Photovoltaics

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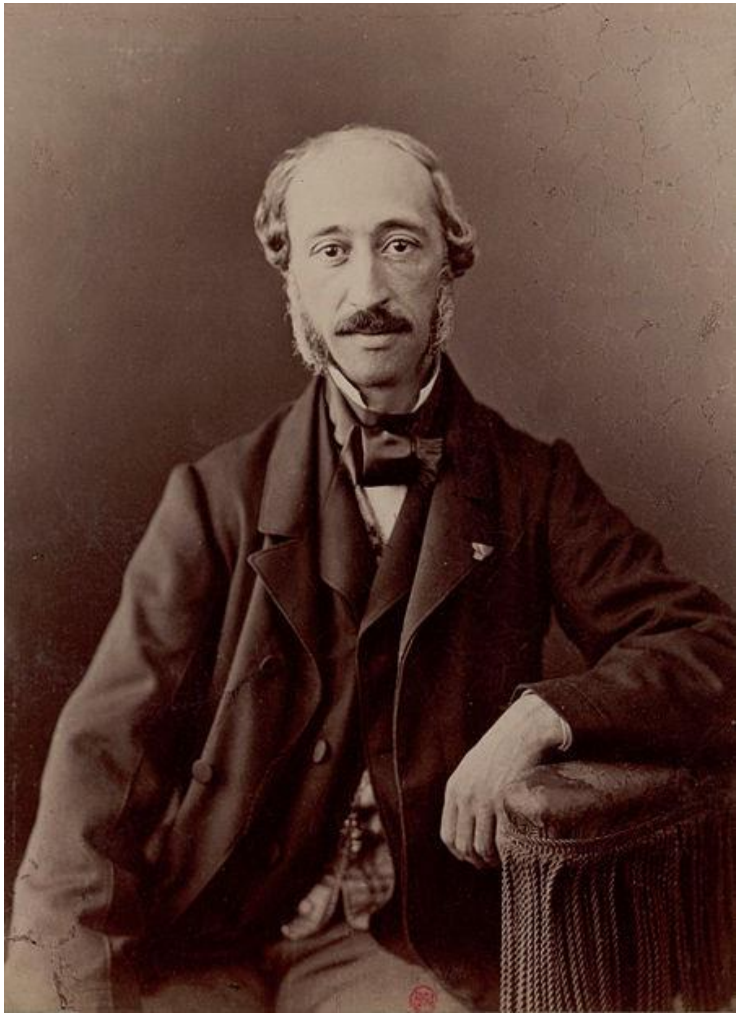
Solar Cells

1839 - Alexandre Edmond Becquerel observes the photovoltaic effect via an electrode in a conductive solution exposed to light.



1941 - Russell Shoemaker Ohl was an American engineer who is generally recognized for patenting the modern solar cell (US Patent 2402662, "Light sensitive device") based on pn-junction device.

1954 - Bell Labs announces the invention of the first practical silicon solar cell. At the National Academy of Science Meeting, solar cells with an efficiency of 6% are shown. The New York Times forecasts that solar cells will eventually lead to a source of "limitless energy of the sun."

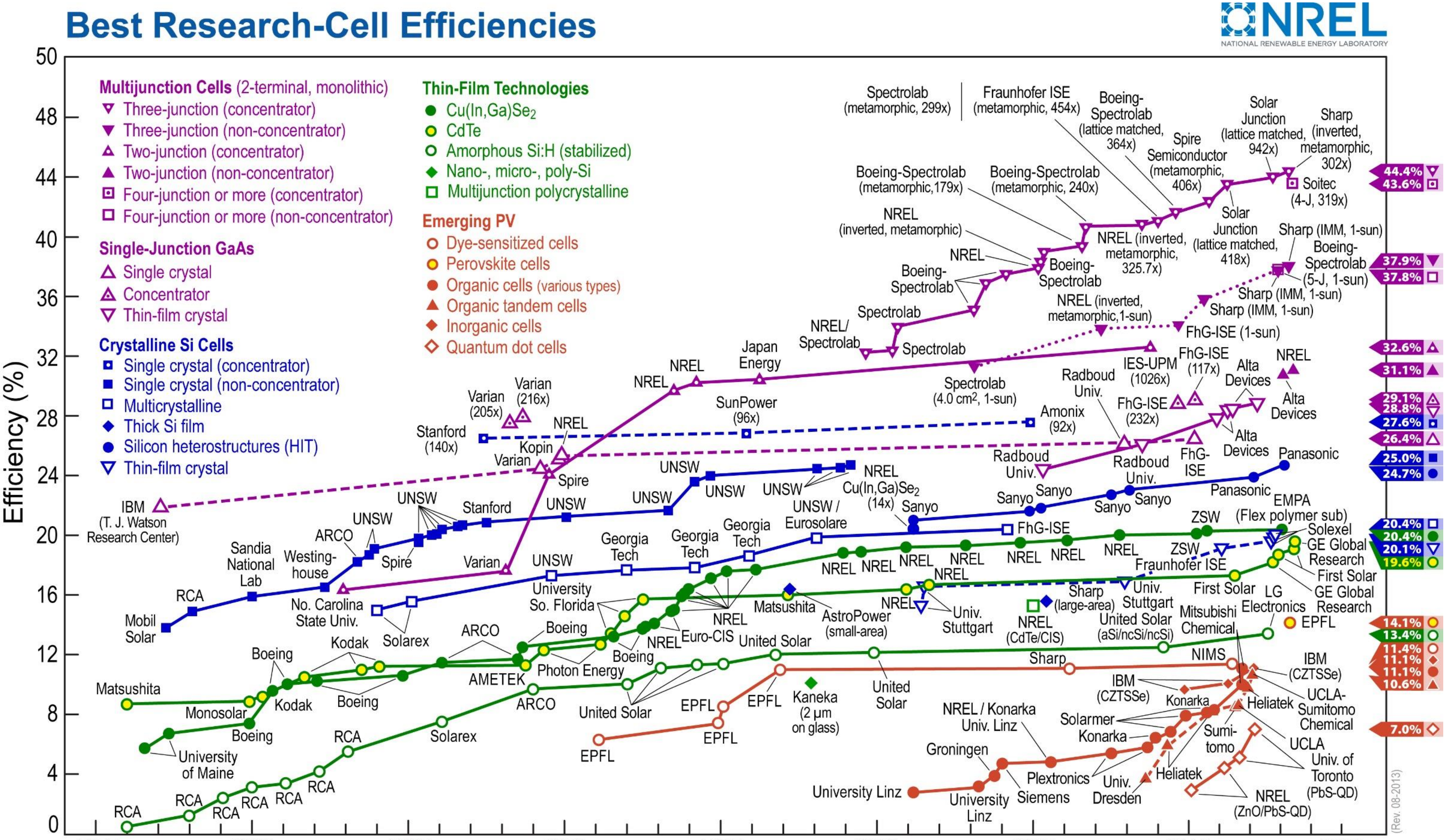
Solar Cells

Most solar cells use crystalline silicon since silicon-based semiconductor fabrication is now a mature technology that enables cost-effective devices to be manufactured.

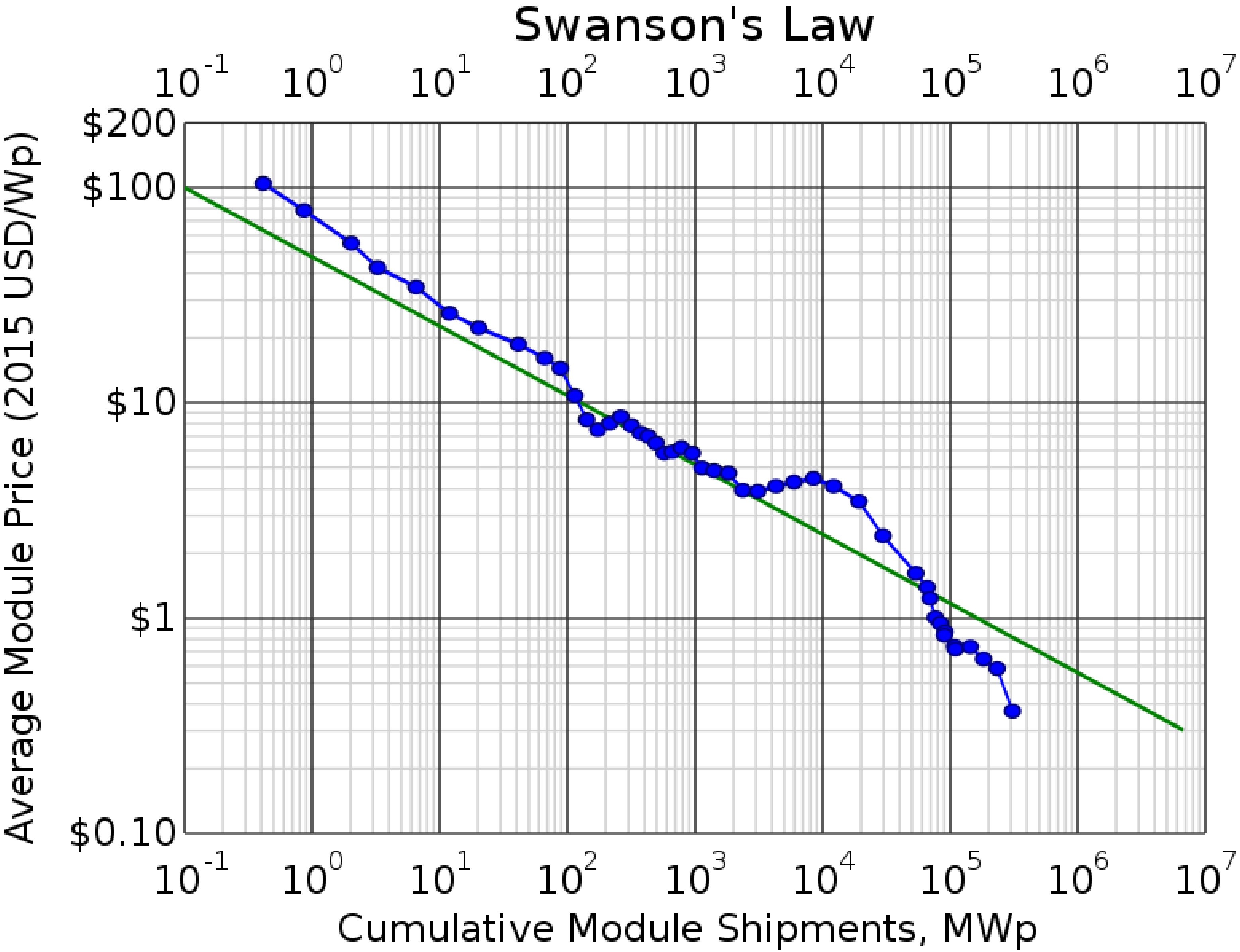
Typical Si-based solar cell efficiencies range from about **18% for polycrystalline** to **22-24% in high-efficiency single-crystal devices** that have special structures to absorb as many of the incident photons as possible.

Solar cells fabricated by making a pn junction in the same crystal are called **homojunctions**.

