Solar Energy for a Decarbonised Future - Knowledge Transfer for Environmental Education and Awareness (SolAware)

Summer Training 2023-2024

Session 3: Photovoltaic System (Photovoltaic system and its fundamentals)

A Project Funded by the British Council Between University of Mosul & Teesside university on Research Environment

This Session is divided into two parts

Photovoltaics System
(Part1)

Fundamentals of PV system
(Part 2)

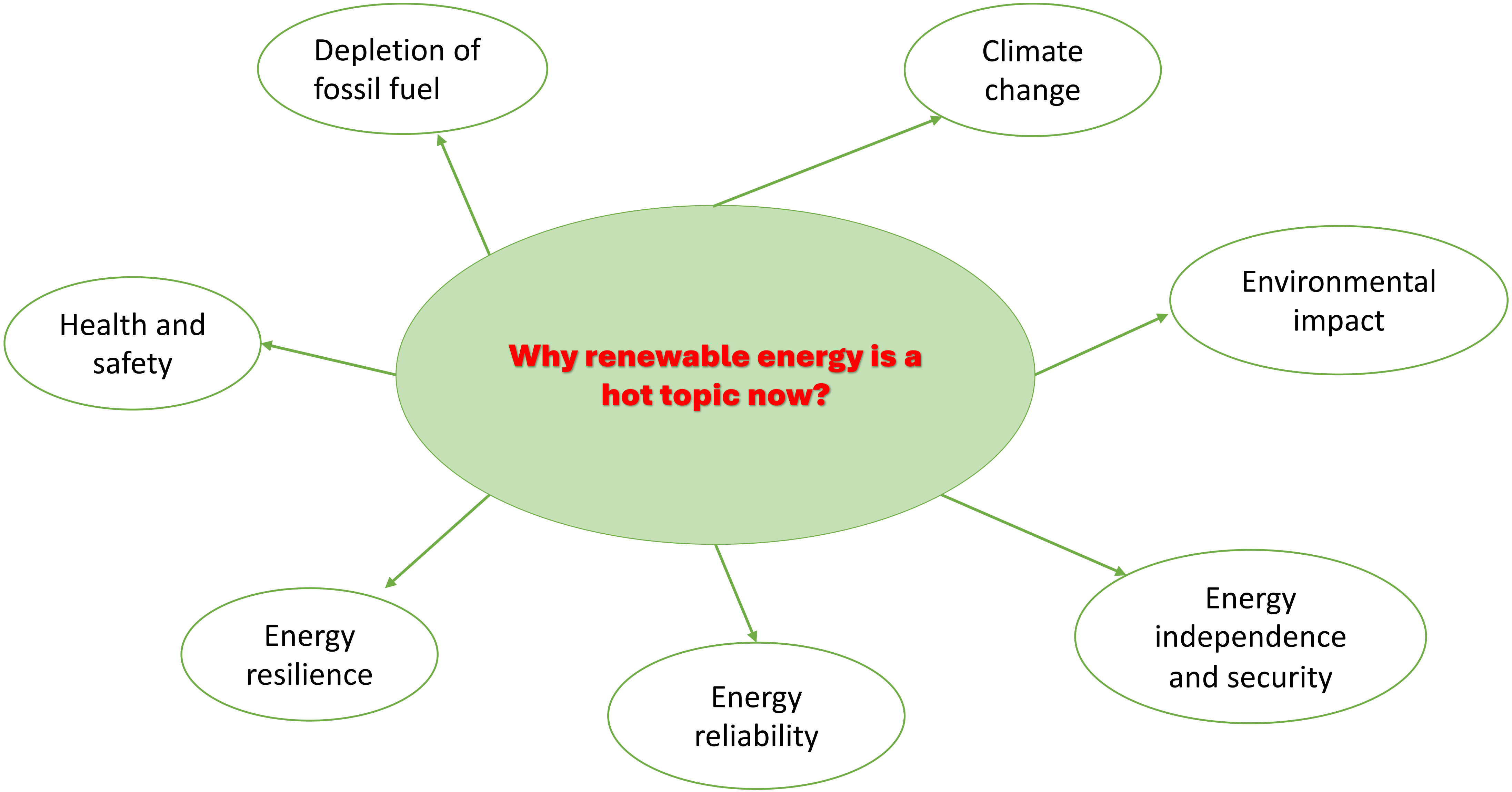
Photovoltaics System (Part1)

Learning Objective

This lecture is an introduction to Photovoltaics, which covers the following:

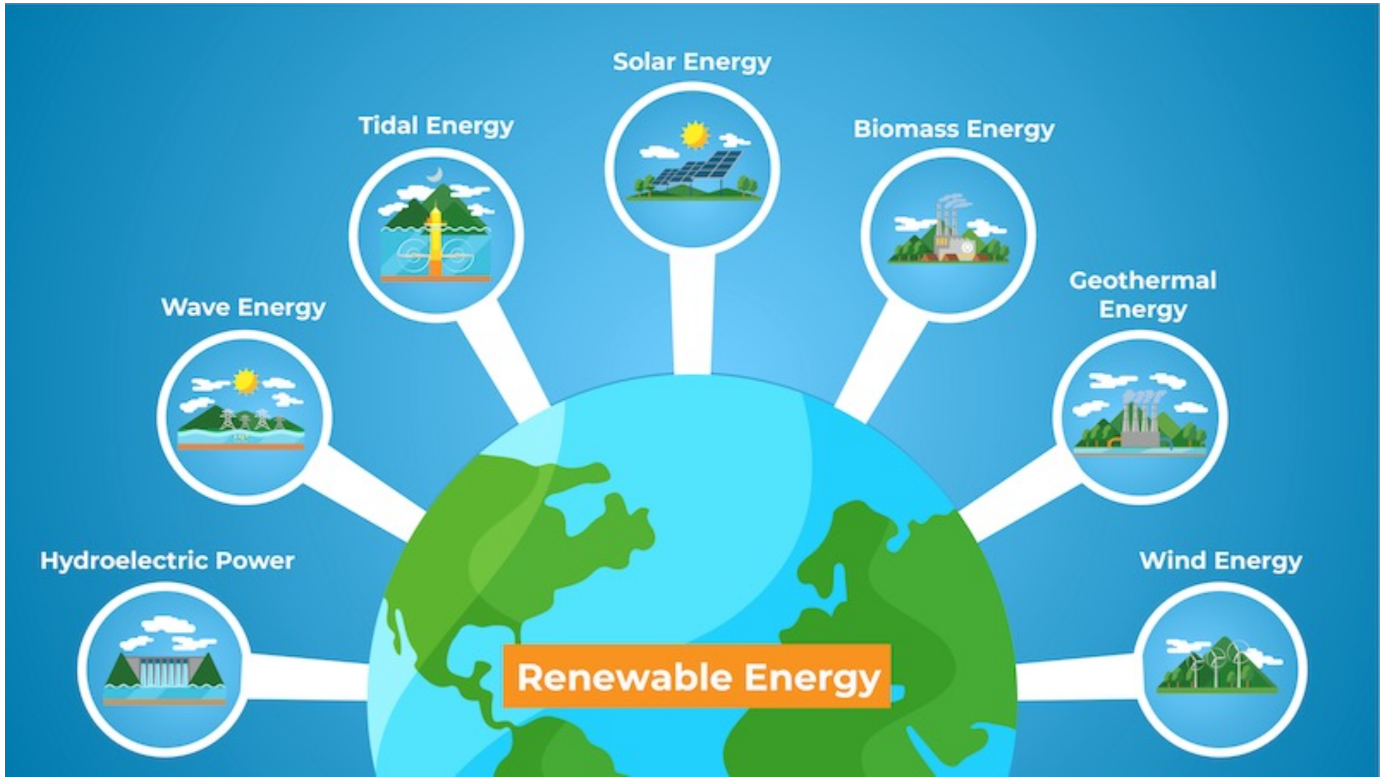
- ❑A background on renewable energy resources.
- ❑Introduction to photovoltaics.
- ❑The emergence of silicon solar cells.
- ❑Growth of PV over the years.
- ❑Application of PV in different areas.

Renewable Energy Resources



Renewable Energy Resources

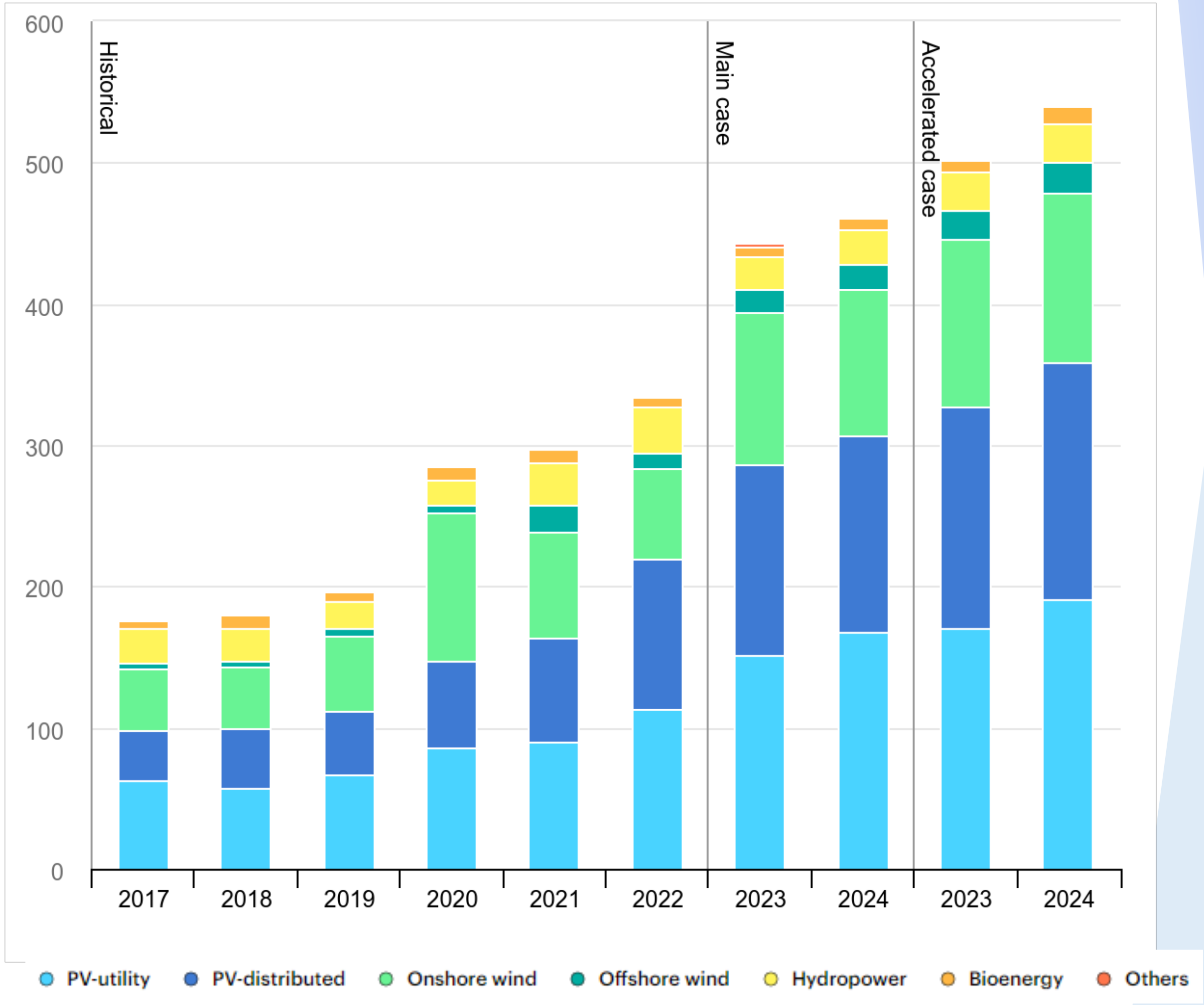
- ❑ Solar Energy.
- ❑ Wind Energy.
- ❑ Hydroelectric Power.
- ❑ Biomass Energy.
- ❑ Geothermal Energy.
- ❑ Wave Energy.
- ❑ Tidal Energy.



Renewable Energy Resources

The growth of renewable electricity capacity in 2023

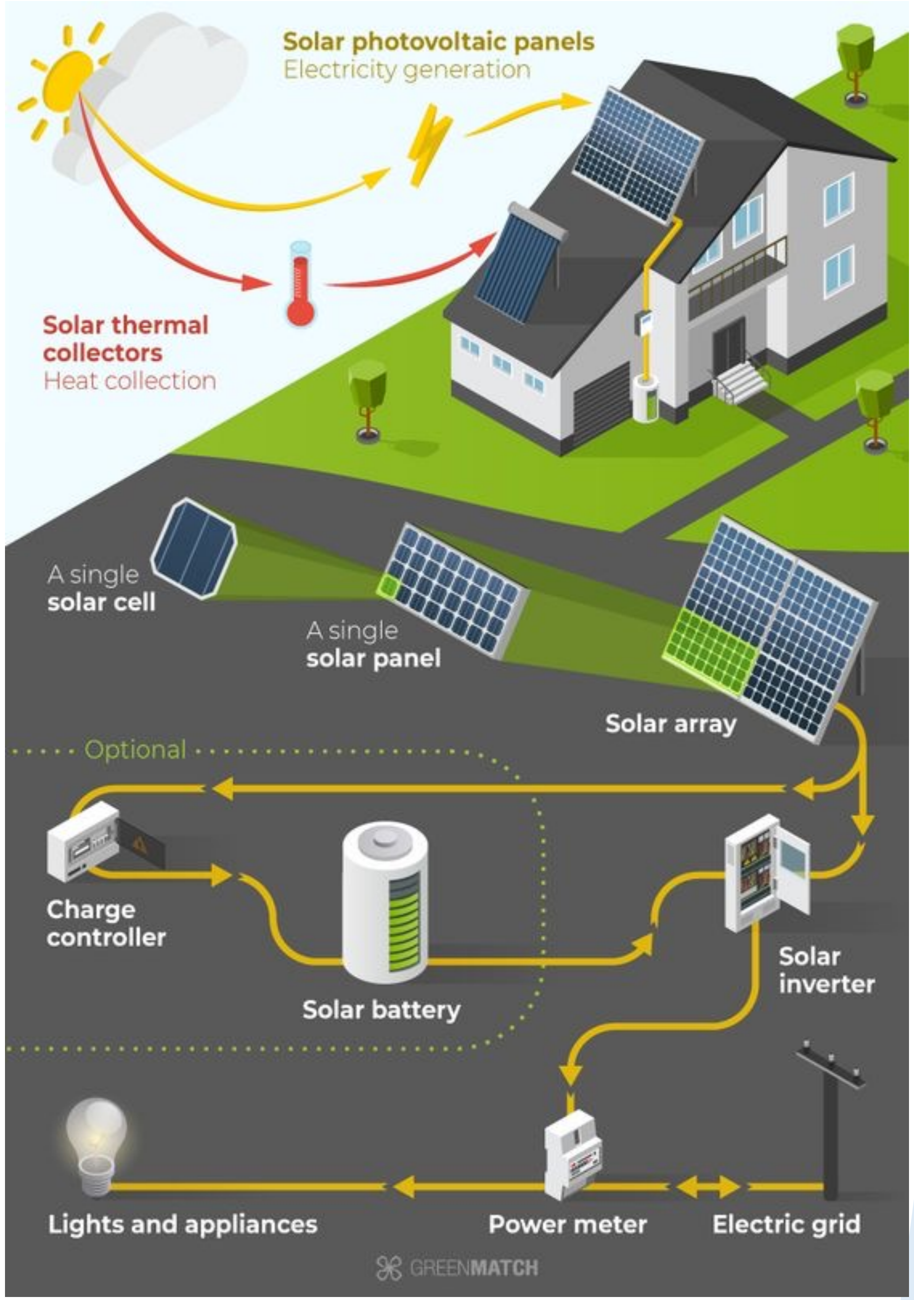
- ❑Solar PV rose to about 346GW. China dominated and alone added roughly 217GW
- ❑Hydropower reached 1270GW
- ❑Wind grew by 13% to a total capacity 1017GW. Dominated by the USA and China
- ❑Bioenergy contributed 4.4GW, less than in 2022 which was 6.4GW.
- ❑Geothermal rises by 193MW. Led by Indonesia.



