CHAPTER 2

PHOTOVOLTAICS

Fig 2.1 Photovoltaic Cell

2.1 PHOTOVOLTAICS: A HISTORICAL PERSPECTIVE

The story of photovoltaics started in 1839 when Becquerel discovered the photovoltaic effect from a silver coated platinum electrode immersed in an electrolyte radiated with light. What is emphasized here is that a number of early thin film cells had already been developed in the 1930s, based on the Schottky barrier device, using a semi-transparent metal layer deposited on top of selenium that provided the asymmetric junction.

Adding to the surprise, the use of thin films that is nowadays changing the PV industry on a global scale was conceived by Chapin at the very beginning of the modern solar PV. Then, in the 1970s, scientists taking part in the US PV Research and Development Program developed thin films of crystalline Si and a whole range of new semiconductor materials

Finally, in the early 1980s, Barnett developed the polycrystalline silicon thin film cell; while Martin Green replaced the silicon serigraphy with a silicon solar cell with greater surface area to catch the sun’s rays with tiny, laser etched grooves in which the wires (contacts) that carry the electric current are buried, leading to 20% efficient cells.

In 1997 the first modules using a triple junction amorphous silicon cell were commercialized by Sharp and also in 2007 Sanyo achieved an efficiency of 22% at the research level with its HIT solar cells. The HIT (heterojunction with intrinsic thin layer) solar cell is composed of a single thin crystalline silicon wafer surrounded by ultra thin amorphous silicon layers. In the meanwhile, highly efficient GaAs cells were developed to power spacecraft that now, exploiting the recent discovery of the near perfect growth of GaAs crystals as well as quantum well solar cells based on the same material, are likely to open the way to third generation solar cells.

2.2 PHOTOVOLTAIC TECHNOLOGIES

Crystalline solar cells

Polycrystalline as well as monocrystalline solar cells belong into this group. The basic form for crystalline solar cells production is silicon ingot. The ingot (block of silicon), sawn with diamond saw into thin silicon wafers, is a foundation for solar cell production. Wafers of 1 mm in thickness sawn with 1/10 mm precision are placed between two plan-parallel metal plates, which rotate into opposite directions. The procedure enables wafer thickness adjustment to 1/1000 mm precisely. The subsequent solar cell production procedure consists of the following steps:

- Doped wafers are first etched some micro-metres deep. The procedure removes crystal-structure irregularities caused by sawing and provides wafer cleaning.
- The material is doped as melt at polycrystal silicon or adequate gas is added whilst extracting pure silicon.
- The above procedure is followed by diffusion. Phosphorus, which is supplied inside the material in gaseous form, diffuses at the temperature of 800°C.
- N doped layer and oxide layer rich with phosphorus form on top of wafers due to oxygen reaction.
- Wafers are then folded to form a cube and etched in oxygen plasma, removing N layer from the edges.
- The following phase removes oxide layers from top of wafer by wet chemical etching.
- In the back, contact surface is produced from silver containing 1% aluminium.
- Special procedures enable silver print over mask on cell surface. Pressed cells are then sintered at high temperatures.
- Similar procedure is used to print contacts in the front cell surface. Anti-reflex layer is applied in a similar manner.

Amorphous solar cells

Amorphous solar cells are produced with similar technological procedures than integrated circuits. Due to the procedure these modules are also known as thin-film solar cells (thin-film modules). Herein, amorphous solar cells production is described briefly:

- Glass substrate is thoroughly cleaned.
- Lower contact layer is applied
- The surface is then structured - divided into bands.
- In vacuum, under high frequency electric field amorphous silicon layer is applied.
- The surface is re-banded.
- Upper metal electrodes are fixated.

