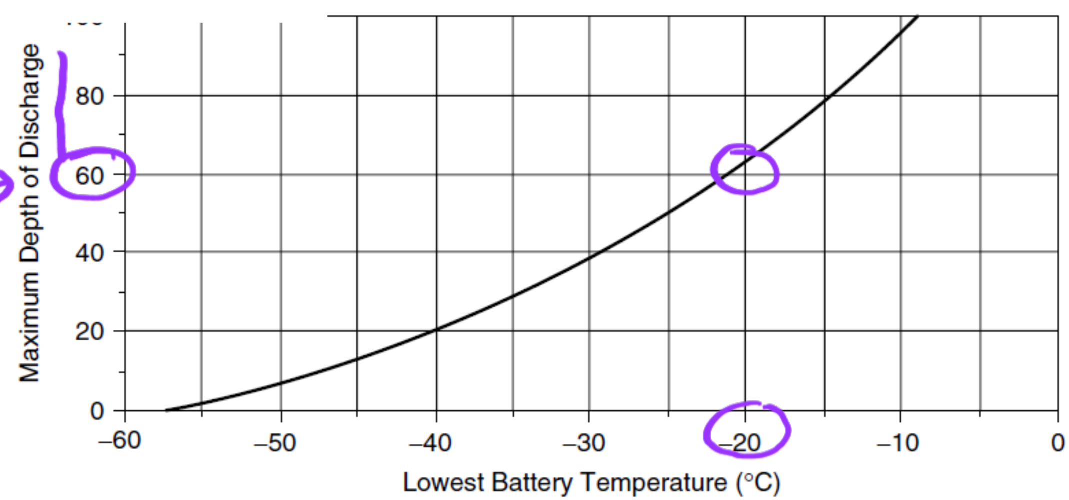
Lead-acid battery capacity depends on discharge rate and temperature. Ratio is based on a rated capacity at *C*/20 and 25◦C.



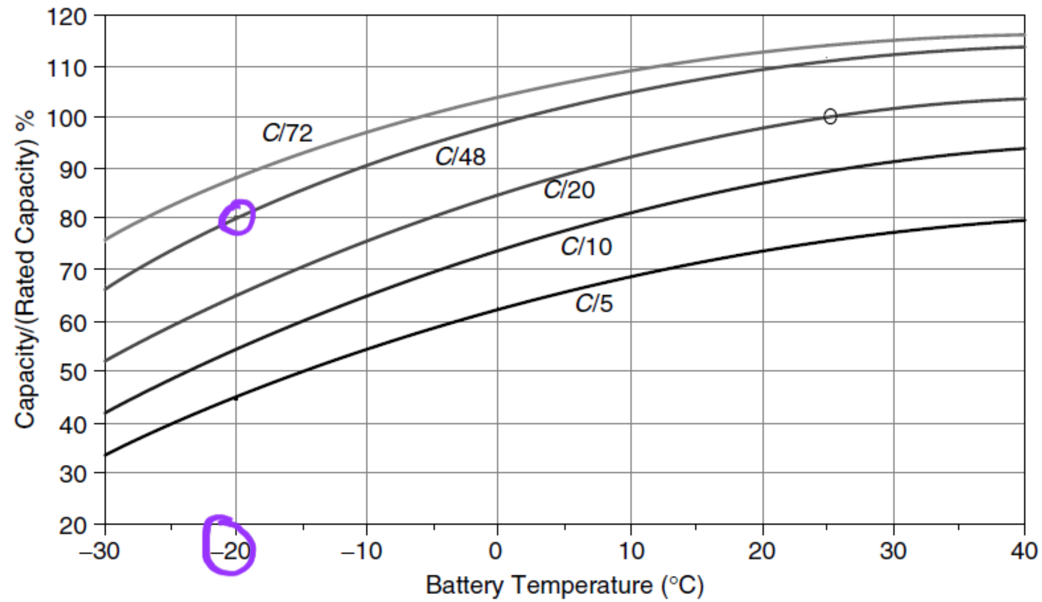
Example 9.16 Battery Storage Calculation in a Cold Climate

- Suppose that batteries located at a remote telecommunications site may drop to −20◦C. If they must provide 2 days of storage for a load that needs 500 Ah/day at 12 V, how many amp-hours of storage should be specified for the battery bank?
- ***Solution.*** From Fig., to avoid freezing, the maximum depth of discharge at −20◦C is about 60%. For 2 days of storage (autonomy), with a discharge of no more than 60%, the batteries need to store

$$\text{Battery storage} = \frac{500 \text{ Ah/day} \times 2 \text{ days}}{0.60} = 1667 \text{ Ah}$$



- Since the rated capacity of batteries is likely to be specified at an assumed temperature of 25◦C at a *C*/20 rate, we need to adjust the battery capacity to account for our different temperature and discharge period.
- From Fig. 9.42, the actual capacity of batteries at −20◦C discharged over a 48-h period is about 80% of their rated capacity. This means that we need to specify batteries with rated capacity

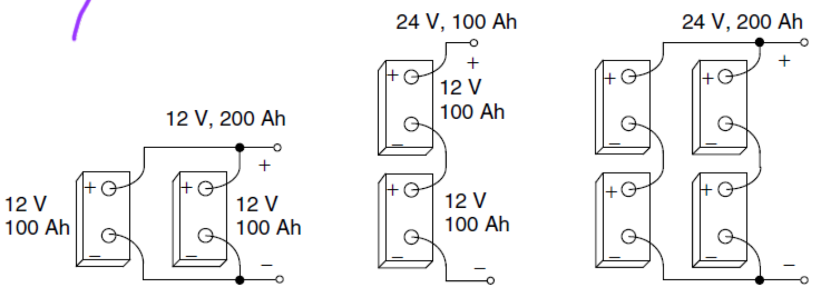


$$\text{Battery storage (25°C, 10-hour rate)} = \frac{1667\ \text{Ah}}{0.8} = 2083\ \text{Ah}$$

TABLE 9.11 Suggested System Voltages Based on Limiting Current to 100 A

Maximum ac Power	System dc Voltage
<1200 W	12 V
1200–2400 W	24 V
2400–4800 W	48 V

- Most PV–battery systems are based on 6-V or 12-V batteries, which may be wired in series and parallel combinations to achieve the needed Ah capacity and voltage rating.
- For batteries wired in series, the voltages add, but since the same current flows through each battery, the amp-hour rating of the string is the same as it is for each battery.
- For batteries wired in parallel the voltage across each battery is the same, but since currents add, the amp-hour capacity is additive.



(a) Parallel, Amp-Hrs add (b) Series, Voltages add (c) Series/Parallel

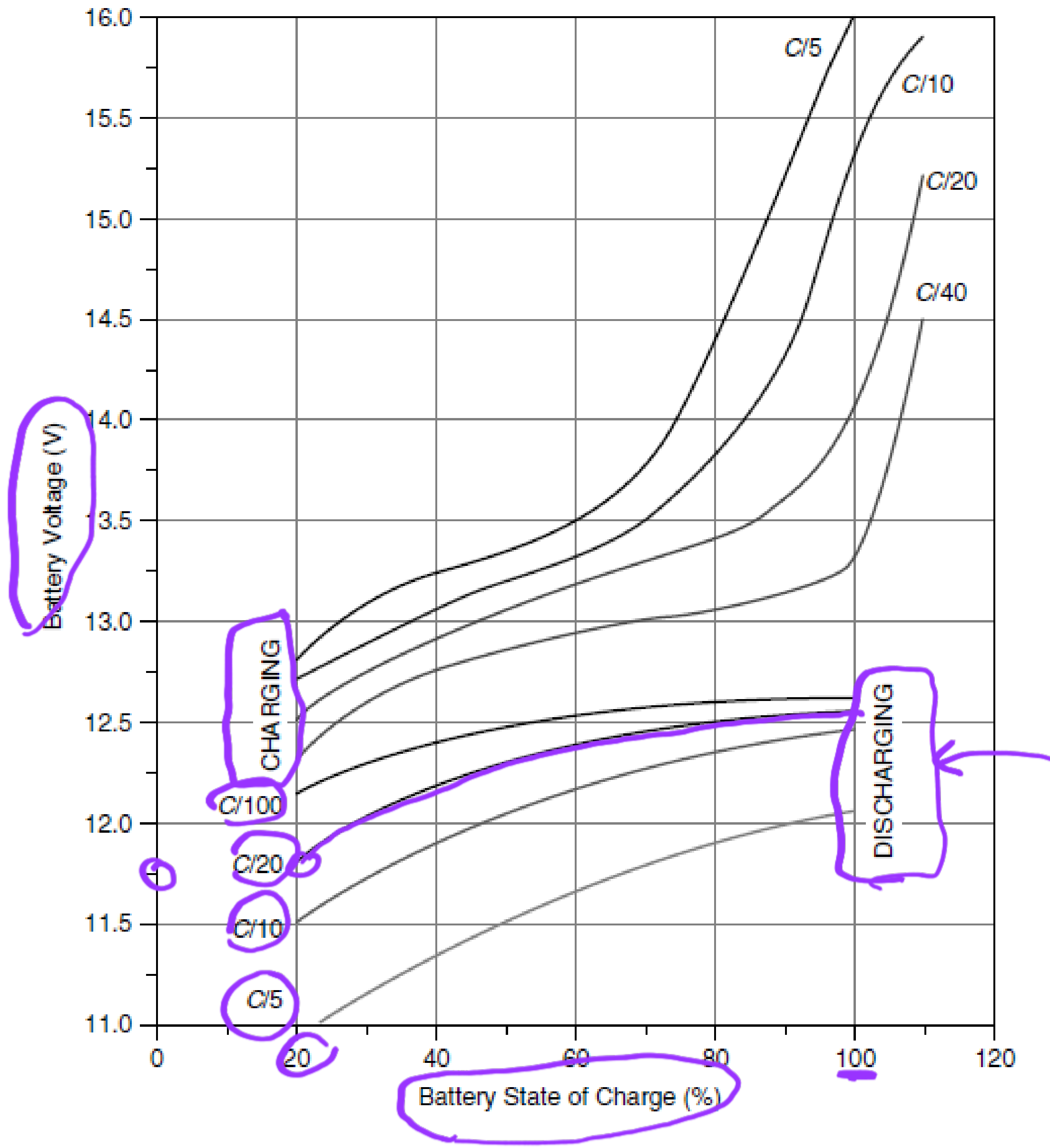
Series and parallel Batteries

- Since there is no difference in energy stored in the two-battery series and parallel example shown in Fig. 9.43, the question arises as to which is better.
- The key difference between the two is the amount of current that flows to deliver a given amount of power. Batteries in series have higher voltage and lower current, which means more manageable wire sizes without excessive voltage and power losses, along with smaller fuses and switches, and slightly easier connections between batteries.
- On the other hand, a storage system consisting of batteries in parallel is easy to expand, one battery at a time.
- In series, a whole new string of batteries must be added to increase storage.

SOC curve

state of charge

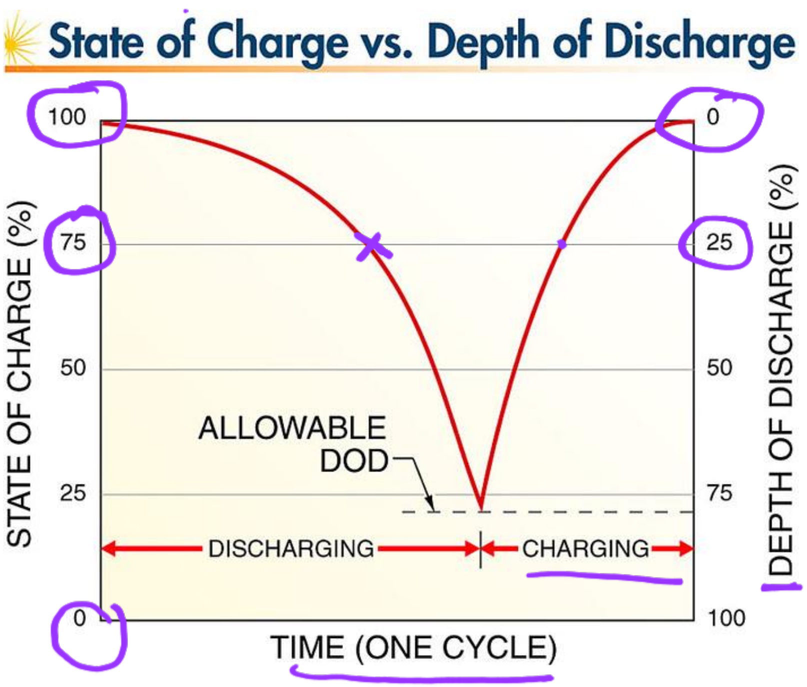
- Figure shows representative values of battery voltage for differing charging and discharging currents as a function of SOC.
- During charging, notice the sudden rise in cell voltage around the 14-V level as the battery nears full charge.
- This is when charging is most inefficient and when gassing occurs.



Gassing

- The release of generated hydrogen and oxygen gases removes water from the battery, which has to be replaced or the plates may be damaged.
- It also creates a potentially dangerous situation since hydrogen gas is so explosive.
- In addition, very small quantities of the poisonous gases arsine (AsH3) and stibine (SbH3) can be released when hydrogen comes in contact with the lead alloys arsenic and antimony.
- Proper ventilation is clearly an important consideration in the design of a safe battery storage system.

- The state of charge (SOC) and depth of discharge (DOD) of a battery always add up to equal 100%.
- SOC+DOD=100%



Battery Sizing

Ah
V

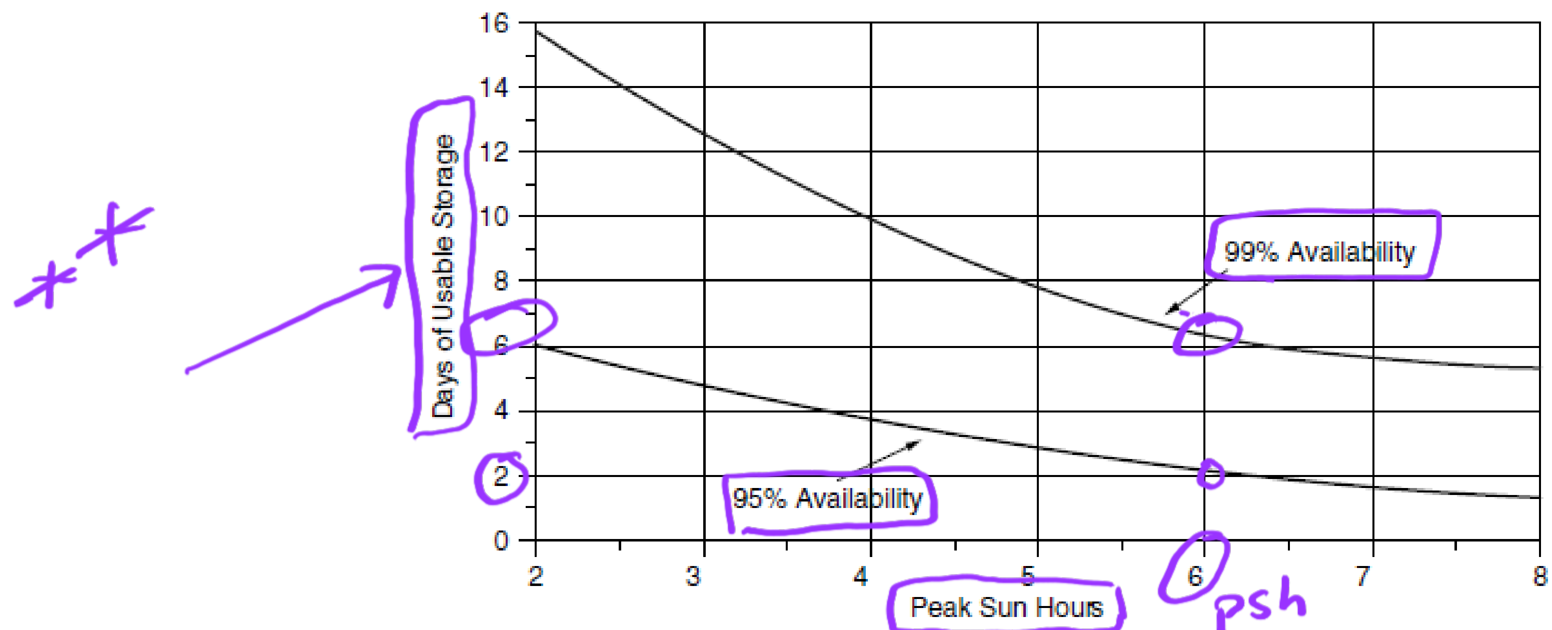
number
how connected

- If good weather could be counted on, battery sizing might mean simply providing enough storage to carry the load through the night and into the next day until the sun picks up the load once again.
- The usual case, of course, is one in which there are periods of time when little or no sunlight is available and the batteries might have to be relied on to carry the load for some number of days.
- During those periods, there may be some flexibility in the strategy to be taken.
- Some noncritical loads, for example, might be reduced or eliminated; and if a generator is part of the system, a trade-off between battery storage and generator run times will be part of the design

Availability

- Given the statistical nature of weather and the variability of responses to inclement conditions, there are no set rules about how best to size battery storage.
- The key trade-off will be **cost.**
- **Sizing a storage system to meet the demand 99% of the time can easily cost triple that of one that meets demand only 95% of the time.**
- As a starting point for estimating the number of days of storage to be provided, consider Fig. next slide,

- Days of battery storage needed for a stand-alone system with 95% and 99% system availability. Peak sun hours are for the worst month of the year and availability is on an annual basis.
- The graph gives an estimate for days of battery storage needed to supply a load as a function of the peak sun hours per day in the *design month*, which is the month with the worst combination of insolation and load. To account for a range of load criticality, two curves are given: one for loads that must be satisfied during 99% of the 8760 h in a year and one for less critical loads, for which a 95% system availability is satisfactory.



- The following can be used.

$$\text{Storage days (99\%)} \approx 24.0 - 4.73\,(\text{Peak sun hours}) + 0.3\,(\text{Peak sun hours})^2$$

$$\text{Storage days (95\%)} \approx 9.43 - 1.9\,(\text{Peak sun hours}) + 0.11\,(\text{Peak sun hours})^2$$

- Figure 9.46 refers to days of "usable storage," which means after accounting for impacts associated with maximum allowable battery discharge, Coulomb efficiency, battery temperature, and discharge rate.
- The relationship between usable storage and nominal, rated storage (at *C*/20, 25◦C) is given by:

$$\text{Nominal } (C/20, 25^{\circ}\text{C}) \text{ battery capacity} = \frac{\text{Usable battery capacity}}{(\text{MDOD})(\text{T, DR})}$$

- where MDOD - maximum depth of discharge (default: 0.8 for lead-acid, deep-discharge batteries, 0.25 for auto SLI; subject to freeze constraints given in and T, DR stands for temperature and discharge-rate factor
- See following example

End of L18
17/5

Example

Battery Sizing for an Off-Grid Cabin.

- A cabin near Salt Lake City, Utah, has an ac demand of 3000 Wh/day in the winter months.
- A decision has been made to size the batteries such that a 95% system availability will be provided, and a back-up generator will be kept in reserve to cover the other 5%.
- The batteries will be kept in a ventilated shed whose temperature may reach as low as −10◦C.
- The system voltage is to be 24 V, and an inverter with overall efficiency of 85% will be used.