The Benefits of Solar Energy

An energy source that is both renewable and inexhaustible by definition

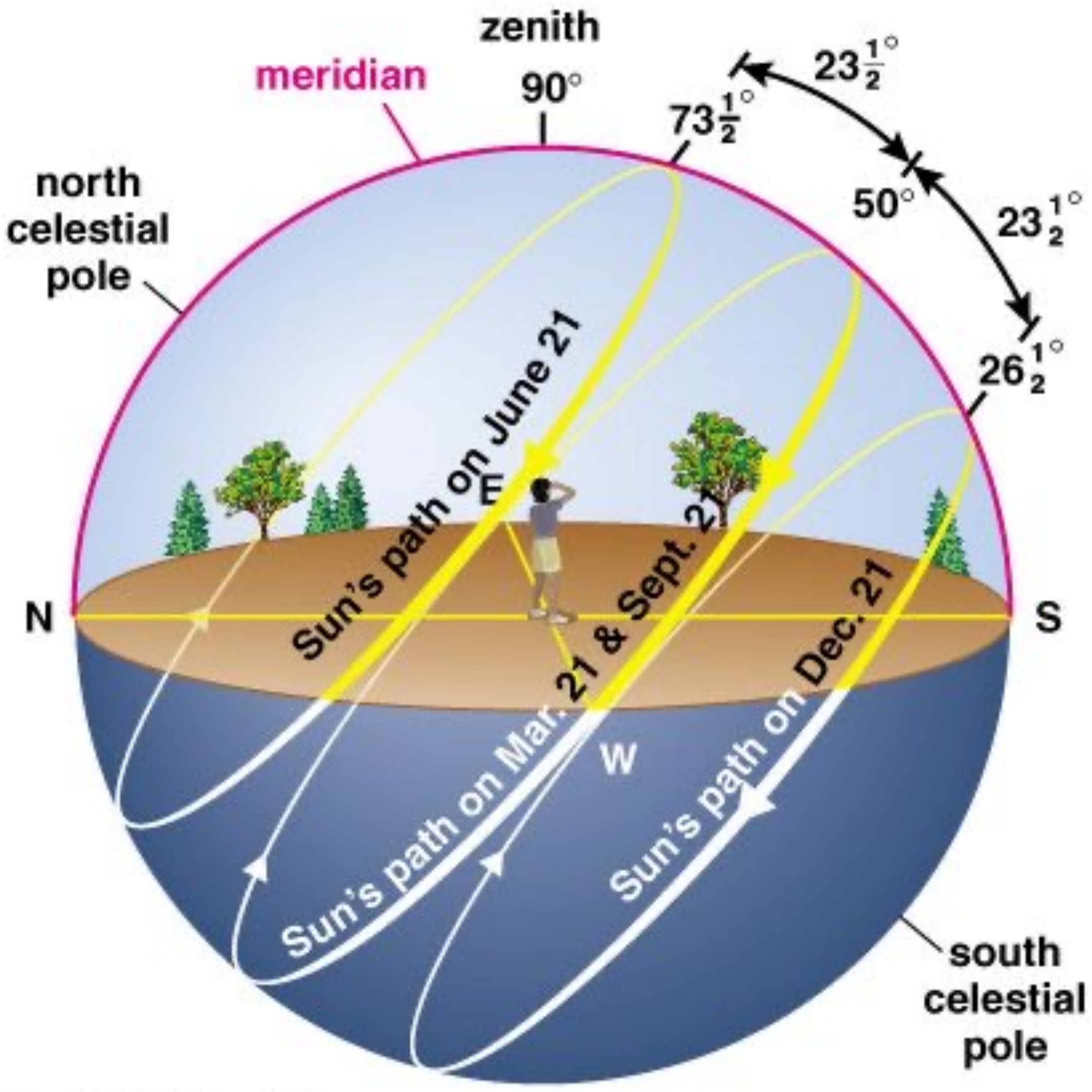
- **The sun remains an unchangeable and inexhaustible source of energy**
- **Need to capture 6% of our solar energy to cover all of humanity's energy needs**



The Benefits of Solar Energy

Everywhere gets sunlight

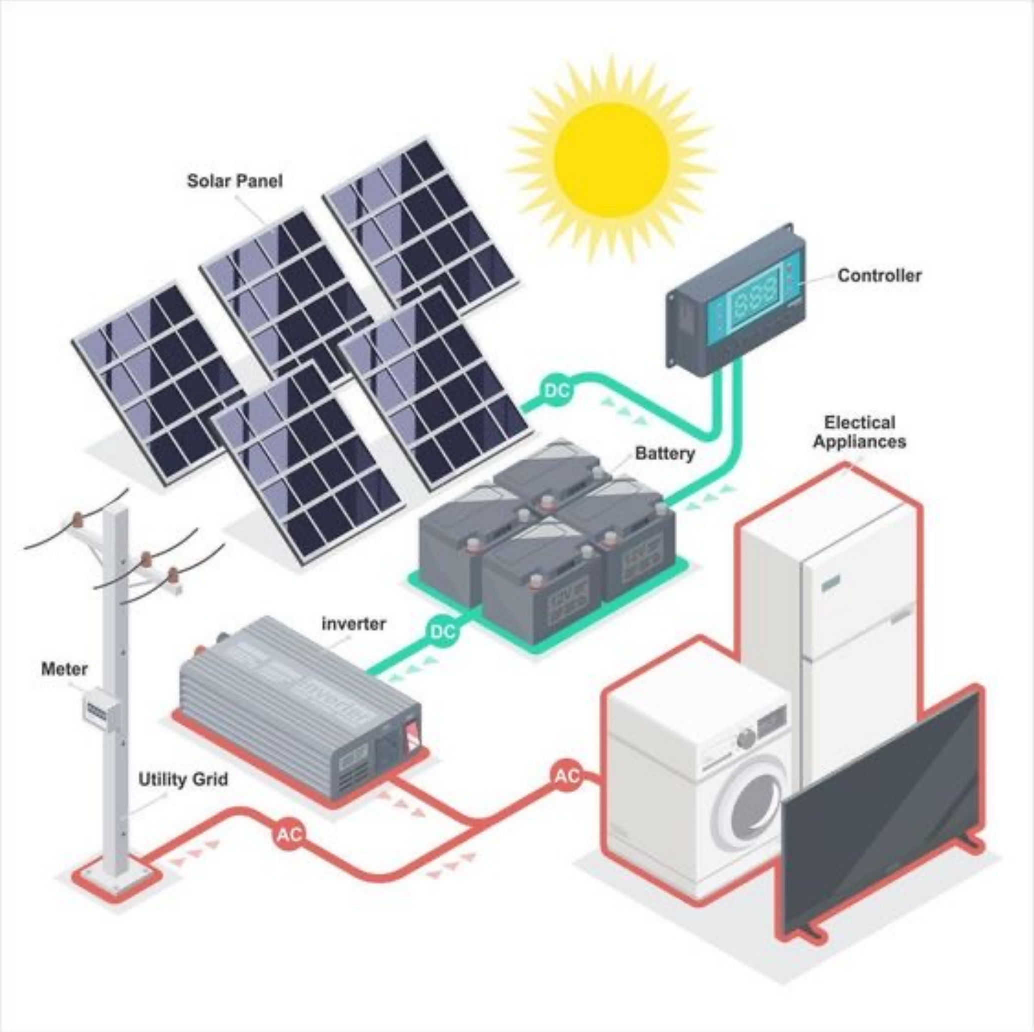
- ❑Sunlight is an energy source that can be used **anywhere on the planet**
- ❑Once converted into electricity, solar energy is very simple to transport



The Benefits of Solar Energy

It's very well suited to batteries and the electricity grid

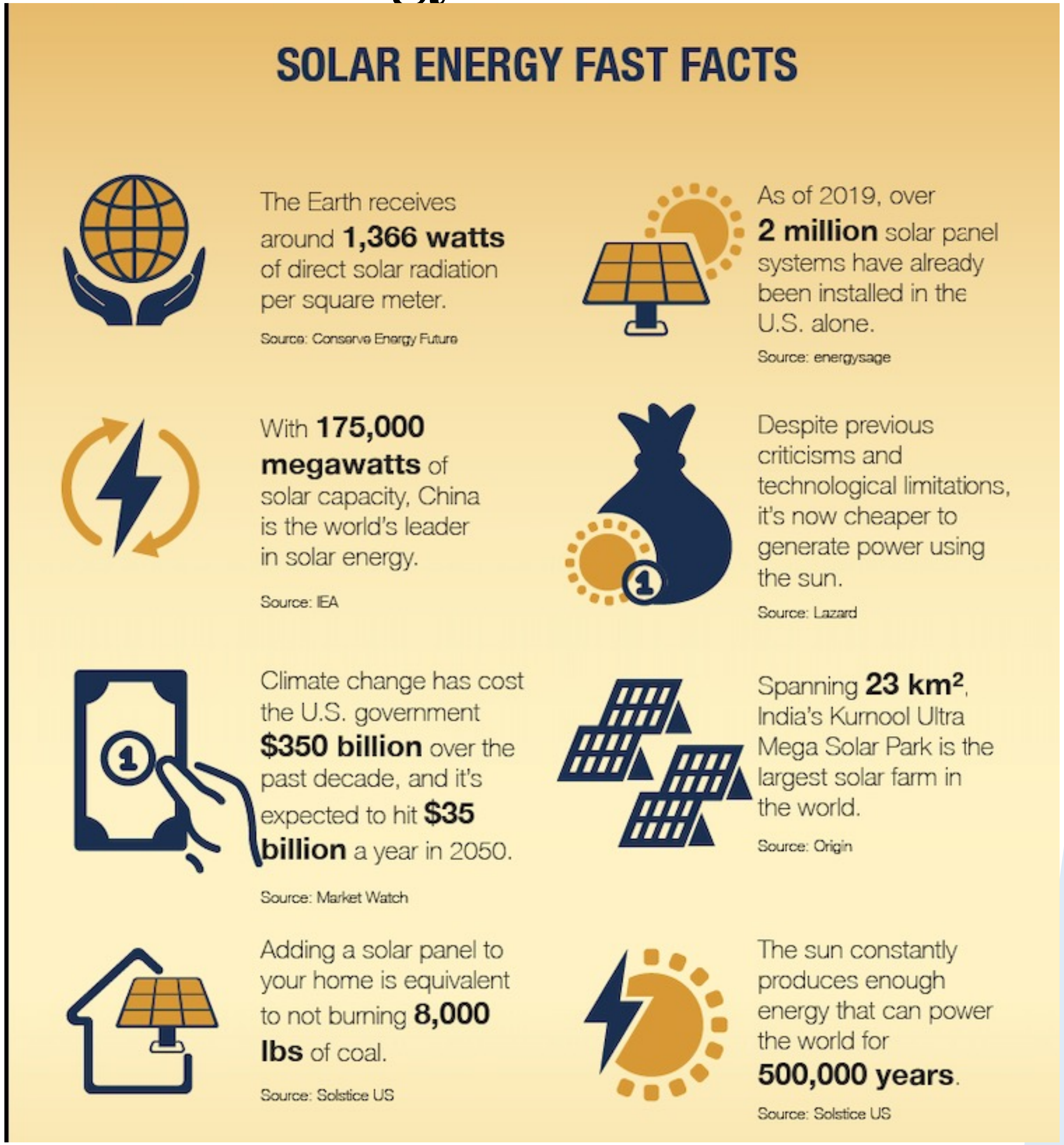
- Photovoltaics produces energy mainly in the middle part of the day, but thanks to larger, more efficient and reliable **storage systems**



The Benefits of Solar Energy

The sun creates local wealth and jobs

- Of all green jobs, solar energy creates the most employment opportunities for developers, builders, installers and maintenance technicians at the power plants



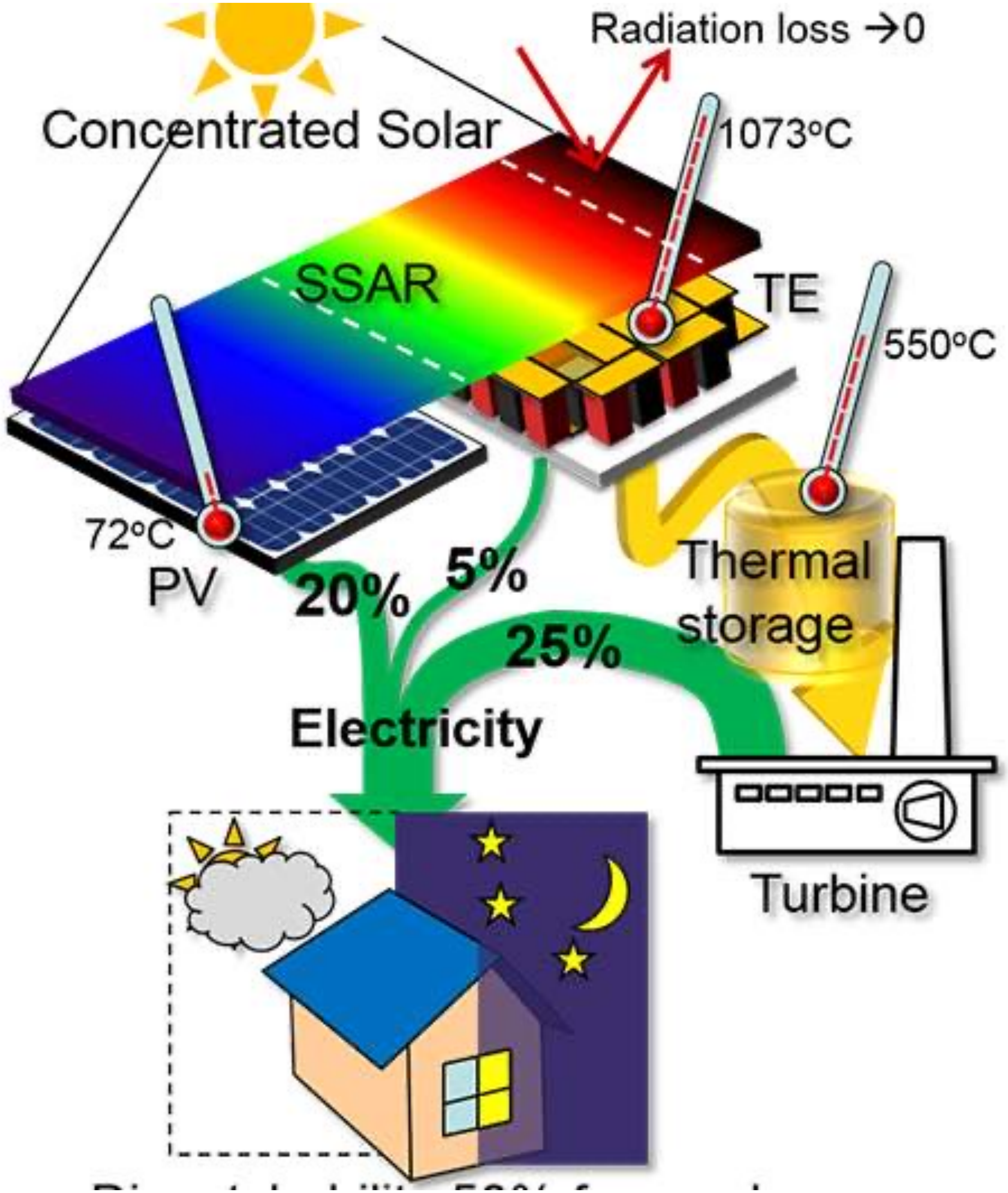
The Benefits of Solar Energy

Green until the end of life

- Solar panels are usually easy to dismantle and the materials used in them can be reclaimed, recycled and **reused**