Other solar cells

Among less frequently used solar cell types we find solar cells produced by EFG (Edge Defined Film fed Growth) method and Apex solar cells from silicon, cadmium telluride solar cells and copper-indium selenide (CIS) solar cells. EFG monocrystalline solar cells are produced directly from silicon melt eliminating sawing to wafers, which results in lower production costs and material saving for there is no waste due to sawing. Using EFG procedure, a silicon ribbon shaped in proper tube with eight flat sides is drawn from silicon melt. The tube length amounts to several metres. Flat sides are sawn by laser into separate solar cells. Most solar cells are square shaped in dimension of 100x100 mm. Consequently, the module power is greater with lesser surface compared to crystal modules of square shaped cells with truncated sides. Contacts are made in shape of copper bands. Separate cells are then combined in a similar manner than with other cell types. EFG cells are produced by Schott Solar. In contrast to EFG cells, Apex cells are poly-crystalline. Their production procedure is protected. Cadmium telluride and copper-indium selenide (CIS) cells are thus far scarcely used, mostly in lab research. Commercial modules from above mentioned materials are still hard to find. In the table 2.1 below, comparison between different solar cell types with their advantages and disadvantages has been shown.

Table 2.1 Comparison among different types of solar cell

Material	Thickness	Efficiency	Colour	Features
Monocrystalline Si solar cells	0.3 mm	15 - 18 %	Dark blue, black with AR coating, grey without AR coating	Lengthy production procedure, wafer sawing necessary. Best researched solar cell material - highest power/area ratio.
Polycrystalline Si solar cells	0.3 mm	13 - 15 %	Blue with AR coating, silver-grey without AR coating	Wafer sawing necessary. Most important production procedure at least for the next ten years.
Polycrystalline transparent Si solar cells	0.3 mm	10 %	Blue with AR coating, silver-grey without AR coating	Lower efficiency than monocrystalline solar cells. Attractive solar cells for different BIPV applications.
Polycrystalline ribbon Si solar cells	0.3 mm	12 %	Blue, with AR coating, silver-grey without AR coating	Limited use of this production procedure, no wafer sawing necessary. Decrease in production costs expected in the future.
Apex (polycrystaline Si) solar cells	0.03 to 0.1 mm plus ceramic substrate	9,5 %	Blue, with AR coating, silver-grey without AR coating	Production procedure used only by one producer, no wafer sawing, production in form of band possible. Significant decrease in production costs expected in the future.
Monocrystalline dendritic web Si solar cells	0.13mm including contacts	13 %	Blue, with AR coating	Limited use of this production procedure, no wafer sawing, and production in form of band possible.
Amorphous silicon	0.0001 mm + 1 to 3mm substrate	5 - 8 %	Red-blue, Black	Lower efficiency, shorter life span. No sawing necessary, possible production in the form of band.
Cadmium Telluride (CdTe)	0.008 mm + 3 mm glass substrate	6 - 9 % (module)	Dark green, Black	Poisonous raw materials, significant decrease in production costs expected in the future.
Copper-Indium-Diselenide (CIS)	0.003 mm + 3 mm glass substrate	7,5 - 9,5 % (module)	Black	Limited Indium supply in nature. Significant decrease in production costs possible in the future.
Hybrid silicon (HIT) solar cell	0.02 mm	18 %	Dark blue, black	Limited use of this production procedure, higher efficiency, better temperature coefficient and lower thickness.

2.2.1 Single-crystal and Polycrystalline Silicon Solar Cells

Single-crystal and Polycrystalline Silicon Solar Cells come under the first generation photovoltaic cells and are the dominant technology in the commercial production of solar cells, accounting for more than 86% of the solar cell market.

- Cells are typically made using a crystalline silicon wafer.
- Consists of a large-area, single layer p-n junction diode.
- Ingots can be either monocrystalline or multi-crystalline.
- Most common approach is to process discrete cells on wafers sawed from silicon ingots.
- More recent approach which saves energy is to process discrete cells on silicon wafers cut from multi-crystalline ribbons
- Band gap ~1.11 eV

Advantages

1. Broad spectral absorption range.
2. High carrier mobility.

Disadvantages

1. Requires expensive manufacturing technologies
2. Growing and sawing of ingots is a highly energy intensive process
3. Fairly easy for an electron generated in another molecule to hit a hole left behind in a previous photo excitation.
4. Much of the energy of higher energy photons, at the blue and violet end of the spectrum, is wasted as heat.