Example-solution

Battery Sizing for an Off-Grid Cabin

Solution. With an 85% efficient inverter, the dc load is

$$\text{DC load} = \frac{\text{AC load}}{\text{Inverter efficiency}} = \frac{3000\ \text{Wh/day}}{0.85} = 3529\ \text{Wh/day}$$

With a 24-V system voltage the batteries need to supply

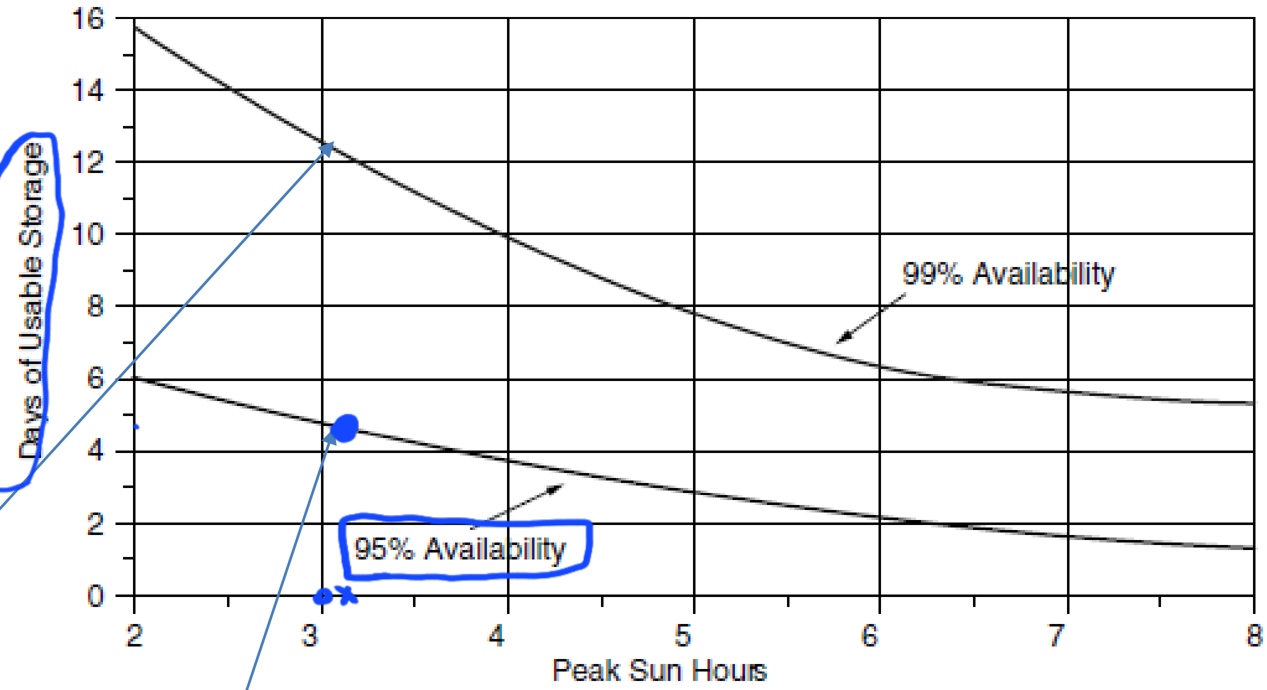
$$\text{Load} = \frac{3529\ \text{Wh/day}}{24\ V} = 147\ \text{Ah/day} \ @\ 24\ \text{V}$$

The following monthly insolation data are found for Salt Lake City:

Tilt	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	2.9	4.0	5.0	5.9	6.6	7.2	7.3	7.0	6.3	5.0	3.3	2.5	5.2
Lat	3.2	4.3	5.2	5.8	6.2	6.6	6.7	6.7	6.4	5.4	3.7	2.9	5.3
Lat + 15	3.4	4.4	5.1	5.4	5.5	5.6	5.8	6.1	6.1	5.5	3.9	3.1	5.0

We use the lowest (worst case) peak sun hours which happens to be for the month of December that have the lowest insolation at latitude +15

- At 95% availability and 3.1 peak sun hours in December, it looks like we need about 4.6 days of storage.

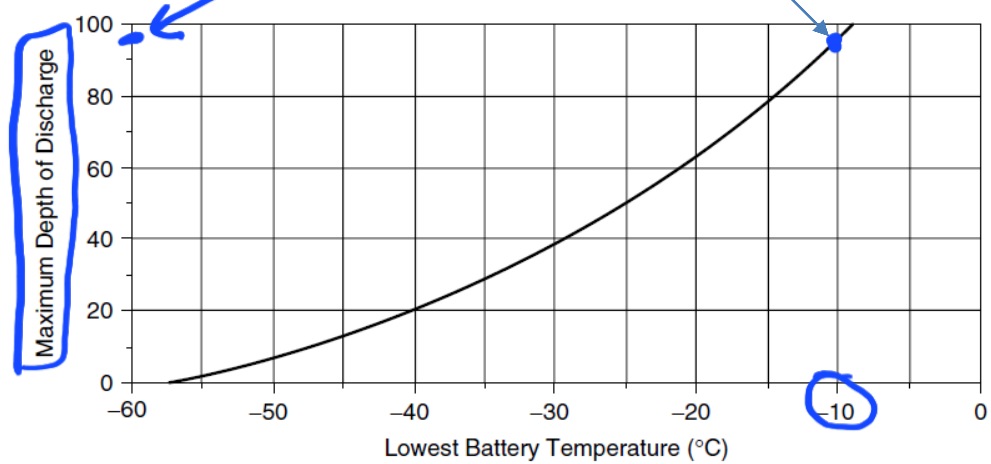


~ 12 days
For 99%
availability

$$\text{Usable storage} = 147\ \text{Ah/day} \times 4.6\ \text{day} = 676\ \text{Ah}$$

@ 24 V

- We'll pick deep discharge lead-acid batteries that can be routinely discharged by 80%. But, we need to check to see whether that depth of discharge will expose the batteries to a potential freeze problem.
- So we continue solution as previous example
- Applying the de-rating factors for temp (0.97) and (0.8) for max discharge rate



$$\text{Nominal } (C/20, 25^\circ\text{C}) \text{ battery capacity} = \frac{676 \text{ Ah}}{0.80 \times 0.97} = 871 \text{ Ah (at 24 V)}$$

- By looking at a list of available batteries of table , different possibilities can be explored

TABLE 9.15 Example Deep-Cycle Lead-Acid Battery Characteristics

BATTERY	Voltage	Weight (lbs)	Ah @ C/20	Ah @ C/100
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

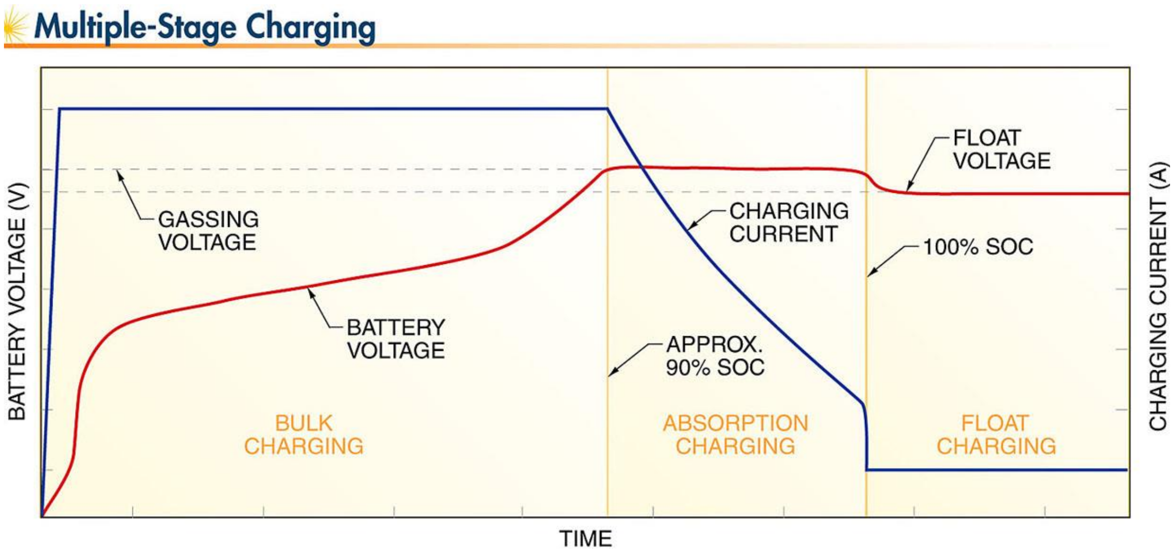
Batteries	Vbat	lb	AH@C/20	Ah@C/100	series (=24V/Vbat)	parallel (=871/Ah@C/20)	total No	tot weight
Concorde PVX 5040T	2	57	495	580	12	2	24	1368
Trojan T-105	6	62	225	250	4	4	16	992
Trojan 1.16	6	121	360	400	4	3	12	1452
Concorde 1080	12	70	105	124	2	9	18	1260
Surrete 12CS11PS	12	272	357	503	2	3	6	1632

- Trojan T-105 provides the choice with less weight
- total number of batteries is 16 (4x4) to get 24V and 900Ah

4X4

The 24-V, 900-Ah battery bank for the cabin in Example

More On Battery Charging

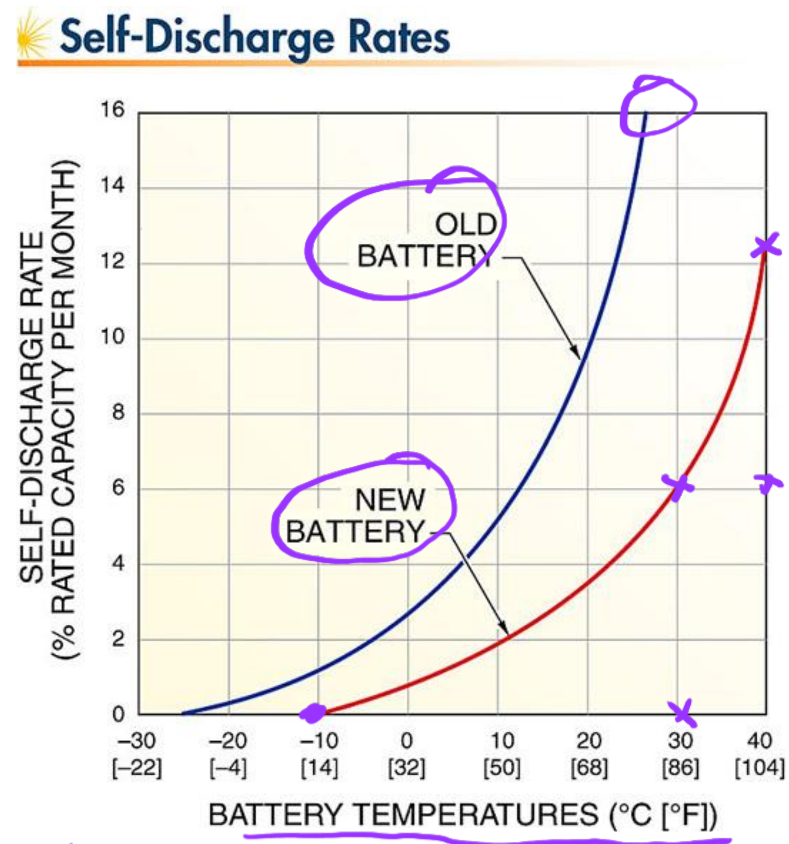


- **Gassing and charging losses can be minimized, by using a charge controller that has been designed to slow the charging rate as the battery approaches its fully charged condition.**

•*Self-discharge*

is the gradual reduction in the state of charge of a battery while at steady-state condition. Self-discharge is also referred to as standby or shelf loss.

- Self-discharge is a result of internal electrochemical mechanisms and losses.
- The rate of self-discharge differs among battery types and increases with battery age.
- Self-discharge rates are typically specified in percentage of rated capacity per month



Batteries exhibit high self-discharge rates at higher temperatures.

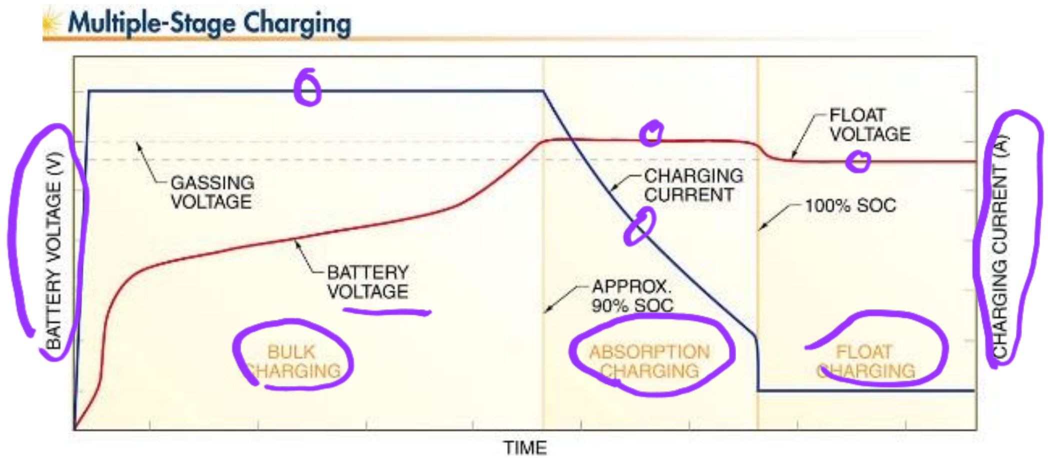
STEADY STATE

- *Steady-state* is an open-circuit condition where essentially no electrical or chemical changes are occurring.
- The *open-circuit voltage* is the voltage of a battery or cell when it is at steady-state.
- The open-circuit voltage of a fully charged lead-acid cell is about 2.1 V.

Voltage Levels

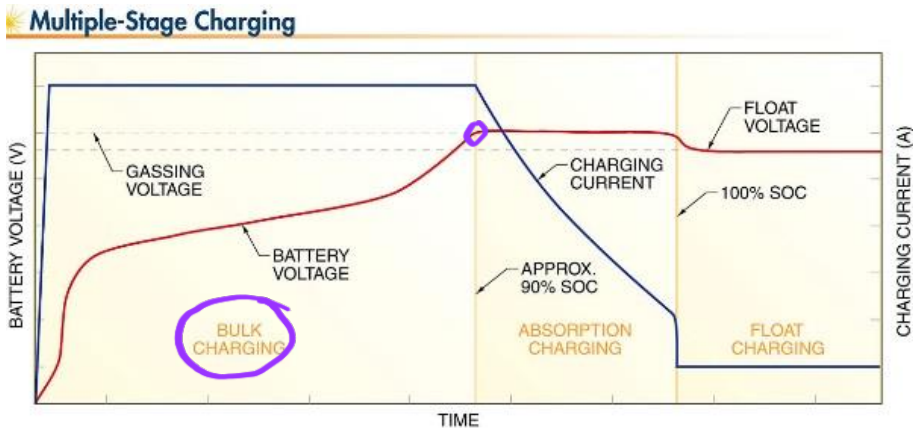
- The voltage of a battery system is not constant but ranges from a few volts above its nominal voltage to a few volts below.
- For example, a nominal 12 V lead-acid battery is between **12.6 V** and **13 V** at steady- state when fully charged.
- The battery voltage falls to a voltage between **10.8 V** and **11 V** during discharge, depending on the discharge current.
- The ***cutoff voltage*** is the minimum battery voltage specified by the manufacturer that establishes the battery capacity at a specific discharge rate.
- Below the cutoff voltage, there is no further usable capacity.

Charging



- Charge rate is quantified in the same way as discharge rate.
- For example, a charging rate of C/50 to a 100 Ah battery applies 2 A of current until the battery reaches a specific fully charged voltage.
- The *gassing voltage* is the voltage level at which battery gassing begins.
- Batteries can be charged in one stage or multiple stages.
- Three stages of battery charging are **bulk charging, absorption charging, and float charging.**
- **Equalizing charging** is an additional type of charging.

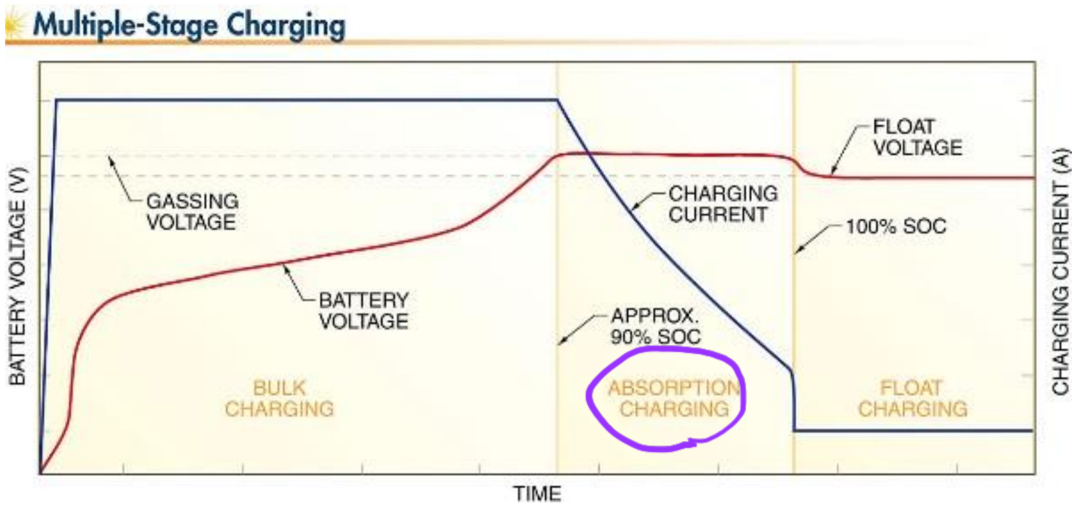
Bulk Charging (up to 90% SOC)



- *Bulk charging* is battery charging at a relatively high charge rate that charges the battery up to a regulation voltage, resulting in a state of charge of about 80% to 90%.
- This is also called normal charging or single stage charging.
- This mode is simple to implement, but does not fully charge the battery.
- Multiple-stage charging includes additional charging modes to reach a higher state of charge.

Absorption Charging

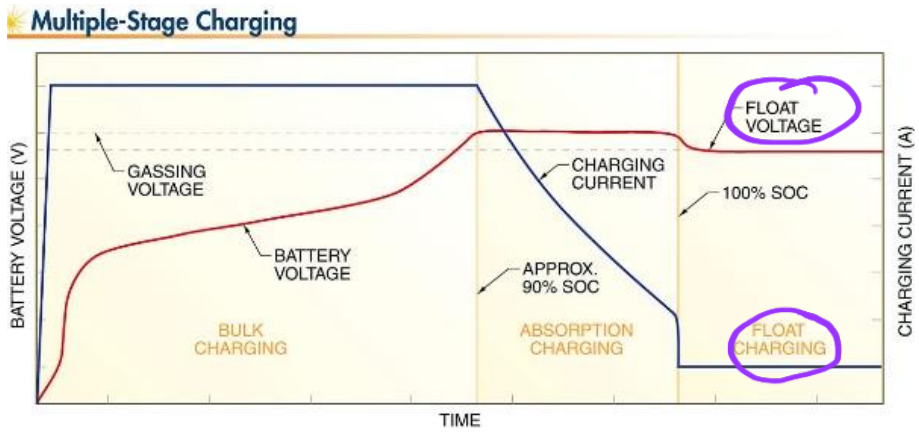
(maintain battery voltage at regulation- low charge current)



- **Once a battery is nearly fully charged, most of the active material in the battery has been converted to its original form, and current regulation is required to limit the amount of overcharge supplied to the battery.**
- ***Absorption charging*** **is battery charging following bulk charging that reduces the charge current to maintain the battery voltage at a regulation voltage for a certain period.**
- **The absorption charging period can be preset or adjustable, and is usually 1 hr to 3 hr. Absorption charging charges another 10% to 15% of battery capacity.**

Float Charging

(counteracting self-discharge)*



- When the battery reaches nearly 100% state of charge, the charging voltage is lowered slightly to the float voltage and the charging current is set to a very low rate.
- ***Float charging*** **is battery charging at a low charge rate that maintains full battery charge by counteracting self-discharge**.
- The float charge rate must not exceed the self-discharge rate or the battery will be overcharged. Float charging is also called trickle charging or finish charging. A charge controller remains in float charge mode until the array current is no longer high enough to maintain the battery at float voltage.

Equalizing Charging

(to maintain consistency among individual lead-acid cells)

- An equalizing, or refreshing, charge is used periodically to maintain consistency among individual lead-acid cells.
- ***Equalizing charging* is current-limited battery charging to a voltage higher than the bulk charging voltage, which brings each cell to a full state of charge.**
- Equalizing charging is a controlled overcharge to produce gassing ensuring that every cell is fully charged.
- Equalizing a battery helps to prevent electrolyte stratification, sulfation, and cell voltage inconsistencies that develop during normal battery operation, and maintains battery capacity at the highest possible levels.

Equalizing Charging

- For batteries that are deeply discharged on a daily basis, an equalizing charge is recommended every one or two weeks.
- For batteries less severely discharged, equalizing may only be required every one or two months.
- An equalizing charge is typically maintained until the cell voltages and specific gravities remain consistent for a few hours.
- Only flooded open-vent batteries need equalization. Sealed or valve-regulated batteries can be damaged by equalization.