Solar Cells

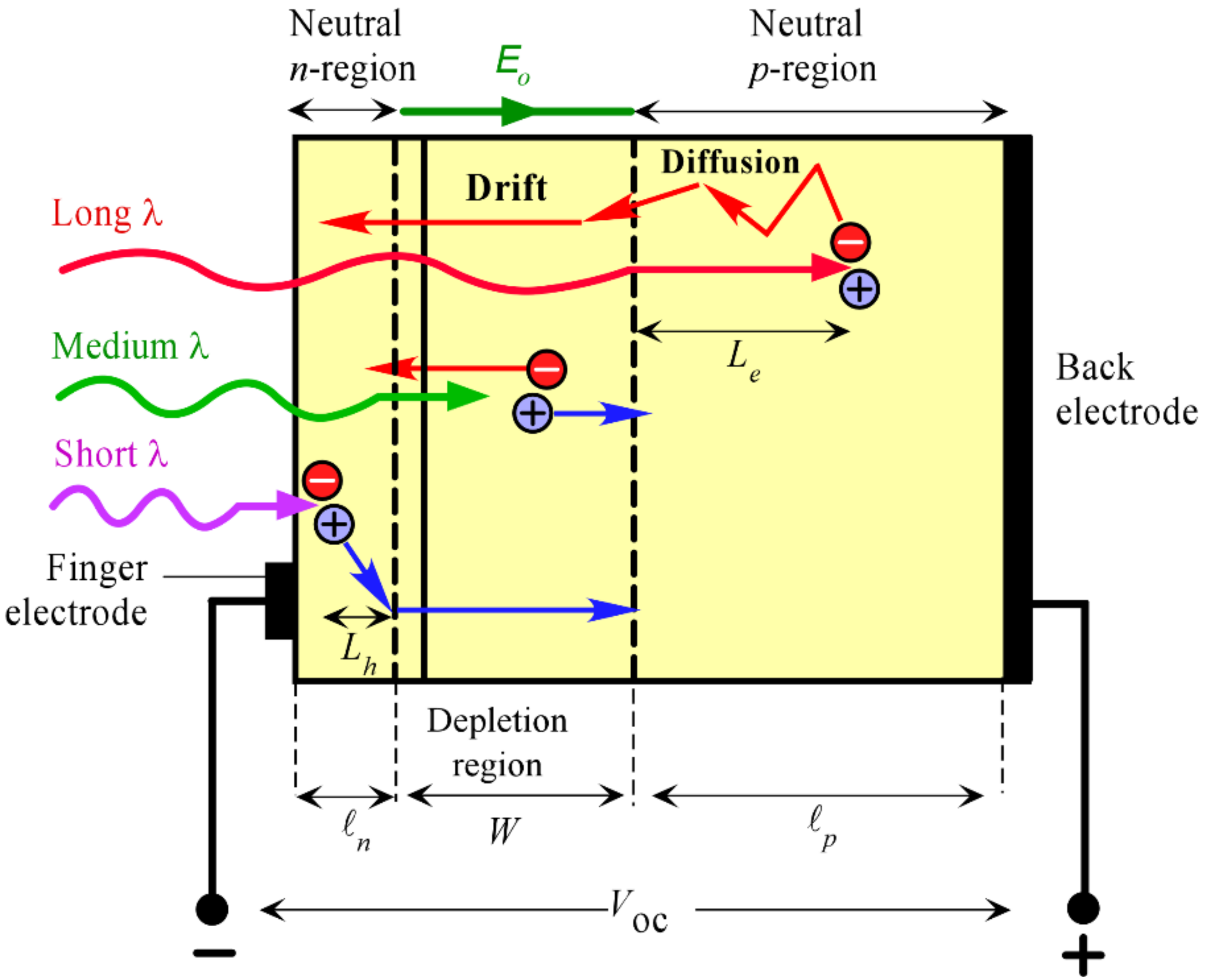

Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
0
4
8
12
16
20
24
28
32
36
40
44
48
50
1975
1980
1985
1990
1995
2000
2005
2010
2015
Multijunction Cells (2-terminal, monolithic)
▽ Three-junction (concentrator)
▼ Three-junction (non-concentrator)
△ Two-junction (concentrator)
▲ Two-junction (non-concentrator)
▣ Four-junction or more (concentrator)
☐ Four-junction or more (non-concentrator)
Single-Junction GaAs
△ Single crystal
△ Concentrator
▽ Thin-film crystal
Crystalline Si Cells
▣ Single crystal (concentrator)
■ Single crystal (non-concentrator)
☐ Multicrystalline
◆ Thick Si film
● Silicon heterostructures (HIT)
▽ Thin-film crystal
Thin-Film Technologies
● Cu(In,Ga)Se2
● CdTe
○ Amorphous Si:H (stabilized)
◆ Nano-, micro-, poly-Si
☐ Multijunction polycrystalline
Emerging PV
○ Dye-sensitized cells
○ Perovskite cells
● Organic cells (various types)
▲ Organic tandem cells
◆ Inorganic cells
◇ Quantum dot cells
Spectrolab (metamorphic, 299x)
Fraunhofer ISE (metamorphic, 454x)
Boeing-Spectrolab (lattice matched, 364x)
Spire Semiconductor (metamorphic, 406x)
Solar Junction (lattice matched, 942x)
Sharp (inverted, metamorphic, 302x)
Boeing-Spectrolab (metamorphic, 179x)
Boeing-Spectrolab (metamorphic, 240x)
Soitec (4-J, 319x)
NREL (inverted, metamorphic)
NREL (inverted, metamorphic, 325.7x)
Solar Junction (lattice matched, 418x)
Sharp (IMM, 1-sun)
Boeing-Spectrolab (5-J, 1-sun)
NREL
Boeing-Spectrolab
Spectrolab
Sharp (IMM, 1-sun)
Sharp (IMM, 1-sun)
NREL (inverted, metamorphic, 1-sun)
FhG-ISE (1-sun)
NREL/ Spectrolab
Spectrolab
Japan Energy
NREL
NREL
Spectrolab (4.0 cm2, 1-sun)
Radboud Univ.
IES-UPM (1026x)
FhG-ISE (117x)
Alta Devices
NREL
Varian (205x)
Varian (216x)
NREL
SunPower (96x)
Amonix (92x)
FhG-ISE (232x)
Alta Devices
Stanford (140x)
Kopin
Varian
Spire
Radboud Univ.
Radboud Univ.
FhG-ISE
Alta Devices
Panasonic
IBM (T. J. Watson Research Center)
UNSW
UNSW
UNSW
UNSW
UNSW
Stanford
UNSW
NREL Cu(In,Ga)Se2 (14x)
Sanyo
Sanyo
Sanyo
Sanyo
Panasonic
EMPA (Flex polymer sub)
ARCO
UNSW
Spire
Sandia National Lab
Westing-house
Varian
UNSW
Georgia Tech
Georgia Tech
Georgia Tech
UNSW / Eurosolare
FhG-ISE
ZSW
ZSW
Solexel
GE Global Research
First Solar
GE Global Research
RCA
Mobil Solar
No. Carolina State Univ.
University So. Florida
NREL
NREL
NREL
NREL
NREL
NREL
NREL
NREL
Fraunhofer ISE
Sharp (large-area)
Univ. Stuttgart
First Solar
LG Electronics
EPFL
Kodak
Solarex
ARCO
Boeing
Matsushita
AstroPower (small-area)
NREL
Univ. Stuttgart
NREL (CdTe/CIS)
United Solar (aSi/ncSi/ncSi)
Mitsubishi Chemical
Boeing
Boeing
Euro-CIS
United Solar
NIMS
IBM (CZTSSe)
Kodak
AMETEK
Photon Energy
Sharp
IBM (CZTSSe)
Konarka
Heliatek
UCLA-Sumitomo Chemical
Matsushita
Monosolar
Kodak
Boeing
ARCO
United Solar
EPFL
EPFL
Kaneka (2 μm on glass)
United Solar
NREL / Konarka Univ. Linz
Solarmer
Konarka
Sumi-tomo
UCLA
Boeing
University of Maine
RCA
Solarex
EPFL
EPFL
Groningen
Plextronics
Univ. Dresden
Heliatek
Univ. of Toronto (PbS-QD)
RCA
RCA
RCA
RCA
RCA
RCA
University Linz
University Linz
Siemens
NREL (ZnO/PbS-QD)
44.4%
43.6%
37.9%
37.8%
32.6%
31.1%
29.1%
28.8%
27.6%
26.4%
25.0%
24.7%
20.4%
20.4%
20.1%
19.6%
14.1%
13.4%
11.4%
11.1%
11.1%
10.6%
7.0%
(Rev. 08-2013)

Solar Cells



Swanson's Law
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
$200
$100
$10
$1
$0.10
Average Module Price (2015 USD/Wp)
Cumulative Module Shipments, MWp

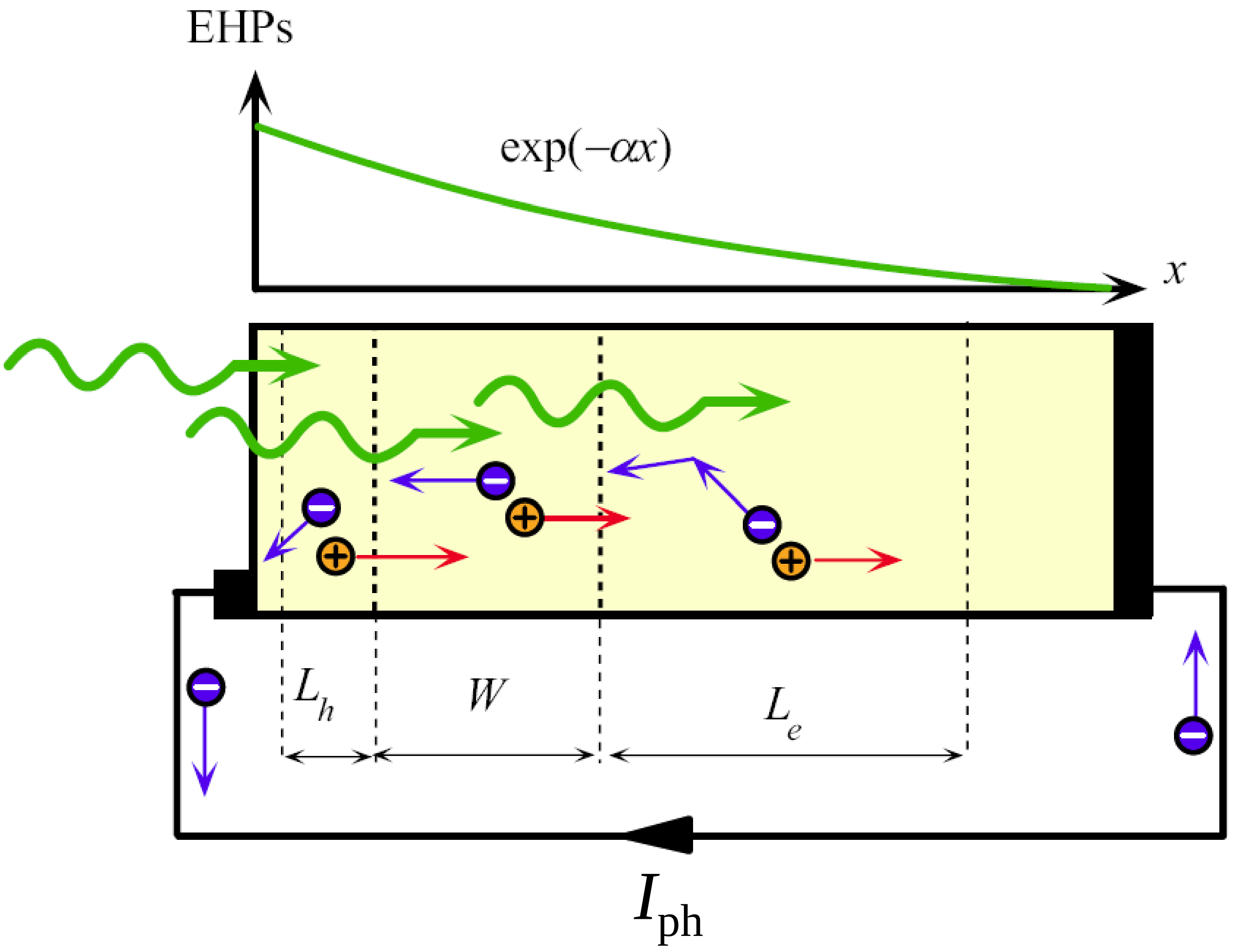
Device Principles



The basic principle of operation of the solar cell (exaggerated features to highlight principles). The built-in field change upon illumination.

From *Principles of Electronic Materials and Devices, Fourth Edition*, S.O. Kasap (© McGraw-Hill Education, 2018)

Device Principles



At long wavelengths, around $1 - 1.2\mu m$, the absorption coefficient α of Si is small and the absorption depth $(1/\alpha)$ is typically greater than $100\mu m$. To capture these long wavelength photons, we therefore need a thick p-side and at the same time a long minority carrier diffusion length L_e. Typically the p-side is $200 - 500\mu m$ and L_e tends to be shorter than this.

An np junction solar cell in short circuit. Photogenerated carriers within the volume $L_h + W + L_e$ give rise to a photocurrent I_{ph}. The variation in the photogenerated EHP concentration with distance is also shown where α is the absorption coefficient at the wavelength of interest.

From *Principles of Electronic Materials and Devices, Fourth Edition*, S.O. Kasap (© McGraw-Hill Education, 2018)

Device Principles

It is important to have **the minority carrier diffusion length L_e large**. This is the reason for choosing this side of a Si pn junction to be p-type which make electrons the minority carriers **(electron diffusion length in Si is longer than the hole diffusion length)**.

Same ideas apply to EHPs photogenerated by shortwavelength photons absorbed in the n-side. Those holes photogenerated within a diffusion length L_h can reach the depletion layer and become swept across to the n-side. EHPs beyond L_h are lost by recombination as lifetime in n-side is very short (due to heavy doping). The n-side is made thin and sometimes **shorter than L_h** ($<0.2\mu m$).

Photogeneration of EHPs that contribute to photovoltaic effect occur in volume covering $L_h + \mathrm{W} + L_e$. If the terminals of the device are shorted then excess electron in the n-side can flow through the external circuit to neutralize the excess hole in the p-side. C**urrent due to flow of the photogenerated carriers is called the photocurrent**.

From *Principles of Electronic Materials and Devices, Fourth Edition*, S.O. Kasap (© McGraw-Hill Education, 2018)

Ideal Solar Cells

Total Current in Solar Cell

$$\underbrace{I = -I_{\text{ph}}}_{I_{sc}} + \underbrace{I_o\left[\exp\left(\frac{eV}{\eta kT}\right)-1\right]}_{I_d}$$

In an open circuit, the net current is **zero**. This means that the photocurrent I_{ph} develops just enough photovoltaic voltage V_{oc} (open circuit voltage) to generate a diode current $I_d = I_{ph}$.

Ideal Solar Cells

The Power

The power delivered to the load is $P_{out} = I'V'$, which is the area of the rectangle bound by the I and V axes and the dashed lines.

Maximum power is delivered to the load when this rectangular area is maximized. Therefore it makes sense to compare the maximum power output $I_m V_m$ with $I_{sc} V_{oc}$.