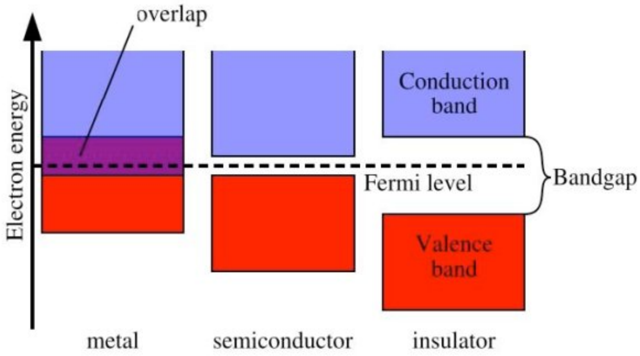


Fig 2.2 Energy band diagram of metal, semiconductor and insulator

2.2.2 Thin Film Solar Cells (Second Generation)

Thin-film Technology

- Based on the use of thin-film deposits of semiconductors.
- Using of thin-films reduces mass of material required for cell design.
- Contributes greatly to reduced costs for thin film solar cells.
- Several technologies/semiconductor materials currently under investigation or in mass production
- Deposition of thin layers of non-crystalline-silicon materials on inexpensive substrates using Plasma enhanced chemical vapor deposition (PECVD)
- Devices initially designed to be high-efficiency, multiple junction Photovoltaic cells.

Plasma Enhanced Chemical Vapor Deposition

Thin-film deposition

- Technique for depositing a thin film of material onto a substrate.
- Layer thickness can be controlled to within a few tens of nm.
- Single layers of atoms can be deposited

- **Chemical vapor deposition (CVD)**
- Chemical process using a gas-phase precursor.
- Often a halide or hydride of the deposited element.

- **PECVD - Plasma Enhanced CVD**
- Uses an ionized vapor, or plasma, as a precursor
- Relies on electromagnetic means (electric current, microwave excitation) to produce plasma.

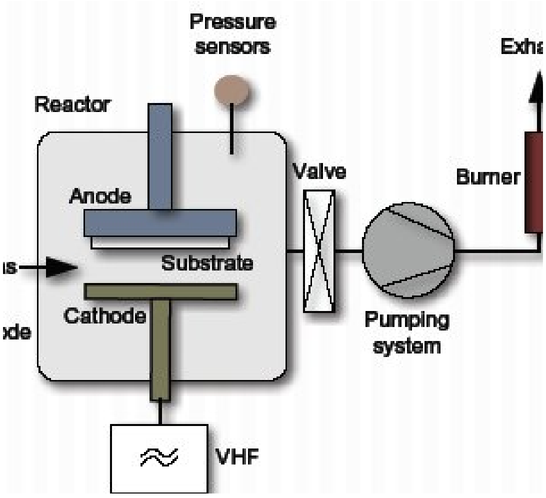


Fig 2.3 Plasma Enhanced Chemical Vapor Deposition

Advantages

1. Lower manufacturing costs.
2. Lower cost per watt can be achieved.
3. Reduced mass.
4. Less support is needed when placing panels on rooftops.
5. Allows fitting panels on light or flexible materials, even textiles.

Disadvantages

1. Typically, the efficiencies of thin-film solar cells are lower compared with silicon (wafer-based) solar cells.
2. Amorphous silicon is not stable.
3. Increased toxicity.

2.2.3 III-V Semiconductors (Third Generation)

Different Semiconductor Technology

- Very different from the previous semiconductor devices.
- Do not rely on a traditional p-n junction to separate photo generated charge carriers.