Gassing and Overvoltage

- When a battery is nearly fully charged, essentially all of the active materials have been converted to their fully charged composition and the cell voltage rises sharply.
- Further charging at this point results in gassing.
- ***Gassing* is the decomposition of water into hydrogen and oxygen gases as the battery charges. Hydrogen forms at the negative plate and oxygen forms at the positive plate.**
- The gases bubble up through the electrolyte and may escape through cell vents, resulting in water loss from the electrolyte

Gassing and Overvoltage

- Some level of gassing is required to achieve full charge, but gassing must be carefully controlled to prevent excessive water loss.
- Water may need to be periodically added to the electrolyte to maintain the proper acid concentration, though this cannot be done for all types of batteries.
- Gassing is useful for gently agitating the electrolyte, which ensures that its concentration is uniform. However, excessive gassing can dislodge active materials from the grids, increase battery temperature, or expose the plates, which can permanently damage the battery.
- The gassing voltage is a function of battery chemistry, temperature, charge rate, voltage, and state of charge.

Gassing and Temperature

- As battery temperature decreases, the corresponding gassing voltage increases, and vice versa.
- At a battery temperature of 0°C (32°F) the gassing voltage of lead-acid cells increases to about 2.5 V.
- The effect of temperature on the gassing voltage is the reason why the charging process should be temperature compensated.
- This ensures that batteries are fully charged in cold weather and not overcharged during warm weather.

Overcharge

- ***Overcharge*** is the ratio of applied charge to the resulting increase in battery charge.
- For example, a 100 Ah battery may require 110Ah of charge to account for charge loss due to gassing.
- The overcharge in this case is 110%.
- Varying amounts of overcharge are required for different battery types and from different states of charge.
- Some batteries may require as much as 120% overcharge while many others require only about 110%.

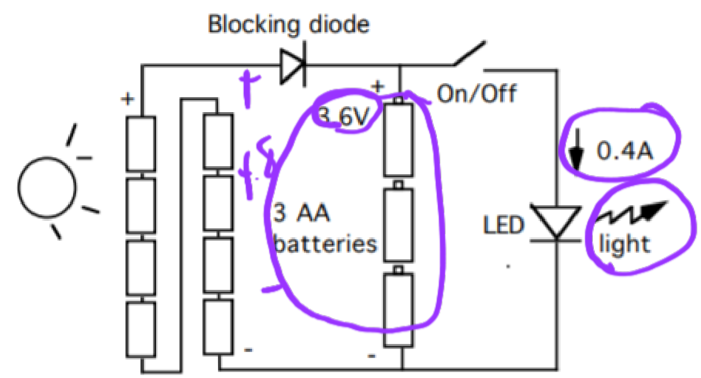
Overcurrent Protection

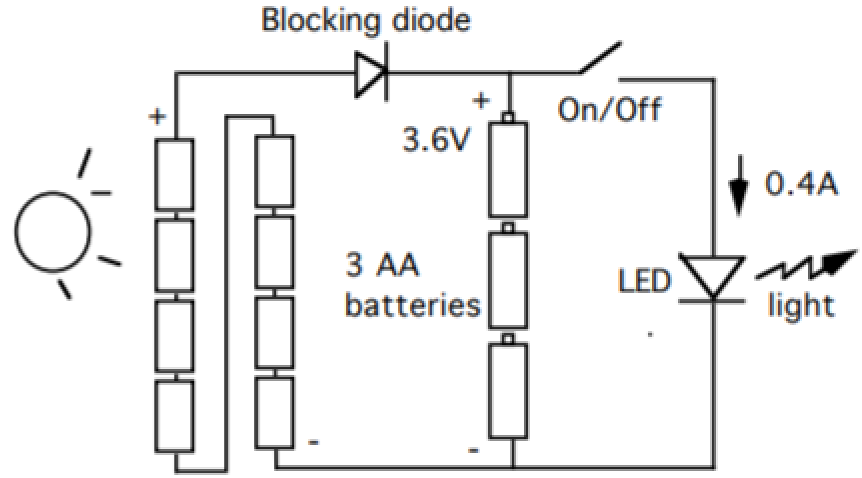
- Like any other electrical system, battery systems must have proper DC-rated overcurrent protection and disconnects to protect system conductors and to isolate the battery bank from the rest of the system for testing and maintenance.
- Batteries can deliver extremely high discharge currents *, so overcurrent protection* devices must have the appropriate interrupting rating
- Other Safety precautions related to ventilation and electrolyte spill must be taken

05/13
IMPORTANT - NONSERVICEABLE
DO NOT ATTEMPT TO OPEN VENTS.
Non-spillable battery, I.C.A.O., I.M.D.G., I.A.T.A., and D.O.T. air transport approved.
Ventilate well. Do NOT install in airtight container.
Charge/Absorption/Equalize between 13.8 – 14.6 volts @ 77°F (25°C).
Float/Standby between 13.4 – 13.6 volts @ 77°F (25°C).
Temperature corrected charging required.
DANGER/POISON
SHIELD EYES.
EXPLOSIVE GASES CAN CAUSE BLINDNESS OR INJURY.
NO •SPARKS •FLAMES •SMOKING
SULFURIC ACID CAN CAUSE BLINDNESS OR SEVERE BURNS.
FLUSH EYES IMMEDIATELY WITH WATER
GET MEDICAL HELP FAST
KEEP OUT OF THE REACH OF CHILDREN
DO NOT OPEN BATTERY!
Remove proper month and year tabs to show date sold.
BATTERY MUST BE RECYCLED.
MADE IN USA
12V
PART NO.
8G31
485 CCA
98 A.H.
@20Hr
C/20

Example

- Consider the design of a small PV-powered light-emitting-diode (LED) flashlight.
- The PV array consists of 8 series cells, each with rated current 0.3A @ 0.6V.
- Storage is provided by three series AA batteries that each store 2Ah at 1.2V when fully charged.
- The LED provides full brightness when it draws 0.4A @ 3.6V
- The batteries have a Coulomb efficiency of 95% and for maximum cycle life can be discharged by up to 80%. Assume the PVs have a 0.90 derating due to dirt and aging.
- a. How many hours of light could this design provide each evening if the batteries are fully charged during the day?





- b. How many kWh/m^2-day of insolation would be needed to provide the amount of light found in (a)?
- c. With 14%-efficient cells, what PV area would be required?

Solution

- SOLN (a) :

2 Ah x 0.80 = 1.6 Ah available.

LED needs 0.4 A so 1.6/0.4 = 4 h of light

SOLN (b) :

Ah battery = I_R x (h @ full sun) x PV derate x Coulomb

1.6 = 0.3 A x (kWh/m^2-day) x 0.90 x 0.95

kWh/m^2 -day = 1.6 /(0.3 x 0.90 x 0.95) = 6.24

SOLN (c) : Each 14%-efficient cell produces 0.3A x 0.6V = 0.18 W at STC

P_R (W) = 1,000 W/m^2 x A (m^2) x η

A = 0.18W/cell x 8 cell/(1000 x 0.14) = 0.01028 m2

L19 part 2

L11-part 2
PV System Sizing and Design
(Standalone Systems)

Sizing Standalone Systems

- Stand-alone PV systems are designed to power **specific on-site loads**, so the size of these systems is directly **proportional to the load** requirements.
- If the system is too small, there will be losses in load availability and system reliability.
- If the system is too large, excess energy will be unutilized and wasted.
- Therefore, sizing of stand-alone systems requires a fine balance between energy supply and demand.
- Because of this necessary balance, sizing stand-alone systems requires more analysis and calculations than are required for interactive systems.
- Most of these calculations build upon one another as the analyses proceed.
- Moreover, sizing stand-alone systems is an iterative process.
- That is, if the final calculations indicate that the components are improperly sized, the starting values must be changed and the calculation process repeated until the system output matches the load requirements

Sizing Standalone Systems

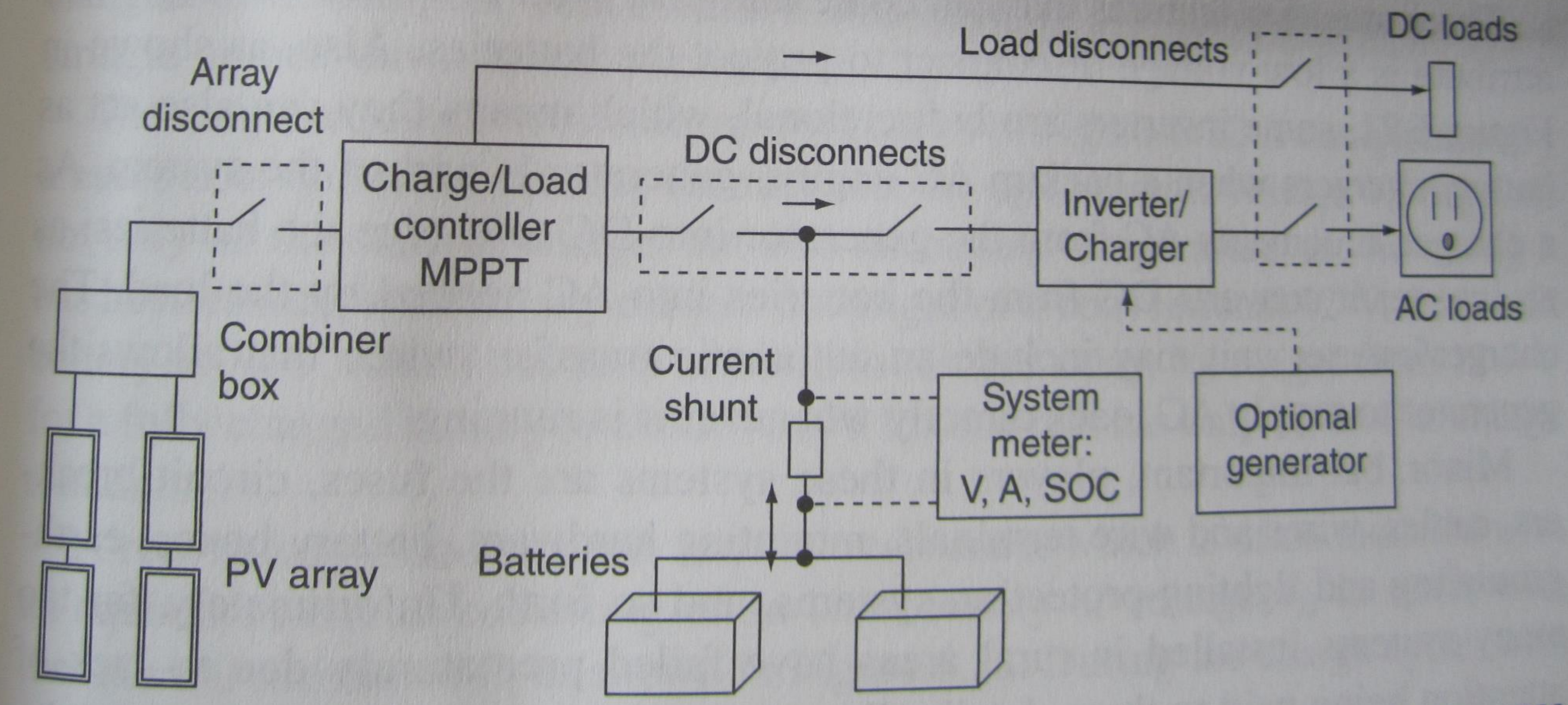


FIGURE 6.21 A "one-line" diagram of the important components in a stand-alone PV system.

Sizing Calculations –Standalone system

- Sizing PV systems for stand-alone operation involves four sets of calculations.

➔ **First, a load analysis** determines the electrical load requirements.

➔ Then, **monthly load requirements** are compared to the local insolation data to determine the critical design month.

➔ Next, the battery bank is sized to be able to independently supply the loads for a certain length of time, such as if cloudy weather educes array output.

➔ Finally, the PV array is sized to fully charge the battery bank under the critical conditions

Load Analysis

- Analyzing the electrical loads is the first and most important step in PV-system sizing.
- The energy consumption dictates the amount of electricity that must be produced.
- All existing and potential future loads must be considered. Underestimating loads will result in a system that is too small and cannot operate the loads with the desired reliability.
- However, overestimating the load will result in a system that is larger and more expensive than necessary.
- Comprehensive yet conservative load estimates will ensure that the system is adequately sized.

Load Analysis

- A load analysis tabulates the various kinds of loads and their power and electrical-energy requirements.

Load Analysis

LOAD ANALYSIS

Month:

AC LOADS

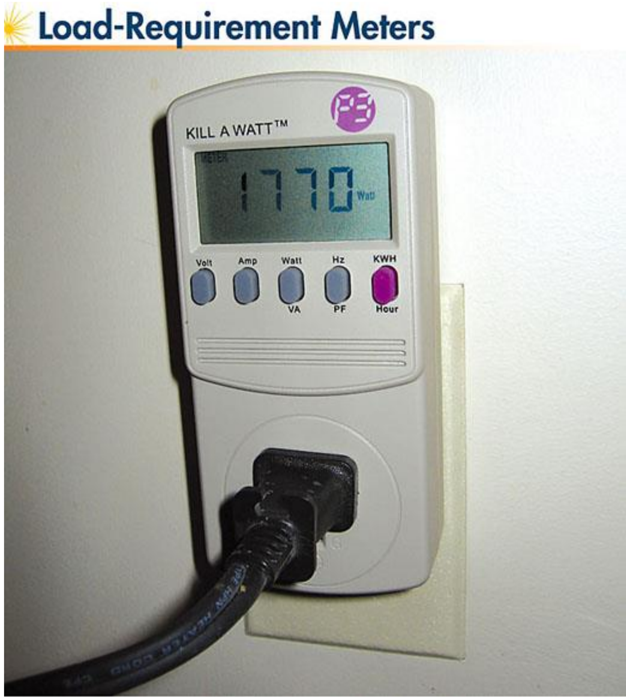
Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)

DC LOADS

Total AC Power		W
Total DC Power		W
Total Daily AC Energy Consumption		Wh/day
Total Daily DC Energy Consumption		Wh/day
Weighted Operating Time		hr/day
Inverter Efficiency		
Average Daily DC Energy Consumption		Wh/day

Power Demand

- Peak-power information is usually found on appliance nameplates or in manufacturer's literature.
- When this information is not available, peak power demand can be estimated by multiplying the maximum current by the operating voltage, though this is less accurate for reactive loads.
- Measurements, meter readings, or electric bills may also be used to help establish existing load requirements.

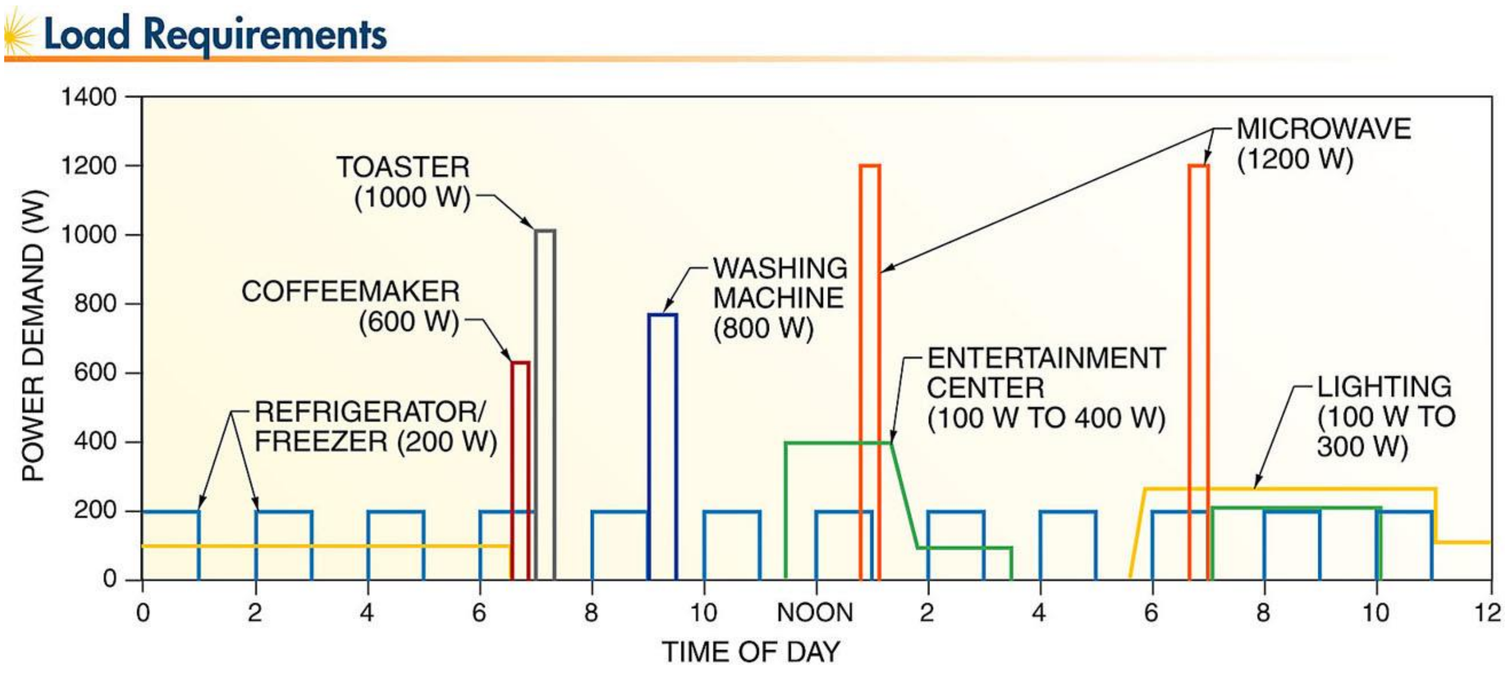


Power Demand & Energy Consumption

- The peak power demands are then summed.
- **The total power demand is considered when determining the required inverter AC-power output rating.**
- **While it is not likely that every load would be ON at the same time, it is recommended to size the inverter with extra capacity.**
- Electrical energy consumption is based on the power demand over time.
- **Loads rarely operate continuously, so each load's operating time must be determined. This is the total number of hours per day that the load is operating.**

Power Demand & Energy Consumption

- **Load requirements include the power demand and electrical-energy consumption for all the expected loads in the system**



Operating time

- The battery-bank discharge rate will change as various loads turn ON and OFF during the day.
- In this case, a weighted average operating time (t_{op}) is calculated using the following formula:

$$t_{op} = \frac{(E_1 \times t_1) + (E_2 \times t_2) + \ldots + (E_n \times t_n)}{E_1 + E_2 + \ldots + E_n}$$

- E_1 = DC energy required for load 1 (in Wh/day)
- t_1 = operating time for load 1 (in hr/day)

Operating Time

- **For example, one DC load uses 2400 Wh/day and operates for 4 hr and another DC load uses 1000 Wh/day and operates for 7 hr.**
- What is the weighted average operating time?

$$t_{op} = \frac{(E_1.t_1) + (E_1.t_1)}{E_1 + E_2}$$

$$t_{op} = \frac{(2400x4) + (1000x7)}{2400 + 1000}$$

$$t_{op} = 4.9hr / day$$

- The two loads have a combined effect of a single 694 W load operating for 4.9 hr/day [(2400 Wh + 1000 Wh) / 4.9 hr = 694 W].
- **If the system includes both AC and DC loads, the AC load energy requirement must be first be converted to equivalent DC energy. This is done by dividing each AC energy consumption amount by the inverter efficiency.**

Inverter Selection

- If the system includes AC loads, an inverter must be selected.
- Several factors must be considered when selecting the inverter.
- **First, the inverter must have a maximum continuous power output rating at least as great as the largest single AC load.**
- A slightly oversized inverter is usually recommended to account for potential future load additions.
- **The inverter must also be able to supply surge currents to motor loads, such as pumps or compressors, while powering other system loads.**

Example

$$E_{SDC} = \frac{E_{AC}}{\eta_{inv}} + E_{DC}$$

where

E_{SDC} = required daily system DC electrical energy (in Wh/day)

E_{AC} = AC energy consumed by loads (in Wh/day)

η_{inv} = inverter efficiency

E_{DC} = DC energy consumed by loads (in Wh/day)

For example, if a load analysis determines that a system requires 800 Wh/day for the AC loads and 200 Wh/day for the DC loads and the inverter efficiency is 90%, what is the daily DC electrical energy required by the system?

$$E_{SDC} = \frac{E_{AC}}{\eta_{inv}} + E_{DC}$$

$$E_{SDC} = \frac{800}{0.90} + 200$$

$$E_{SDC} = 889 + 200$$

$$E_{SDC} = \mathbf{1089\ Wh/day}$$

Critical Design Analysis

- A stand-alone system must produce enough electricity to meet load requirements during any month.
- **Therefore, systems are sized for the worst-case scenario of high load and low insolation.**
- A critical design analysis compares these two factors throughout a year, and the data for the worst case is used to size the array.
- **The *critical design ratio* is the ratio of electrical energy demand to average insolation during a period.**
- The load data comes from the load analysis, which is usually performed for each month.
- The insolation data is available from the solar radiation data sets. (or can be estimated for any given location based on previous lectures).
- The ratio is calculated for each month.