The Benefits of Solar Energy

Technological versatility (Hybrid system)

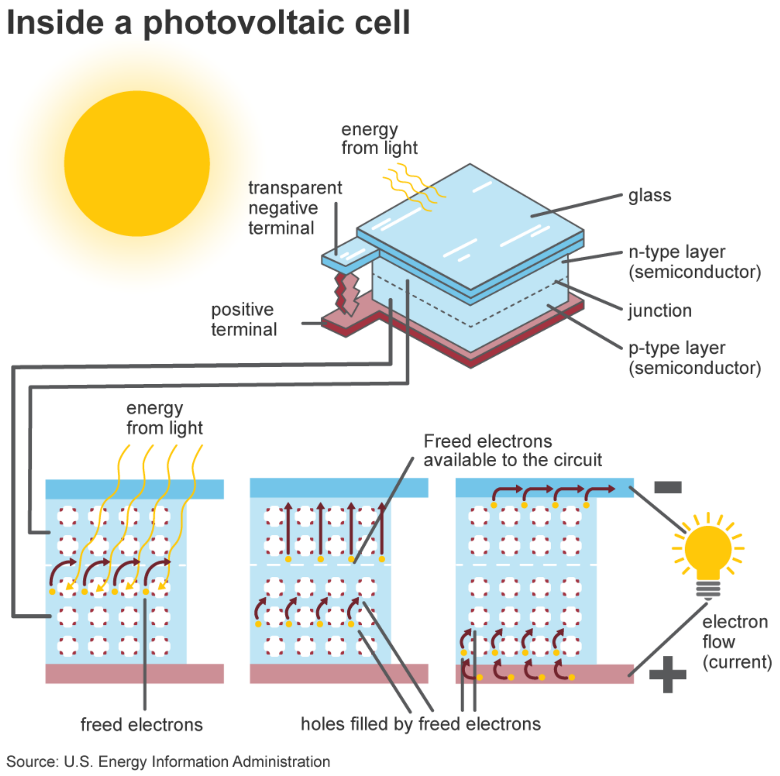


- Solar energy can also be used to create **thermal energy** by heating fluids
- Compared to a fossil fuel system or even many other renewables, solar energy creates **very little noise**

Introduction to Photovoltaic System

What is a photovoltaic system?

- ➢The term "photos" is a Greek word means *light*. And "Volt" is from the last name of an Italian scientist Alessandro Volta.
- ➢A photovoltaic system or a PV system means it transforms the light energy (mainly from the sun) to electrical energy.
- ➢A PV system consists of solar cells which collect sun's energy (light/photon) and converts it into direct current (DC).
- ➢Later we will learn more on solar cell physics, how they are connected and other electrical parameters.



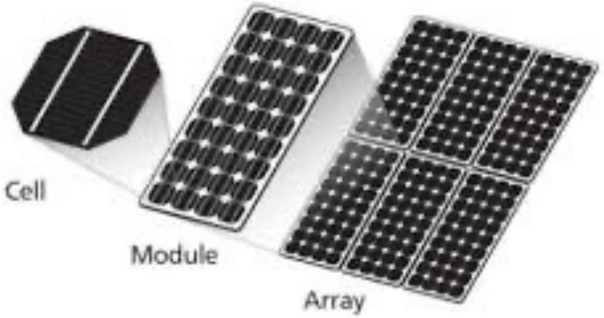
A conventional crystalline silicon solar cell

Emergence of solar cell

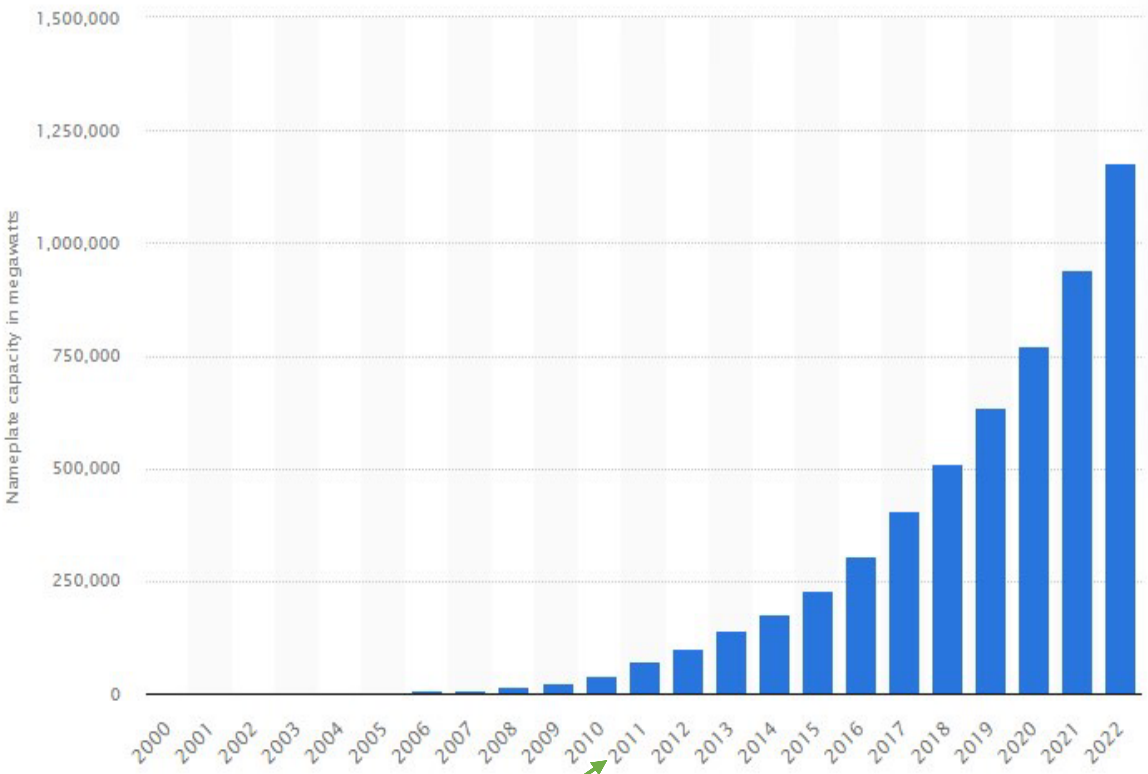
The first solar cell development

- In 1954, the first solar cell was developed in Bell labs by Daryl Chapin, Calvin Fuller and Gerald Pearson. The solar cell had an area of $2cm^2$, and the efficiency was about 6%.
- Later, the further development of solar cell is made by combining the concept of pn junction (Shockly), silicon crystal growth (Jan Czocharlski) and the theory of photovoltaic effect (Einstein).
- At the very stage, the solar cell application was limited to few applications mostly to space craft and satellite.
- Very limited application on earth.
- With the advancement of technology and the price getting down, the solar module is now readily available and used in variety of applications in earth and in the space.

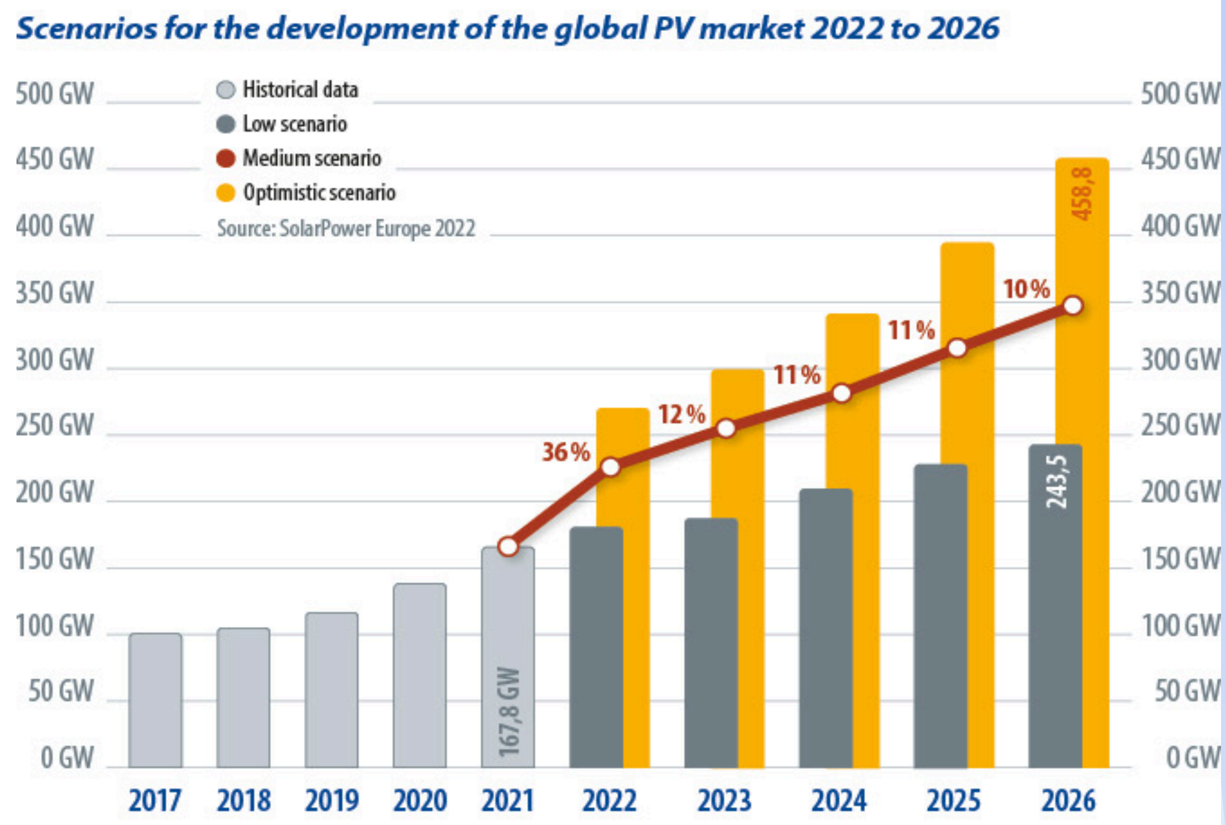
The three inventors are checking the amount of electricity from the solar cell by illuminating lamp.



Growth of PV



Total PV capacity installed over the last two decades.