- Devices include:
    - Nanocrystal solar cells.
    - Photoelectrochemical cells.
    - Gräetzel Cell.
    - Dye-sensitized hybrid solar cells

Polymer solar cells

- Bulk heterojunctions between an organic polymer and organic molecule as electron acceptor.
- Fullerene embedded into conjugated polymer conductor
- Lightweight, disposable, inexpensive to fabricate, flexible, designable on the molecular level, and have little potential for negative environmental impact.
- Present best efficiency of polymer solar cells lies near 5 percent.
- Cost is roughly one-third of that of traditional silicon solar cell technology.
- Band gaps > 2eV

Advantages

- Low-energy, high-throughput processing technologies.
- Polymer cells - solution processable, chemically synthesized.
- Polymer cells - low materials cost.
- Gräetzel cells - attractive replacement for existing technologies in “low density” applications like rooftop solar collectors.
- Gräetzel cells - Work even in low-light conditions.
- DSSC - potentially rechargeable.

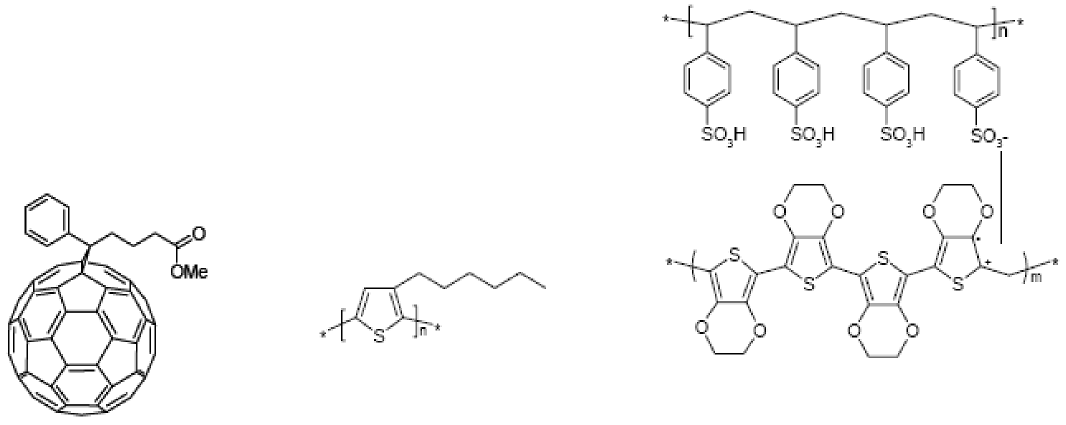
Disadvantages

- Efficiencies are lower compared with silicon (wafer-based) solar cells.
- Degradation effects: efficiency is decreased over time due to environmental effects.
- High band gap.
- PEC cells suffer from degradation of the electrodes from the electrolyte.

2.2.4 Photo Electrochemical Solar Cells (Fourth Generation)

Use of polymers with nanoparticles mixed together to make a single multispectral layer.

- Significant advances in hybrid solar cells have followed the development of elongated nanocrystal rods and branched nanocrystals.
- More effective charge transport.
- Incorporation of larger nanostructures into polymers required optimization of blend morphology using solvent mixtures.
- Cell Design:
- Solid state nanocrystals (Si, In, CuInS2, CdSe)
    - Embedded in light absorbing polymer (P3HT).
    - P-type, polymeric conductor, such as PEDOT: PSS carries ‘holes’ to the counter electrode.
    - Coated on a transparent semi-conducting oxide (ITO).