Critical Design Month

- **The *critical design month* is the month with the highest critical design ratio.**
- This is the worst-case scenario, and the associated load and insolation data are used to size the rest of the system.
- If the loads are constant over the entire year, the critical design month is the **month with the lowest insolation** on the array surface.
- For most locations in the Northern Hemisphere, this is a winter month, either December or January.
- However, when the load requirements vary from month to month, the critical design month must take into account both the loads and the available insolation.
- Because of these two factors, the critical design month may turn out to be any month of the year.

Critical Design Month

- Sizing for the critical design month typically results in excess energy at other times of the year.
- If this excess is significant, the system designer may want to consider adding diversion loads or changing to a different system configuration, such as a hybrid system, that better matches the available electrical energy to the loads.

Array Orientation

- Since array orientation has a significant effect on receivable solar radiation, array orientation must also be accounted for in a critical design analysis.
- If the mounting surface restricts the array to only one possible orientation, then the analysis is conducted to determine the critical design factors for that orientation.
- However, if multiple orientations are possible, separate analyses are performed for each orientation. A critical design month can be identified for each of the array orientations, since the receivable solar radiation will be different for each.
- Of the resulting critical design months, the one with the smallest design ratio is the best choice.

Array Sizing

- The orientations most commonly used in a critical design analysis are tilt angles equal to the latitude, latitude +15°, and latitude-15°, each at an azimuth of due south.
- **The greater array tilt angle maximizes the received solar energy in winter months, and the smaller array tilt angle maximizes the received solar energy in summer months.**
- For azimuth angles other than due south, the insolation data must be adjusted to obtain the most accurate results.
- **Computer models are available to predict average monthly insolation for alternate orientations.**

- A critical design analysis compares the load requirements and insolation for each month to determine the critical design month.

Critical Design Analysis

CRITICAL DESIGN ANALYSIS

Month	Average Daily DC Energy Consumption (Wh/day)	Array Orientation 1		Array Orientation 2		Array Orientation 3	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							

Critical Design Month

Optimal Orientation

Average Daily DC Energy Consumption **Wh/day**

Insolation **PSH/day**

DC-System Voltage

- The DC-system voltage is established by the battery-bank voltage in battery-based systems.
- This voltage dictates the operating voltage and ratings for all other connected components, including DC loads, charge controllers, inverters, and (for battery-based systems) the array.
- DC voltage in battery-based systems is critically important.
- The DC voltage for battery- based PV systems is usually an integer multiple of 12 V, usually 12 V, 24 V, or 48 V.

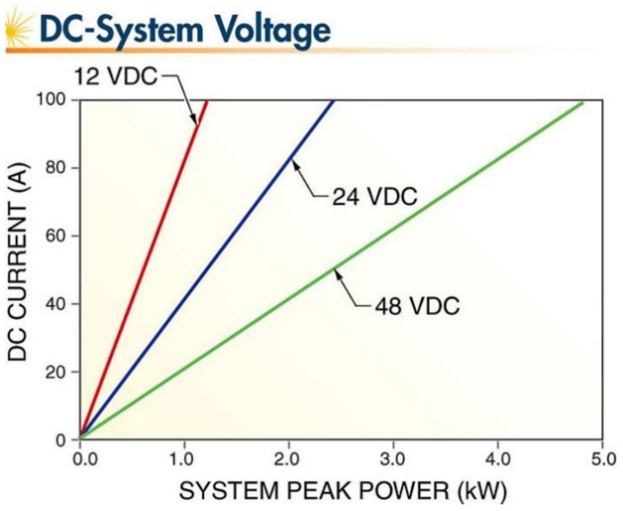
DC-System Voltage

- The selection of the battery-bank voltage affects system currents
- **For example, a 1200 W system operating at 12 V draws 100A(1200W/12 V= 100 A).**
- The same 1200 W system draws only 50 A at 24 V, or 25 A at 48 V.
- Lower current reduces the required sizes of conductors, overcurrent protection devices, disconnects, charge controllers, and other equipment.
- Also, since voltage drop and power losses are smaller at lower currents, higher-voltage systems are generally more efficient.

DC-System Voltage

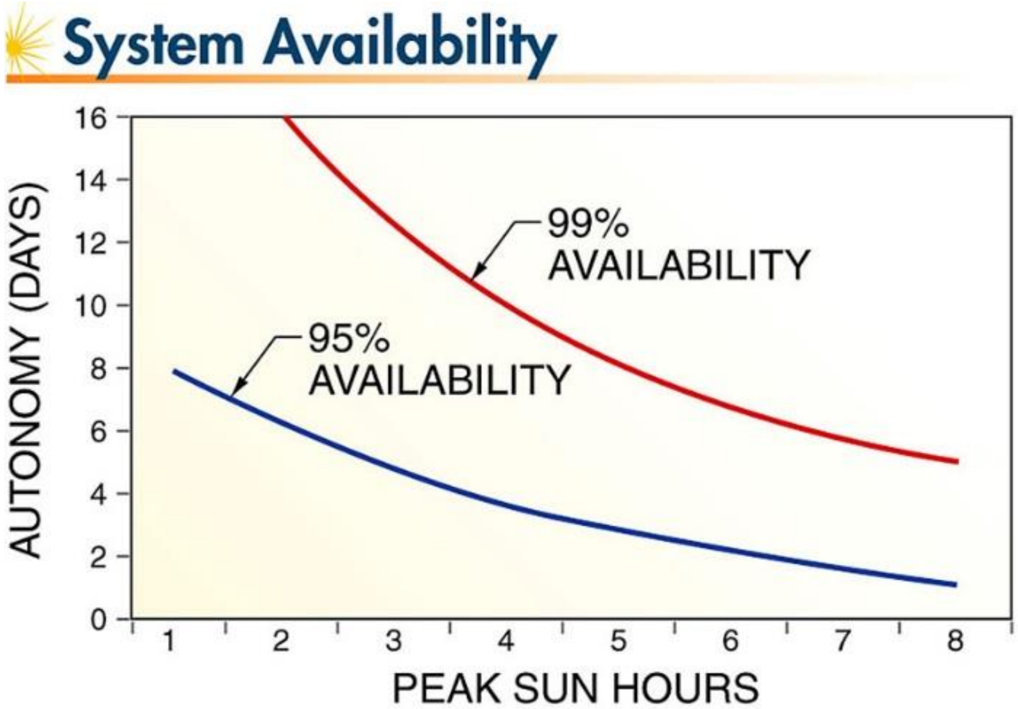
•DC-system voltage is chosen in proportion with the array size and to keep the operating current below 100 A.

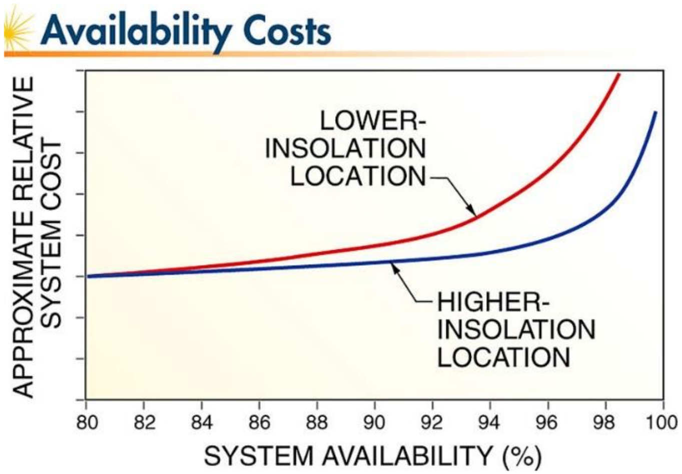
- As a rule of thumb, stand-alone systems up to 1 kW use a minimum 12V battery-bank voltage, which limits DC currents to less than 84 A.
- Similarly, battery voltages of at least 24 V are used for systems up to 2 kW,
- and at least 48 V for systems up to 5 kW.
- Very large standalone systems may use battery voltages of 120 V,
- though battery banks over 48 V involve additional code requirements and safety measures.



Availability

- **System availability is approximated from the local insolation and the autonomy period.**





- **Increasing system availability significantly increases the cost of the system.**

Battery Bank Sizing

- Batteries for stand-alone PV systems are sized to store enough energy to meet system loads for the desired length of autonomy without any further charge or energy contributions from the PV array.
- Greater autonomy requires larger and costlier battery banks, but reduces the average daily depth of discharge, which prolongs battery life.

- The required battery-bank capacity is determined from the electrical-energy requirements to operate the loads during the critical design month for the length of the autonomy period and at the desired battery-system voltage.
- Battery Capacity ***Bout*** is calculated: kWh/day

$$\text{Capacity} = B_{out} = \frac{E_{crit} \times t_a}{V_{SDC}} \qquad I_{dc} < 100\,A$$

- where
- B_{out} = required battery-bank output (in Ah) or Capacity
- E_{crit} = daily electrical-energy consumption during critical design month (in Wh/day)
- t_a = autonomy (in days) based on availability requirements
- V_{SDC} - nominal DC-system voltage (in V)

The average discharge rate

- The average discharge rate is determined from the total operating time over the period of autonomy, taking the allowable depth of discharge into account.

$$r_d = \frac{t_{op} \times t_a}{DOD_a}$$

- where
- *rd* - average discharge rate (in hours)
- *top =* weighted average operating time (in h/day)
- *ta =* autonomy (in days)
- *DODa =* allowable depth of discharge

- The required capacity is calculated using the following formula:

$$B_{rated} = \frac{B_{out}}{DOD_a \times C_{T,rd}}$$

- where
- *Brated =* battery-bank rated capacity (in Ah)
- *Bout* = battery-bank required output (in Ah)
- *DODa =* allowable depth of discharge
- $C_{T,rd}$ *=* temperature and discharge-rate derating factor

Array Current

- The required PV array current is calculated using the following formula:

$$I_{array} = \frac{E_{crit}}{(\eta_{batt})(V_{SDC})(t_{PSH})}$$

- where

I_{array} required array maximum-power current (in A)

E_{crit} daily electrical-energy consumption during critical design month (in Wh/day)

η_{batt} battery-system charging efficiency

V_{SDC} nominal DC system voltage (in V)

t_{PSH} peak sun hours for critical design month (in hr/day)

For example, consider a nominal 24 V system in a location with 4.9 peak sun hours that must supply 1580 Wh per day. The battery-system charging efficiency is estimated at 0.90. What is the required array current?

$$I_{array} = \frac{E_{crit}}{\eta_{batt} \times V_{SDC} \times t_{PSH}}$$

$$I_{array} = \frac{1580}{0.90 \times 24 \times 4.9}$$

$$I_{array} = \frac{1580}{105.8}$$

$$I_{array} = \mathbf{14.9\ A}$$

Array Sizing

ARRAY SIZING

Average Daily DC Energy Consumption for Critical Design Month		Wh/day
DC System Voltage		VDC
Critical Design Month Insolation		PSH/day
Battery Charging Efficiency		
Required Array Maximum-Power Current		A
Soiling Factor		
Rated Array Maximum-Power Current		A
Temperature Coefficient for Voltage		/°C
Maximum Expected Module Temperature		°C
Rating Reference Temperature		°C
Rated Array Maximum-Power Voltage		VDC
Module Rated Maximum-Power Current		A
Module Rated Maximum-Power Voltage		VDC
Module Rated Maximum Power		W
Number of Modules in Series		
Number of Module Strings in Parallel		
Total Number of Modules		
Actual Array Rated Power		W

Figure 9-18. *The array sizing worksheet uses insolation data and load requirements to size the array.*

Array Rated Output and Soiling Factor

- *Soiling* is the accumulation of dust and dirt on an array surface that shades the array and reduces electrical output. The magnitude of this effect is difficult to accurately determine, but estimates will account for most of this effect.
- A derating factor of 0.95 is used for light soiling conditions with frequent rainfall and/or a higher tilt angle, and a derating factor of 0.90 or less is used for heavy soiling conditions with long periods between rainfalls or cleanings.
- The rated array maximum-power current is calculated using the following formula:

$$I_{rated} = \frac{I_{array}}{C_s}$$

- Cs – soiling factor

Temperature Effect

- High temperature reduces voltage output. A temperature coefficient of -0.004/°C is applied to voltage, indicating that voltage falls by about 0.4% for every degree above the reference or rating temperature, which is usually 25°C (77°F).
- In addition, the array voltage must be higher than the nominal battery-bank voltage in order to charge the batteries.
- An array with a 12 V maximum-power voltage will not charge a nominal 12V battery because the actual voltage of a nearly charged battery is about 14.5 V.
- The array voltage must be at least 14.5 V to charge a nominal 12 V battery.
- **Therefore, the rated array maximum-power voltage is multiplied by 1.2 to ensure that the array voltage is sufficient to charge the battery bank.**

- The rated array maximum-power voltage is calculated using the following formula:

PV array

$$V_{rated} = 1.2 \times \{V_{SDC} - [V_{SDC} \times C_{\%V} \times (T_{max} - T_{ref})]\}$$

V_{rated} = rated array maximum-power voltage (in V)

V_{SDC} = nominal DC-system voltage (in V)

$C_{\%V}$ = temperature coefficient for voltage (in /°C)

T_{max} = maximum expected module temperature (in °C)

T_{ref} = reference (or rating) temperature (in °C)

- For example, consider an array for a nominal 24 V DC system that must output 18 A.
- The soiling conditions are expected to be light and the maximum module temperature is estimated at 50°C.
- What are the minimum rated maximum power current and voltage parameters?

$$I_{rated} = \frac{I_{array}}{C_S}$$

$$I_{rated} = \frac{18}{0.95}$$

$$I_{rated} = \mathbf{18.95\ A}$$

$$V_{rated} = 1.2 \times \{V_{SDC} - [V_{SDC} \times C_{\%V} \times (T_{max} - T_{ref})]\}$$

$$V_{rated} = 1.2 \times \{24 - [24 \times -0.004 \times (50 - 25)]\}$$

$$V_{rated} = 1.2 \times [24 - (24 \times -0.004 \times 25)]$$

$$V_{rated} = 1.2 \times (24 + 2.4)$$

$$V_{rated} = \mathbf{31.7\ V}$$

Module Selection

- For each module, three parameters are needed for sizing:

  the maximum power, the maximum-power operating current, and the maximum-power operating voltage.

- As with batteries, modules should be chosen to result in an array that is as close as possible to the desired array ratings, but slightly higher.
- The number of parallel strings of modules required is determined by dividing the rated array current output by the selected module maximum-power current output and rounding up to the next whole number.

Design Example (Standalone System)

- A home is being constructed near Albuquerque, NM and needs standalone power, this home power consumption is detailed in the next slide
- Design a suitable PV system

LOAD ANALYSIS

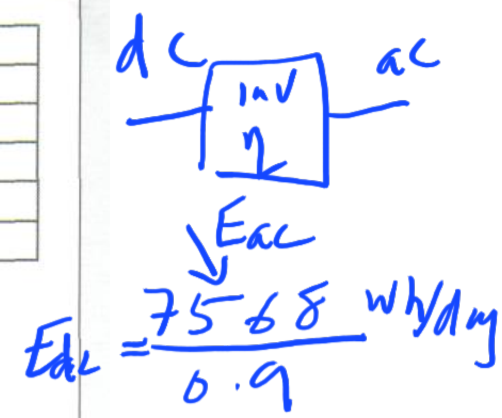
Month: August

AC LOADS

Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)
Refrigerator/Freezer	1	200	10	2000
Microwave	1	1200	0.5	600
Toaster	1	1000	0.05	50
Coffeemaker	1	600	0.25	150
Washing Machine	1	800	0.29	232
Entertainment Center	1	200	3	600
Computer System	1	100	2	200
Plug Loads	1	200	1	200
Water Pump	1	800	0.33	264
Ceiling Fans	2	50	24	2400
Fluorescent Lighting	4	15	6	360
Fluorescent Lighting	4	32	4	512

DC LOADS

Total AC Power	5388 W
Total DC Power	0 W
Total Daily AC Energy Consumption	7568 Wh/day
Total Daily DC Energy Consumption	0 Wh/day
Weighted Operating Time	11.2 hr/day
Inverter Efficiency	0.90
Average Daily DC Energy Consumption	**8409** Wh/day



For the month of August, the load analysis yields a total AC-power demand of about 5.4 kW and a daily energy consumption of 7568 Wh/day.

If all loads operate at the same time, the inverter must have a continuous power output rating of at least 5.4 kW. Although it is unlikely that all loads will be operating simultaneously, a 5.5 kW inverter is selected to allow for future load additions.

Since the efficiency of the inverter is 90%, the total average daily DC energy required is **8409 Wh/day.** This number will be used in the critical design analysis, along with energy requirements for every other month, to determine the critical design month. The weighted operating time for the critical design month will be used in the battery-sizing calculations.

Critical Design Analysis

CRITICAL DESIGN ANALYSIS

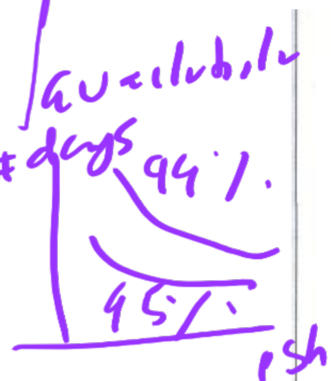
Month	Average Daily DC Energy Consumption (Wh/day)	Array Orientation 1 Latitude – 15		Array Orientation 2 Latitude		Array Orientation 3 Latitude + 15	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
January	6532	4.6	1420	5.3	1232	5.8	1126
February	6436	5.4	1192	6.0	1073	6.2	1038
March	6254	6.3	993	6.5	962	6.5	962
April	6197	7.3	849	7.2	861	6.6	939
May	6160	7.7	800	7.2	856	6.3	978
June	7568	7.8	970	7.1	1066	6.1	1241
July	8300	7.4	1122	6.9	1203	6.0	1383
August	8409	7.2	1168	6.9	1219	6.3	1335
September	7834	6.6	1187	6.8	1152	6.5	1205
October	6160	5.9	1044	6.5	948	6.6	933
November	6327	4.8	1318	5.5	1150	5.9	1072
December	6578	4.3	1530	5.0	1316	5.5	1196

- **Critical Design Month: December**
- **Orientation: Latitude**
- **Average Daily DC Energy Consumption: 6578**
- **Insolation: 5.0 PSH/day**

- The critical design ratio is calculated for each month.
- For each orientation, the highest ratio of load requirement to insolation corresponds to the critical design month. For two of the orientations, the month is December.
- For the latitude + 15° orientation, the month is July.
- Of the three possible critical design months, the month of December at the latitude orientation produces the lowest ratio.
- This indicates the optimal orientation.
- For this designated critical design month, the load requirement value is used for battery-bank sizing and the insolation value is used for array sizing.

Battery Bank

- A 48 V system is used
- Autonomy is set for 3 days
- A small engine generator should be aslo available



$$B_{out} = \frac{(E_{crit})(t_a)}{(V_{SDC})} = \frac{(6578)(3)}{(48)} = 411Ah$$

$$B_{rated} = \frac{B_{out}}{(DOD_a)(C_{T,rd})} = \frac{411}{(0.8)(0.9)} = 571Ah$$

$$r_d = \frac{(t_{op})(t_a)}{DOD_a} = \frac{(11.2)(3)}{0.8} = 42\text{ h}$$

- Flooded lead acid batteries with 295 Ah capacity are used , so 4 in series are required to provide 48V bus, and two strings in parallel to provide required capacity

BATTERY-BANK SIZING

Average Daily DC Energy Consumption for Critical Design Month	6578	Wh/day
DC System Voltage	48	VDC
Autonomy	3	days
Required Battery-Bank Output	411	Ah
Allowable Depth-of-Discharge	0.80	
Weighted Operating Time	11.2	hrs
Discharge Rate	42	hrs
Minimum Expected Operating Temperature	0	°C
Temperature/Discharge Rate Derating Factor	0.90	
Battery-Bank Rated Capacity	571	Ah
Selected Battery Nominal Voltage	12	VDC
Selected Battery Rated Capacity	295	Ah
Number of Batteries in Series	4	
Number of Battery Strings in Parallel	2	
Total Number of Batteries	8	
Actual Battery-Bank Rated Capacity	590	Ah

In this application, the load fraction is estimated at 0.75. The average daily depth of discharge is 17%. From the manufacturer's data, this battery has an expected life of 4000 cycles at 20% average daily depth of discharge. Correspondingly, at least 10 years of service should be expected in this application.