Definition of Fill Factor

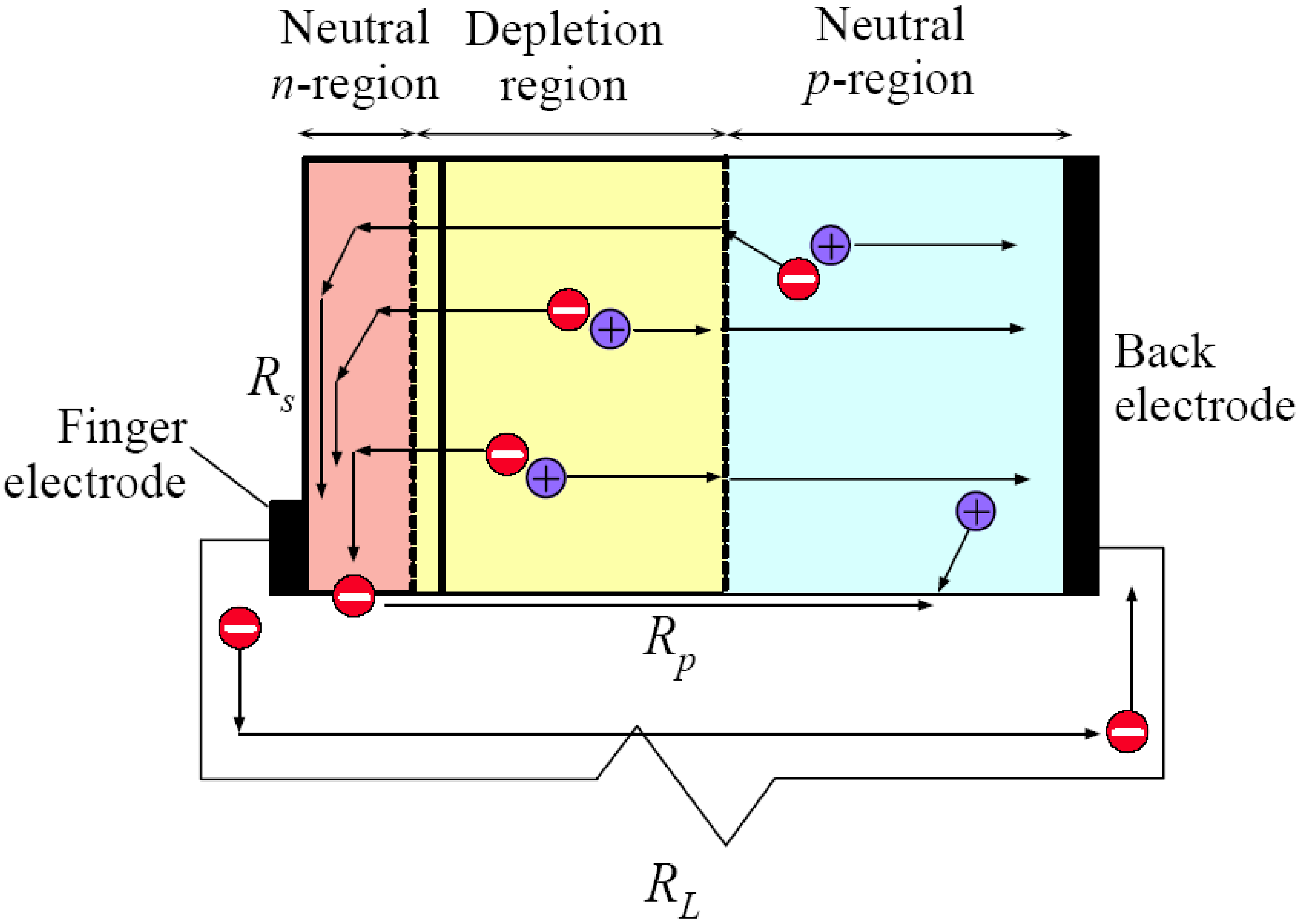
$$\mathrm{FF} = \frac{I_m V_m}{I_{\mathrm{sc}} V_{\mathrm{oc}}}$$

The FF is a measure of the closeness of the solar cell *I*-*V* curve to the rectangular shape (the ideal shape).

Practical Solar Cells

Series Resistance:

Photogenerated electrons have to traverse a surface semiconductor region to reach the nearest finger electrode. All these electron paths in the n-layer surface region to finger electrodes introduce an effective **series resistance R_s** into the photovoltaic circuit.



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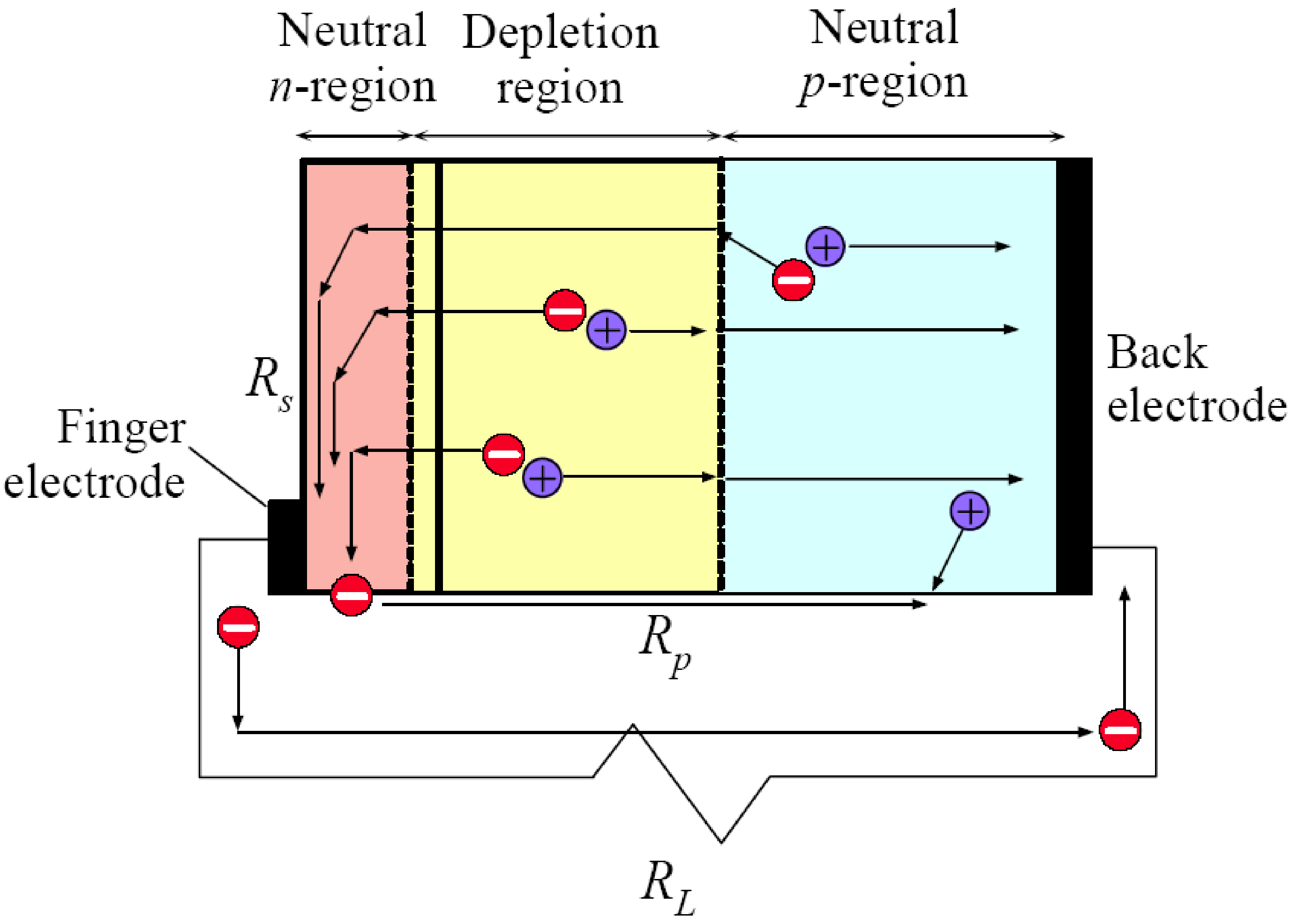
Practical Solar Cells

Shunt Resistance:

Photogenerated carriers can also flow through the crystal surfaces (edges of the device) or through grain boundaries in polycrystalline devices instead of flowing though R_L . These effects that prevent photogenerated carriers from flowing in external circuit can be represented by a **shunt resistance R_p** that diverts photocurrent away from R_L. Typically R_p is less important than R_s.



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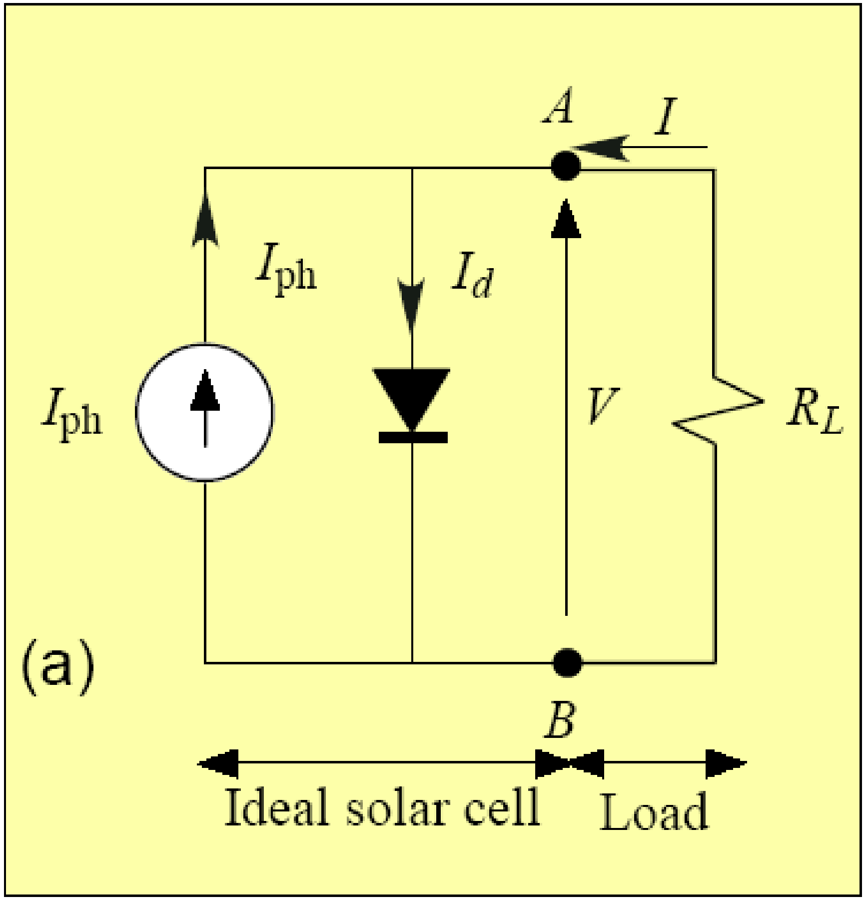
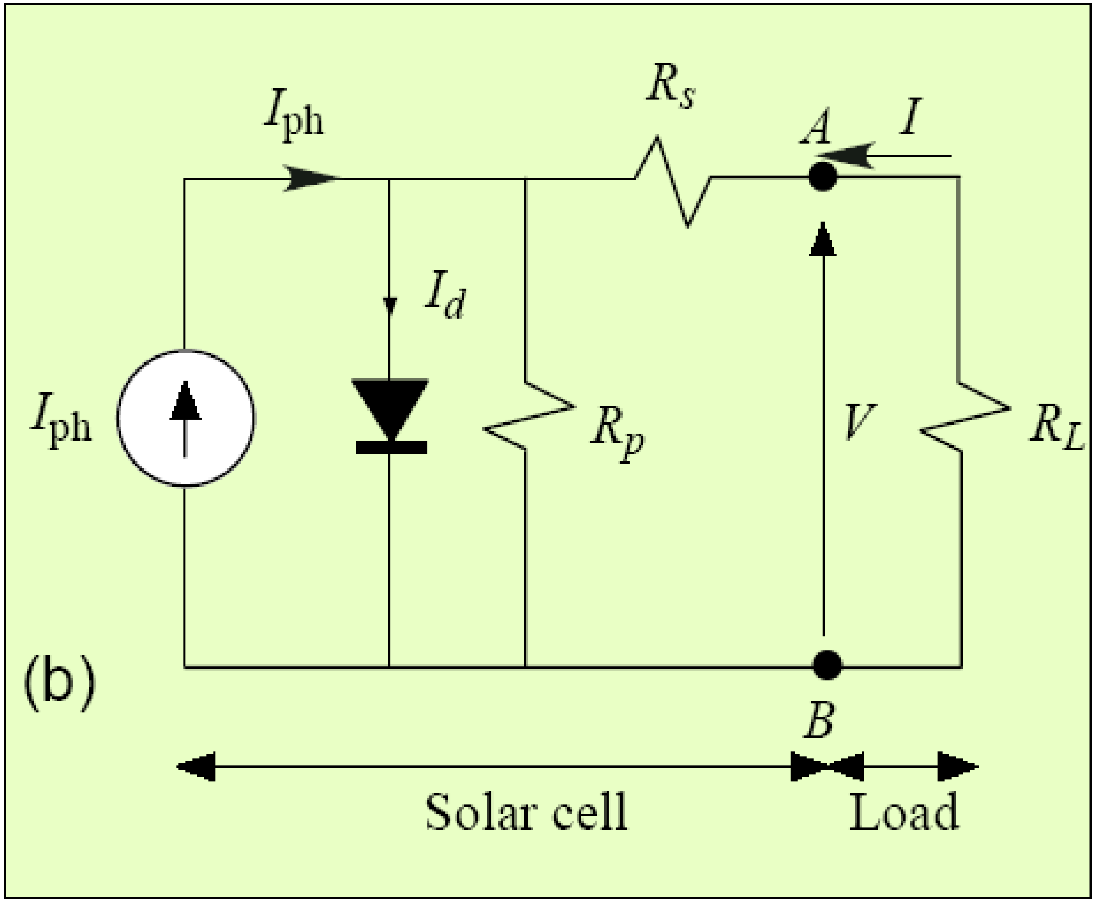
Equivalent Circuit of a Solar Cell



Ideal *pn* junction



Parallel and series resistances R_s and R_p.