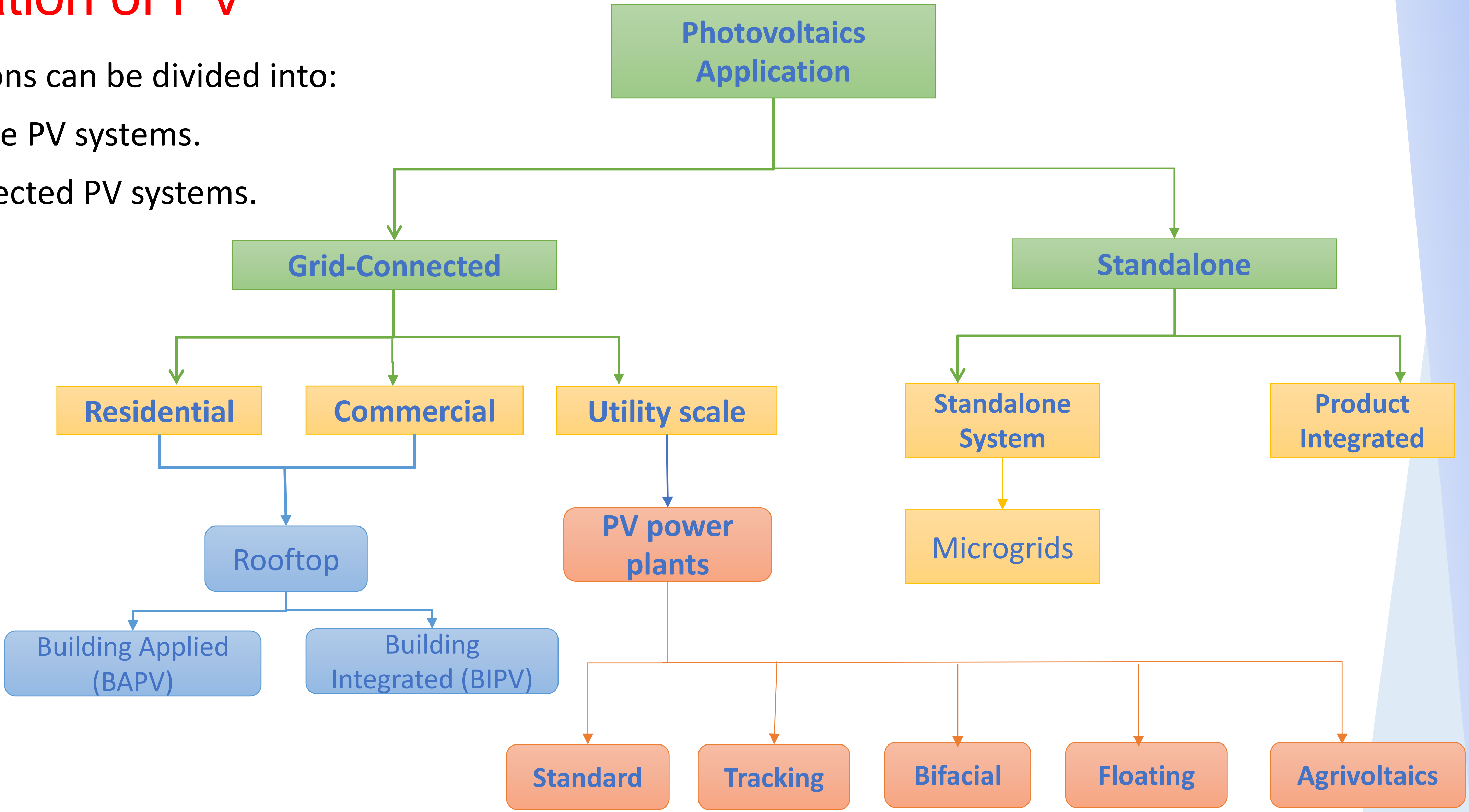


PV growth prediction till 2026

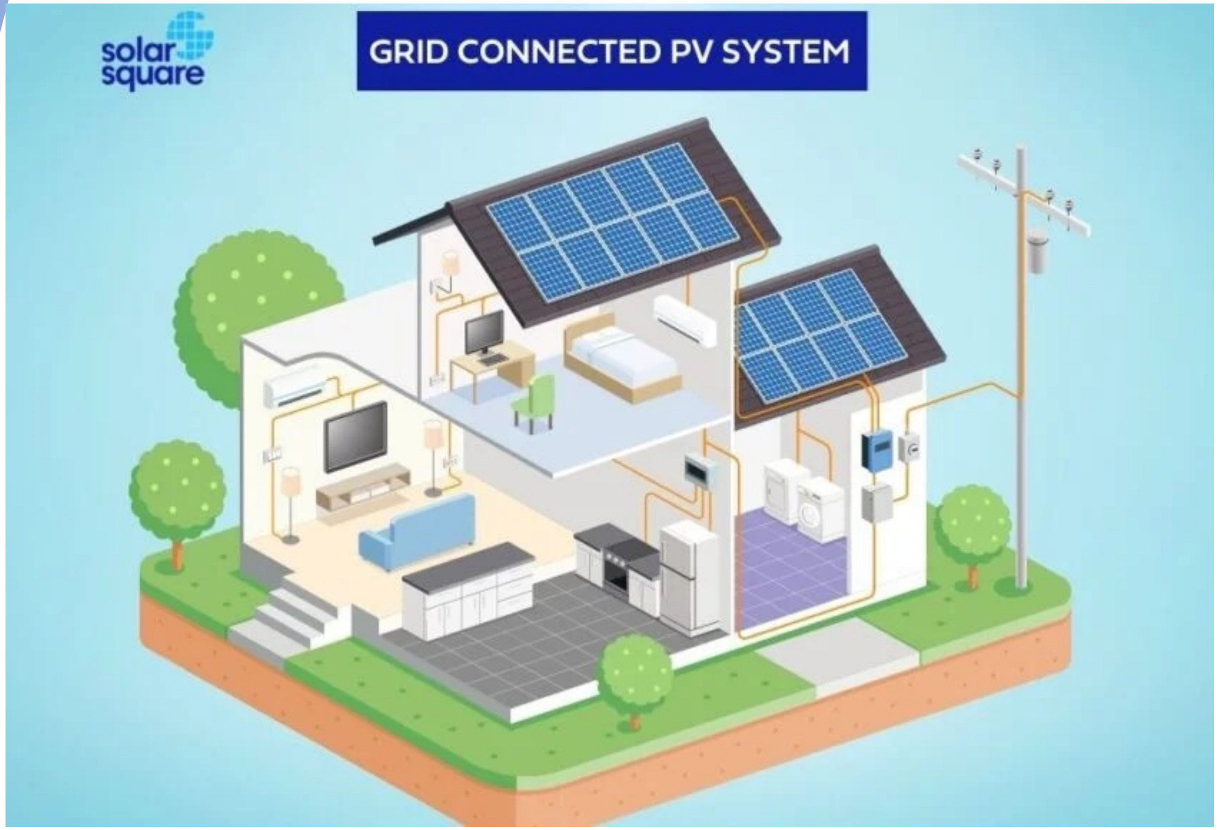
Application of PV

PV applications can be divided into:

- Stand-alone PV systems.
- Grid-Connected PV systems.

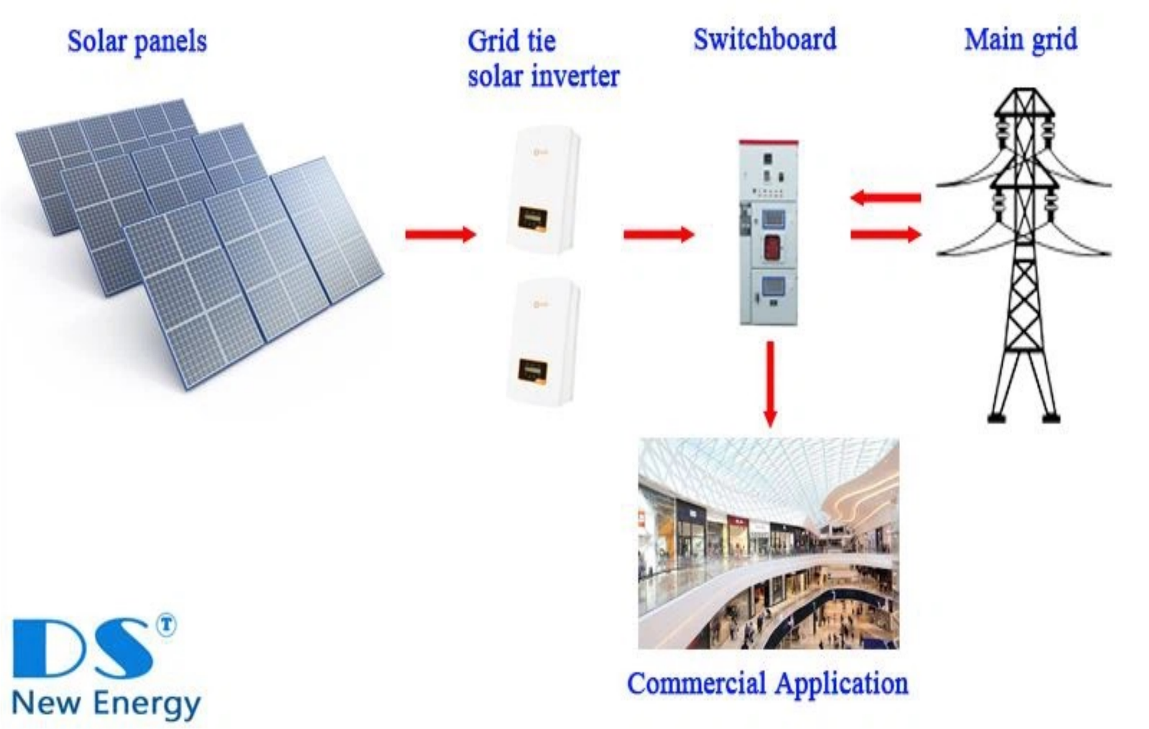


Application of PV



Some Examples- Grid Connected

Residential and Commercial



Application of PV

Some Examples- Grid Connected Utility Scale- Fixed angle

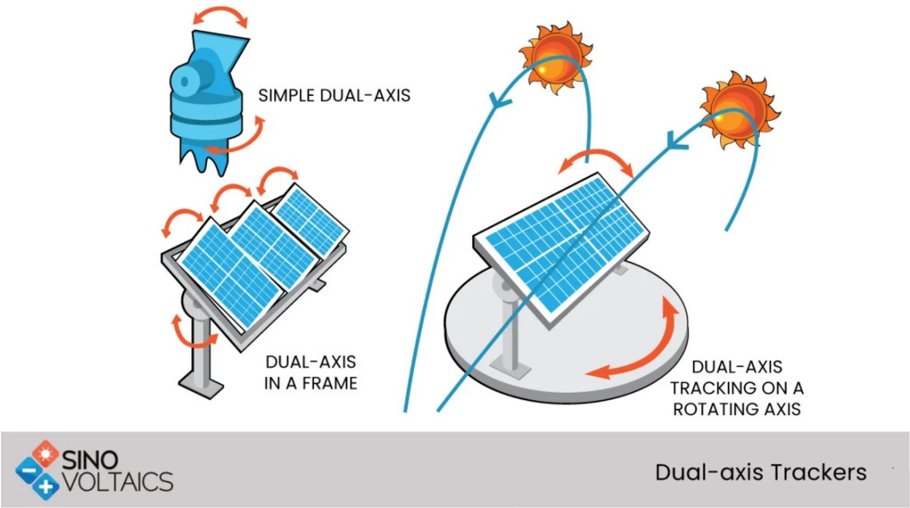
The Aura Solar III plant, La Paz, Mexico. Capacity 32MW

Solar Park, Mymensingh, Bangladesh. Capacity 73.1MW

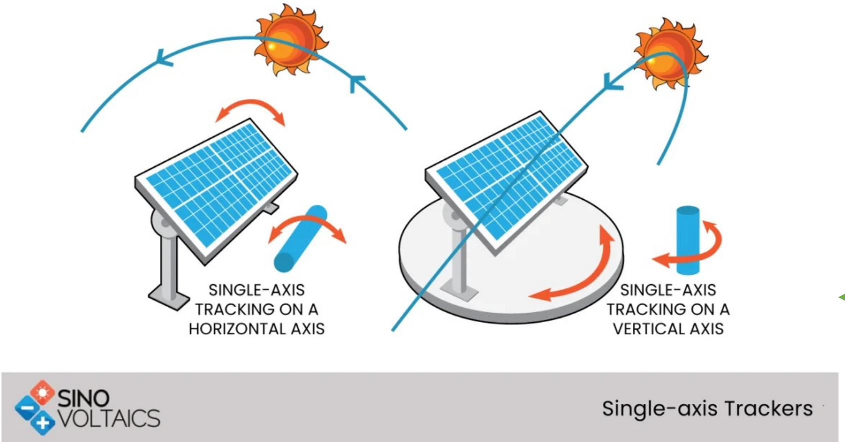
Application of PV

- Trackers are used to enhance the PV energy production.
- Connected to the PV modules.
- That can rotate to a proper angle to get maximum sunlight.
- Single axis tracker – Horizontal and vertical.
- Dual axis tracker.

Some Examples- Grid Connected Tracking



Dual axis tracker



Single axis tracker

Application of PV

Some Examples- Grid Connected

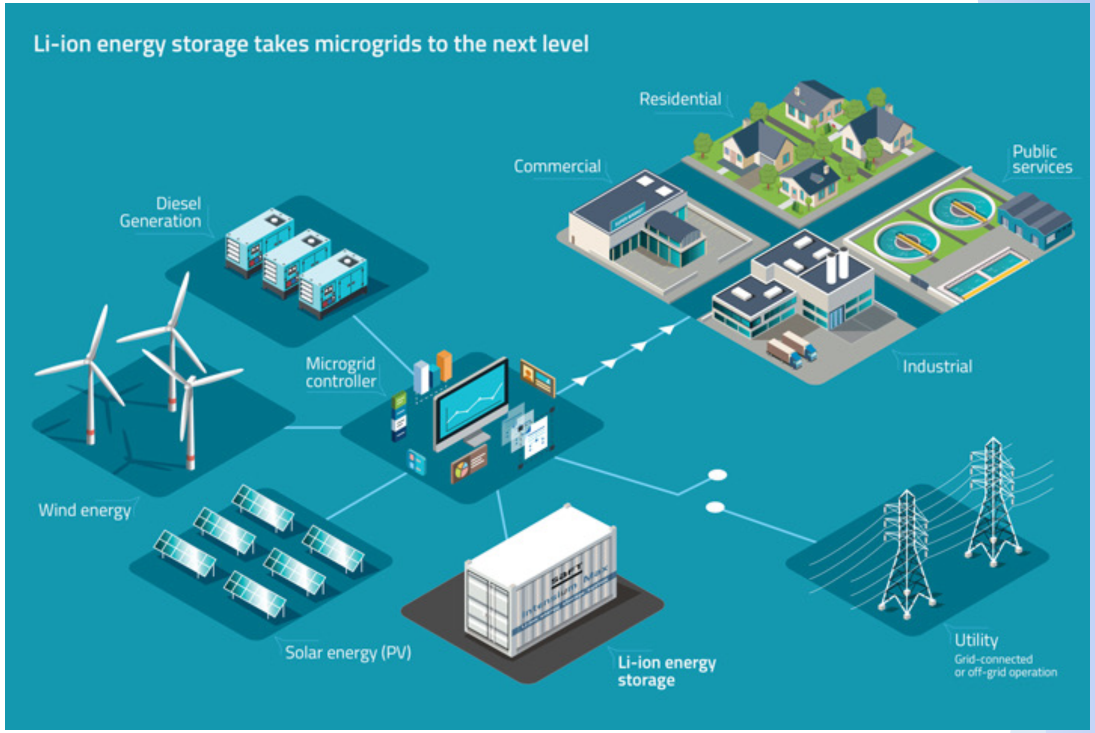
BAPV and BIPV

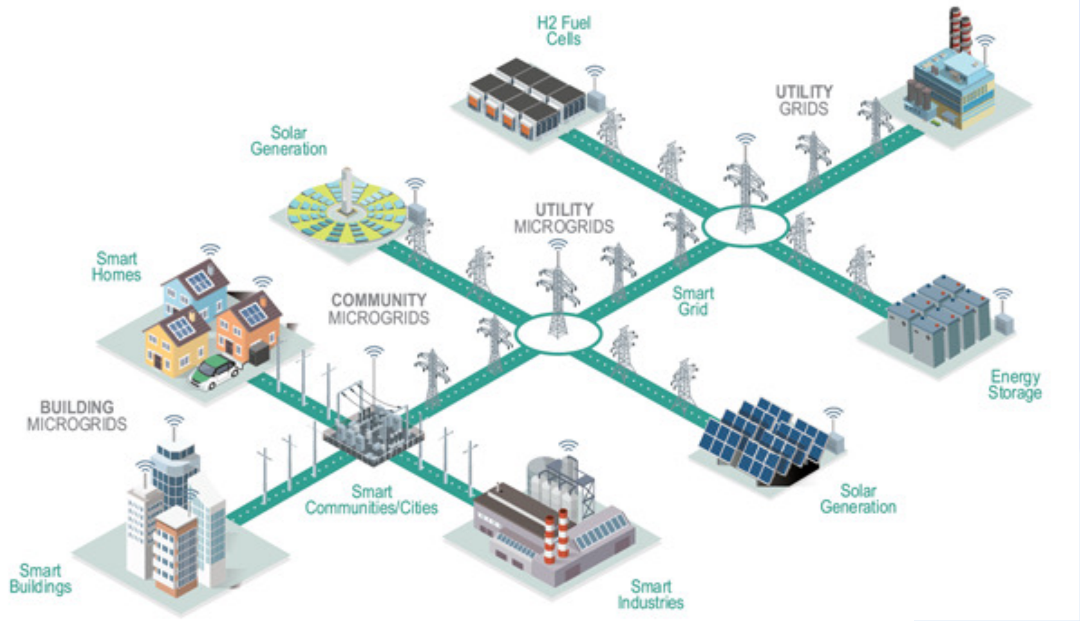
BAPV

BIPV

Applications of PV

Standalone system – Microgrids	Local electric grid that generate, distribute, and store electricity (Batteries) in a small geographic location.	Operate alone or in conjunction with gird.
Energy sources – PV, Wind, Batteries, Backup generators.	Allow greater resilience, efficiency and integration of renewable energy resources.	The system can be disconnected from the main grid during power disruption and can power the local community or area independently.





Application of PV-Agrivoltaics

- ❑ Agrivoltaics farming is a recent hot topic.
- ❑To grow plants underneath the solar panels.
- ❑Many advantages – Preserving soil moisture, saving water by reducing evaporation, generating green electricity, increase crop productivity.
- ❑Also, there disadvantages – Hight cost, some areas need deeper foundation, some countries have rules and regulation acting as a barrier for farmers.
- ❑China, leading from the front – 1.9GW of electricity production out of world’s total 2.9GW in 2020.
- ❑EU – 2.4GW under development.

Summary (Part 1)

- Learned about need for renewable energy and their sources.
- PV system.
- Making of first solar cell.
- Learned about growth of PV over the last two decades.
- PV applications and some examples in real life application.

Fundamentals of PV system (Part 2)

Learning objective

This lecture covers the following:

- ❑Fundamentals of solar radiation.
- ❑Solar geometry.
- ❑Principles of photovoltaic effect.
- ❑Standard Test Condition.
- ❑PV cell technologies.
- ❑Balance of System (BOS).
- ❑PV module design and fabrication.