Array Sizing

$$I_{array\_rated} = \frac{E_{crit}}{(\eta_{batt})(V_{SDC})(t_{PSH})(Cs)} = \frac{6578}{(0.85)(48)(5)(0.95)} = 33.9A$$

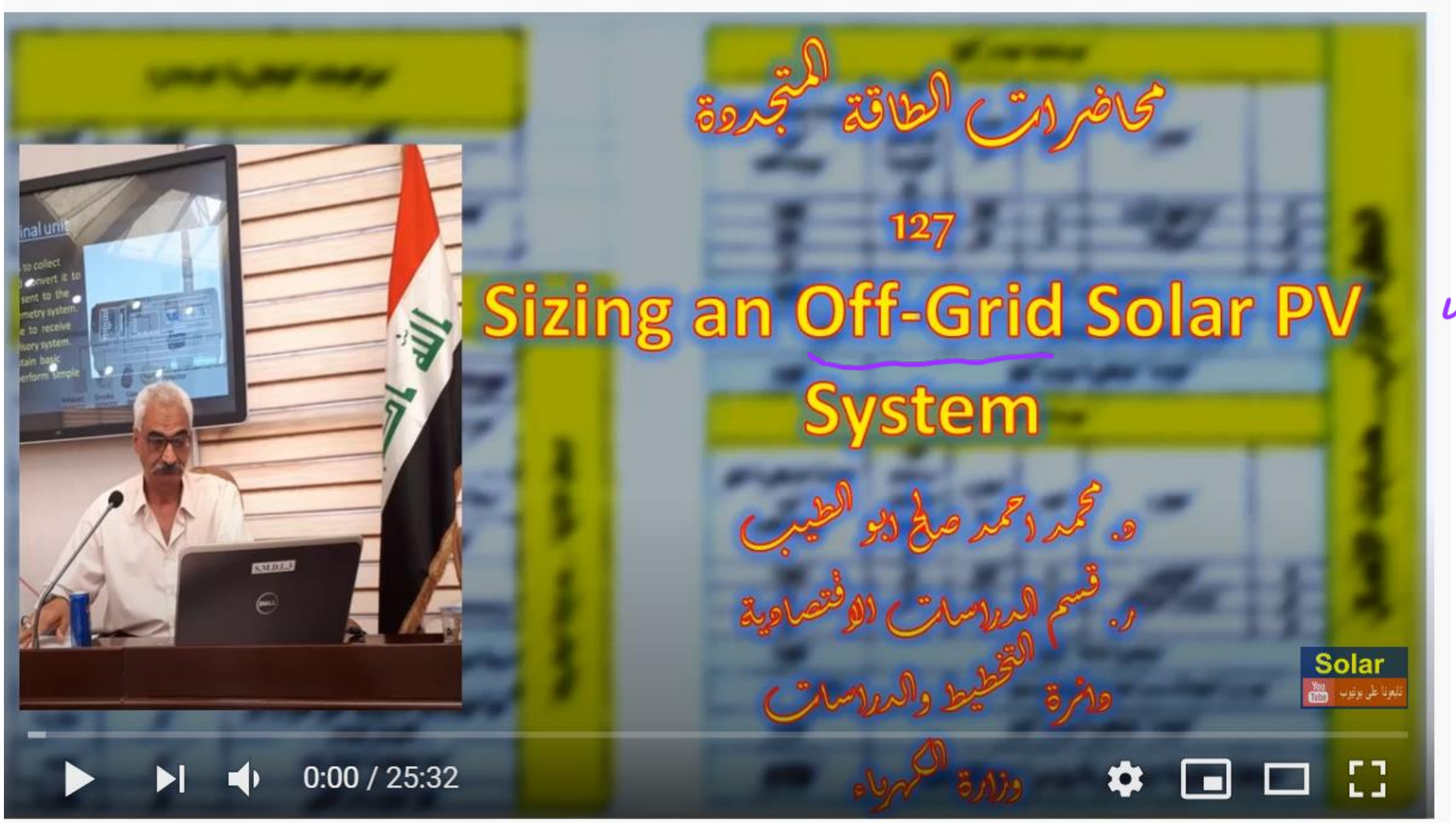
$$V_{array\_rated} = 1.2x\{(V_{SDC}) - [(V_{SDC}).(C_{\%V}).(T_{max} - T_{ref})]\}$$
$$= 1.2x\{(48) - [(48).(-0.004\%/V).(50-25)]\}$$
$$= 63.4\ V$$

- A 185 Wp module with
- Imax=5.11 A, Vmax=36.2 V is chosen
- Ns=63.4/36.2=1.74 ➔ Ns=2
- Np=33.9/5.1=6.65, Np=7
- Total modules Nt=Ns*NP=14
- Total rated power= 14*185=2590 W

ARRAY SIZING

Average Daily DC Energy Consumption for Critical Design Month	6578	Wh/day
DC System Voltage	48	VDC
Critical Design Month Insolation	5.0	PSH/day
Battery Charging Efficiency	0.85	
Required Array Maximum-Power Current	32.2	A
Soiling Factor	0.95	
Rated Array Maximum-Power Current	33.9	A
Temperature Coefficient for Voltage	−0.004	/°C
Maximum Expected Module Temperature	50	°C
Rating Reference Temperature	25	°C
Rated Array Maximum-Power Voltage	63.4	VDC
Module Rated Maximum-Power Current	5.11	A
Module Rated Maximum-Power Voltage	36.2	VDC
Module Rated Maximum Power	185	W
Number of Modules in Series	2	
Number of Module Strings in Parallel	7	
Total Number of Modules	14	
Actual Array Rated Power	2590	W

https://www.youtube.com/watch?v=Cm6ks0Rp-z8



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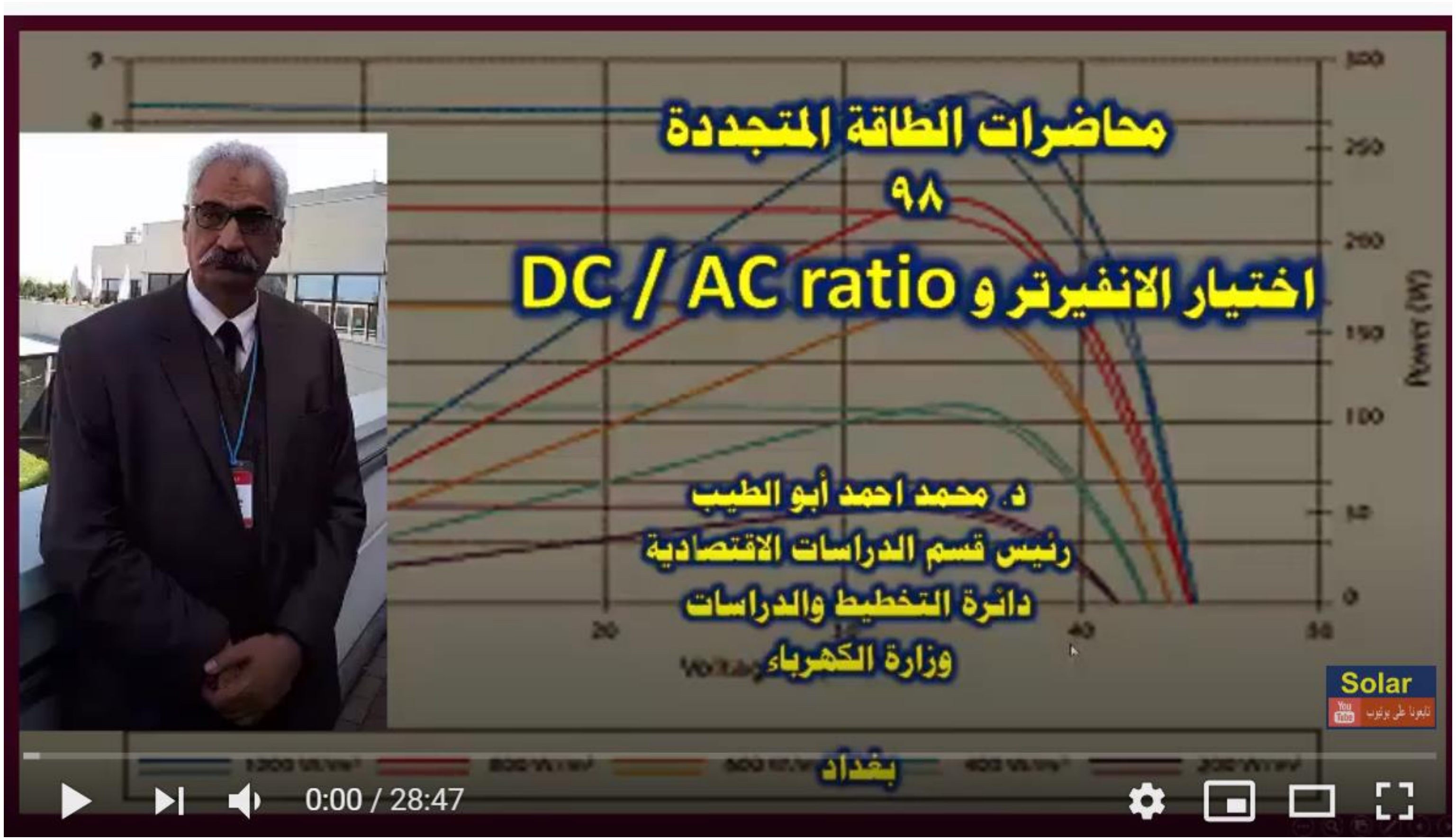


* End of PV Topics

↓ next

Wind Energy

Compare the energy at 15◦C,1 atm pressure, contained in 1 m^2 of the following wind regimes:

$$P_w = \frac{1}{2}\rho A v^3$$

a. 100 hours of 6-m/s winds (13.4 mph),

b. 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., an average wind

- ***Solution***
- a. With steady 6 m/s winds, all we have to do is multiply power times hours:

Energy (6 m/s) $= \frac{1}{2}\rho A v^3 t = \frac{1}{2}(1.225\ \text{kg}/m^3).(1m^2).\left(\frac{6m}{s}\right)^3 (100h)$ = 13,230 Wh

- b. With 50 h at 3 m/s

Energy (3 m/s) $= \frac{1}{2}\rho A v^3 t = \frac{1}{2}(1.225\ \text{kg}/m^3).(1m^2).\left(\frac{3m}{s}\right)^3 (50h)$ = 827 Wh

- And 50 h at 9 m/s contain Energy (9 m/s) $= \frac{1}{2}(1.225\ \text{kg}/m^3).(1m^2).\left(\frac{9m}{s}\right)^3 (50h)$ = 22,326 Wh
- for a total of 827 + 22,326 = 23,152 Wh

L20 - part 2
24/5/2021

Wind Energy Systems

HISTORICAL DEVELOPMENT OF WIND POWER

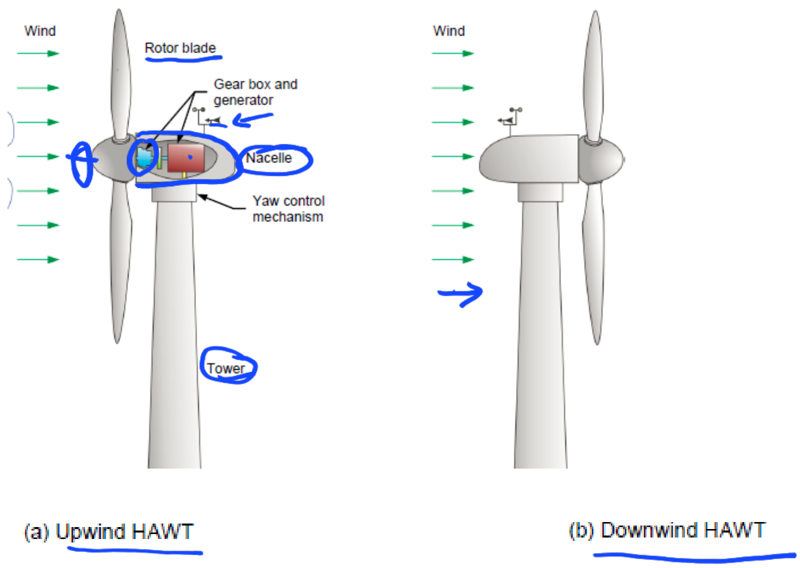
- Wind has been utilized as a source of power for thousands of years for such tasks as propelling sailing ships, grinding grain, pumping water, and powering factory machinery.
- The world's first wind turbine used to generate electricity was built by a Dane, Poul la Cour, in 1891.
- In the United States the first wind-electric systems were built in the late 1890s; by the 1930s and 1940s, hundreds of thousands of small-capacity, wind electric systems were in use in rural areas not yet served by the electricity grid.
- In 1941 one of the largest wind-powered systems ever built went into operation at Grandpa's Knob in Vermont.
- Designed to produce 1250 kW from a 175-ft-diameter, two-bladed prop, the unit had withstood winds as high as 115 miles per hour before it catastrophically failed in 1945 in a modest 25-mph wind (one of its 8-ton blades broke loose and was hurled 750 feet away).

Wind turbine classification

- A **wind turbine** is a rotating device used to convert the **kinetic energy** of the wind into electrical energy.
- In the last decades, a variety of wind turbines have been used to produce electricity. These turbines can be classified into two types, based on the axis around which their blades rotate:
- The **horizontal-axis wind turbine (HAWT)**: the axis of rotation is parallel to the ground and the direction the wind is blowing.
- The **vertical-axis wind turbine (VAWT)**: the axis of rotation is perpendicular to the ground and the direction the wind is blowing.
- Most turbines used today are of the **horizontal-axis** type. This occurs because these turbines are subjected to faster wind speeds than vertical-axis turbines, since their **rotor** is perched on top of high towers, allowing them to generate more electrical energy.

Horizontal-axis wind turbines (HAWT)

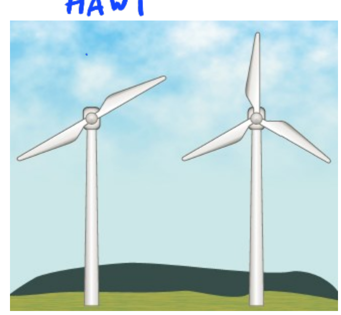
- Horizontal-axis wind turbines consist of a two- or three-bladed rotor turning a horizontal shaft. The shaft is connected to a gear box and a generator.
- The generator converts the rotational (mechanical) energy into electrical energy.
- The rotor and generator are mounted at the top of a tower.,
- HAWT can be of two types : upwind and downwind.



Two-bladed wind turbines versus three-bladed wind turbines

- **Two-bladed** turbines are usually cheaper than three-bladed turbines.
- They need less structural material than three-bladed turbines, making them lighter and easier to install. They can operate at faster rotation speeds than three-bladed turbines before their operation becomes seriously affected by turbulence.
- However, two-bladed turbines are usually harder to design because they are subjected to high dynamic loads.
- They can have stability problems

because when one blade is at the highest point in the rotation circle, where it receives the maximum wind power, the other blade passes infront or behind the wind turbine tower where some fluctuation in air flow is experienced.



Two-bladed wind turbines versus three-bladed wind turbines

- **Three-bladed** turbines require lower wind speeds than two-bladed turbines to produce comparable power levels, since they present a larger area facing the wind. Their operation is smoother and quieter than two-bladed turbines.
- They are less affected by the undesirable effects caused by the presence of the tower and the variations in wind speed.
- However, three-bladed turbines

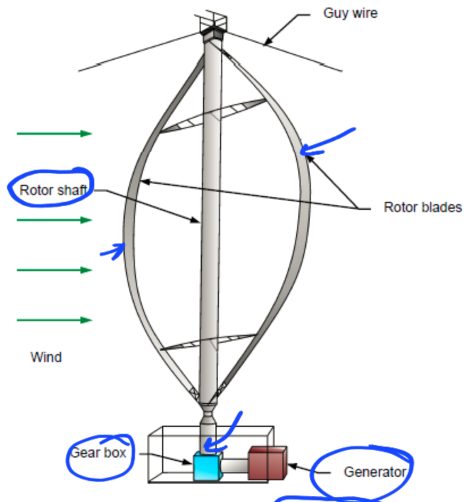
are usually heavier and more expensive than two-bladed turbines.

Also, they are generally more difficult to install

Vertical-axis wind turbines (VAWT)

- Vertical-axis wind turbines have a shaft whose axis of rotation is perpendicular to the ground and the direction of the wind.
- The main advantage of vertical-axis wind turbines is that they do not need to be oriented into the wind, so that there is no need for a yaw control mechanism.
- Furthermore, they do not need a tower. These turbines can therefore be constructed and installed at a lower cost.
- The main drawback of vertical-axis wind turbines is that they operate at lower speeds than horizontal-axis wind turbines, because they are not perched on towers.
- Furthermore, the air flow is more turbulent near the ground, which can result in vibrations, noise, blade stress, and poor overall efficiency.

Vertical-axis wind turbines (VAWT)



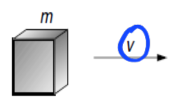
Vertical-axis wind turbine (Darrieus rotor).

Generated Power

- The amount of electrical power produced by the generator is primarily determined by the factors below:
- The speed of wind. The faster the **wind speed**, the higher the generated electrical power.
- The diameter and shape of the rotor blades. The wider the diameter of the blades and the higher the **rotor efficiency coefficient,** CP (determined mainly by the shape of the rotor blades), the higher the generated electrical power.
- The height of the tower. The wind speed increases at higher altitudes, therefore, taller towers can catch more powerful wind and allow more electrical power to be generated.

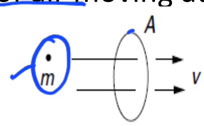
POWER IN THE WIND

- Consider a "packet" of air with mass *m* moving at a speed *v*. Its kinetic energy K.E., is given by the familiar relationship:



$$K.E. = \frac{1}{2} m v^2$$

- Since power is energy per unit time, the power represented by a mass of air moving at velocity *v* through area *A* will be



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right) v^2 \qquad (6.2)$$

- The mass flow rate $\dot{m}$, through area *A*, is the product of air density *ρ*, speed *v*, and cross-sectional area *A*:

$$\left(\frac{\text{Mass passing through A}}{\text{Time}}\right) = \dot{m} = \rho A v$$

POWER IN THE WIND

$$P_w = \tfrac{1}{2} \rho A v^3$$

- In S.I. units;
- *Pw* - is the power in the wind (watts);
- *ρ* - is the air density (kg/m3) (at 15◦C and 1 atm, *ρ* = 1.225 kg/m^3);
- *A* - is the cross-sectional area through which the wind passes (m^2)
- *v* = wind speed normal to A (m/s) (a useful conversion: 1 m/s = 2.237 mph).
- A plot of this equation and a table of values are shown next
- Notice that the power shown there is per square meter of cross section, a quantity that is called the *specific power* or *power density*.