In reality, of course, the solar cell current is negative, as explained in slide 18 which represents a current that is flowing out into the load

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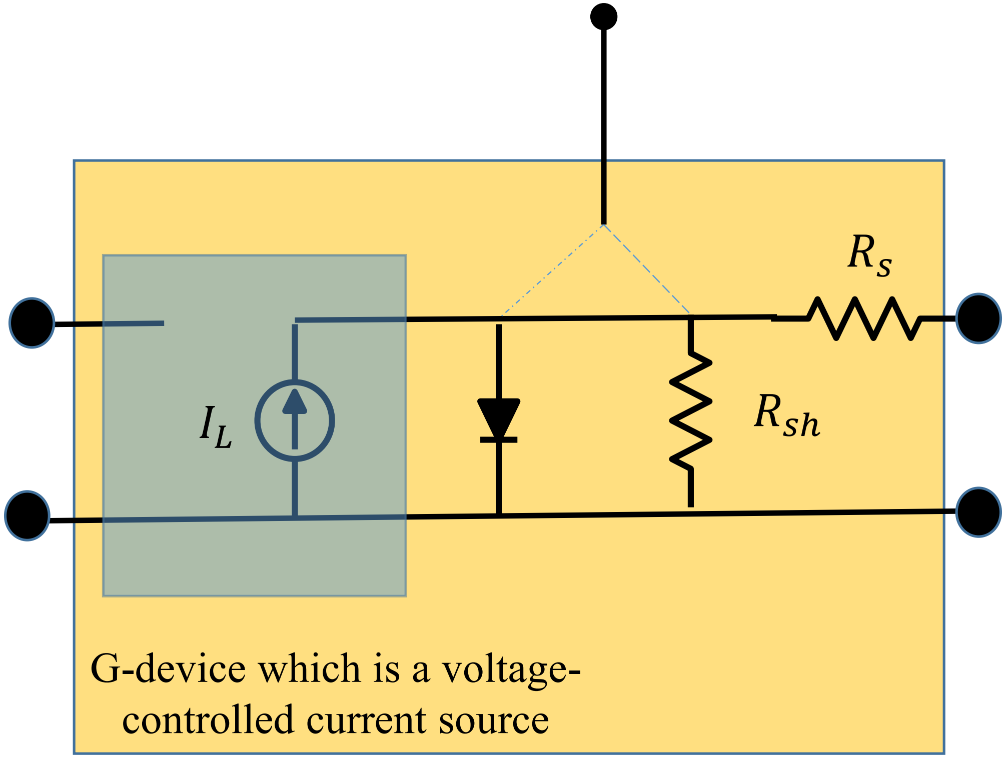
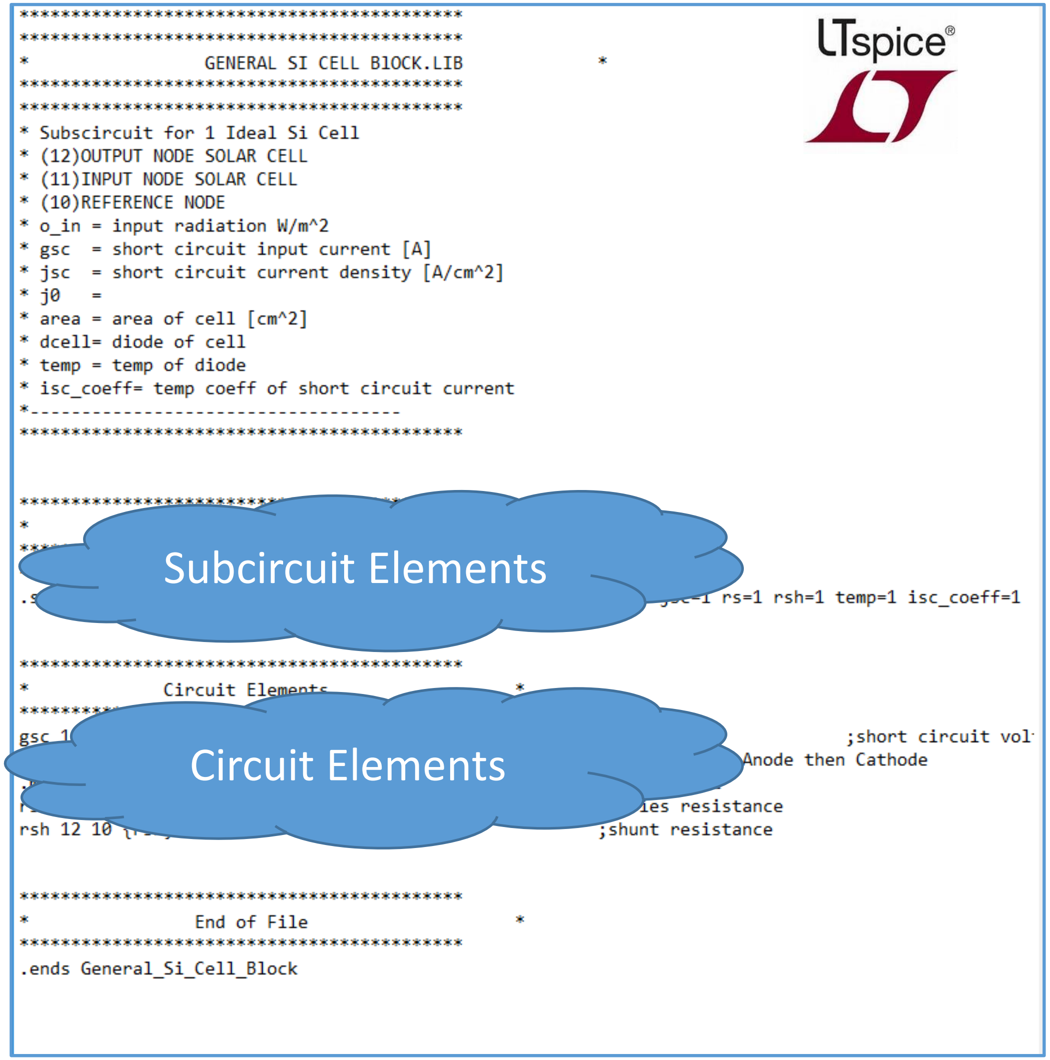
General Model of Solar Cell



G-device which is a voltage-controlled current source

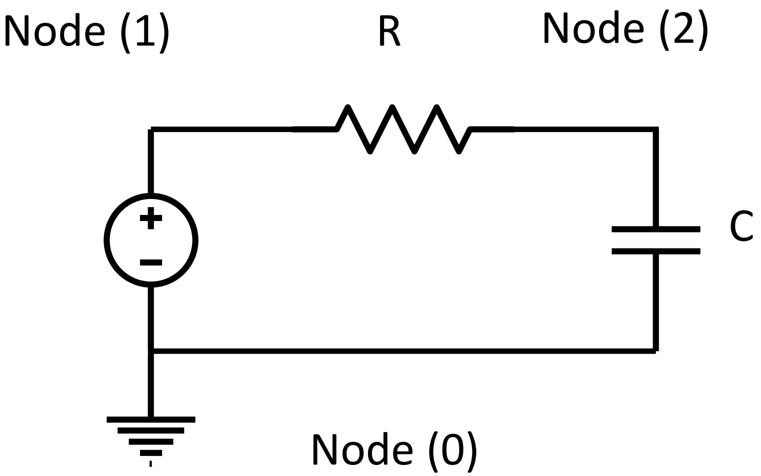


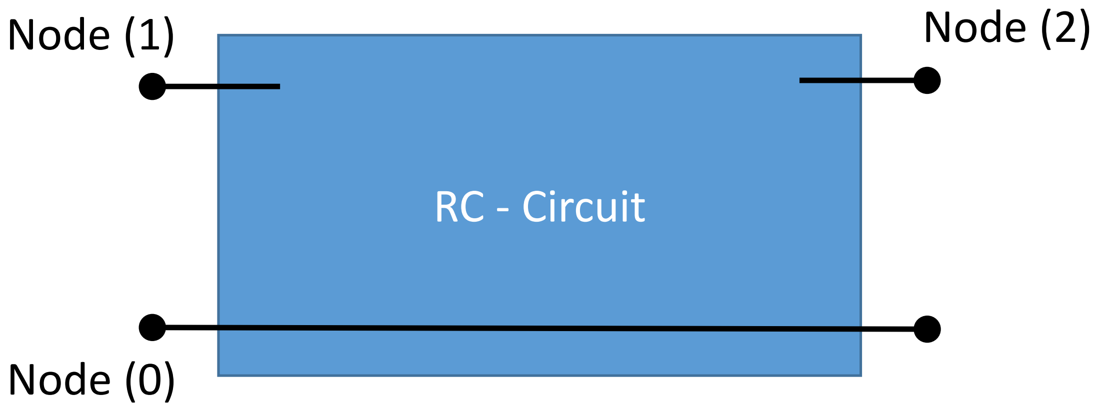
```
*******************************************
*******************************************
*                GENERAL SI CELL B1OCK.LIB            *
*******************************************
*******************************************
* Subscircuit for 1 Ideal Si Cell
* (12)OUTPUT NODE SOLAR CELL
* (11)INPUT NODE SOLAR CELL
* (10)REFERENCE NODE
* o_in = input radiation W/m^2
* gsc  = short circuit input current [A]
* jsc  = short circuit current density [A/cm^2]
* j0   =
* area = area of cell [cm^2]
* dcell= diode of cell
* temp = temp of diode
* isc_coeff= temp coeff of short circuit current
*------------------------------------
*******************************************


*******************
*
**
.s                                    rs=1 rsh=1 temp=1 isc_coeff=1


*******************************************
*              Circuit Elements               *
*******
gsc 1                                                    ;short circuit vol
                                              Anode then Cathode

r                                        ies resistance
rsh 12 10 {r                            ;shunt resistance


*******************************************
*                 End of File                 *
*******************************************
.ends General_Si_Cell_Block
```

$$I_L = girrad = \frac{J_{sc}A}{1000}G$$

G = Irradiance values ($100W/m^2$, $500W/m^2$, …etc)

Spice Basics

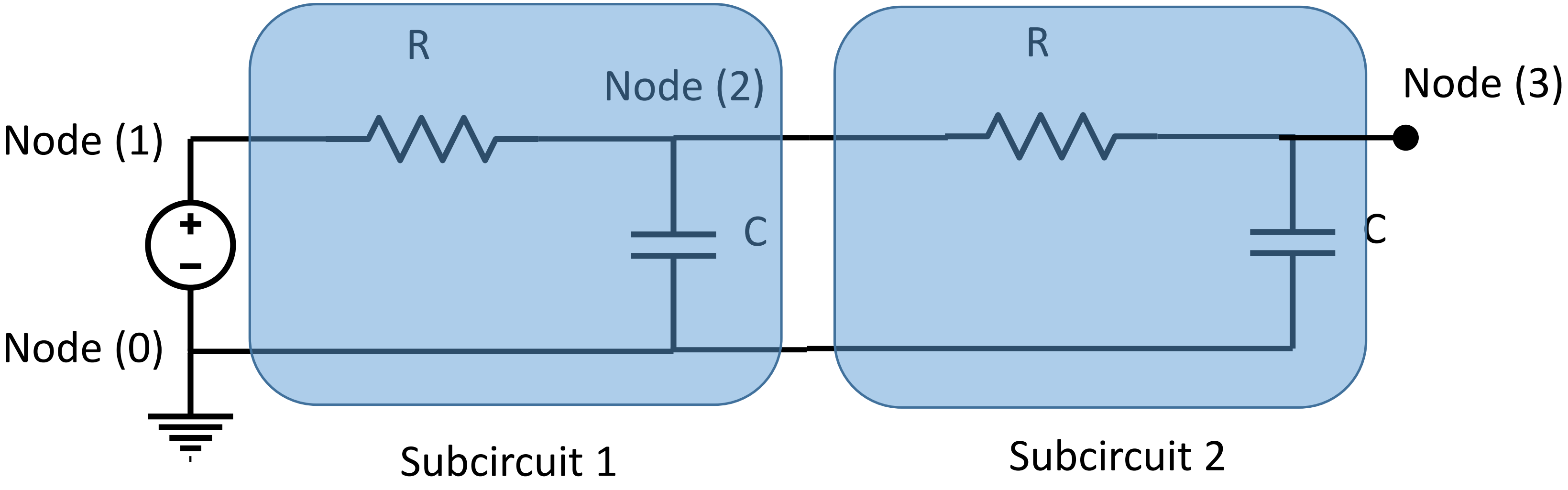




Resistor Syntax :	rxx node_a node_b {value}
Capacitor Syntax :	cxx node_a node_b {value}
Pulse V. Source :	vxx node+ node- pulse (initial_value pulse_value delay risetime falltime pulse_length period)
Transient analysis:	….
Postprocess :	.probe
Plot results :	.plot tran {variable1} {variable2}
End file :	.end

```
*learning.cir

r1 1 2 1K; resistor between node (1) and node (2) value 1 KOhm

c1 2 0 1n; capacitor between node (2) and node (0) value 1 nF

vin 1 0 pulse (0 5 0 1u 1u 10u 20u); voltage source between node (1) and node (0)

.tran 0 40u

.probe

.plot tran v(1) v(2)

.end
```