Fundamentals of PV system Solar Radiation

Understanding solar radiation

❑Sun – Source of solar energy in our solar system. This energy is produced through fusion reaction between the hydrogen atom at extreme high temperature and forms Helium.

❑A by-product (Energy) of this reaction is *light* and *heat*.

❑Solar radiation – Energy from the sun that reaches the earth.

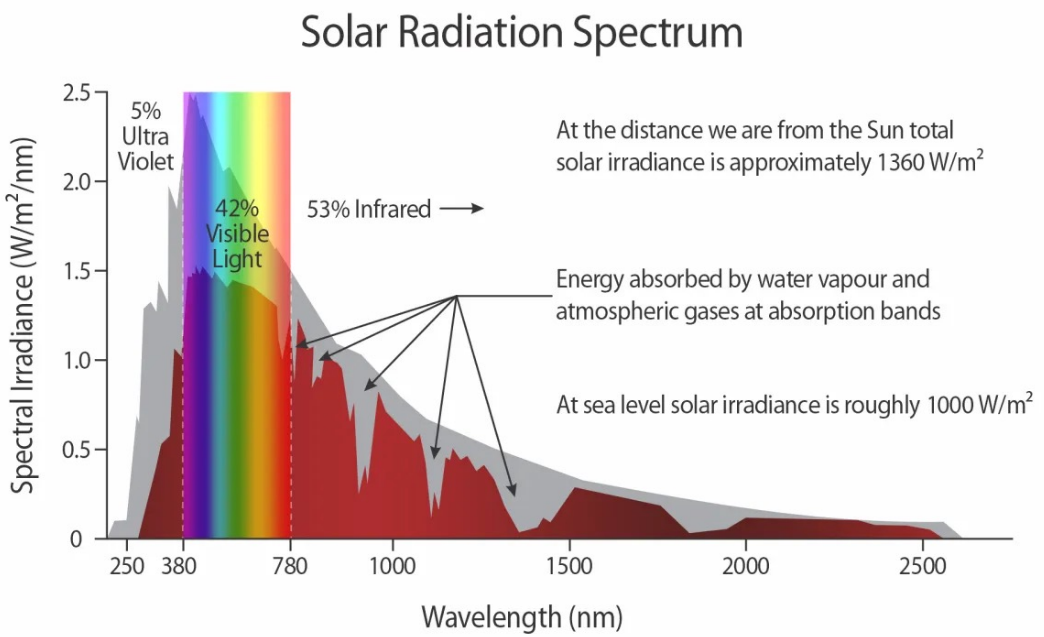
❑The light energy emitted by the sun is inversely proportional to the wavelength: $E = \frac{hc}{\lambda}$, where h = Plank's constant ($6.62x10^{-34}$ J/Hz), C = speed of light 2.99 x $10^8\ m/s$, λ = the wavelength in m.

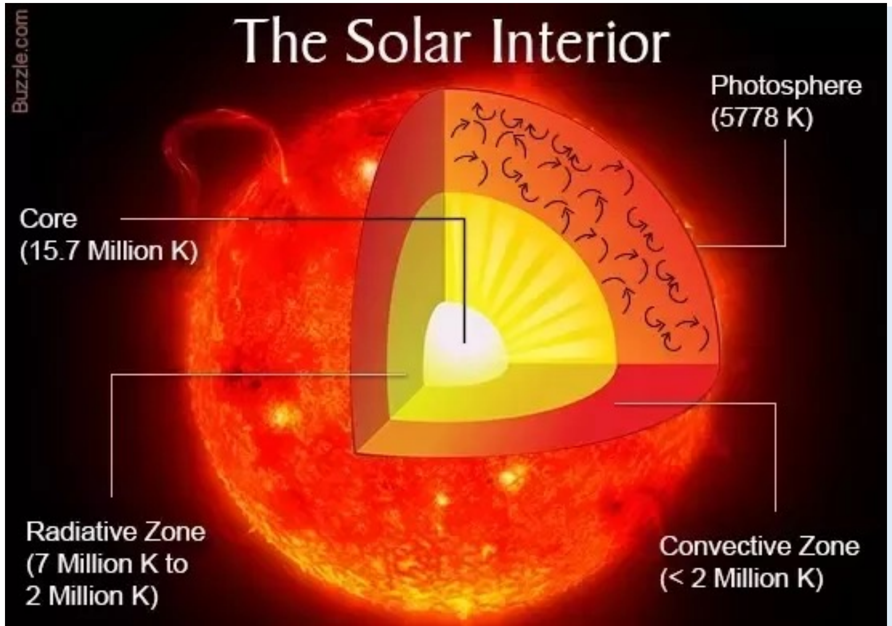
❑Light energy comes from the sun consists of different wavelength.

❑The solar energy [electromagnetic (EM) radiation] – 5% UV, 42% visible light and 53% near infrared radiation.

❑The sun – known as back body emitter. Means it emits all energy based on its temperature.

❑The surface temperature of the sun is around 5800 K.

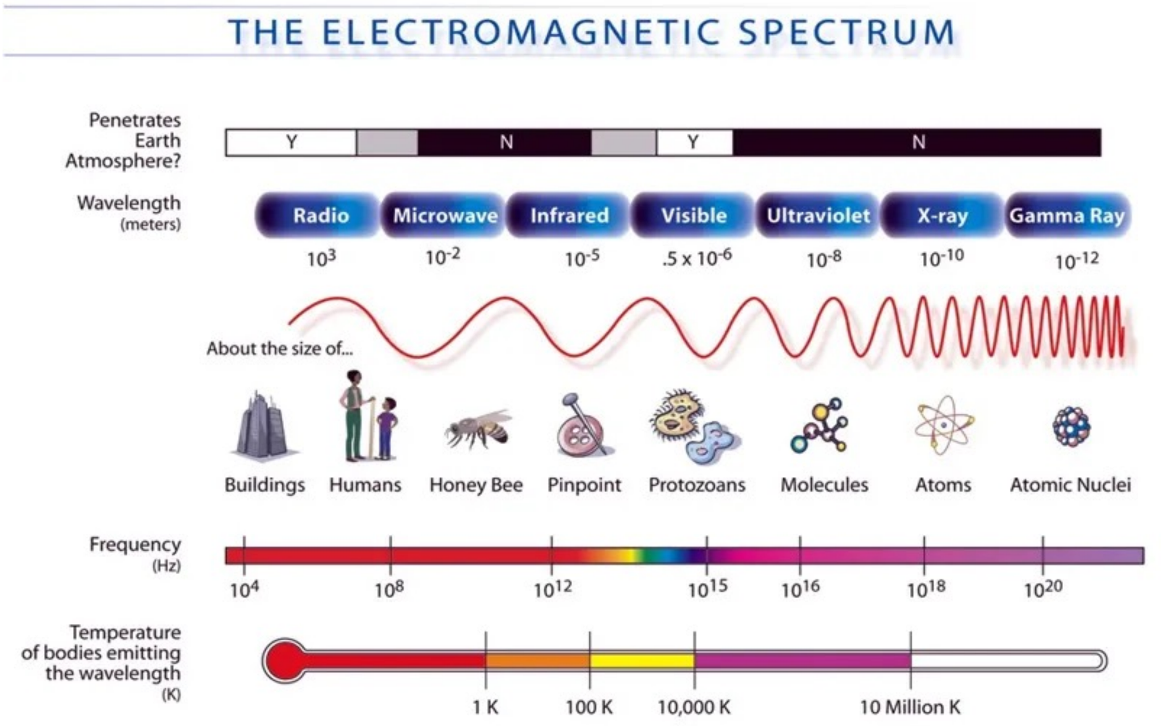


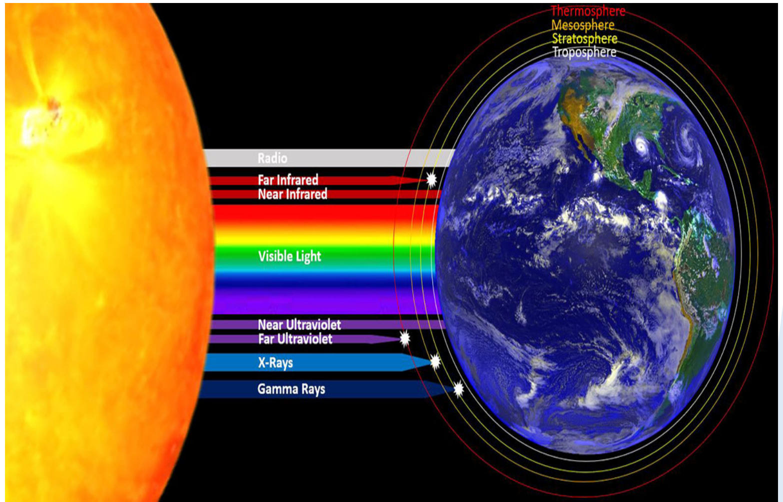


Fundamentals of PV system –Solar Radiation

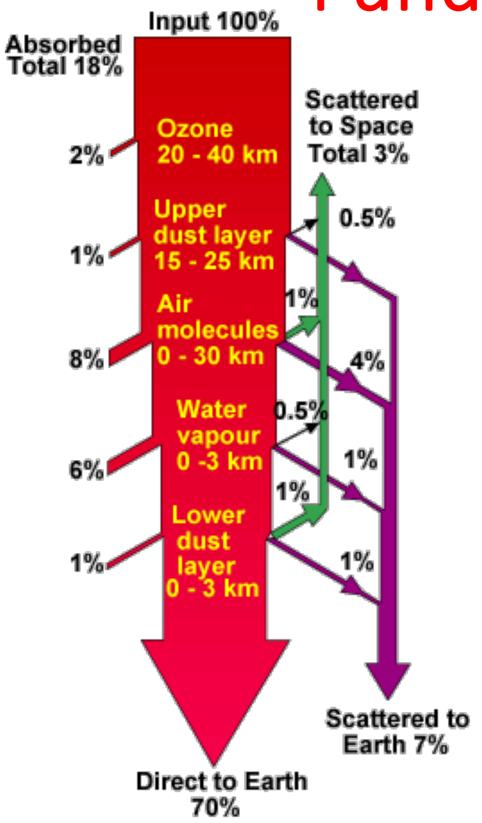
Understanding solar radiation

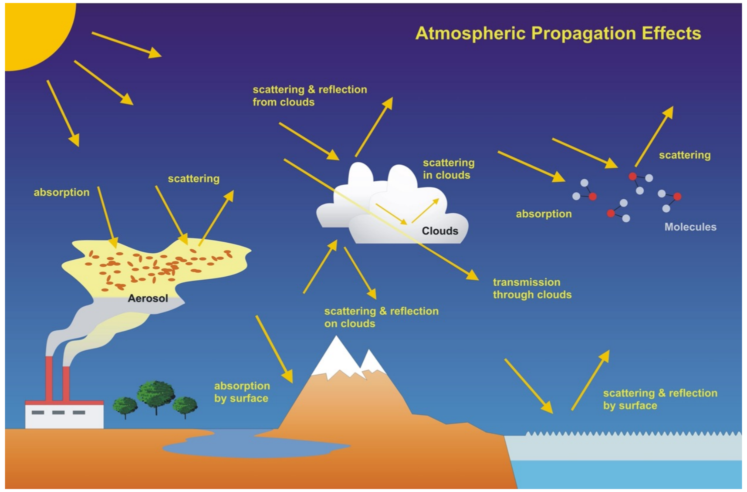
- Solar radiation that reaches earth composed of one part of EM.
- The visible light consists of – 7 colours (ROYGBIV – Red, Orange, Yellow, Green, Blue, Indigo, Violet).
- Red has the longest wavelength while violet has the shortest.
- The intensity of the solar irradiance or the power of the irradiance is measured in W/m^2 (Watt per meter square).
- The irradiance outside the earth's atmosphere is 1366 W/m^2. The irradiance on the earth's surface is 1000 W/m^2, 30% lost due the earth's atmosphere.
- The solar spectrum is almost constant regardless of the distance. However, the intensity decreases with increasing the distance.





Fundamentals of PV system- Solar Geometry





Solar Geometry

❑Solar geometry is used to measure and analyse the position and angle of the sun relative to the Earth.

❑*Crucial for designing the position of solar panels*.

❑This helps to design more efficient solar energy systems, as the panels can be angled and oriented to receive the greatest possible amount of sunlight.

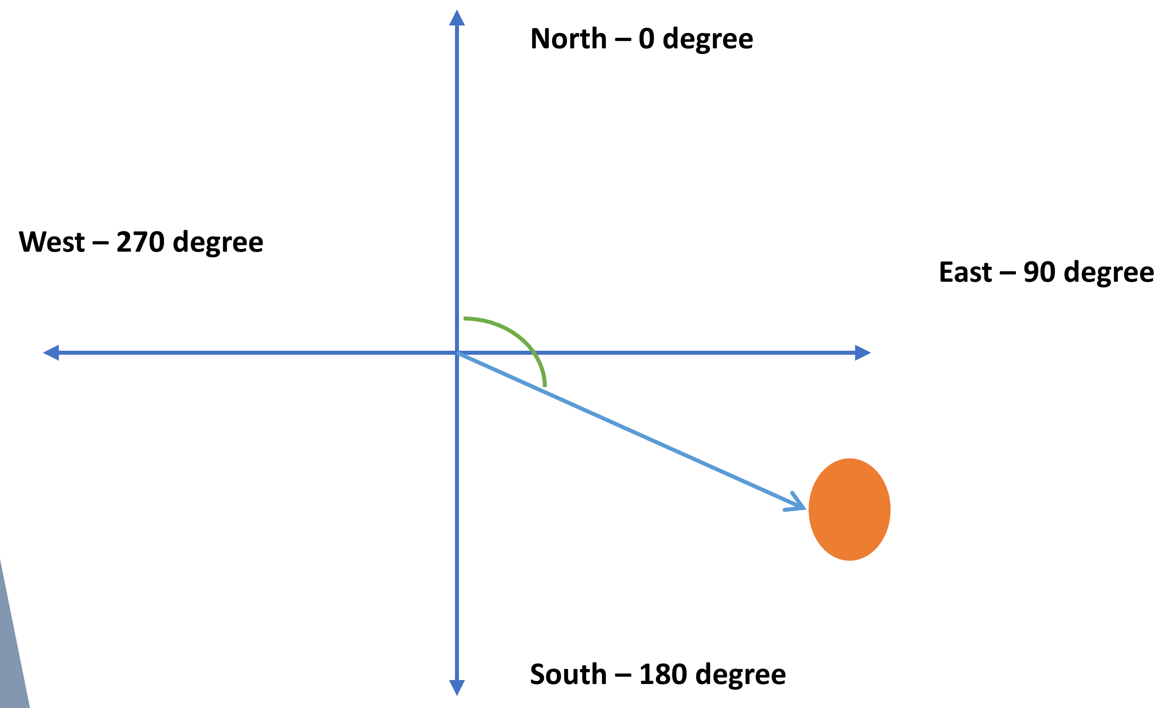
❑Earth's atmosphere affects the solar spectrum- Reflection of light by the atmosphere- Absorption of the light in the atmosphere, Rayleigh scattering – Light scatters in different direction, and finally scattering due to aerosols and dust particles.