POWER IN THE WIND

$$P_w = \frac{1}{2}\rho A v^3$$

- Notice that the power in the wind increases as the *cube* of wind-speed.
- Later we will see that most wind turbines aren't even turned on in low-speed winds,
- Wind power is proportional to the swept area of the turbine rotor.
- For a conventional horizontal axis turbine,
- the **area** ***A*** **is obviously just**

$A = (\pi/4)D^2$,

$A = \pi\left(\frac{D}{2}\right)^2$

Windspeed (m/s)	Windspeed (mph)	Power (W/m²)
0	0	0
1	2.[illegible]	1
2	4.[illegible]7	5
3	6.71	17
4	8.[illegible]5	39
5	11.[illegible]	77
6	13.[illegible]	132
7	15.[illegible]6	210
8	17.[illegible]0	314
9	2[illegible].[illegible]3	447
10	2[illegible].37	613
11	2[illegible].61	815
12	2[illegible].84	1058
13	2[illegible].08	1346
14	[illegible]1.32	1681
15	33.56	2067

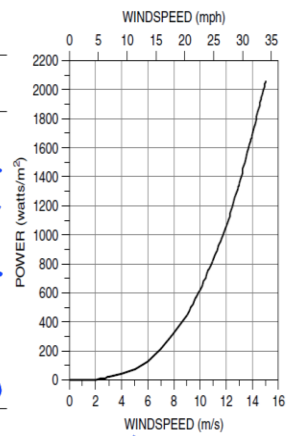
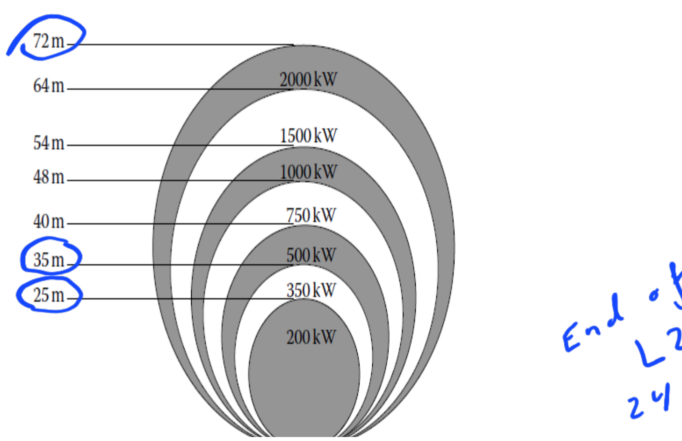


Figure 6.5 Power in the wind, per square meter of cross section, at 15°C and 1 atm.

POWER For different rotor diameters

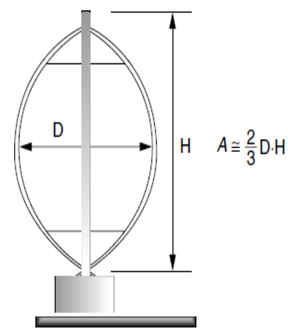


Turbine output power for different wind turbine diameters.

End of L20 24/5

- Doubling the diameter increases the power available by a factor of four.
- That simple observation helps explain the economies of scale that go with larger wind turbines.
- The cost of a turbine increases roughly in proportion to blade diameter, but power is proportional to diameter squared, so bigger machines have proven to be more cost effective.
- The swept area of a vertical axis Darrieus rotor is a bit more complicated to figure out.
- One approximation to the area is that it is about two-thirds the area of a rectangle with width equal to the maximum rotor width and height equal to the vertical extent of the blades, as shown in Fig

(for info only)



Showing the approximate area of a Darrieus rotor.

- Of obvious interest is the energy in a combination of windspeeds.
- **Given the nonlinear relationship between power and wind, we can't just use *average* windspeed in to predict total energy available, as the following example illustrates.**

- **Example 6.1 Don't Use Average Windspeed.** Compare the energy at 15◦C,1 atm pressure, contained in 1 m^2 of the following wind regimes:

a. 100 hours of 6-m/s winds (13.4 mph),

b. 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., an average windspeed of 6 m/s)

Compare the energy at 15◦C,1 atm pressure, contained in 1 m^2 of the following wind regimes:
a. 100 hours of 6-m/s winds (13.4 mph),
b. 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., speed of 6 m/s)

$$P_w = \frac{1}{2}\rho A v^3$$

- *Solution*

[redacted]

Average wind speed

- Previous Example dramatically illustrates the inaccuracy associated with using average wind speeds.
- While both of the wind regimes had the same *average* wind speed, the combination of 9-m/s and 3-m/s winds (average 6 m/s) produces 75% more energy than winds blowing a steady 6 m/s.
- Later we will see that, under certain common assumptions about wind speed probability distributions , energy in the wind is typically almost twice the amount that would be found by using the average wind speed.

$$P_w = \frac{1}{2}\rho A v^3$$

Temperature Correction for Air Density (FYI)

air density is affected by temperature according to the following table

TABLE 6.1 Density of Dry Air at a Pressure of 1 Atmosphere[a]

Temperature (°C)	Temperature (°F)	Density (kg/m^3)	Density Ratio (K_T)
−15	5.0	1.368	1.12
−10	14.0	1.342	1.10
−5	23.0	1.317	1.07
0	32.0	1.293	1.05
5	41.0	1.269	1.04
10	50.0	1.247	1.02
15	**59.0**	**1.225**	1.00
20	68.0	1.204	0.98
25	77.0	1.184	0.97
30	86.0	1.165	0.95
35	95.0	1.146	0.94
40	104.0	1.127	0.92

[a] The density ratio K_T is the ratio of density at T to the density at the standard (boldfaced) 15°C.

IMPACT OF TOWER HEIGHT

- Since power in the wind is proportional to the cube of the wind speed, the economic impact of even modest increases in wind speed can be significant.
- One way to get the turbine into higher winds is to mount it on a taller tower. In the first few hundred meters above the ground, wind speed is greatly affected by the friction that the air experiences as it moves across the earth's surface.
- Smooth surfaces, such as a calm sea, offer very little resistance, and the variation of speed with elevation is only modest.
- At the other extreme, surface winds are slowed considerably by high irregularities such as forests and buildings.
- One expression that is often used to characterize the impact of the roughness of the earth's surface on wind speed is the following:

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

- where v is the wind speed at height H, v_0 is the wind speed at height H_0 (often a reference height of 10 m), and α is the friction coefficient.

IMPACT OF TOWER HEIGHT

- The friction coefficient α is a function of the terrain over which the wind blows.
- Table 6.3 gives some representative values for rather loosely defined terrain types.

Friction Coefficient

Terrain Characteristics	Friction Coefficient (α)
Smooth hard ground, calm weather	0.10
Tall grass on level ground	0.15
High cops, hedges, and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

IMPACT OF TOWER HEIGHT

- While the power law given previously is very often used in the United States, there is another approach that is common in Europe. The alternative formulation is

$$\left(\frac{v}{v_0}\right) = \frac{\ln(H/z)}{\ln(H_0/z)}$$

TABLE 6.4 Roughness Classifications for Use in (6.16)

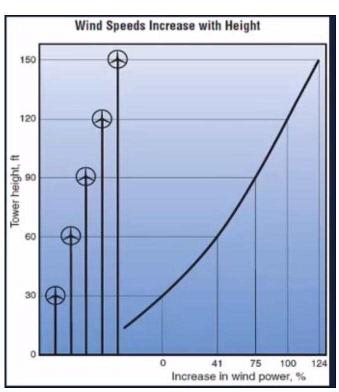
Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

(for info only)

IMPACT OF TOWER HEIGHT

- *z* is called the roughness length.
- The second equation is preferred by some since it has a theoretical basis in aerodynamics while the first one does not.∗
- Obviously, both the exponential formulation only provide a first approximation to the variation of wind speed with elevation.
- In reality, nothing is better than actual site measurements.

Impact of friction coefficient on windspeed



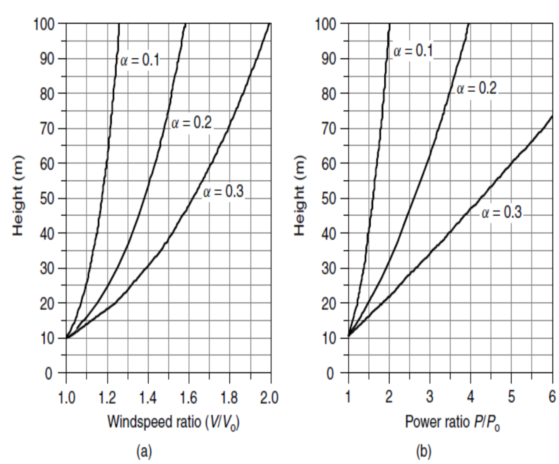
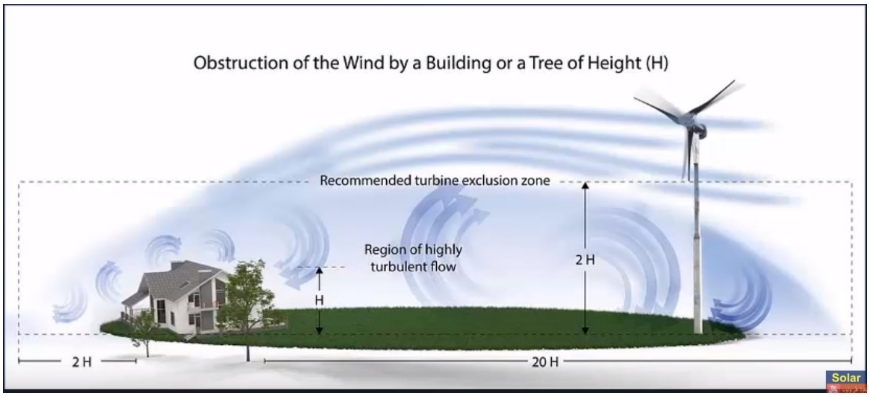


Figure 6.8 Increasing (a) windspeed and (b) power ratios with height for various friction coefficients α using a reference height of 10 m. For $\alpha = 0.2$ (hedges and crops) at 50 m, windspeed increases by a factor of almost 1.4 and wind power increases by about 2.6.

Placement of wind Turbines



Example 6.5 Increased Windpower with a Taller Tower. An anemometer mounted at a height of 10 m above a surface with crops, hedges, and shrubs shows a windspeed of 5 m/s. Estimate the windspeed and the specific power in the wind at a height of 50 m. Assume 15°C and 1 atm of pressure.

Solution. From Table 6.3, the friction coefficient α for ground with hedges, and so on, is estimated to be 0.20. From the 15°C, 1-atm conditions, the air density is $\rho = 1.225\ \text{kg/m}^3$. Using (6.15), the windspeed at 50 m will be

$$v_{50} = 5 \cdot \left(\frac{50}{10}\right)^{0.20} = 6.9\ \text{m/s}$$

Specific power will be

$$P_{50} = \frac{1}{2}\rho v^3 = 0.5 \times 1.225 \times 6.9^3 = 201\ \text{W/m}^2$$

That turns out to be more than two and one-half times as much power as the 76.5 W/m^2 available at 10 m.

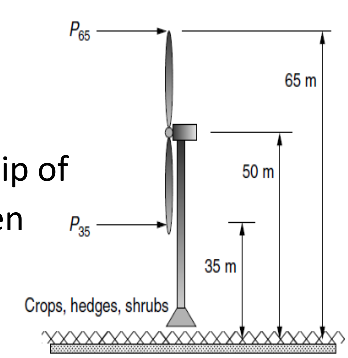
- Since power in the wind varies as the cube of windspeed,
- We can rewrite the equations to indicate the relative power of the wind at height *H* versus the power at the reference height of H_0:

$$\left(\frac{P}{P_0}\right) = \left(\frac{1/2\rho A v^3}{1/2\rho A v_0^3}\right) = \left(\frac{v}{v_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha} \qquad (6.17)$$

Example 6.6 Rotor Stress. A wind turbine with a 30-m rotor diameter is mounted with its hub at 50 m above a ground surface that is characterized by shrubs and hedges. Estimate the ratio of specific power in the wind at the highest point that a rotor blade tip reaches to the lowest point that it falls to.

Solution. From Table 6.3, the friction coefficient α for ground with hedges and shrubs is estimated to be 0.20. Using (6.17), the ratio of power at the top of the blade swing (65 m) to that at the bottom of its swing (35 m) will be

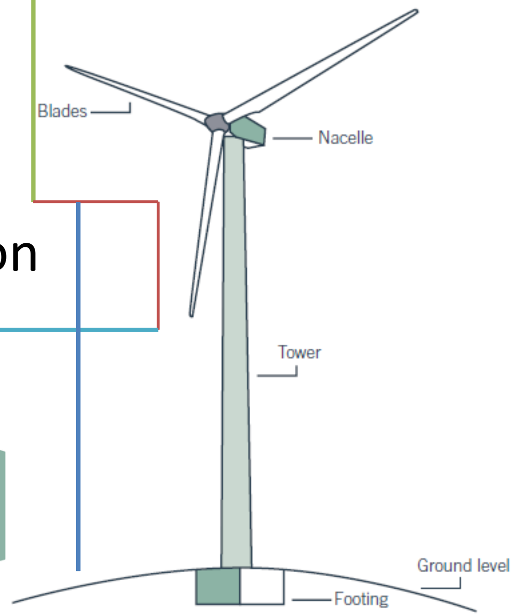
$$\left(\frac{P}{P_0}\right) = \left(\frac{H}{H_0}\right)^{3\alpha} = \left(\frac{65}{35}\right)^{3\times 0.2} = 1.45$$

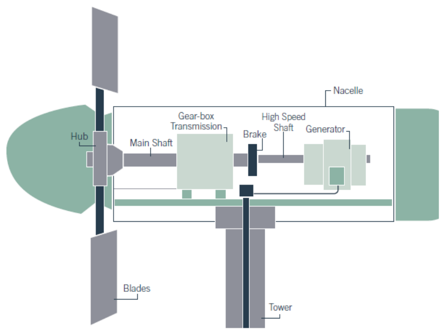


- The power in the wind at the top tip of the rotor is 45% higher than it is when the tip reaches its lowest point.

- Example 6.6 illustrates an important point about the variation in wind speed and power across the face of a spinning rotor. For large machines, when a blade is at its high point, it can be exposed to much higher wind forces than when it is at the bottom of its arc.
- This variation in stress as the blade moves through a complete revolution is compounded by the impact of the tower itself on wind speed—especially for downwind machines, which have a significant amount of wind “shadowing” as the blades pass behind the tower.
- The resulting flexing of a blade can increase the noise generated by the wind turbine and may contribute to blade fatigue, which can ultimately cause blade failure.

WE System Components &Power Calculation





Summary of previous lecture

POWER IN THE WIND

$$P_w = \frac{1}{2}\rho A v^3$$

- ρ- is the air density (kg/m3) (at 15◦C and 1 atm, ρ = 1.225 kg/m^3);
- A - is the cross-sectional area through which the wind passes (m^2)
- v = wind speed normal to A (m/s) (a useful conversion: 1 m/s = 2.237 mph).

POWER IN THE WIND

$$P_w = \frac{1}{2}\rho A v^3$$

- Notice that the power in the wind increases as the *cube* of wind-speed.
- Later we will see that most wind turbines aren't even turned on in low-speed winds,
- Wind power is proportional to the swept area of the turbine rotor.
- For a conventional horizontal axis turbine,
- the **area** A **is obviously just**

$A = (\pi/4)D^2,$

Windspeed (m/s)	Windspeed (mph)	Power (W/m^2)
0	0	0
1	2.24	1
2	4.47	5
3	6.71	17
4	8.95	39
5	11.19	77
6	13.42	132
7	15.66	210
8	17.90	314
9	20.13	447
10	22.37	613
11	24.61	815
12	26.84	1058
13	29.08	1346
14	31.32	1681
15	33.56	2067

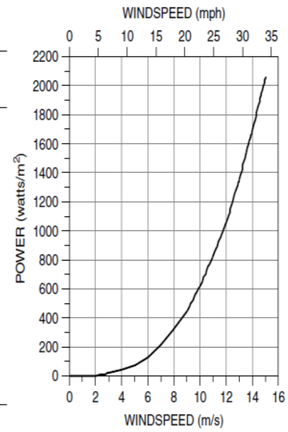
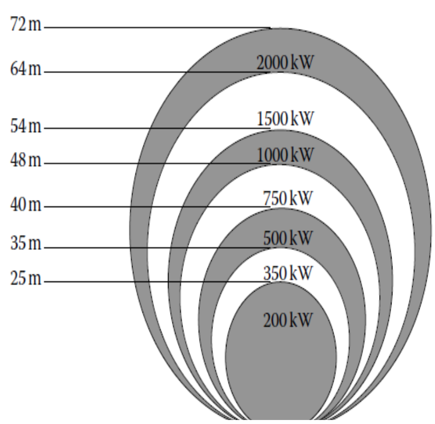


Figure 6.5 Power in the wind, per square meter of cross section, at 15°C and 1 atm.

POWER For different rotor diameters



Turbine output power for different wind turbine diameters.

Average wind speed

- Previous Example dramatically illustrates the inaccuracy associated with using average wind speeds.
- While both of the wind regimes had the same *average* wind speed, the combination of 9-m/s and 3-m/s winds (average 6 m/s) produces 75% more energy than winds blowing a steady 6 m/s.
- Later we will see that, under certain common assumptions about wind speed probability distributions , energy in the wind is typically almost twice the amount that would be found by using the average wind speed.

$$P_w = \frac{1}{2}\rho A v^3$$

IMPACT OF TOWER HEIGHT (important)

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

Friction Coefficient

Terrain Characteristics	Friction Coefficient (α)
Smooth hard ground, calm weather	0.10
Tall grass on level ground	0.15
High cops, hedges, and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

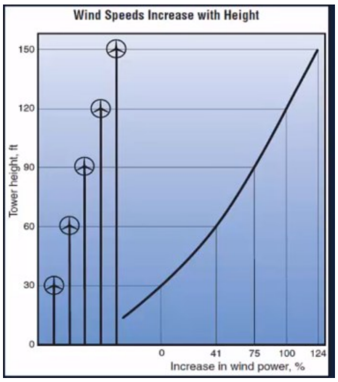
$$\left(\frac{v}{v_0}\right) = \frac{\ln(H/z)}{\ln(H_0/z)}$$

TABLE 6.4 Roughness Classifications for Use in (6.16)

Roughness Class	Description	Roughness Length $z(m)$
0	Water surface	0.0002
1	Open areas with a few windbreaks	0.03
2	Farm land with some windbreaks more than 1 km apart	0.1
3	Urban districts and farm land with many windbreaks	0.4
4	Dense urban or forest	1.6

ENE

Impact of friction coefficient on windspeed



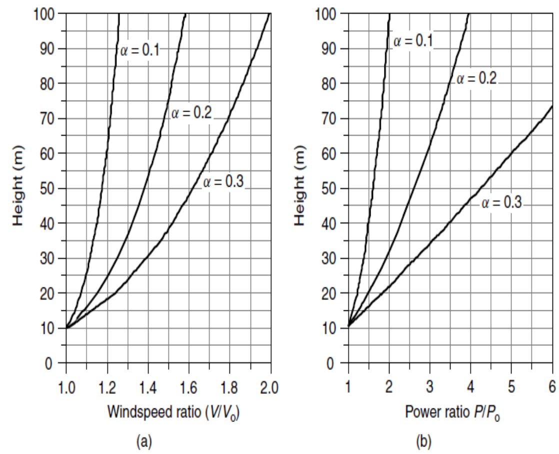
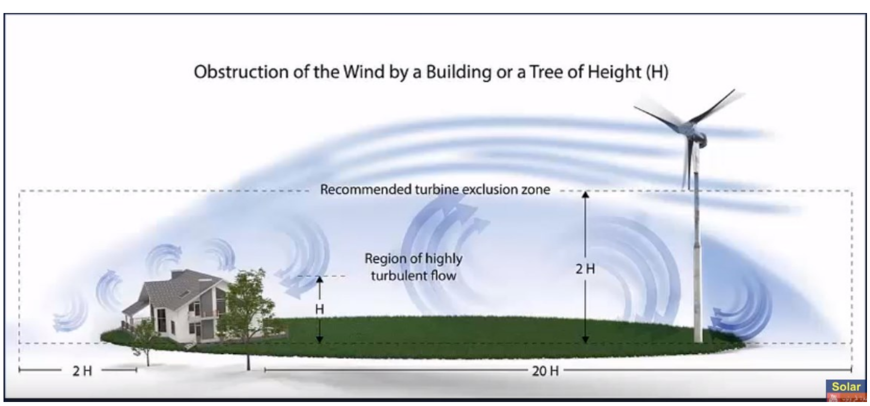


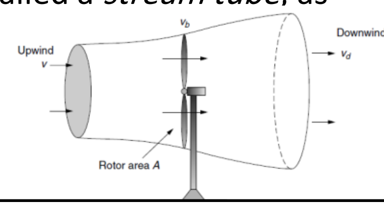
Figure 6.8 Increasing (a) windspeed and (b) power ratios with height for various friction coefficients α using a reference height of 10 m. For $\alpha = 0.2$ (hedges and crops) at 50 m, windspeed increases by a factor of almost 1.4 and wind power increases by about 2.6.