Spice Basics

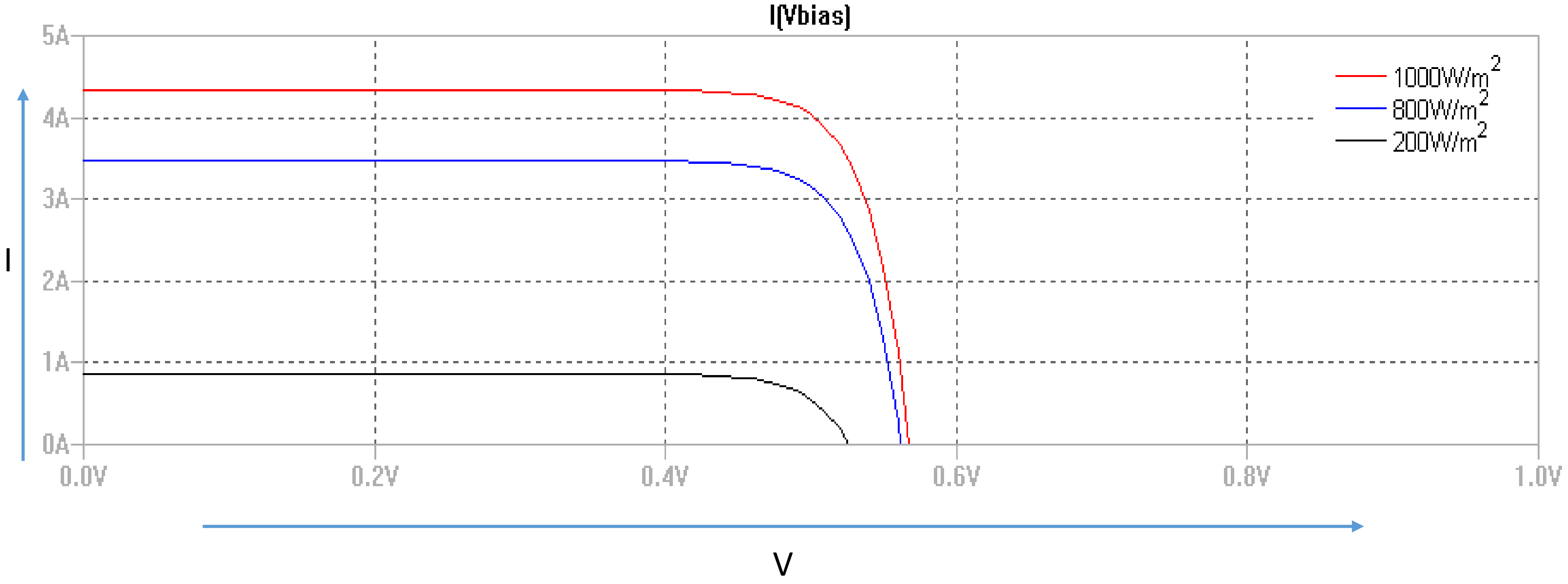


```
* rc.lib
.subckt rc 12 11 10 params: r=1 c=1
r1 11 12 {r}
c1 12 10 {c}
.ends rc
```

```
* learning_subckt.cir
.include rc.lib
xrc1 2 1 0 rc params: r=1k c=1n
xrc2 3 2 0 rc params: r=10k c=10 n

vin 1 0 pulse (0 5 0 1 u 1 u 10 u 20 u)
.tran 0.1 u 40 u
.probe
.plot tran v(1) v(2) v(3)
.end
```

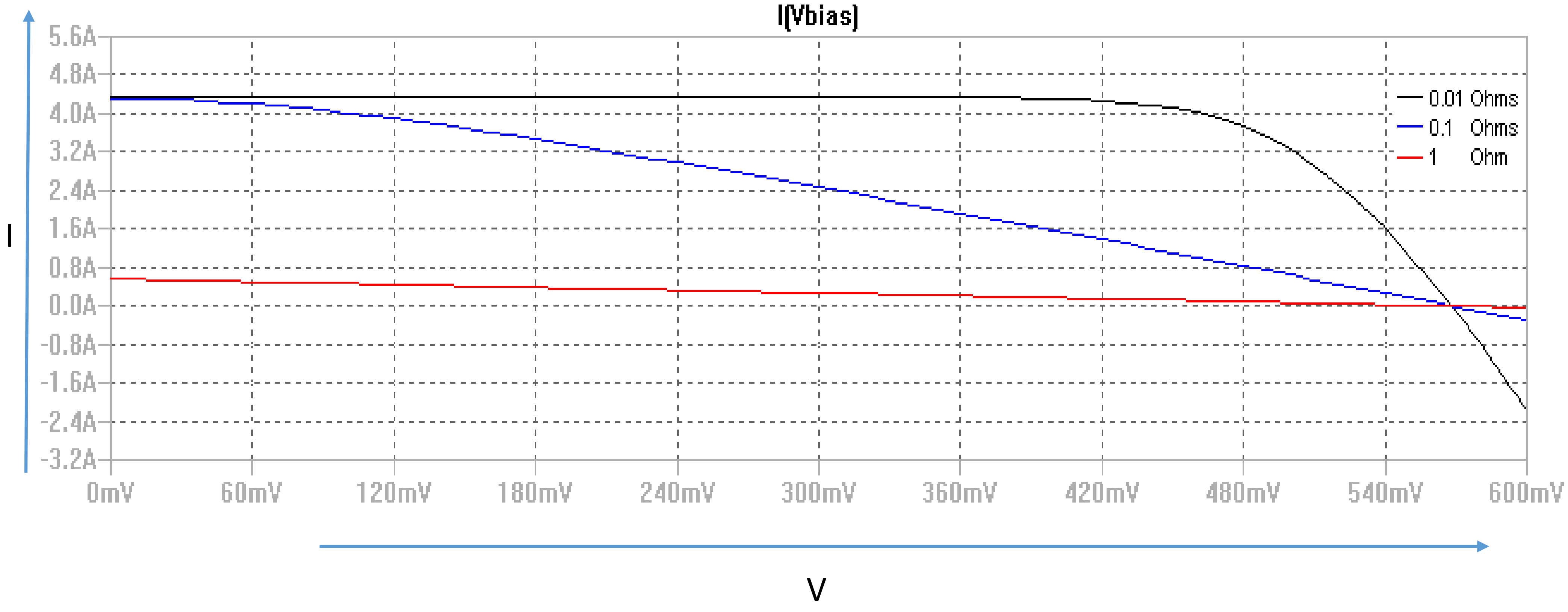
Effect of Illumination

Ideal solar cell with area=$126.6cm^2$ $J_{sc} = 34.3A/cm^2$, $J_0 = 10pA/cm^2$



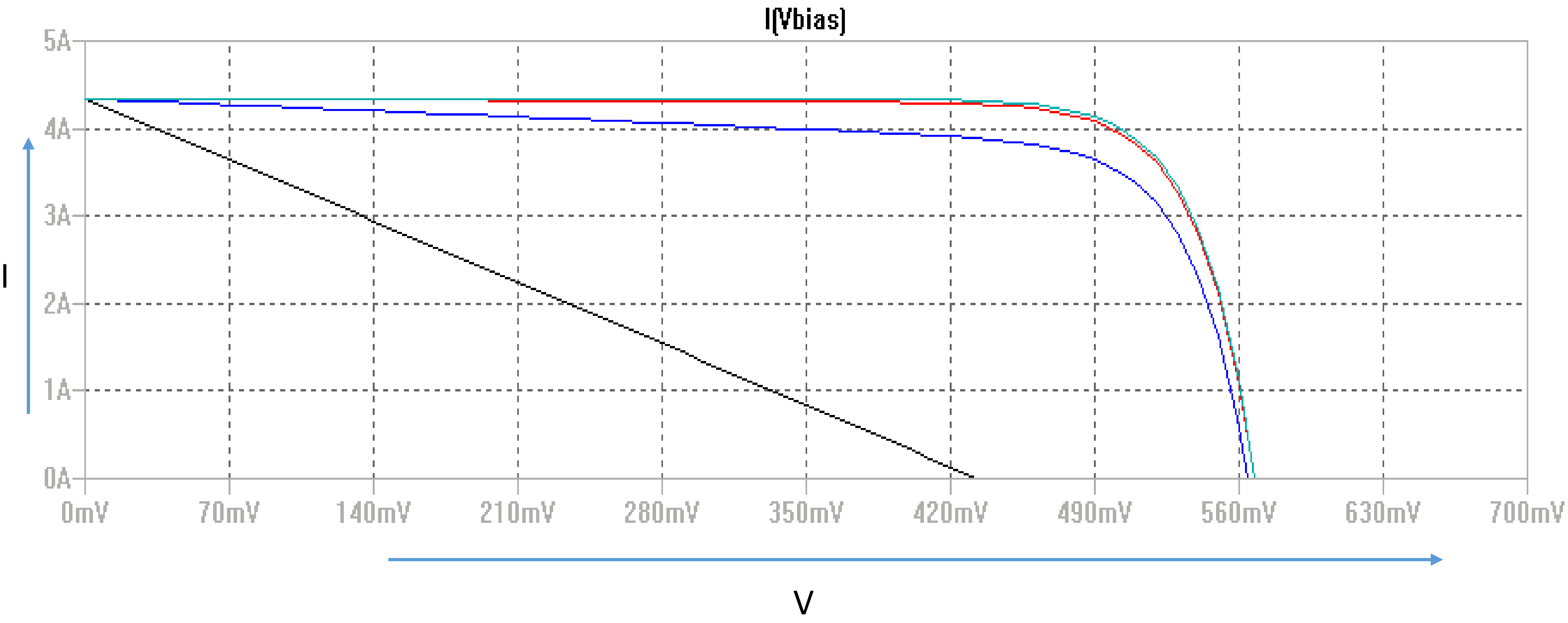
Effect of Series Resistance

Ideal solar cell with area=$126.6cm^2$ $J_{sc} = 34.3A/cm^2$, $J_0 = 10pA/cm^2$, $R_{sh} = 10k\Omega$ and varying the Series Resistance.



Effect of Shunt Resistance

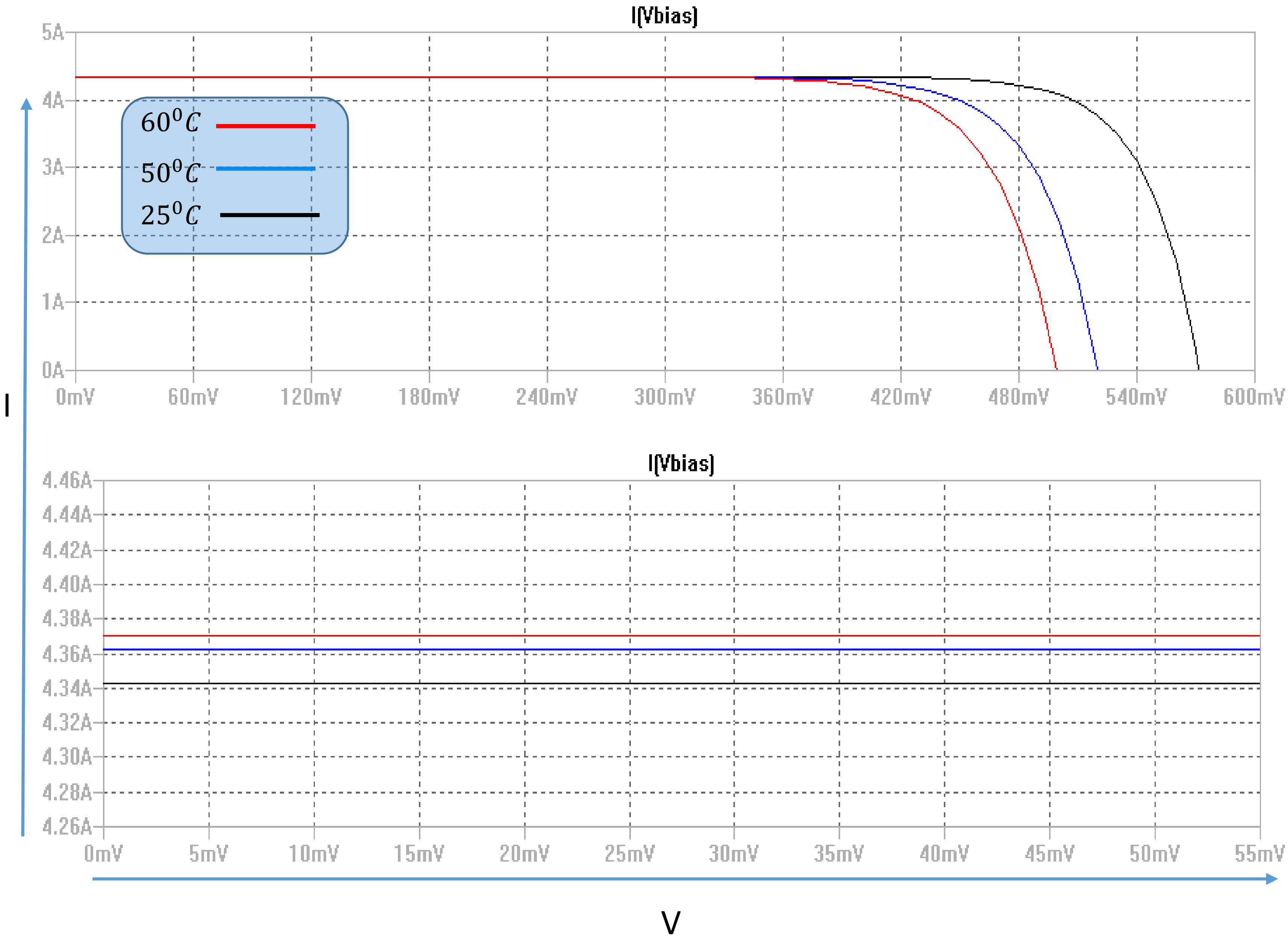
Ideal solar cell with area=126.6 cm^2 $J_{sc} = 34.3\ A/cm^2$, $J_0 = 10\ pA/cm^2$, $R_s = 1\ \mu\Omega$ and varying the Shunt Resistance from 0.1 Ω, 1 Ω, 10 Ω, 10000 Ω