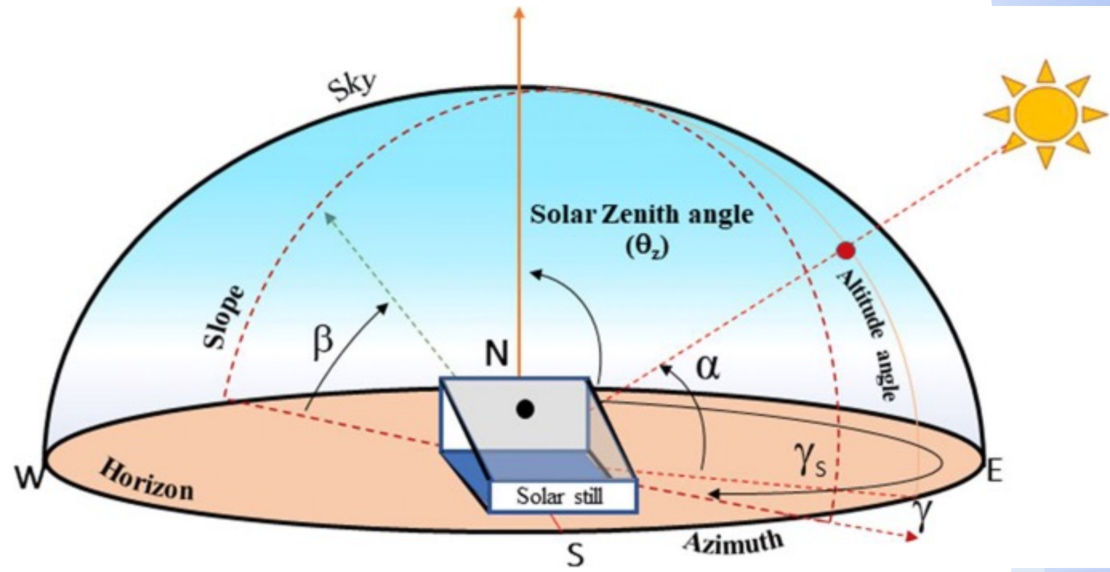
❑After all these phenomenon's, the light then reach the surface of the earth. The distance between the atmosphere and the surface of the earth is called optical path. The Air mass describes how long this optical path is.

Fundamentals of PV system- Solar Geometry

The sun rise to sun set, the position of the sun changes throughout the day. This means the sun's angles relative to the location also changes. The angles which are used:

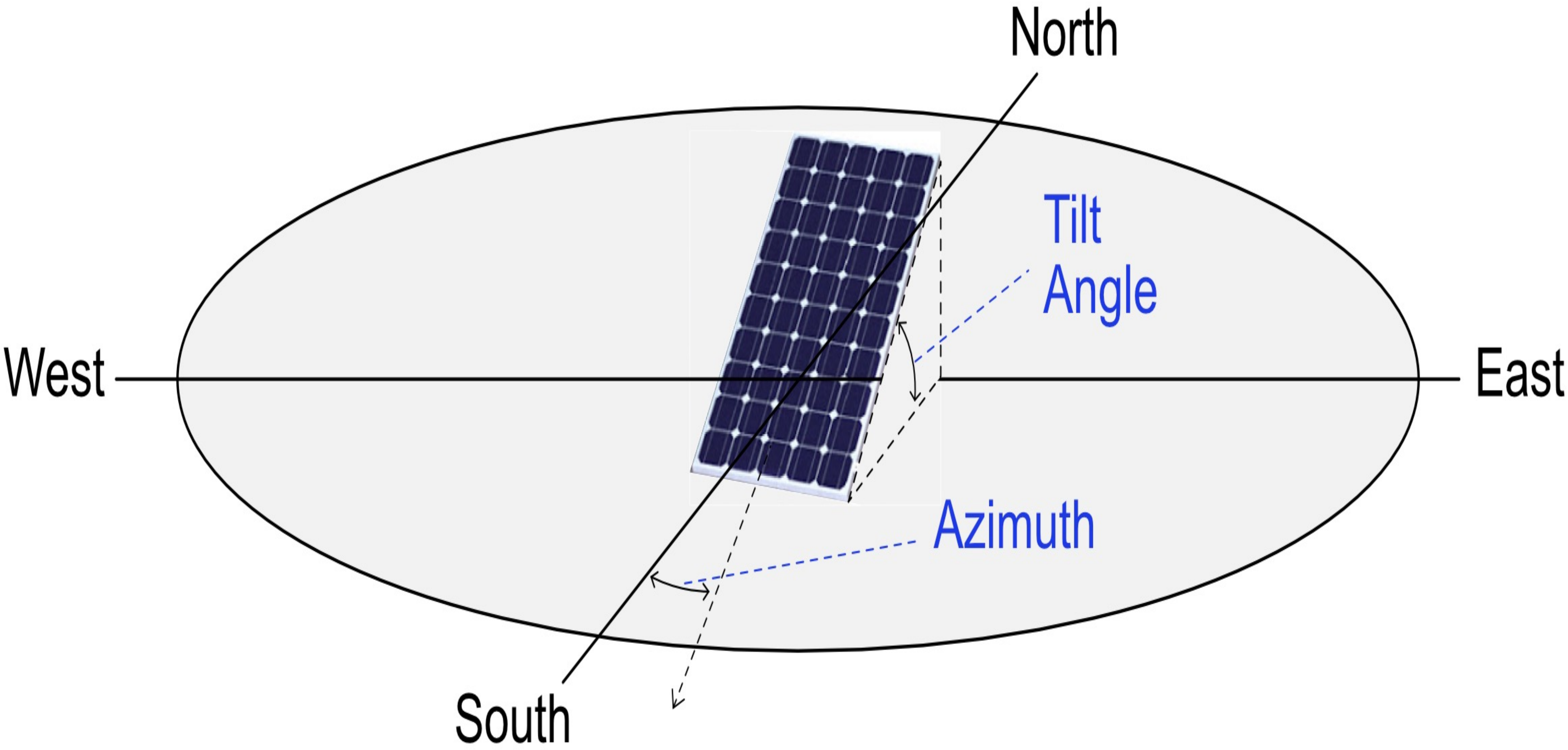
- Azimuth angle (γ_s).
- Altitude or elevation angle (α_s).
- Zenith angle (θ_z).





- Northern hemisphere – South facing.
- Observing from a point. Reference point is North.
- At a particular time of the day, the sun is at a certain height.
- Relative to zero degree (north), the angle between the reference line and the imaginary horizontal line of the sun is the Azimuth angle.
- **Altitude angle or elevation angle** is the elevation of the sun from the horizontal.
- Zenith angle is the angle between the sun and the vertical.

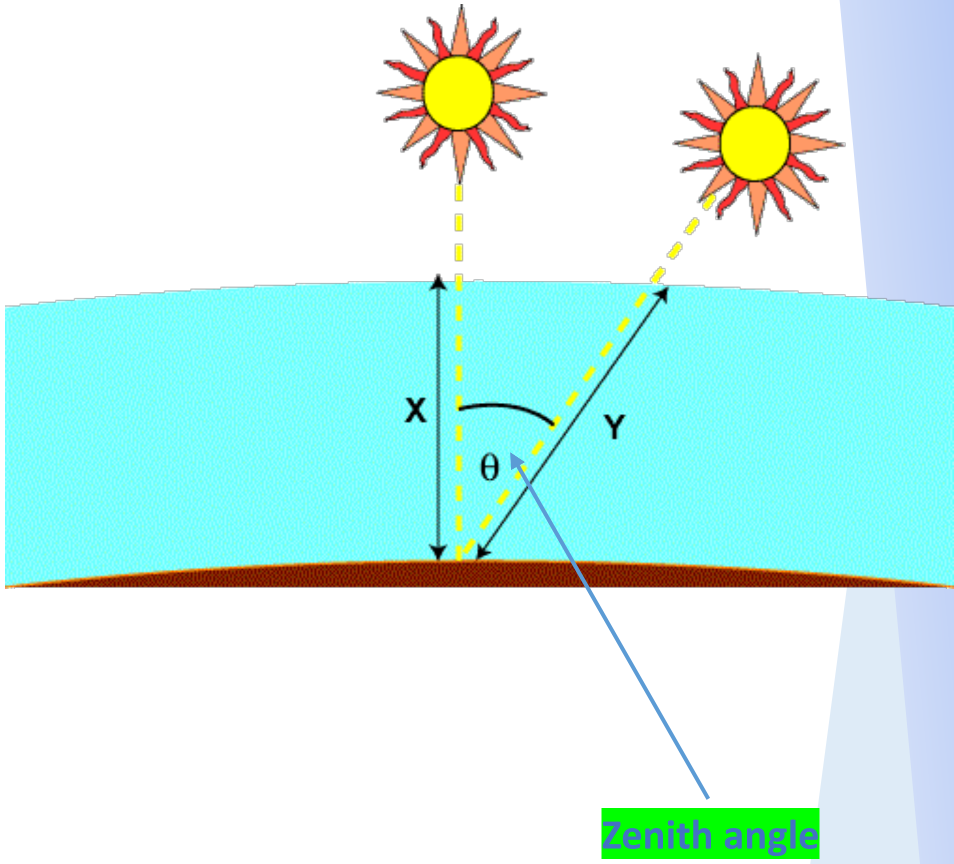
Fundamentals of PV system- Solar Geometry



Fundamentals of PV system – Solar Geometry

Air Mass

- AM0 – Travelling of the light without any medium (atmosphere).
- AM1 – The shortest path the light can travel to the earth's surface (vertical).
- When sun's position is not vertical, the optical path is longer. The path is 1.5times the vertical distance. This new distance is AM1.5.
- The air mass (AM) is calculated by using zenith angle or elevation angle: AM = $\frac{1}{\cos\theta_z} = \frac{1}{\sin\alpha_s}$
- There are some more complex calculations are there to calculate the AM by considering altitude, air pressure and the curvature of the earth.
- At AM1.5, the corresponding zenith angle is 48.19^0.
- **This AM 1.5 is used as at STC (standard test condition) for solar cells and PV modules**.

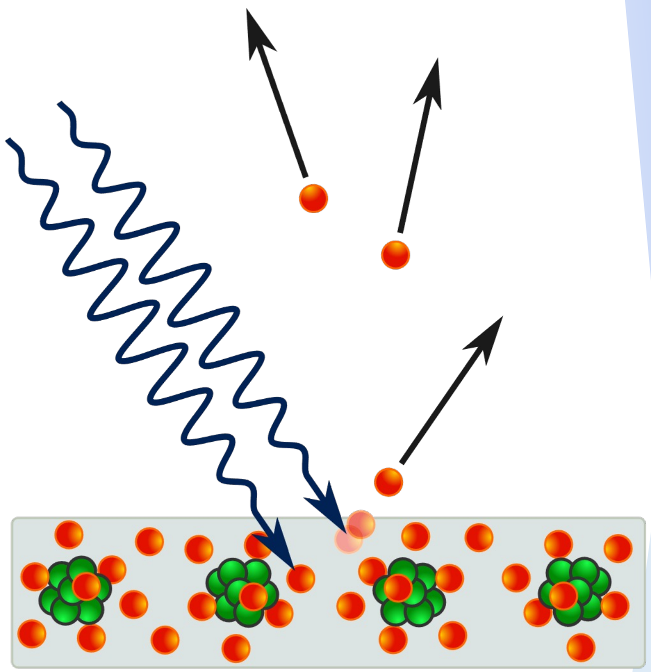


Fundamentals of PV system- Photovoltaic effect.

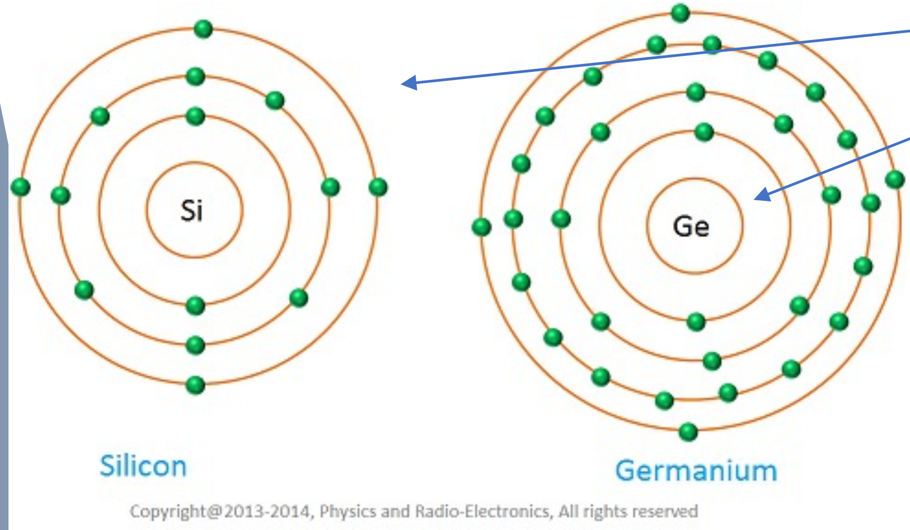
Photovoltaic effect

Previously we have learned solar cell transforms light energy to electric energy. How is it done ?

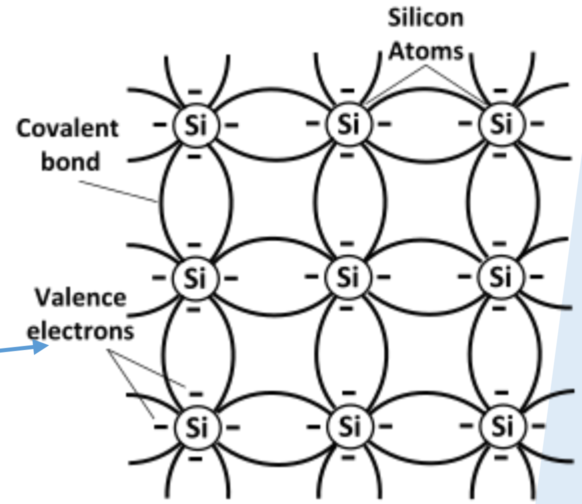
- When electrons are released from its valance band to conduction band by the electromagnetic radiation (light).
- When a semiconductor material is exposed to light, the photons of incident light is absorbed by the electrons which is significant enough to release it from its energy band.
- Semiconductor materials are made from silicon (Si) and germanium (Ge). Its conductivity level is between a conductor and an insulator.