Placement of wind Turbines



System Components

- The original derivation for the maximum power that a turbine can extract from the wind is credited to a German physicist, **Albert Betz**, who first formulated the relationship in 1919. The analysis begins by imagining what must happen to the wind as it passes through a wind turbine.
- **As can be seen, wind approaching from the left is slowed down as a portion of its kinetic energy is extracted by the turbine.**
- The wind leaving the turbine has a lower velocity and its pressure is reduced, causing the air to expand downwind of the machine.
- An envelope drawn around the air mass that passes through the turbine forms what is called a *stream tube*, as suggested in the figure.

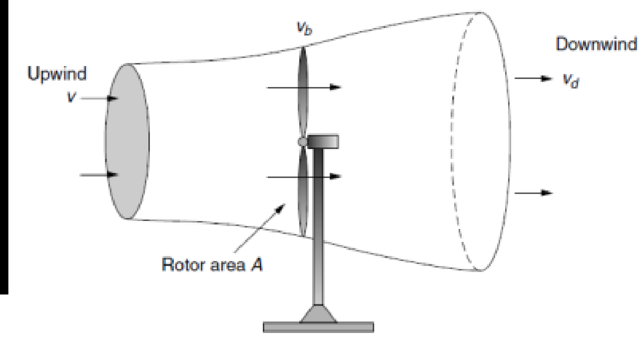


Maximum Rotor Effeciency

- It is interesting to note that a number of energy technologies have certain fundamental constraints that restrict the maximum possible conversion efficiency from one form of energy to another.
- For PV, it is the **band gap of the material** that limits the conversion efficiency from sunlight into electrical energy.
- And now, we will explore the constraint that limits the ability of a wind turbine to convert kinetic energy in the wind to mechanical power.

System Components

[redacted]



Mass Flow Rate

(for info only)

[redacted]

Power Extracted from wind

(for info only)

[redacted]

(for info only)

Power Extracted from wind

[redacted]

Maximum Power

(for info only)

- To find the maximum possible rotor efficiency, we simply take the derivative of Pb with respect to λ and set it equal to zero:

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0$$
$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)] = \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

- Which has a solution:

$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

Blade Efficiency

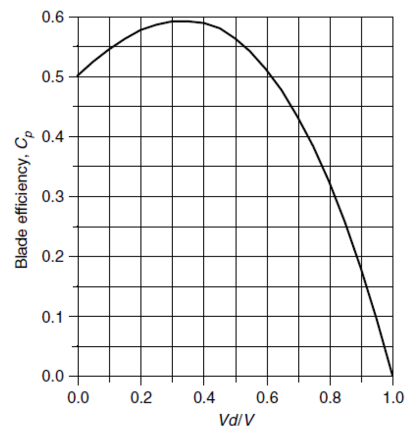
- If we now substitute $\lambda = 1/3$ into the equation for rotor efficiency Cp (we find that the theoretical maximum blade efficiency is

$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27} = 0.593 = 59.3\%$$

- This conclusion, that the maximum theoretical efficiency of a rotor is 59.3%, is called the *Betz efficiency* or, sometimes, *Betz' law*. A plot, showing this maximum occurring when the wind is slowed to one-third its upstream rate, is shown

Blade Efficiency

- The blade efficiency reaches a maximum when the wind is slowed to one-third of its upstream value.



Modern wind Turbine Blades

- **The obvious question is, how close to the Betz limit for rotor efficiency of 59.3 percent are modern wind turbine blades?**
- Under the best operating conditions, they can approach 80 percent of that limit, which puts them in the range of about 45 to 50 percent efficiency in converting the power in the wind into the power of a rotating generator shaft.
- For a given wind speed, rotor efficiency is a function of the rate at which the rotor turns.
- If the rotor turns too slowly, the efficiency drops off since the blades are letting too much wind pass by unaffected. If the rotor turns too fast, efficiency is reduced as the turbulence caused by one blade increasingly affects the blade that follows.

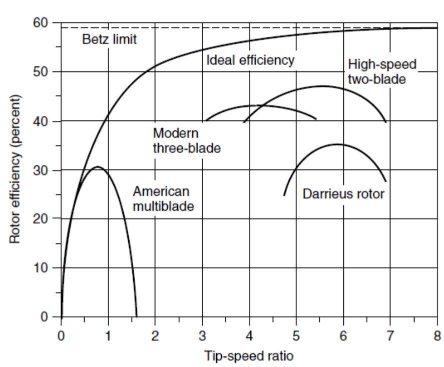
- **The usual way to illustrate rotor efficiency is to present it as a function of its *tip-speed ratio* (TSR).**
- **The tip-speed-ratio is the speed at which the outer tip of the blade is moving divided by the wind speed:**

$$\text{Tip-Speed-Ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

- where rpm is the rotor speed, revolutions per minute; *D* is the rotor diameter (m); and *v* is the wind speed (m/s) upwind of the turbine.

Tip speed Ratio (TSR)

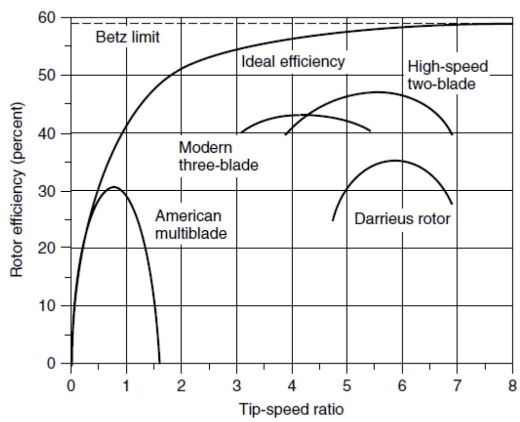
- A plot of typical efficiency for various rotor types versus TSR is given in Figure
- The American multi-blade spins relatively slowly, with an optimal TSR of less than 1 and maximum efficiency just over 30%.
- The two- and three-blade rotors spin much faster, with optimum TSR in the 4–6 range and maximum efficiencies of roughly 40–50%.



Rotors with fewer blades reach their optimum efficiency at higher rotational speeds.

Tip speed Ratio (TSR)

- Also shown is a line corresponding to an "ideal efficiency," which approaches the Betz limit as the rotor speed increases.
- The curvature in the maximum efficiency line reflects the fact that a slowly turning rotor does not intercept all of the wind, which reduces the maximum possible efficiency to something below the Betz limit.



Example: Important

- **Example 6.7 How Fast Does a Big Wind Turbine Turn?**
- A 40-m, three bladed wind turbine produces 600 kW at a wind speed of 14 m/s. Air density is the standard 1.225 kg/m3. Under these conditions,
- a. At what rpm does the rotor turn when it operates with a TSR of 4.0?
- b. What is the tip speed of the rotor?
- c. If the generator needs to turn at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed?
- d. What is the efficiency of the complete wind turbine (blades, gear box, generator) under these conditions

Example

a) Using 6.27

$$rpm = \frac{\text{TSR x 60 v}}{\pi D} = \frac{\text{4x60 s/min x14 m/s}}{40\pi \text{ m/rev}} = 26.7 \text{ rev/min}$$

This is about 2.2 seconds per revolution ....which seems slow

b) The tip of the blade is moving at

$$\text{Tip Speed} = \frac{\text{26.7 rev/min x } 40\pi \text{ m/rev}}{\text{60 s/min}} = 55.9 \text{ m/sec}$$

Even though 2.2 s/rev sounds slow, but the tip of rotor is rotating at 55 m/sec or 55.9 x60 sec /min x60 min/hour = 20124 m/h = 201.24 km/h or 125.77 mph

c) the generator needs to spin at 1800 rpm, then thegear box must increase the rotor shaft speed by a factor equal to gear ratio

$$\text{Gear Ratio} = \frac{1800}{26.7} = 67.4$$

Example

d) Power in the wind

$$P_W = \frac{1}{2}\rho A v_w^{\ 3}$$

$$= \frac{1}{2}(1.225)\text{x}\frac{\pi}{4}\text{x}40^2\text{x}14^3$$

$$= 2112 \text{ kW}$$

So the overall effeciency of the turbine, from wind to electricity is :

$$\text{Overall Efficiency} = \frac{600 \text{ kW}}{2112 \text{ kW}} = 0.284 \text{ or } 28.4\%$$

The rotor itself is about 43% efficient, $\xrightarrow{\text{then}}$

$$\text{efficieny of gear box} = \frac{28.4}{43} \cong 66\ \%$$

Blade Efficiency

- The answers derived in the above example are fairly typical for large wind turbines.
- That is, a large turbine will spin at about 20–30 rpm; the gear box will speed that up by roughly a factor of 50–70; and the overall efficiency of the machine is usually in the vicinity of 25–30%.
- In later presentations, we will explore these factors more carefully.

AVERAGE POWER IN THE WIND

- Having presented the equations for *power* in the wind and described the essential components of a wind turbine system, it is time to put the two together to determine how much *energy* might be expected from a wind turbine in various wind regimes,
- The cubic relationship between power in the wind and wind velocity tells us that we cannot determine the average power in the wind by simply substituting average wind speed into (6.4).
- We can begin to explore this important nonlinear characteristic of wind by rewriting (6.4) in terms of average values:

$$P_{avg} = \left(\tfrac{1}{2}\rho A v^3\right)_{avg} = \tfrac{1}{2}\rho A \left(v^3\right)_{avg}$$

- In other words, we need to find the average value of the cube of velocity.
- To do so will require that we introduce some statistics.

- Suppose, for example, that during a 10-h period, there were 3 h of no wind, 3 h at 5 mph, and 4 h at 10 mph.
- The average wind speed would be

$$v_{\text{avg}} = \frac{\text{Miles of wind}}{\text{Total hours}} = \frac{3\text{ h} \cdot 0\text{ mile/hr} + 3\text{ h} \cdot 5\text{ mile/h} + 4\text{ h} \cdot 10\text{ mile/h}}{3 + 3 + 4\text{ h}}$$

$$= \frac{55\text{ mile}}{10\text{ h}} = 5.5\text{ mph}$$

- By regrouping some of the terms above, we could also think of this as having no wind 30% of the time, 5 mph for 30% of the time, and 10 mph 40% of the time:

$$v_{\text{avg}} = \left(\frac{3\text{ h}}{10\text{ h}}\right) \times 0\text{ mph} + \left(\frac{3\text{ h}}{10\text{ h}}\right) \times 5\text{ mph} + \left(\frac{4\text{ h}}{10\text{ h}}\right) \times 10\text{ mph} = 5.5\text{ mph}$$

$$v_{\text{avg}} = \frac{\sum_i [v_i \cdot (\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i \cdot (\text{fraction of hours @ } v_i)]$$

$$v_{\text{avg}} = \sum_i [v_i \cdot \text{probability}(v = v_i)]$$

- **We know that the quantity of interest in determining average power in the wind is not the average value of *v*, but the average value of *v*^3.**
- The averaging process yields the following:

$$(v^3)_{avg} = \frac{\sum_i [v_i{}^3 \cdot (\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i{}^3 \cdot (\text{fraction of hours @ } v_i)]$$

Or, in probabilistic terms,

$$(v^3)_{avg} = \sum_i [v_i{}^3 \cdot \text{probability}(v = v_i)]$$

v (m/s)	Hrs/yr
0	24
1	276
2	527
3	729
4	869
5	941
6	946
7	896
8	805
9	690
10	565
11	444
12	335
13	243
14	170
15	114
16	74
17	46
18	28
19	16
20	9
21	5
22	3
23	1
24	1
25	0
Total hrs	8,760

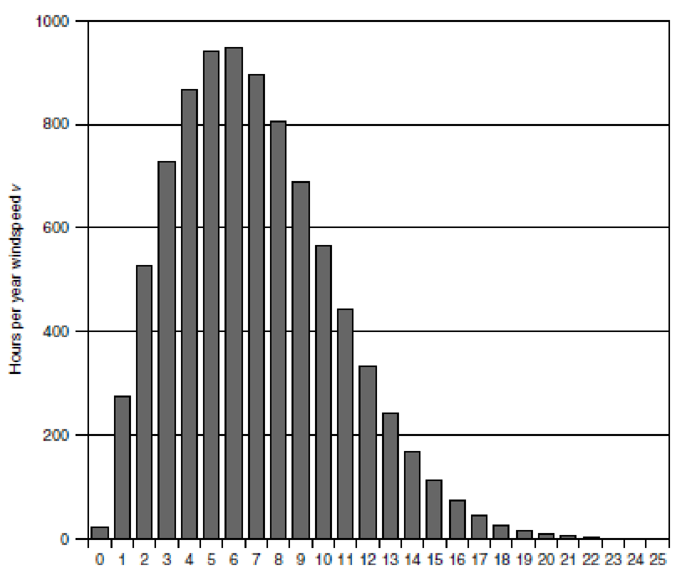


Figure 6.22 An example of site data and the resulting wind histogram showing hours that the wind blows at each windspeed.

Example 6.9 Average Power in the Wind. Using the data given in Fig. 6.22, find the average windspeed and the average power in the wind (W/m^2). Assume the standard air density of 1.225 kg/m^3. Compare the result with that which would be obtained if the average power were miscalculated using just the average windspeed.

Solution. We need to set up a spreadsheet to determine average wind speed v and the average value of v^3. Let's do a sample calculation of one line of a spreadsheet using the 805 h/yr at 8 m/s:

$$\text{Fraction of annual hours at 8 m/s} = \frac{805 \text{ h/yr}}{24 \text{ h/d} \times 365 \text{ d/yr}} = 0.0919$$

$$v_8 \cdot \text{Fraction of hours at 8 m/s} = 8 \text{ m/s} \times 0.0919 = 0.735$$

$$(v_8)^3 \cdot \text{Fraction of hours at 8 m/s} = 8^3 \times 0.0919 = 47.05$$

The rest of the spreadsheet to determine average wind power using (6.29) is as follows:

Wind Speed v_i (m/s)	Hours @ v_i per year	Fraction of Hours @ v_i	$v_i \times$ Fraction Hours @ v_i	$(v_i)^3$	$(v_i)^3 \times$ fraction Hours @ v_i
0	24	0.0027	0.000	0	0.00
1	276	0.0315	0.032	1	0.03
2	527	0.0602	0.120	8	0.48
3	729	0.0832	0.250	27	2.25
4	869	0.0992	0.397	64	6.35
5	941	0.1074	0.537	125	13.43
6	946	0.1080	0.648	216	23.33
7	896	0.1023	0.716	343	35.08
8	805	0.0919	0.735	512	47.05
9	690	0.0788	0.709	729	57.42
10	565	0.0645	0.645	1,000	64.50
11	444	0.0507	0.558	1,331	67.46
12	335	0.0382	0.459	1,728	66.08
13	243	0.0277	0.361	2,197	60.94
14	170	0.0194	0.272	2,744	53.25
15	114	0.0130	0.195	3,375	43.92
16	74	0.0084	0.135	4,096	34.60
17	46	0.0053	0.089	4,913	25.80
18	28	0.0032	0.058	5,832	18.64
19	16	0.0018	0.035	6,859	12.53
20	9	0.0010	0.021	8,000	8.22
21	5	0.0006	0.012	9,261	5.29
22	3	0.0003	0.008	10,648	3.65
23	1	0.0001	0.003	12,167	1.39
24	1	0.0001	0.003	13,824	1.58
25	0	0.0000	0.000	15,625	0.00
Totals:	8760	1.000	7.0		653.24

The average windspeed is

$$v_{avg} = \sum_i [v_i \cdot (\text{Fraction of hours @ } v_i)] = 7.0 \text{ m/s}$$

The average value of v^3 is

$$(v^3)_{avg} = \sum_i [v_i{}^3 \cdot (\text{Fraction of hours @ } v_i)] = 653.24$$

The average power in the wind is

$$P_{avg} = \frac{1}{2}\rho(v^3)_{avg} = 0.5 \times 1.225 \times 653.24 = 400 \text{ W/m}^2$$

If we had miscalculated average power in the wind using the 7 m/s *average* windspeed, we would have found:

$$P_{average}(\text{WRONG}) = \frac{1}{2}\rho(v_{avg})^3 = 0.5 \times 1.225 \times 7.0^3 = 210 \text{ W/m}^2$$

In the above example, the ratio of the average wind power calculated correctly using $(v^3)_{avg}$ to that found when the average velocity is (mis)used is $400/210 = 1.9$. That is, the correct answer is nearly twice as large as the power found when average windspeed is substituted into the fundamental wind power equation $P = \frac{1}{2}\rho A v^3$. In the next section we will see that this conclusion is always the case when certain probability characteristics for the wind are assumed.

- Rayleigh pdf

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] \quad \text{Rayleigh p.d.f.}$$

AVERAGE POWER IN THE WIND 345

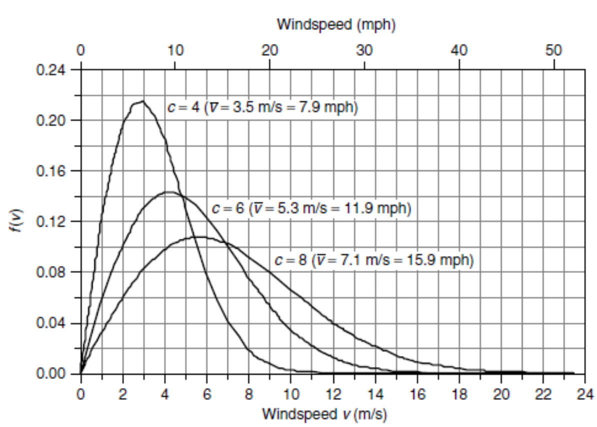


Figure 6.25 The Rayleigh probability density function with varying scale parameter c. Higher scaling parameters correspond to higher average windspeeds.

Important

$$\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2} \rho A \overline{v}^3 \qquad \text{(Rayleigh assumptions)} \qquad (6.48)$$

That is, with Rayleigh statistics, *the average power in the wind is equal to the power found at the average windspeed multiplied by 6/π or 1.91.*

Example 6.10 Average Power in the Wind. Estimate the average power in the wind at a height of 50 m when the windspeed at 10 m averages 6 m/s. Assume Rayleigh statistics, a standard friction coefficient $\alpha = 1/7$, and standard air density $\rho = 1.225 \text{ kg/m}^3$.

Solution. We first adjust the winds at 10 m to those expected at 50 m using

$$\overline{v}_{50} = \overline{v}_{10} \left(\frac{H_{50}}{H_{10}} \right)^{\alpha} = 6 \cdot \left(\frac{50}{10} \right)^{1/7} = 7.55 \text{ m/s}$$

So, using (6.48), the average wind power density would be

$$\overline{P}_{50} = \frac{6}{\pi} \cdot \frac{1}{2} \rho \overline{v}^3 = \frac{6}{\pi} \cdot \frac{1}{2} \cdot 1.225 \cdot (7.55)^3 = 504 \text{ W/m}^2$$

Example 6.11 Annual Energy Delivered by a Wind Turbine. Suppose that a NEG Micon 750/48 (750-kW generator, 48-m rotor) wind turbine is mounted on a 50-m tower in an area with 5-m/s average winds at 10-m height. Assuming standard air density, Rayleigh statistics, Class 1 surface roughness, and an overall efficiency of 30%, estimate the annual energy (kWh/yr) delivered.