PCBM **P3H** **PEDOT: PSS**

Fig 2.4 Polymers used in fourth generation

Advantages

- Solution processable.
- Lower materials cost (polymer).
- Self-assembly.
- Printable nanocrystals on a polymer film.
- Improved conversion efficiency (potentially)

Disadvantages

- Efficiencies are lower compared to silicon (wafer-based) solar cells.
- Potential degradation problems similar to polymer cells.
- Optimize matching conductive polymers and nanocrystal

2.3 BASICS OF PHOTOVOLTAIC ENERGY CONVERSION

The operation of a photovoltaic cell can be generally divided into three basic Steps:

1. Light absorption.
2. Charge separation.
3. Charge collection.

The physical or chemical processes behind these principal steps vary between different types of solar cells and photovoltaic materials. The efficiency of a solar cell depends on the efficiency of each of these steps and is maximized by the materials selection and the cell design.
To sum up, in the standard PN-junction solar cell, light absorption occurs via band gap excitation of electrons in the bulk of the semiconductor, charge separation in the internal electric field of the pn-junction and charge collection by transport of electrons and holes (electric current) through the bulk of the semiconductor to the electrical contacts.

2.3.1 Solar irradiation and availability of solar electricity

The intensity of solar radiation in the earth's distance from the sun is approximately 1353 kW/m^2, a number also called the solar constant. The solar radiation is emitted from the sun's photosphere at 6000 K temperature, which gives it a spectral distribution resembling closely that of a black body at the corresponding temperature. Passing through the earth's atmosphere the solar radiation is attenuated by scattering from the air molecules, aerosols and dust particles, as well as by absorption by the air molecules, in particular oxygen, ozone, water vapor, and carbon dioxide. This gives a characteristic fingerprint to the solar radiation spectrum on the earth's surface (Figure 2.5)

The available solar irradiation in a certain place depends on the latitude, the altitude and the climatic type in a yearly basis, and on the season, the time of day and the weather conditions in a specific time. The total yearly solar irradiation on horizontal surface is 700-1000 kWh/m^2 in North Europe, 900-1300 kWh/m^2 in Middle Europe, 1300-1800 kWh/m^2 in South Europe, 1800-2300 kWh/m^2 in the equator, and 2000- 2500 kWh/m^2 in the so called "solar belt" i.e. between 20° and 30° latitude

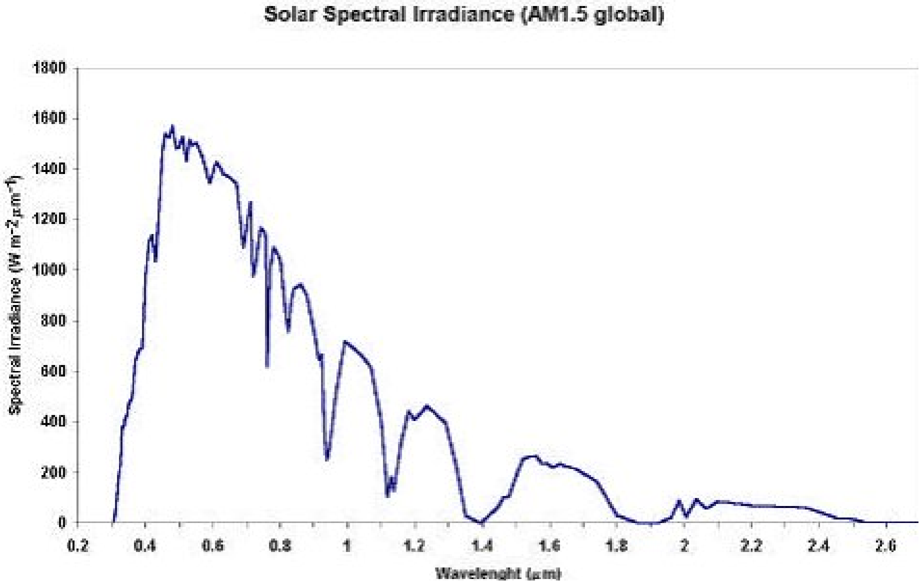


Fig 2.5 Standard AM1.5 global solar spectrum. [Source:http://www.pv.unsw.edu.au/am1.5.html]

2.3.2 Principles of Photoconductivity

The conductivity of semiconductors changes upon light irradiation. The steps leading to photoconductivity are shown in Figure2.6.