Atomic Structure of Si and Ge



Covalent bonding of silicon

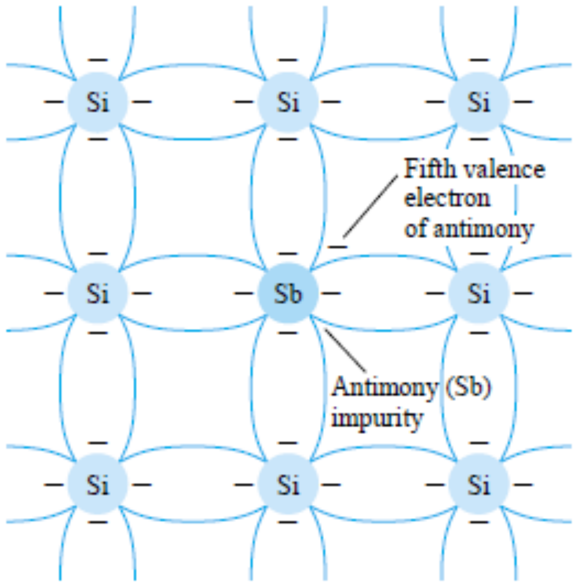


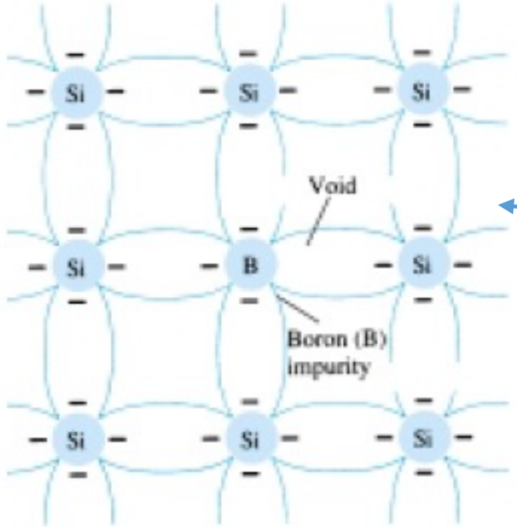
Fundamentals of PV system- Photovoltaic effect

Semiconductor types

- ❑Intrinsic semiconductor and Extrinsic semiconductor.
- ❑Intrinsic semiconductor- Refined carefully to reduce impurities to a very low level (pure semiconductor)
- ❑Extrinsic semiconductor - Impurities are added, known as doping. They are of two types: i. n-type ii. p-type.
- ❑N-Type material: n-Type semiconductor is made by adding impurity elements that have *five valence electrons*, such as phosphorous, antimony and arsenic.
- ❑*Five valence electrons – donor atoms*. Electrons are majority carriers.
- ❑P-Type material: They are made by adding impurity elements that have *three valence electrons*, such as boron, gallium, and indium.
- ❑*Three valence electrons – acceptor atoms*. Holes are majority carriers.

N-Type semiconductor



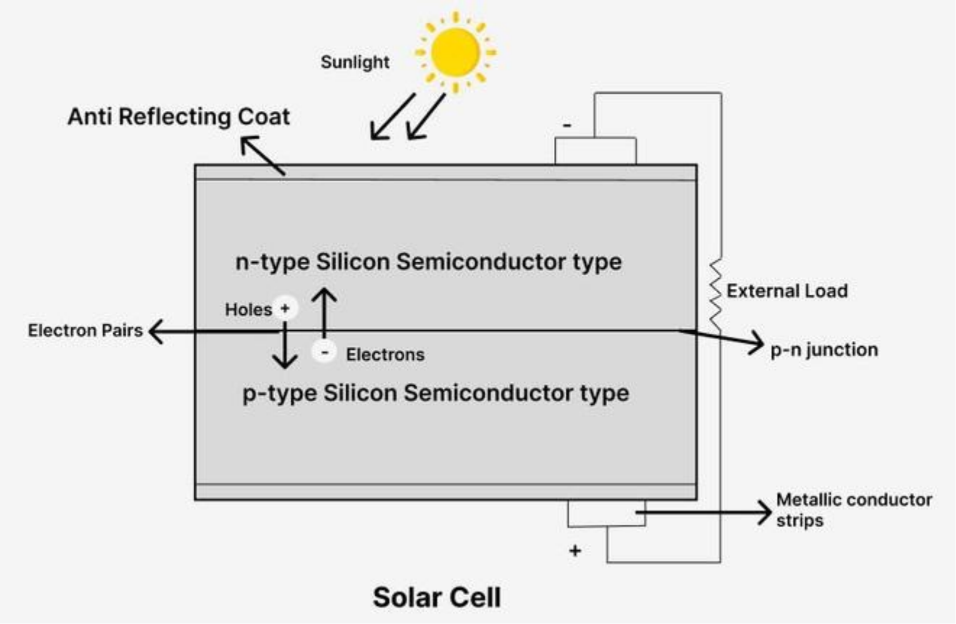


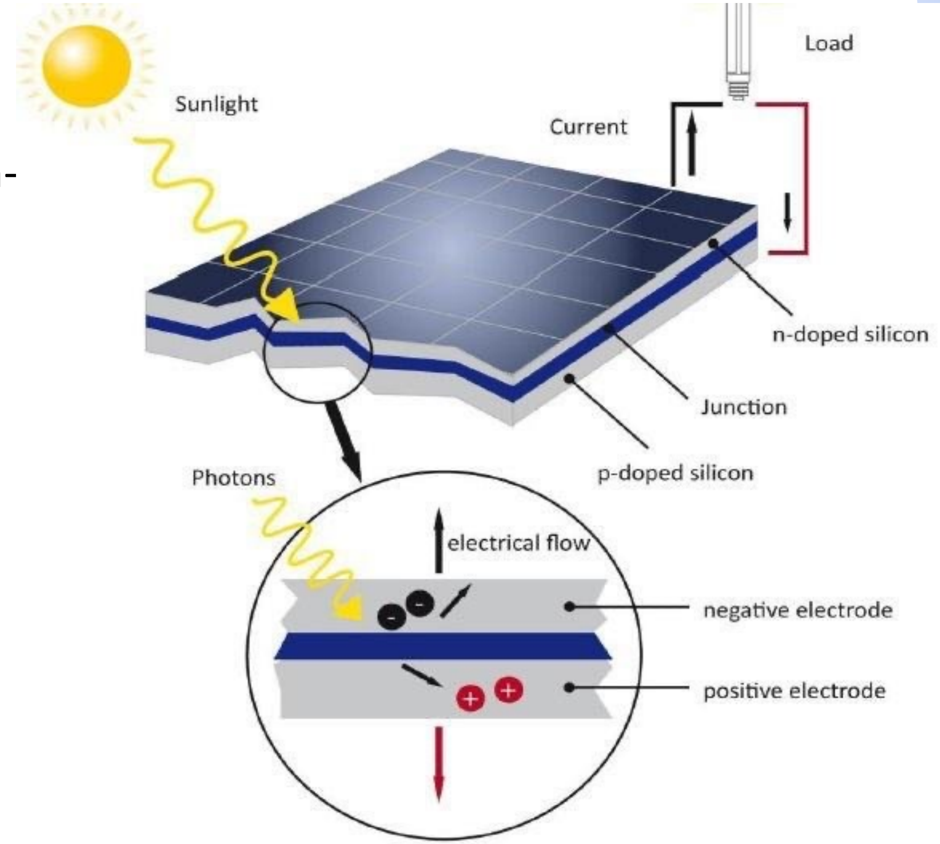
P-Type semiconductor

Fundamentals of PV system – Photovoltaic effect

The solar cell is made by imposing p-type and n-type materials together.

- Light is composed of photons (small bundles of electromagnetic radiation).
- When sunlight hits the surface of a solar cell, the photons are absorbed by the electrons.
- Electrons jump to the conduction band creating a hole.
- The movement of electrons and holes create charge carriers – electron-hole pair.





Fundamentals of PV system – Standard Test Conditions (STC)

Understanding how module perform

- ❑The performance of solar module varies with irradiance and temperature.
- ❑Measure output performance under a certain testing condition used by manufacturers and testing bodies.
- ❑Industry wide standard, Temperature = 25^0C, Irradiance 1000W/m^2 , Air mass (AM) = 1.5 [**IEC 61853-1**]
- ❑In the data sheet, all the values are given at STC.

Module type	CLM-330M-60 Series			
Rated Maximum Power (Pmax/W)	320	325	330	335
Maximum Power Voltage (Vmp/V)	33.4	33.6	33.8	34.0
Open-circuit Voltage (Voc/V)	40.9	41.1	41.3	41.5
Maximum Power Current (Imp/A)	9.59	9.68	9.77	9.87
Short-circuit Current (Isc/A)	10.15	10.20	10.31	10.36
Module Efficiency (%)	19.18	19.48	19.78	20.08
STC: Irradiance 1000W/m, Cell Temperature 25°C, AM = 1.5				

Solar module Data sheet

https://www.ise.fraunhofer.de/en/rd-infrastructure/accredited-labs/testlab-pv-modules/power-measurements.html

Fundamentals of PV system – PV cell technologies

Photovoltaic cells or PV cells are manufactured from different materials and ways.

Three types of PV cell technologies dominate the world market:

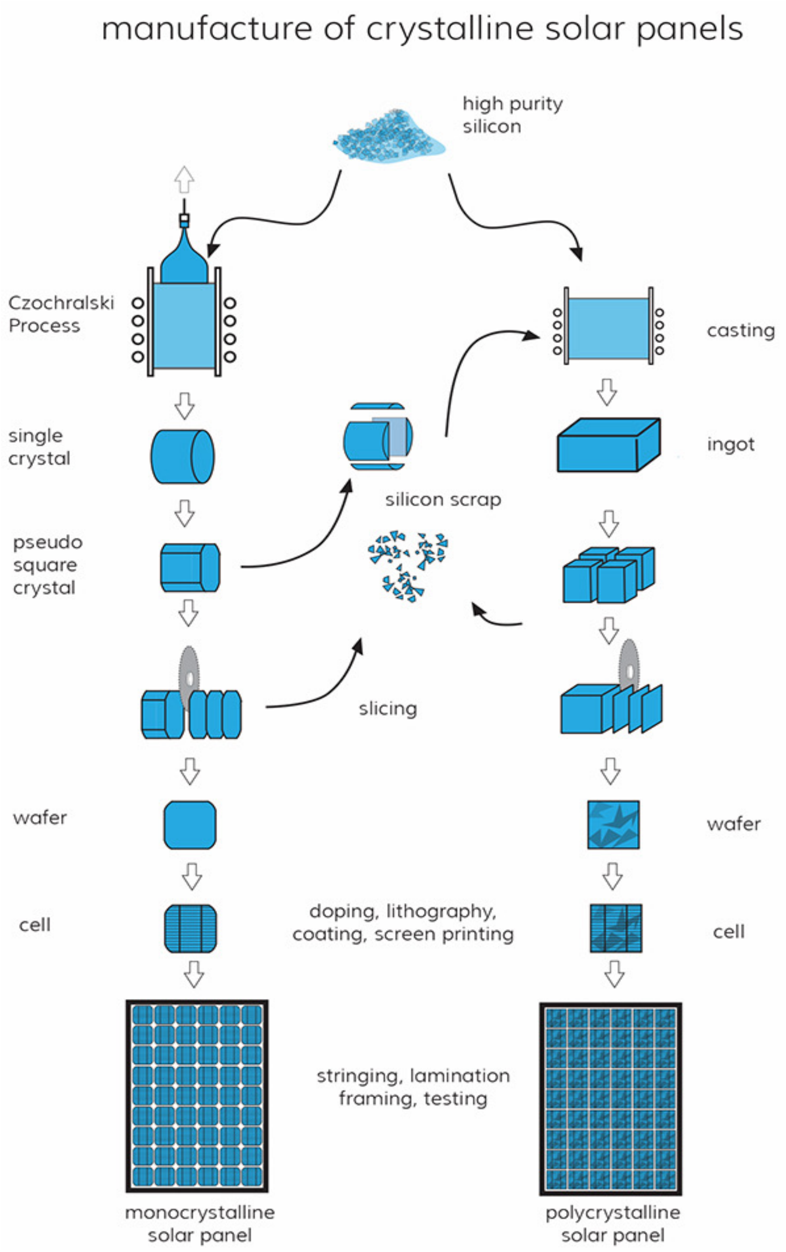
❑Monocrystalline silicon.

❑Polycrystalline silicon.

❑Thin-film (Amorphous Si, Cadmium Indium, Diselenide (CIS).

Monocrystalline silicon

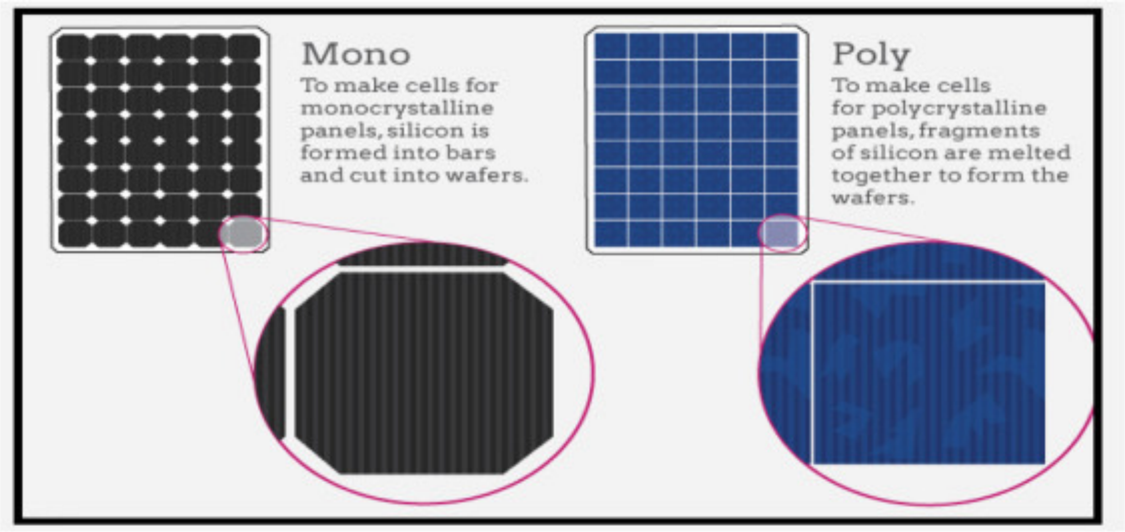
- Highly pure silicon melt is used to grow mono-crystals in the form of blocks. The silicon block is sawed into cell wafers each 200 to 300 µm thick.
- The final phase of manufacture involves doping followed by installation of contact surfaces and an anti-reflective layer
- Mono-crystalline solar cells manufactured on an industrial scale have an efficiency of 15 - 24%, the highest among the variety of PV cells presently available.
- However, monocrystalline cells require more energy and time to manufacture compared to polycrystalline cells.



Fundamentals of PV system – PV cell technologies

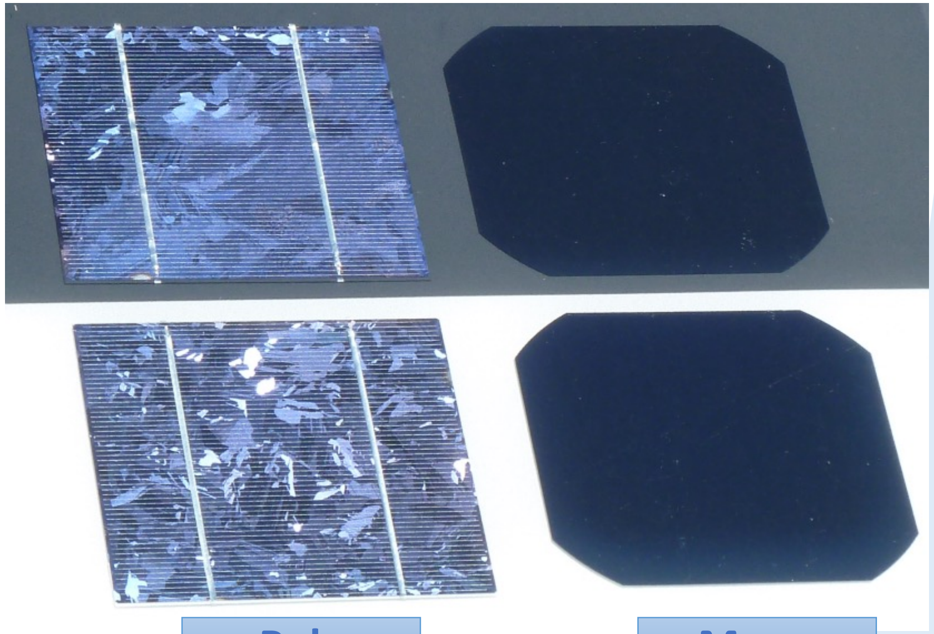
Polycrystalline silicon

- Highly pure silicon melt also serves as the initial material for polycrystalline cells.
- However, these cells are manufactured not by growing mono-crystals, but through controlled cooling of the silicon melt in square-shaped moulds.
- The balance of manufacturing process is similar to that of monocrystalline cells.
- Polycrystalline solar cells have an efficiency of 13 to 17%.