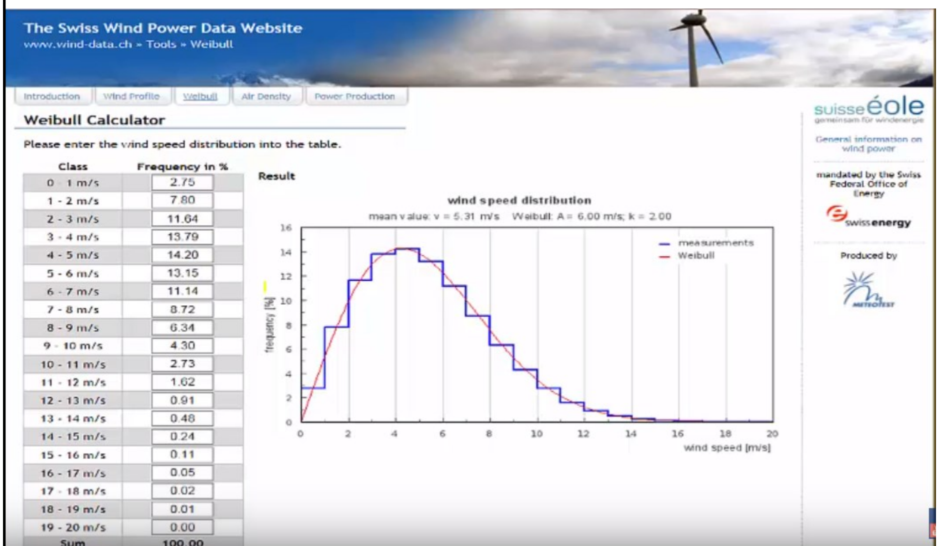
Solution. We need to find the average power in the wind at 50 m. Since "surface roughness class" is given rather than the friction coefficient α, we need to use (6.16) to estimate wind speed at 50 m. From Table 6.4, we find the roughness length z for Class 1 to be 0.03 m. The average windspeed at 50 m is thus

$$v_{50} = v_{10} \frac{\ln(H_{50}/z)}{\ln(H_{10}/z)} = 5 \text{ m/s} \cdot \frac{\ln(50/0.03)}{\ln(10/0.03)} = 6.39 \text{ m/s}$$

Average power in the wind at 50 m is therefore (6.48)

$$\overline{P}_{50} = \frac{6}{\pi} \cdot \frac{1}{2} \rho \overline{v}^3 = 1.91 \times 0.5 \times 1.225 \times (6.39)^3 = 304.5 \text{ W/m}^2$$

Websites for wind data



Class	Frequency in %
0 - 1 m/s	2.75
1 - 2 m/s	7.80
2 - 3 m/s	11.64
3 - 4 m/s	13.79
4 - 5 m/s	14.20
5 - 6 m/s	13.15
6 - 7 m/s	11.14
7 - 8 m/s	8.72
8 - 9 m/s	6.34
9 - 10 m/s	4.30
10 - 11 m/s	2.73
11 - 12 m/s	1.62
12 - 13 m/s	0.91
13 - 14 m/s	0.48
14 - 15 m/s	0.24
15 - 16 m/s	0.11
16 - 17 m/s	0.05
17 - 18 m/s	0.02
18 - 19 m/s	0.01
19 - 20 m/s	0.00
Sum	100.00

Since this 48-m machine collects 30% of that, then, in a year with 8760 hours, the energy delivered would be

$$\text{Energy} = 0.3 \times 304.5\ \text{W/m}^2 \times \frac{\pi}{4}(48\ \text{m})^2 \times 8760\ \text{h/yr} \times \frac{1\ \text{kW}}{1000\ \text{W}}$$
$$= 1.45 \times 10^6\ \text{kWh/yr}$$

- Optimum Spacing

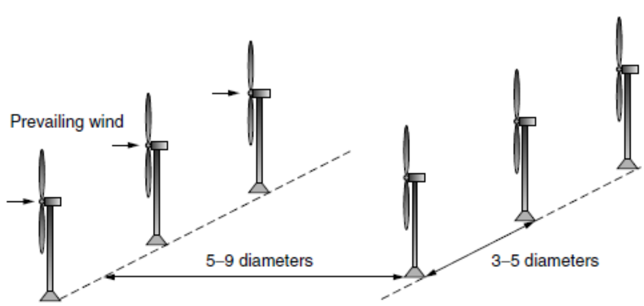


Figure 6.29 Optimum spacing of towers is estimated to be 3–5 rotor diameters between wind turbines within a row and 5–9 diameters between rows.

Power Curve

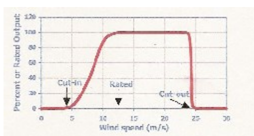


Figure 2-28: Typical WTG power curve.

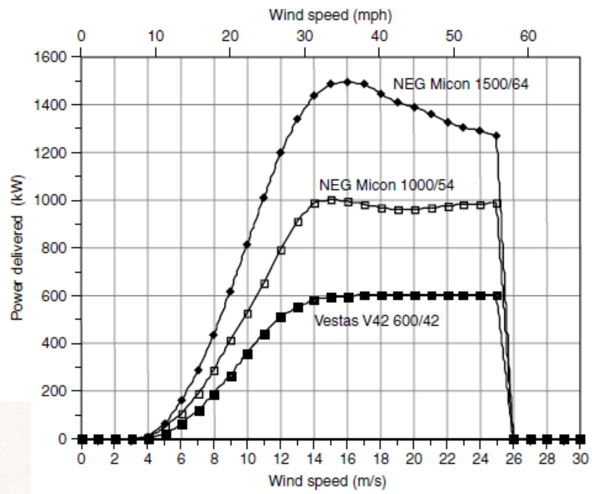


Figure 6.35 Power curves for three large wind turbines.

WIND TURBINE GENERATORS

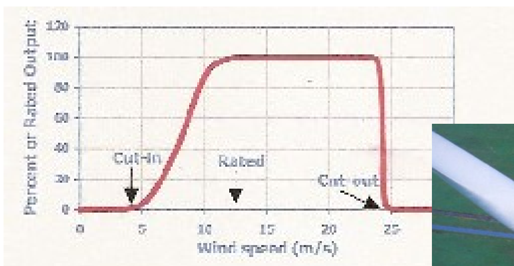


Figure 2-28: Typical WTG power curve.

Wind Turbine Siting

- Wind turbines can be grid connected or independently operated from isolated locations.
- The two critical factors in finding the most suitable locations for wind turbines are wind speed and the quality of wind.
- The most suitable sites for wind turbines are turbulence-free locations since turbulence makes wind turbines less efficient and affects overall stability of the turbine.
- Wind turbulence is influenced by the surface of the earth. Depending on the roughness of the terrain, the wind can be more or less turbulent.

Wind Turbine Siting

- It is only at 3000 ft and above ground level that the wind speed is not affected by friction against the earth's surface and therefore there is no turbulence.
- Wind power can be categorized into seven classes according to the wind speed (m/s) and wind power density (W/m^2).
- It should be noted that in this table each wind power class corresponds to two power densities.
- For example, wind power class 4 represents the wind power density range between 200 and 250W/m^2.

Wind Turbine Siting

Wind Power Classes

	At a Height of 10 m (33 ft)		At a Height of 50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Wind Speed (m/s)	Wind Power Density (W/m^2)	Wind Speed (m/s)
1	0	0	0	0
1–2	100	4.4	200	5.6
2–3	150	5.1	300	6.4
3–4	200	5.6	400	7.0
4–5	250	6.0	500	7.5
5–6	300	6.4	600	8.0
6–7	400	7.0	800	8.8
7	1000	9.4	2000	11.9

Wind Turbine Siting

- Another important factor for wind turbine siting is **roughness of terrain**. There are roughness classes, which explain the relation between wind speeds and landscape conditions.
- Roughness class varies from 0 to 4, where class 0 represents water surfaces and open terrains with smooth surfaces, and class 4 represents very large cities with tall buildings and skyscrapers.
- Two key parameters regarding the different geographical locations affect the wind turbine siting: the friction coefficient and the roughness classification .
- The friction coefficients are based on different terrain characteristics and were shown previously

Different Electrical Machines in Wind Turbines

- There are various types of electrical machines that are used in wind turbines.
- There is no clear criterion for choosing a particular machine to work as a wind generator.
- The wind generator can be chosen based on the **installed power, site of the turbine, load type, and simplicity of control.**
- BLDC generators, permanent magnet synchronous generators (PMSGs), induction generators, and synchronous generators are the machine types that are used in wind turbine application.

Different Electrical Machines in Wind Turbines

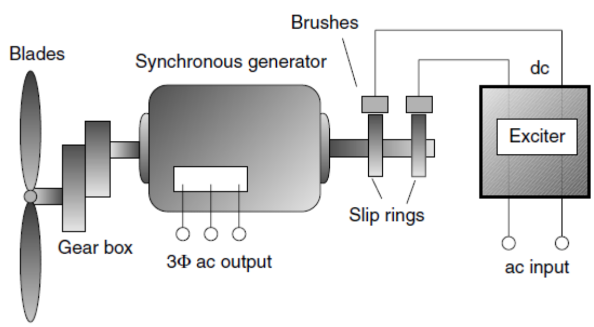
- **Squirrel cage induction or BLDC generators** are generally used for **small wind turbines** in household applications.
- **Doubly fed induction generators (DFIGs**) are usually used for **megawatt size turbines**.
- **Synchronous machines and permanent magnet synchronous machines** (PMSMs) are the other machines that are used for **various wind turbine applications.**

Synchronous Generators

- Synchronous generators are forced to spin at a precise rotational speed determined by the number of poles and the frequency needed for the power lines.
- Their magnetic fields are created on their rotors.
- While very small synchronous generators can create the needed magnetic field with a permanent magnet rotor, almost all wind turbines that use synchronous generators create the field by running direct current through windings around the rotor core.
- The fact that synchronous generator rotors needs dc current for their field windings creates two complications.
- First, dc has to be provided, which usually means that a rectifying circuit, called the *exciter*, is needed to convert ac from the grid into dc for the rotor.
- Second, this dc current needs to make it onto the spinning rotor, which means that slip rings on the rotor shaft are needed, along with brushes that press against them.
- Replacing brushes and cleaning up slip rings adds to the maintenance needed by these synchronous generators.

Synchronous Generators

- Figure below shows the basic system for a wind turbine with a synchronous generator, including a reminder that the generator and blades are connected through a gear box to match the speeds required of each.



BLDC Machines

- BLDC machines are widely used in small wind turbines (up to 15 kW) due to their control
- simplicity, compactness, lightness, ease of cooling, low noise levels, and low maintenance.
- Due to the existence of a magnetic source inside the BLDCs, they are the most efficient electric machines.
- Recent introduction of high-energy density magnets (rare-earth magnets) has allowed the achievement of very high flux densities in these machines bringing compactness.
- There is no current circulation in the rotor for the magnetic field; therefore, the rotor of a BLDC generator does not heat up.

BLDC Machines

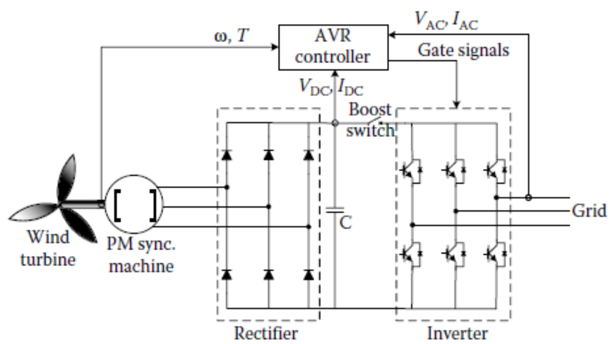
- The absence of brushes, mechanical commutators, and slip rings suppresses the need for regular maintenance and suppresses the risk of failure associated with these elements.
- Moreover, there is no noise associated with the mechanical contact. The switching frequency of the driving converter is high enough so that the harmonics are not audible
- Due to its mechanical performance, the BLDC generator drive system can provide additional increase in power density with the advanced control techniques.

Permanent Magnet Synchronous Machines

- This type of machine can be used in both fixed and variable speed applications.
- The PMSG is very efficient and suitable for wind turbine applications.
- PMSGs allow direct-drive (DD) energy conversion for wind applications.
- DD energy conversion helps eliminate the gearbox between the turbine and generator; thus these systems are less expensive and require less maintenance.
- However, the lower speed determined by the turbine shaft is the operating speed for the generator.

Permanent Magnet Synchronous Machines

- The boost converter controls the electromagnetic torque. The supply side converter regulates the DC link voltage and controls the input power factor.
- The grid side converter (GSC) can be used to control the active and reactive power being fed to the grid.
- The automatic voltage regulator (AVR) collects the information on the turbine's speed, DC link voltage, current, and grid side voltage, and it calculates the pulse width modulation (PWM) pattern (control scheme) for the converter
- This configuration has been considered for small size (<50 kW)

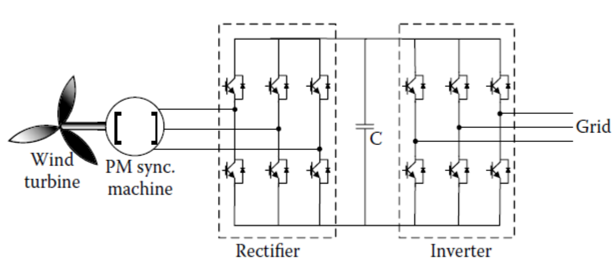


PMSG with a rectifier/inverter.

PMSG

- **The turbine can be operated at its maximum efficiency and the variable speed operation of the PMSG** can be controlled by using a power converter that is able to handle the maximum power flow.
- The stator terminal voltage is controlled, utilizing the field orientation control (FOC) allows the generator to operate near its optimal working point in order to minimize the losses in the generator and power electronic circuit.
- However, the performance depends on the knowledge of the generator parameter that varies with temperature and frequency.
- The main drawbacks are the cost of the PMs that increases the price of the machine, and the demagnetization of the PMs.
- **In addition, it is not possible to control the power factor of the machine**

PMSG with a back-to-back inverter.



Induction Machines

Induction machines used as electric **power generators need an external reactive power source that will excite the induction machine**, which is certainly not required for synchronous machines in similar applications.

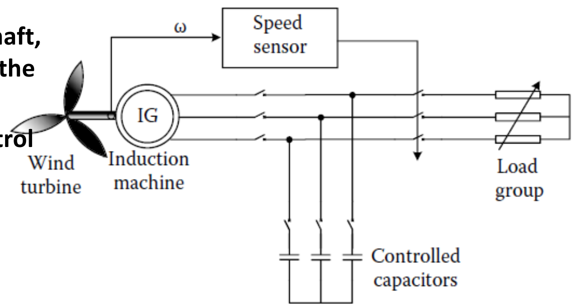
- If the induction machine is connected to the grid, the required reactive power can be provided by the power system .
- The induction machine may be used in cogeneration with other synchronous generators or the excitation can be supplied from capacitor banks (only for stand-alone self-excited generators application)

Induction Machines

- For stand-alone induction generator applications, the reactive power required for excitation can be supplied using static Volt-Ampere-reactive (VAR) compensators or static compensators (STATCOMs)
- Brushless rotor construction does not need a separate source for excitation; hence its cost can be relatively low.
- Induction generators are often used in wind turbine applications since they require no maintenance and they offer self-protection against severe overloads and short circuits.

IG Conventional Control Scheme

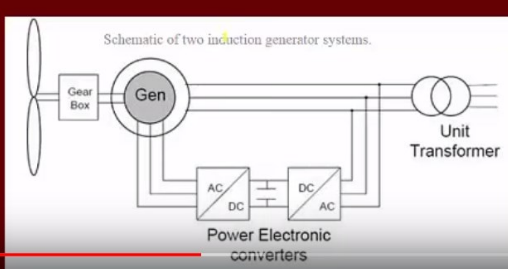
- The conventional scheme for frequency control of an induction generator consists of a speed governor, which regulates the prime mover, and switched capacitor banks, to provide reactive power to the load and excitation of the induction generator,
- The input power for the induction generator has to match the load power demand. The speed of the wind is not controllable; therefore, the induction generator should be controlled according to the load variations .
- Increasing the speed of the shaft, in the case of any increase of the load, is very difficult.
- Therefore, the frequency control technique has a very poor performance.
- Another issue is that voltage regulation requires precise control of the reactive power source



Doubly-Fed Induction Generator DFIG

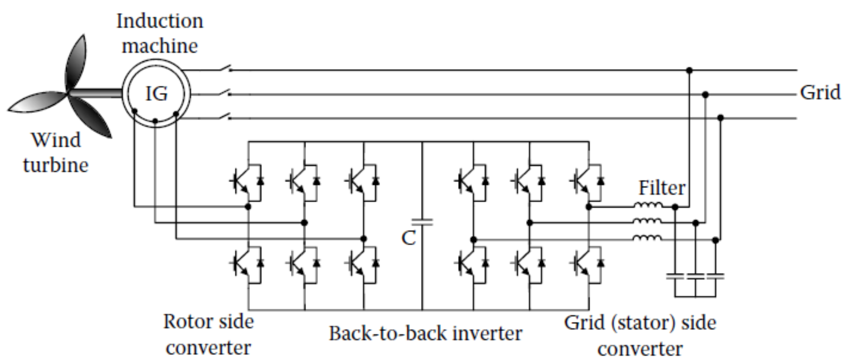
Nowadays, over 85% of the installed wind turbines utilize DFIGs and the largest capacity for the commercial wind turbine product with DFIG has increased towards 5MW in industry.

In the DFIG topology, the stator is directly connected to the grid through transformers and the rotor is connected to the grid through PWM power converters. The converters can control the rotor circuit current, frequency and phase angle shifts. Such induction generators are capable of operating at a wide slip range (typically ±30% of synchronous speed).



DFIG

- In the DFIG topology, the induction generator is not a squirrel cage machine and the rotor windings are not short circuited.
- Instead, the rotor windings are used as the secondary terminals of the generator to provide the capability of controlling the machine power, torque, speed, and reactive power.



DFIG

- To control the active and reactive power flow of the DFIG topology, the rotor side converter (RSC) and (GSC) should be controlled separately .
- The speed and the torque of the wound rotor induction machine can be controlled by regulating voltages from both the rotor and the stator sides of the machine.
- In the DFIG, like the synchronous generator, the real power depends on the rotor voltage magnitude and angle.
- In addition, like the induction machine, the slip is also a function of the real power

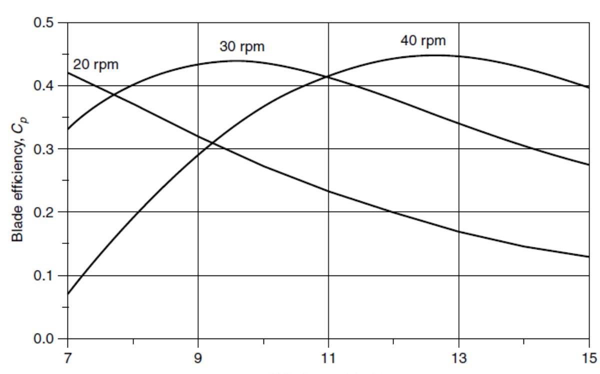
DFIG Advantages

- **The inverter cost and size are considerably reduced**
- **It has an improved effeciency of approximately 2–3% can be obtained.**
- **DFIG topology offers a decoupled control of generator active and reactive powers .**
- **The cost and size of the inverter and EMI filters can be reduced since the inverter size is reduced.**
- **In addition, the inverter harmonics are lowered since the inverter is not connected to the main stator windings.**

Importance of Variable Rotor Speeds

- Figure below shows the impact of rotor speed on blade efficiency,
- what is more important is electric power delivered by the wind turbine.

Blade efficiency is improved if its rotation speed changes with changing wind speed. In this figure, three discrete speeds are shown for a hypothetical rotor.



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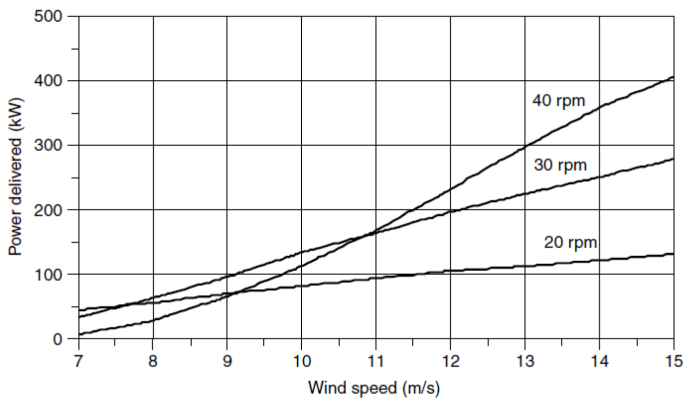
Importance of Variable Rotor Speeds

- Figure below shows the impact of varying rotor speed from 20 to 30 to 40 rpm for a 30-m rotor with efficiency given in previous Figure , along with an assumed gear and generator efficiency of 70%.



Example of the impact that a three-step rotational speed adjustment has on delivered power.
For winds below 7.5 m/s, 20 rpm is best; between 7.5 and 11 m/s,
30 rpm is best; and above 11 m/s, 40 rpm is best.

Pole changing IG

- Induction generators spin at a frequency that is largely controlled by the number of poles.
- A two-pole, 60-Hz generator rotates at very close to 3600 rpm; with four poles it rotates at close to 1800 rpm; and so on.
- If we could change the number of poles, we could allow the wind turbine to have several operating speeds
- The stator can have external connections that switch the number of poles from one value to another without needing any change in the rotor.
- This approach is common in household appliance motors such as those used in washing machines and exhaust fans to give two- or three-speed operation.

Multiple Gearboxes

- Some wind turbines have two gearboxes with separate generators attached to each, giving a low-wind-speed gear ratio and generator plus a high-wind-speed gear ratio and generator.