Following are the points under consideration:

a) If a photon has energy h_v larger than the band gap energy E_g, the photon is absorbed by the semiconductor and an electron (•) is excited from the valence band to the conduction band. The place in the valence band, from where the electron was removed, is called hole (o). The hole has a positive (plus) charge.

b) In inorganic semiconductors, the excited electron and the resulting hole migrate freely to opposite electrodes. In conducting polymers, however, the electron and the hole, which are generated by the incident photon, are bound into an exciton (Figure 2.7).

c) Normally, these electron-hole pairs recombine after a short time, in part under emission of a photon, and the initial state will be obtained.

d) In the presence of an electric field or at interfaces, these pairs can split into free electrons and holes, which are carriers of electricity (photocurrent).

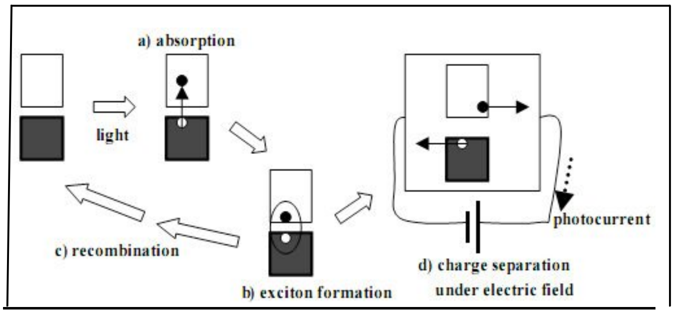


Fig 2.6 Steps to photoconductivity

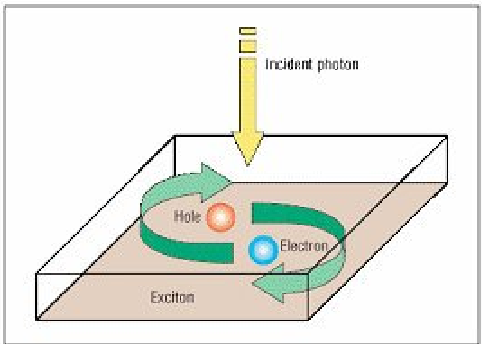


Fig 2.7 Excitons (bound electron–hole pairs) are generated after light photon absorption in conjugated polymers

2.3.3 Terms Used In Solar Cell Characterization

A photovoltaic cell is a device, which converts incident light to electrical energy. Generation of electrical power under illumination is achieved by the capability of the photovoltaic device to produce voltage over an external load and current through the load at the same time. This is characterized by the current-voltage (IV) curve of the cell at certain illumination and temperature.
When the cell is short circuited under illumination, the maximum current, the *Short Circuit Current (I_{SC})*, is generated, while under open circuit conditions no current can flow and the voltage is at its maximum, called the *Open Circuit Voltage (V_{OC})*.

The point in the IV-curve yielding maximum product of current and voltage, i.e. power, is called the M*aximum Power Point (MPP)*. Thus we can define these as:
Air Mass (AM): A measure of how much atmosphere sunlight must travel through to reach the earth’s surface. This is denoted as ‘AM(x)’, where x is the inverse of the cosine of the zenith angle of the sun. A typical value for solar cell measurements is AM 1.5, which means that the sun is at an angle of about 48°.
Air mass describes the spectrum of radiation, but not its intensity. For solar cell purposes, the intensity is commonly fixed at 100 W/cm^2.

Open-Circuit Voltage (Voc): The maximum possible voltage across a photovoltaic cell; the voltage across the cell in sunlight when no current is flowing.

Short-Circuit Current (Isc): This is the current that flows through an illuminated solar cell when there is no external resistance (i.e., when the electrodes are simply connected or short-circuited). The short-circuit current is the maximum current that a device is able to produce. Under an external load, the current will always be less than Isc.