Effect of Temperature

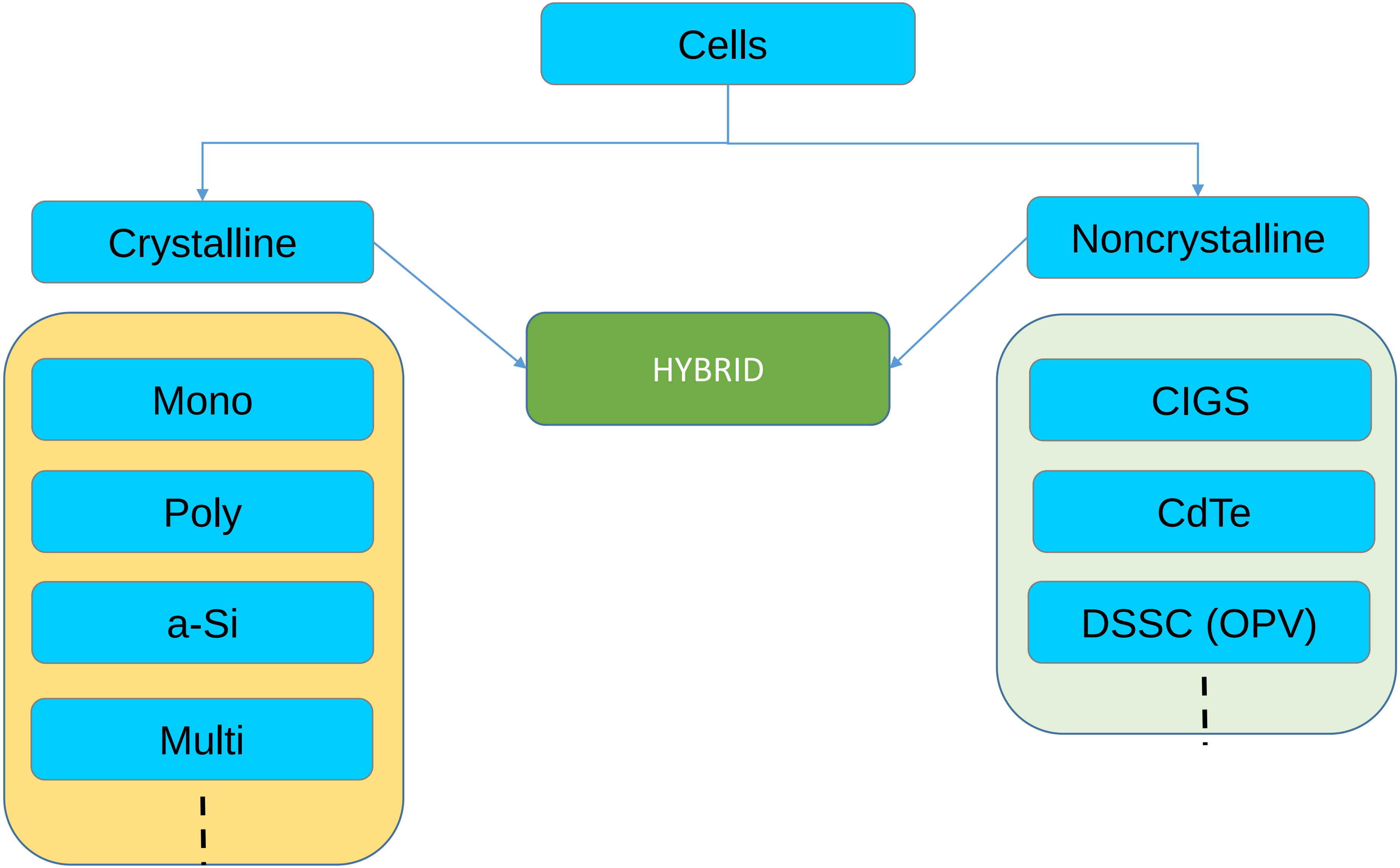
$R_s = 1\mu\Omega$,
$R_{sh} = 10k\Omega$.
Temperature varied from 25^0C (black line), to 60^0C (red line).

As temperature increases the open circuit voltage decreases since the band gap of the intrinsic semiconductor shrinks.



Types of Solar Cells

Solar Cells can be classified:


Cells

Crystalline

Noncrystalline

HYBRID

Mono

Poly

a-Si

Multi

CIGS

CdTe

DSSC (OPV)

Polycrystalline Solar Cells

1) Silicon material melted and cast into cuboid form.

2) Controlled heating and cooling to allow block to cool in one direction, to allow for homogeneous silicon crystal growth,

3) The large block is cut into smaller ingots.

4) Ingots sawn into bars then into wafers.

5) After cleaning, wafers are doped and antireflection coating applied.

6) Contacts printed and edges etched.

Mono vs Poly Crystalline

- Main characteristics of mono-crystalline cells:
  - Colour = Dark blue/black
  - Efficiency = 16-19%
  - Thickness = 0.2-0.3mm
  - Size = 4-8” (10x10cm – 15x15cm)

- Main characteristics of poly-crystalline cells:
  - Colour = blue
  - Efficiency = 14-17%
  - Thickness = 0.2-0.3mm
  - Size = 4-8” (10x10cm – 21x21cm)

Thin Film Solar Cells

High cost of PV is a major factor hindering further adoption.

Instead of using silicon, photoactive semiconducting materials are deposited onto a low cost substrate (e.g. glass)

These “thin” layers are deposited using an evaporation or a sputtering technique

The process requires temp of 200-500C instead of traditional silicon manufacturing process requiring 1450C. → lower manufacturing cost.

Thin Film Solar Cells

Examples of these semiconducting materials include

- Cadmium Telluride (CdTe)
- Amorphous silicon
- Copper Indium Diselenide (CIS)

The above materials are highly absorptive, therefore a small layer is sufficient (1-5microns).

Thin Film cells are not restricted to any particular size or shape

- They can be deposited on any substrate

Thin Film cells are connected monolithically during coating process (show interconnection stages)

Thin Film Solar Cells

The advantages of Thin Film Cells are:

- Low cost
- Low degradation of efficiency with temp (in comparison with silicon)
- Less susceptible to shading effects

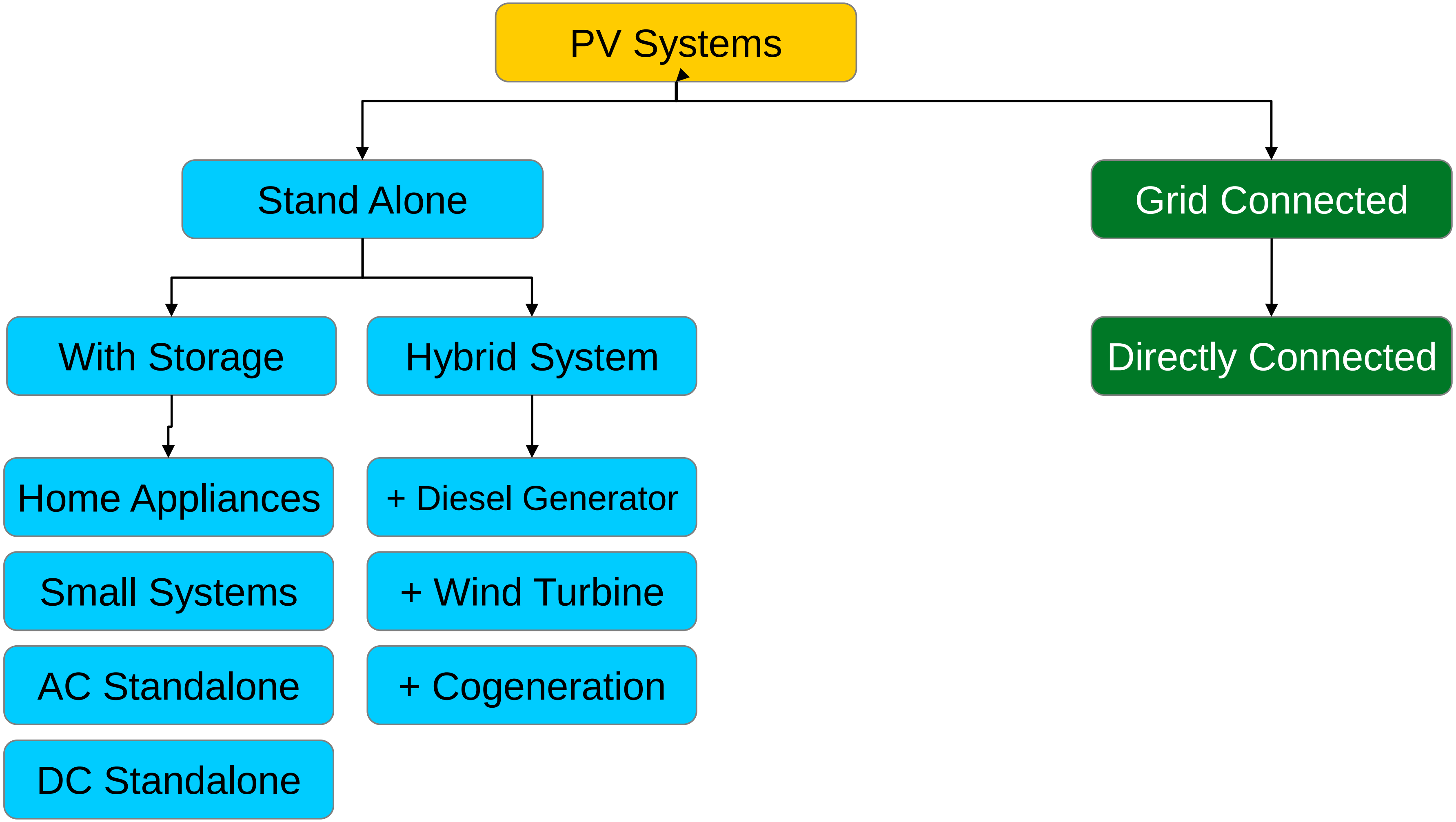
The disadvantages are:

- Low efficiency (9-13%)
  - New light trapping techniques aiming to combat this.

Main manufacturers are:

- Fuji, Sanyo, Schott, PowerFilm, TEL (formerly Oerlikon) Solar.

PV System Types



PV Systems

Stand Alone

Grid Connected

With Storage

Hybrid System

Directly Connected

Home Appliances

Small Systems

AC Standalone

DC Standalone

+ Diesel Generator

+ Wind Turbine

+ Cogeneration

PV System Types

- Stand Alone Systems:
  - Very first application of PV, in case there was no electricity supply from national grid
  - Applications ranging from pocket chargers large water pumping systems
  - Main components include:
    - (1) PV Modules
    - (2) Charge Controller
    - (3) Battery Bank
    - (4) Inverter
    - (5) Loads

Stand Alone Systems

PV System Types

- Grid Connected Systems
  - PV Systems that directly feed electricity to the national grid
  - Variety ranging from ground mounted to building mounted, motorway mounted, ...etc
  - Main components include:
    - (1) PV Modules
    - (2) PV array combiner box
    - (3) DC (main) isolator switch
    - (4) Inverter
    - (5) Meter (supply and feed)

Grid Connected Systems




BOS Components

Apart from the PV modules, all remaining components in the PV system are called **Balance of System (BOS) components**. BOS components include, but are not limited to:

- Batteries
- Inverters
- Charge controllers
- Bypass/Blocking diode(s)
- Cables and connectors
- Over-current protection and disconnectors
- Combiner boxes
- Grounding hardware
- Lightning protection
- Mounting and stainless fastening hardware
- Other essential system and associated components.

Batteries

Batteries are the heart of an autonomous solar electric system. They are where your power is stored - **your reservoir**. A **cycle in a solar battery occurs when it is discharged and then recharged back to its original level**. The amount a solar battery is discharged is called the depth of discharge (DOD).

There are two basic types of batteries that are available for use in a standard solar energy production system: sealed batteries (also called AGM or Gel cell) and flooded lead acid (or FLA) batteries.

Batteries

Battery Capacity:

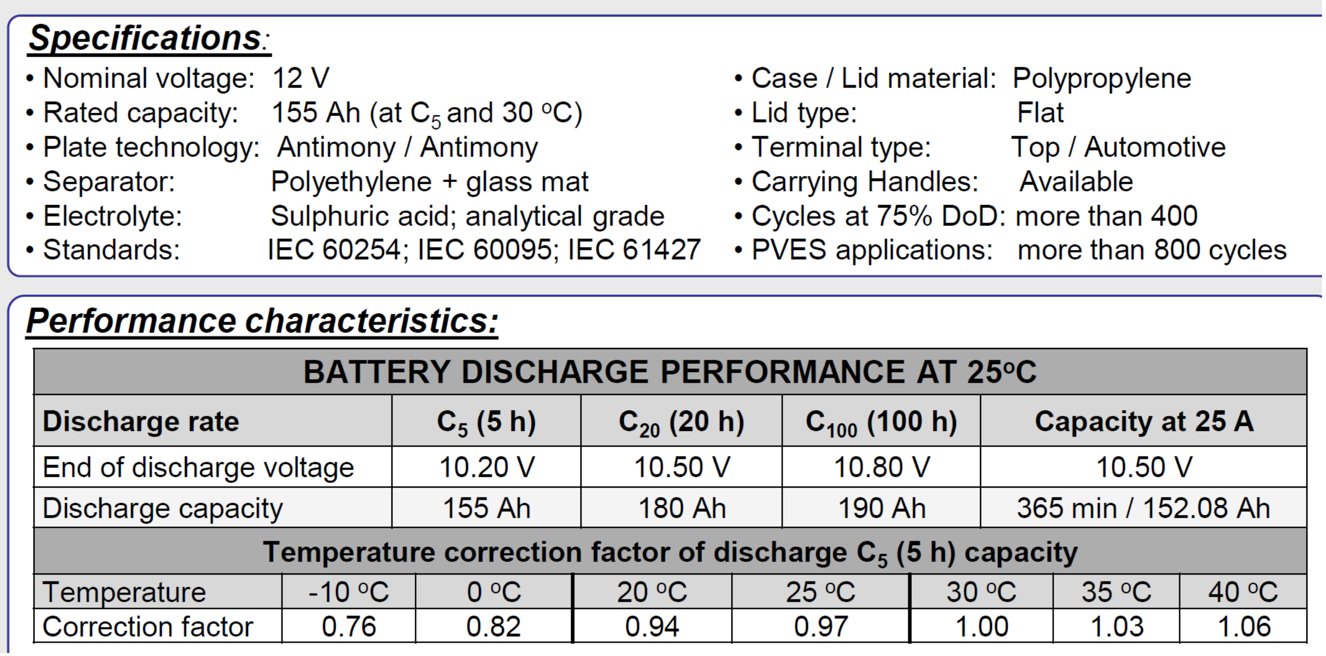
Battery capacity is determined by the amount of electrical energy the battery can deliver over a certain period of time and is measured in Ampere hours (Ah) when discharged at a uniform rate over a given period of time. Ampere hours (Ah) are calculated by multiplying the current (in amperes) by time (in hours) the current is drawn.