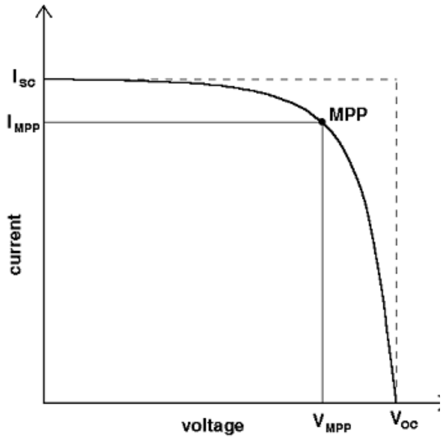


Fig 2.8 Typical shape of the current-voltage curve of a photovoltaic cell showing the open- circuit voltage VOC, short circuit current ISC, and the maximum power point MPP, and the current and voltage at the MPP: IMPP, VMPP.

Fill Factor: The ratio of a photovoltaic cell's actual maximum power output to its theoretical power output if both current and voltage were at their maxima, I_{SC} and Voc, respectively. This is a key quantity used to measure cell performance. It is a measure of the 'squareness' of the I–V curve. The formula for FF in terms of the above quantities is:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

where, V_{MPP} = Voltage at Maximum Power Point
I_{MPP} = Current at Maximum Power Point

Using the fill factor, the Maximum Power Output (P_{MAX}) of the solar cell can be written as:

$$P_{MAX} = V_{OC} \cdot I_{SC} \cdot FF$$

While the physical principles behind the operation of different types of photovoltaic cells are generally different, the current-voltage curve of well performing cells are similar, and can be characterized and compared with each other in terms of FF, V_{OC}, and I_{SC}.
Finally, the energy conversion efficiency of the solar cell is defined as the power produced by the cell (P_{MAX}) divided by the power incident on the representative area of the cell (P_{light}):

$$\eta = \frac{P_{MAX}}{P_{light}}$$

Power Conversion Efficiency (PCE or η or η_e): The ratio of power output to power input. In other words, PCE measures the amount of power produced by a solar cell relative to the power available in the incident solar radiation (Pin). Pin here is the sum over all wavelengths and is generally fixed at 100 W/cm2 when solar simulators are used. This is the most general way to define efficiency. The Formula for PCE, in terms of quantities defined above is:

$$\eta_e = \frac{I_{\mathrm{mpp}} V_{\mathrm{mpp}}}{P_{\mathrm{in}}} = \frac{I_{\mathrm{sc}} V_{\mathrm{oc}} \mathrm{FF}}{P_{\mathrm{in}}}$$

Quantum Efficiency (QE): The efficiency of a device as a function of the energy or wavelength of the incident radiation. For a particular wavelength, it specifically relates the number of charge carriers collected to the number of photons shining on the device. QE can be reported in two ways: internal QE and external QE.

External Quantum efficiency: This type of quantum efficiency includes losses by reflection and transmission. External quantum efficiency is also called IPCE (Incident Photon to Current Efficiency).

Internal Quantum Efficiency: This quantum efficiency factors out losses due to reflection and transmission of photons such that it considers processes only involving absorbed photons. By accounting for transmission and reflection processes, external QE can be transformed into internal QE.

The efficiency of the solar cell depends on the temperature of the cell, and which is even more important, on the quality of the illumination, i.e. the total light intensity and the spectral distribution of the intensity. For this reason, a standard measurement condition has been developed to facilitate comparable testing of the solar cells between different laboratories. In the standard condition used for testing of terrestrial solar cells the light intensity is 1000 W/m^2, the spectral distribution of the light source is that of AM1.5 global standard solar spectrum, and temperature of the cell is 25°C. The power output of the solar cell at these conditions is the nominal power of the cell, or module, and is reported in peak watts, W_p. In practice, special solar simulator light sources are used for the standard measurements.