For example: A battery which delivers 1 ampere for 20 hours would have a 20 amp-hour battery rating (1 * 20 = 20Ahr).

Batteries

Charging & Discharging

When a battery is **discharged and then recharged** it is said to have completed a battery **cycle**. Battery life is determined by the number of cycles it can yield.



Specifications:

- Nominal voltage: 12 V
- Rated capacity: 155 Ah (at C_5 and 30 °C)
- Plate technology: Antimony / Antimony
- Separator: Polyethylene + glass mat
- Electrolyte: Sulphuric acid; analytical grade
- Standards: IEC 60254; IEC 60095; IEC 61427
- Case / Lid material: Polypropylene
- Lid type: Flat
- Terminal type: Top / Automotive
- Carrying Handles: Available
- Cycles at 75% DoD: more than 400
- PVES applications: more than 800 cycles

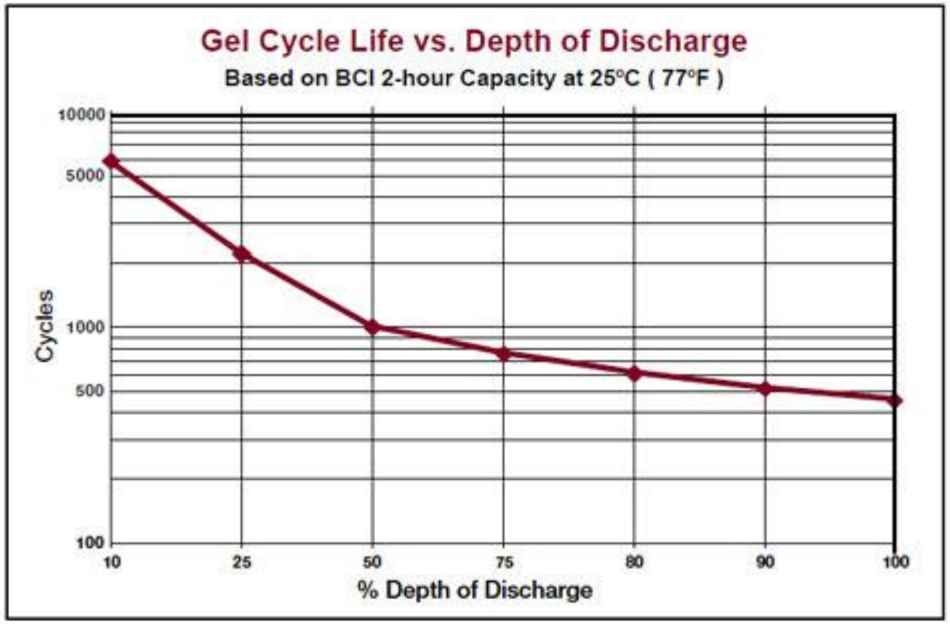
Performance characteristics:

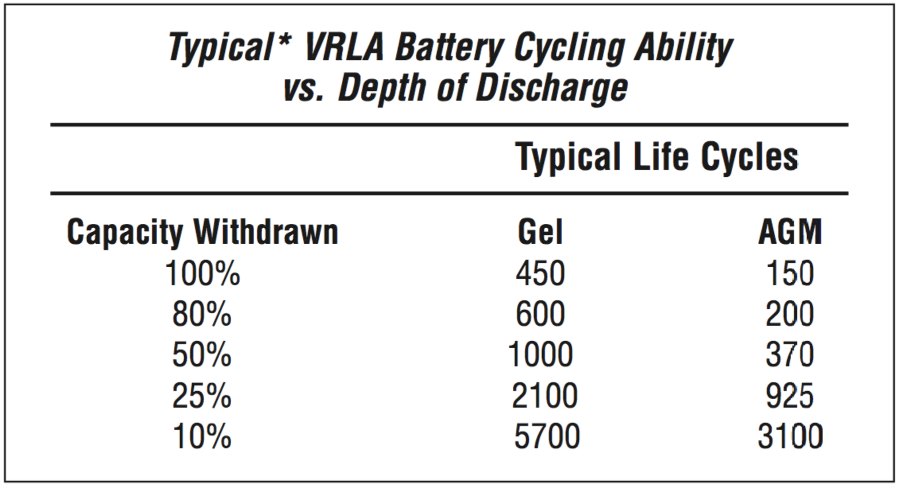
BATTERY DISCHARGE PERFORMANCE AT 25°C

Discharge rate	**C_5 (5 h)**	**C_{20} (20 h)**	**C_{100} (100 h)**	**Capacity at 25 A**
End of discharge voltage	10.20 V	10.50 V	10.80 V	10.50 V
Discharge capacity	155 Ah	180 Ah	190 Ah	365 min / 152.08 Ah

Temperature correction factor of discharge C_5 (5 h) capacity

Temperature	-10 °C	0 °C	20 °C	25 °C	30 °C	35 °C	40 °C
Correction factor	0.76	0.82	0.94	0.97	1.00	1.03	1.06





Typical* VRLA Battery Cycling Ability vs. Depth of Discharge

	Typical Life Cycles	
Capacity Withdrawn	**Gel**	**AGM**
100%	450	150
80%	600	200
50%	1000	370
25%	2100	925
10%	5700	3100

Batteries

Sizing the Battery Bank

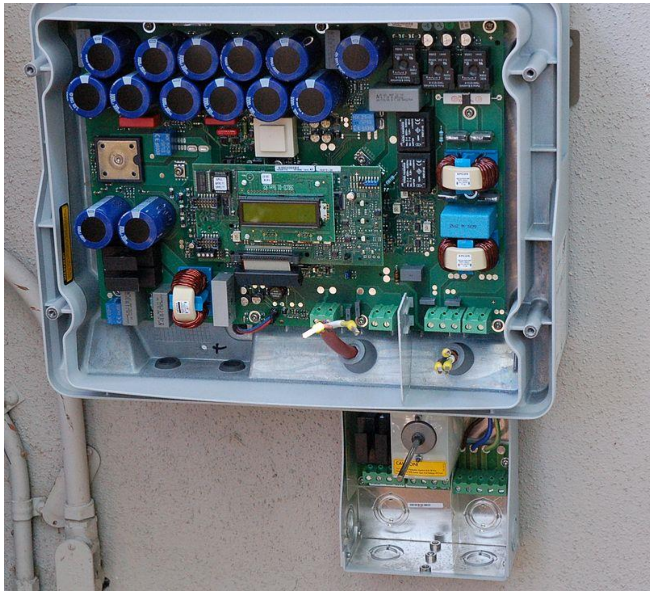
The number of batteries in the battery bank depends on many factors such as:

- The number of appliances you use and the amount of power they take.
- The number of days the batteries go without charging, due to bad weather or other factors.
- The level of discharge you wish to go to before re-cycling.
- The temperature of the area where the batteries are stored.
- The size of your budget.

……we shall discuss this topic later in the slides.

Inverters

A solar inverter, or PV inverter, converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or used by a local, off-grid electrical network.



Provide basic level of monitoring, which often includes instantaneous power output, daily energy production, and total to-date energy production

Charge Controller

A charger controller, charger regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may protect against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. It may also prevent completely draining ("deep discharging") a battery, or perform controlled discharges, depending on the battery technology, to protect battery life.

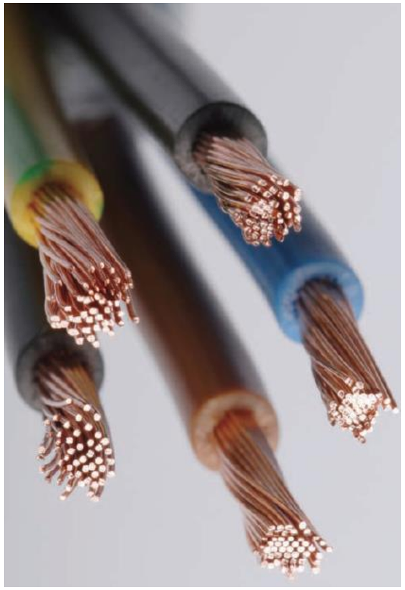
Maximum power point tracking (MPPT) charge controllers aim to achieve the maximum possible power from the PV array. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency. It is the purpose of the MPPT system to sample the output of the cells and determine a resistance (load) to obtain maximum power for any given environmental condition.

Cabling

DC Cabling - General Guidelines:

- DC Connectors should always be used.
- DC Cable from the PV modules should follow the shortest route to the array combiner boxes.
- All DC cable should be clearly identifiable.
- Cables should be laid in parallel and loops should be avoided – except where they enter a building
- Cables should never be lain in a hazardous space.
- Power losses in DC systems are due to voltage drop. Stand-alone DC systems typically operate at voltages of 12V, 24V or 48V DC.

Cross sectional area (mm2)	Resistance Ohms per metre
2.5	0.0074
4	0.0046
6	0.0031
10	0.0018
16	0.0012
25	0.00073
35	0.00049



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Protection

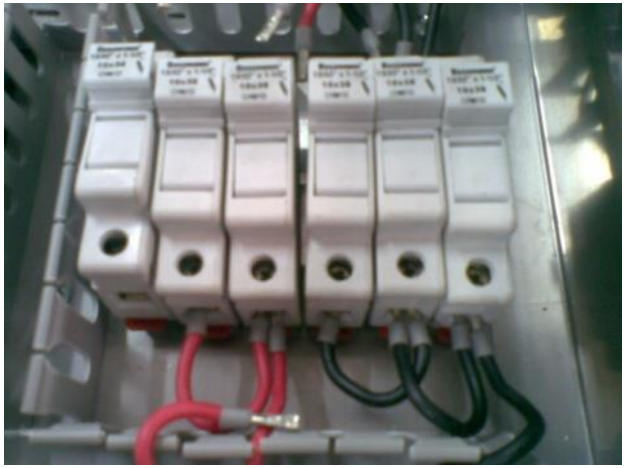
All PV strings should be protected with an over-current protection device.

- The protection devices shall be installed in both active conductors.
- It is a requirement to install circuit breaker (MCB) at each string cable.
- It is essential when the number of parallel strings is more than two. The reason being most manufacturers guarantee* their modules can stand up to 2 x Isc.

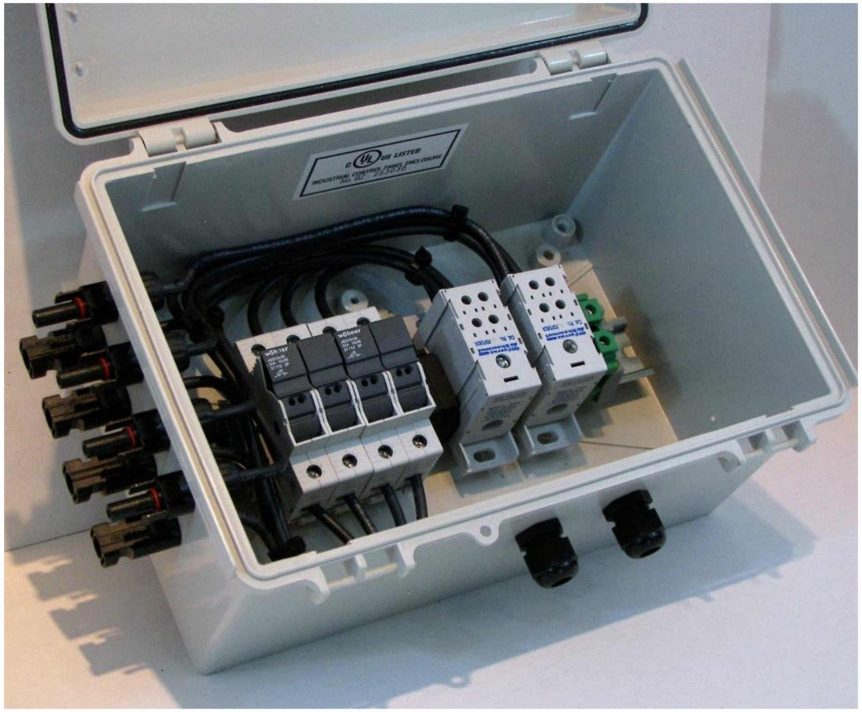
AC/DC Disconnect PV Systems:

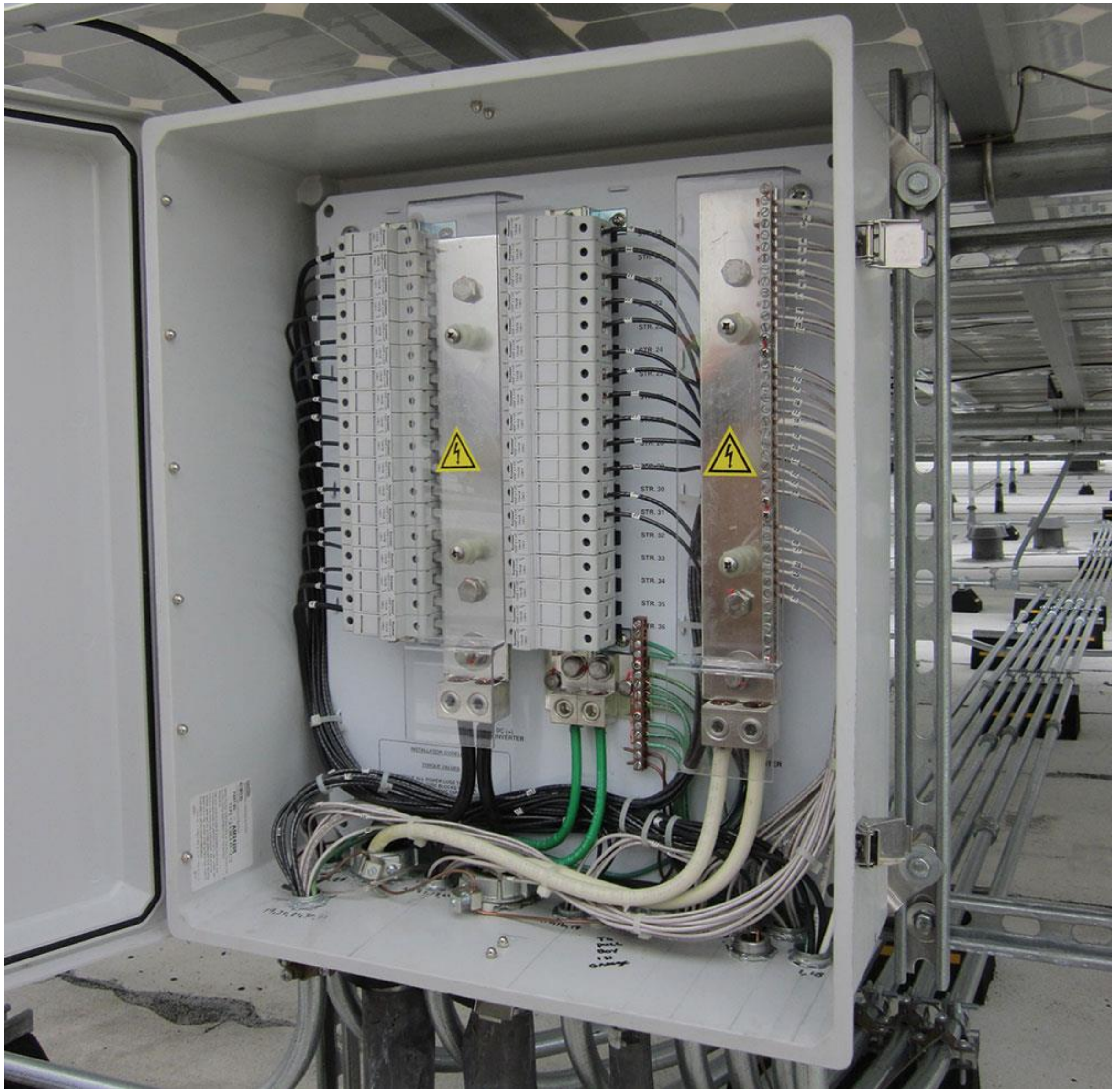
A solar PV system typically has two safety disconnects. **The first is the PV disconnect (or Array DC Disconnect)**. The PV disconnect allows the DC current between the modules (source) to be interrupted before reaching the inverter.

The second disconnect is the AC Disconnect. **The AC Disconnect** is used to separate the inverter from the electrical grid. In a solar PV system the AC Disconnect is usually mounted to the wall between the inverter and utility meter



Combiner Boxes





Combiner boxes are an integral part of many PV installations, serving as the “meeting place” where the wiring from array series strings come together in parallel connections.

Autonomous PV System

Also called **stand-alone** systems, are self-sufficient and not backed up by another generating source. They normally include battery storage.

Areas of application:

- Isolated facilities (cottages, fish farms, hunting lodges, etc.).
- Telecommunication systems (transmitters, repeaters, base stations).
- Street lighting, bus stops, parking lots, various signaling.
- Mobile Units, camping cottages, campers and boats.
- Systems for automatic acquisition and tracking data.

Advantages:

- Easy installation, photovoltaic modules are lightweight and portable, system scalability, longevity, no maintenance, complete energy independence.
- Autonomous System protects the environment and has no electricity bills.

Autonomous PV System

Load: Anything in an electrical circuit that, when the circuit is turned on, draws power from that circuit.

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

The daily energy use will be:

<Number of appliances × Power consumption × operating per day >

Example: A house has the following electrical appliance usage:
One 18 Watt fluorescent lamp with electronic ballast used 4 hours per day. Two 60 Watt fan used for 2 hours per day. One 75 Watt refrigerator that runs 24 hours per day with compressor run 12 hours and off 12 hours.

Total appliance use = (1x18 W x 4 hr) + (2x60 W x 2 hr) + (1x75 W x 24 x 0.5 hr)

= 1,212 Wh/day

Autonomous PV System

- If the inverter AC voltage is 120 VAC and the battery DC voltage is 24 VDC then the conversion factor is 5.0. For every AC amp drawn there will be 5 times as many DC amps.

- The inverter's conversion efficiency from DC to AC is not 100%. There is an internal loss in the inverter which is normally about 10 to 15% [See inverter/charger manufacturer's efficiency specifications].

- Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac.

Example

AC Load = 6 kWh/Day / 120 VAC = 50 AH/Day @ 120 VAC
Convert to DC Battery Load. Inverter's Charger is 48 VDC. Therefore, the conversion factor is 2.5 to 1 and the efficiency is 90%.
DC Load = 50 AH/Day X 2.5 [conversion factor] = 125 AH/Day / 0.9 [efficiency] = 139 AH/Day battery load

Energy from Batteries

Autonomy: The number of consecutive days a stand-alone system battery bank will meet a defined load without solar energy input. A cloudy, stormy day would result in one day of autonomy.

The battery provides a reserve of energy (system autonomy) that can be used during days of autonomy or, if some part of the PV system fails.

Batteries perform three main functions in a stand-alone PV system

- **Autonomy** – by meeting the load requirements at all times, including at night, during overcast periods, or during the winter when PV input is low or absent.
- **Surge Current Capability** – by supplying, when necessary, currents higher than the PV array can deliver, especially to start motors or other inductive equipment.
- **Voltage Control** – thereby preventing large voltage fluctuations that may damage the load

Energy from Batteries

Battery Voltage

The voltage calculated from equilibrium conditions is typically known as the nominal battery voltage.

Cut-Off Voltage

The battery cannot be discharged below a certain level or permanent damage may be done to the battery. and depends on the type of battery, its temperature and the battery's rate of discharge.

Battery voltage will increase with the temperature of the system.

Energy from Batteries

Battery State of Charge (SOC)

The fraction of the total energy or battery capacity that has been used over the total available from the battery.

Depth of Discharge (DOD)

The Depth of Discharge (DOD) of a battery determines the fraction of power that can be withdrawn from the battery.

If the DOD of a battery is given by the manufacturer as 25%, then only 25% of the battery capacity can be used by the load.

SOC	DOD
100%	0%
75%	25%
50%	50%
25%	75%
0%	100%

The notation to specify battery capacity is written as **<u>Cx</u>**, where **x** is the time in hours that it takes to discharge the battery. For example, **C10 = xxx** means that the battery capacity is xxx when the battery is discharged in 10 hours.

Energy from Batteries

Battery Capacity

- Is a measure (typically in Amp-hr) of the charge stored by the battery.

- Represents the maximum amount of energy that can be extracted from the battery under certain specified conditions.

- Defined as the number of hours for which a battery can provide a current equal to the discharge rate at the nominal voltage of the battery.

- At higher temperatures, the battery capacity is typically higher than at lower temperatures. However, intentionally elevating battery temperature is not an effective method to increase battery capacity as this also decreases battery lifetime.

The higher the discharge rate - the lower the battery voltage

Energy from Batteries

Battery Efficiency

The overall battery efficiency is specified by two efficiencies: **the Coulomb Efficiency and the Voltage Efficiency.**

Coulombic Efficiency

The Coulomb Efficiency is the ratio of the number of charges that enter the battery during charging compared to the number that can be extracted from the battery during discharging.

Voltage Efficiency

The Voltage Efficiency is determined using the voltage difference between the charging and discharging voltages of the battery.

Energy from Batteries

Self-discharge

It is the loss of charge of a battery if left at open circuit for an appreciable time.

Cycle life

This is a measure of how many cycles a battery can deliver over its useful life.

It is normally quoted as the number of discharge cycles to a specified DOD that a battery can deliver before its available capacity is reduced to a certain fraction (normally 80%) of the initial capacity.

Energy from Batteries

Examples of rechargeable battery systems are:

- **Lead-acid**
- **Nickel-cadmium**
- **Nickel-iron**
- **Nickel-hydride**
- **Rechargeable lithium of various types**

Types of Battery Used in PV Systems

Only lead-acid and to a small extent nickel-cadmium batteries are used in PV systems.

➢ Nickel-iron batteries suffer from a particularly high self-discharge rate.

➢ Nickel-hydride and rechargeable lithium batteries are considerably more expensive today per kWh than lead-acid batteries and often need some rather sophisticated protection in their charging circuitry which is not easy to adapt to the changing nature of PV charge currents.

Energy from Batteries

The battery type recommended for using in solar PV system is a deep cycle battery.

Deep cycle battery: Type of battery that can be discharged to a large fraction of capacity many times without damaging the battery.

Factors Affecting Battery Life and Performance in PV Systems

In order to obtain the fullest possible life of a battery in a PV system, we first have to avoid the following:

- ***Manufacturing faults***
- ***User abuse***
- ***Accidents***
- ***Sulphation***
- ***Stratification***
- ***Freezing***

Attention needed when:

- ***Choosing a reliable and trusted battery manufacturer.***
- ***Providing proper documentation and supervision*** *or training for commissioning, operation and maintenance.*
- ***Being careful*** (e.g. avoid dropping a metal spanner across the battery terminals).

System Sizing

Required inputs for PV system sizing

1- Daily ($E_{req,d}$) or yearly ($E_{req,y}$) energy use.

2- Location parameters: latitude (φ), longitude (λ) as well as physical installation parameters: tilt angle (β) and azimuth angle (γ).

3- Long-term daily values of the irradiation on a horizontal surface (G_d) and the maximum daily temperature at 10m above the surface of the location (T_{max}). These are obtained as daily averaged data [*] from the NASA SSE database for a 22-year timespan.

4- Expected lifetime of PV system use and other financial parameters, such as the required Return on investment (ROI), as chosen by the user.

System Sizing

5- Off Grid Photovoltaic (PV) System Component Efficiencies:

- PV modules: efficiencies (η_{PV}), power temperature coefficient , module power (W_p or W), module area A_{PV}.
- Inverters: Efficiency $\eta_{Inv,Eu}$, maximum DC and AC rated power ($P_{DC,max}$, $P_{AC,nom}$), power rating.
- Charge Controllers: Efficiency, η_{reg}
- Bidirectional inverters: AC-DC and DC-AC conversion efficiencies (η_{ACDC} & η_{DCAC}), as well as the energy capacity of the bidirectional inverter $E_{Inv,Bidir}$
- Batteries: Voltage level V_{batt} and discharging capacity C_{batt} (Ah), as well as typical efficiency η_{batt}

PV Array Sizing

The required PV module power is given as:

$$P_{PV} = \frac{Load \ * hr}{\eta_{system} * S_{pk-hr}}$$

S_{pk-hr} is the pk sun hours*

$$\eta_{system} = \eta_{cable} \times \eta_{inv} \times \eta_{reg} \times \eta_{batt}$$

The number of panels required to provide this power is:

$$N = \frac{P_{PV}}{\eta_{PV}.A_{PV}.G_t} = \frac{P_{PV}}{Panel_{pk}}$$

η_{pv} is the instantaneous PV generator efficiency, A_{PV} is the area of a single module used in a system (m^2), G_t is the global irradiance incident on the titled plane (W/m^2) and N is the number of modules.

Battery Sizing

1. First calculate the daily energy use or load in the system:

2. Then calculate E_{Tbat}

3. Divide by system voltage to obtain Ahr_{Tbat}

4. Then divide by battery capacity to obtain N_{bat} in parallel

5. Number of batteries in series obtained from system voltage

Battery Sizing

$$E_{Tbat} = N_{aut} * \frac{E_{load}}{DOD}$$

with N_{aut} the number of days of autonomy and DOD_{max} the maximum depth-of-discharge (DOD) of the batteries

The number of batteries (parallel) N_{batt} can then be calculated

$$N_{bat} = \frac{E_{Tbat}}{E_{bat}}$$

Inverter Sizing

An inverter is a device that converts DC power from the battery bank to AC power for various loads

The simplest method is to take the PV module peak power and divide this by the efficiency of the inverter.

$$P_{inv}, AC = \frac{P_{PV}}{\eta_{inv}}$$

Remember that the maximum AC power that the inverter needs to deliver is estimated by adding the power demand of all of the loads that will ever be anticipated to be operating simultaneously.

Charge Controller Sizing

The primary function of a charge controller is to prevent the battery bank from being overcharged when there is abundant solar insolation available. Overcharging a battery can lead to electrolyte imbalances and depletion

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

Solar charge controller rating = Total short circuit current of PV array × 1.3

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