Thin film

- ❖ In physics, substances whose atoms form irregular patterns are termed amorphous. Atoms arranged in ordered patterns are said to be crystalline.
- ❖ To manufacture amorphous cells, silicon is vapour-deposited on a carrier, e.g. glass.
- ❖ The vapour-deposited silicon layer has a thickness of 0.5 to 2 µm.
- ❖ Besides lowering silicon consumption, this also dispenses with elaborate sawing of silicon blocks.
- ❖ However, amorphous solar cells only have an efficiency of 6 to 8%.



Poly Mono

Fundamentals of PV system-Balance of System (BOS)

What is Balance of System (BOS)?

➢BOS refers to all components of a PV systems other than the module.

➢Components which are part of BOS – Inverters, rack, cables/wires, switches, enclosures, fuses, combiner box, meters etc.

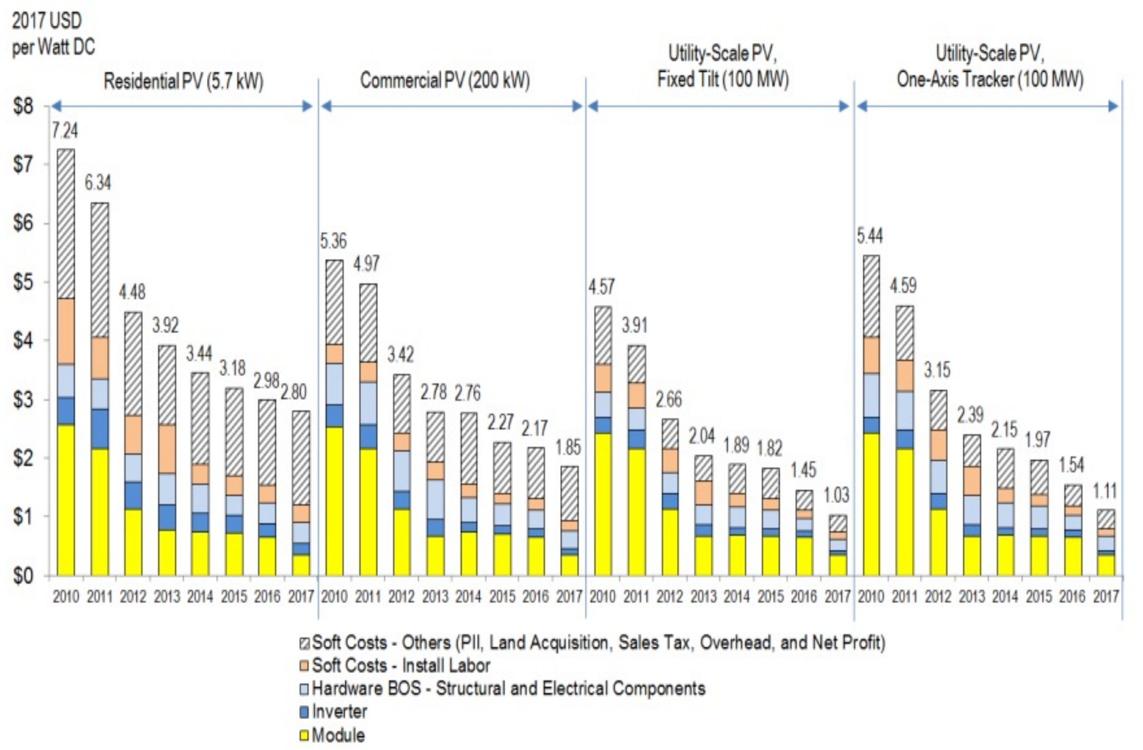
➢BOS helps to control cost, increase efficiency and modernise solar PV system.

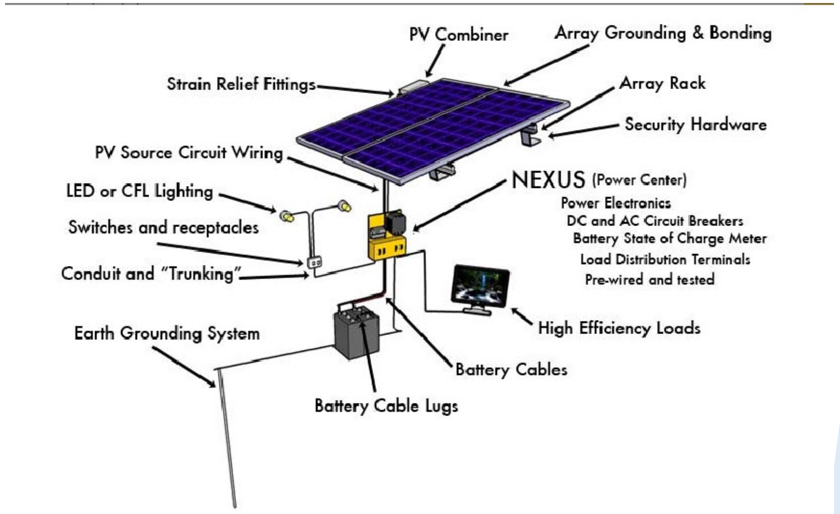
➢BOS can be further divided into two – Hard BOS and Soft BOS.

➢Hard BOS – All the hardware parts.

➢Soft BOS – Cost of labours.

➢Important to consider for safe plant operation and significant cost contributor to plant (Optimisation is important)





Fundamentals of PV system- Balance of System (BOS)

Variations	2.50mm²	4.00mm²	6.0mm²	10.00mm²
AWG	14	12	10	8
Part Number:	050001	050002	050003	050004
Sheath Diameter	5.00mm	5.40mm	6.20mm	7.50mm
Current Rating: On Surface	39A	52A	67A	93A

Photovoltaic solar cables H1Z2Z2-K available from alfanar electric, offers the following construction:

Conductor: High-quality annealed flexible tinned copper conductors.
Insulation: Halogen-free, cross-linked flame retardant compound (HFFR).
Outer Sheath: Black Halogen-free, cross-linked flame retardant compound (HFFR).

Technical Specifications:

- Operating voltage of 1.0 KVAC , 1.5 KVDC
- Maximum operating voltage of 1.2 KVAC , 1.8 KVDC
- Ambient temperature ranges from -40°C to +90°C
- Short circuit temperature is 250°C.
- Resistant to impact tear and abrasion.
- Weathering-UV resistance.
- very good resistance to oil and chemicals with acid and alkaline resistance .

Hard BOS

➢Hard BOS – i. Electrical BOS ii. Mechanical BOS

➢Electrical BOS- Cables, connectors, combiner boxes. Inverters are not a part of electrical BOS.

Fundamentals of PV system

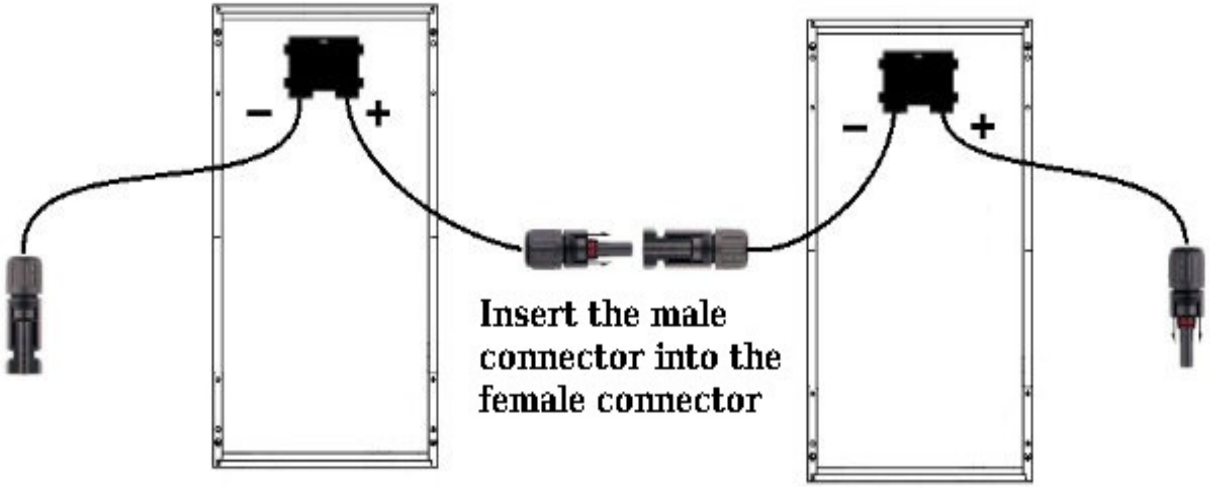
PV connectors

❖MC 4 (male and female connector)

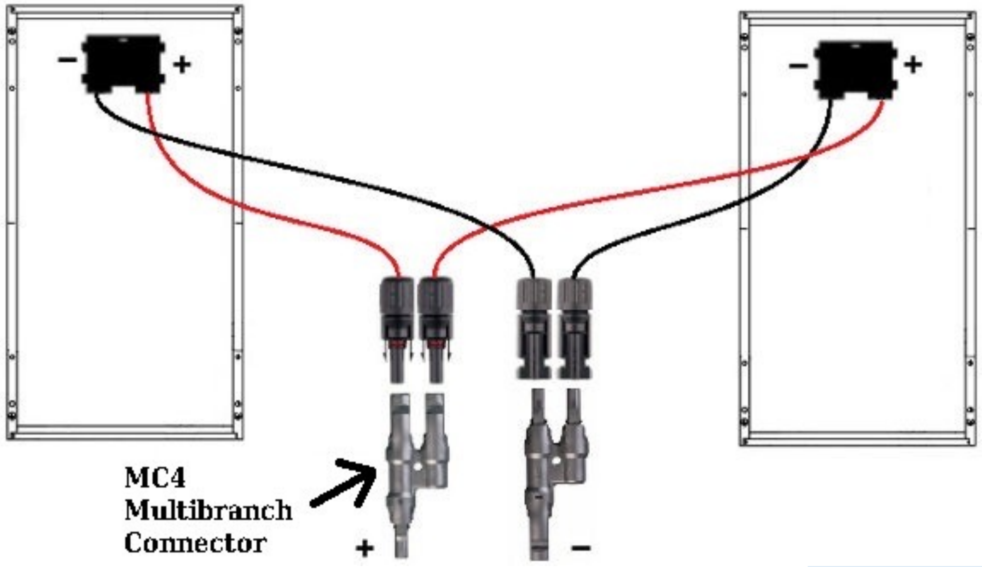
❖UL rated – certified to meet scientific safety, quality or security standards. UL6703.

❖IEC 62548 design requirement for PV systems - PV connectors to be of the same origin.

❖Rating – Between 500V and 1500V.



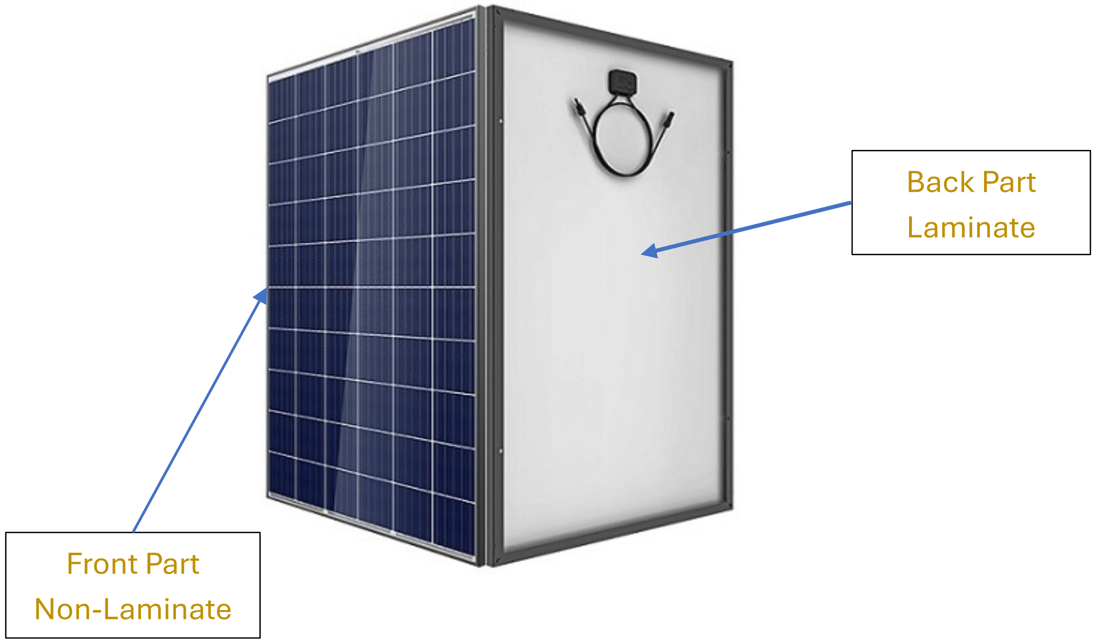
Series Connection

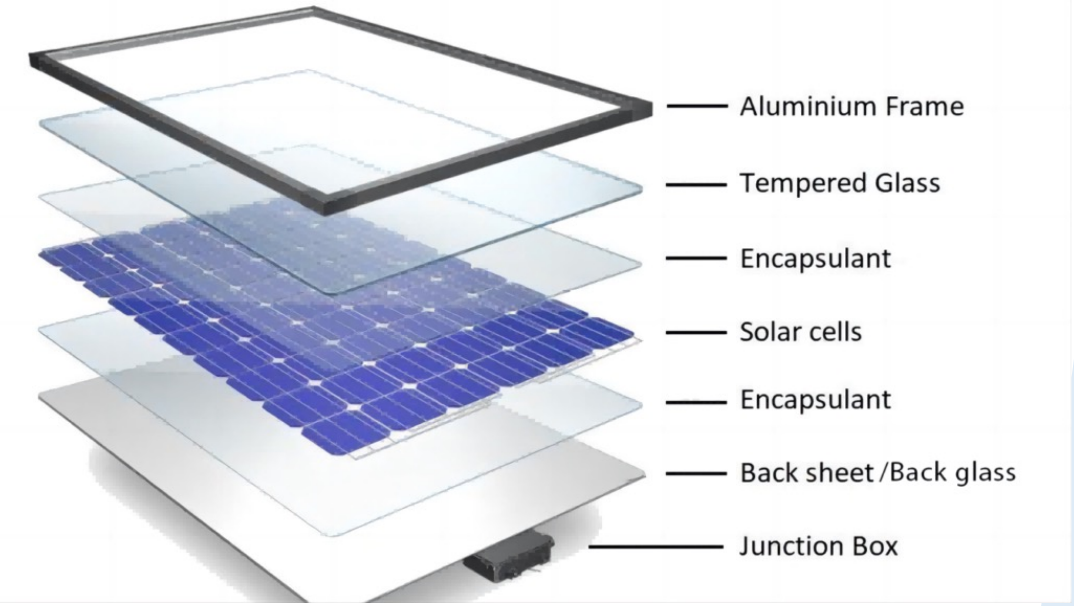


Parallel Connection

Fundamentals of PV system - Fabrication

- This section will cover how the PV modules are designed and fabricated, starting with bill of materials (BOM) as well as their properties.





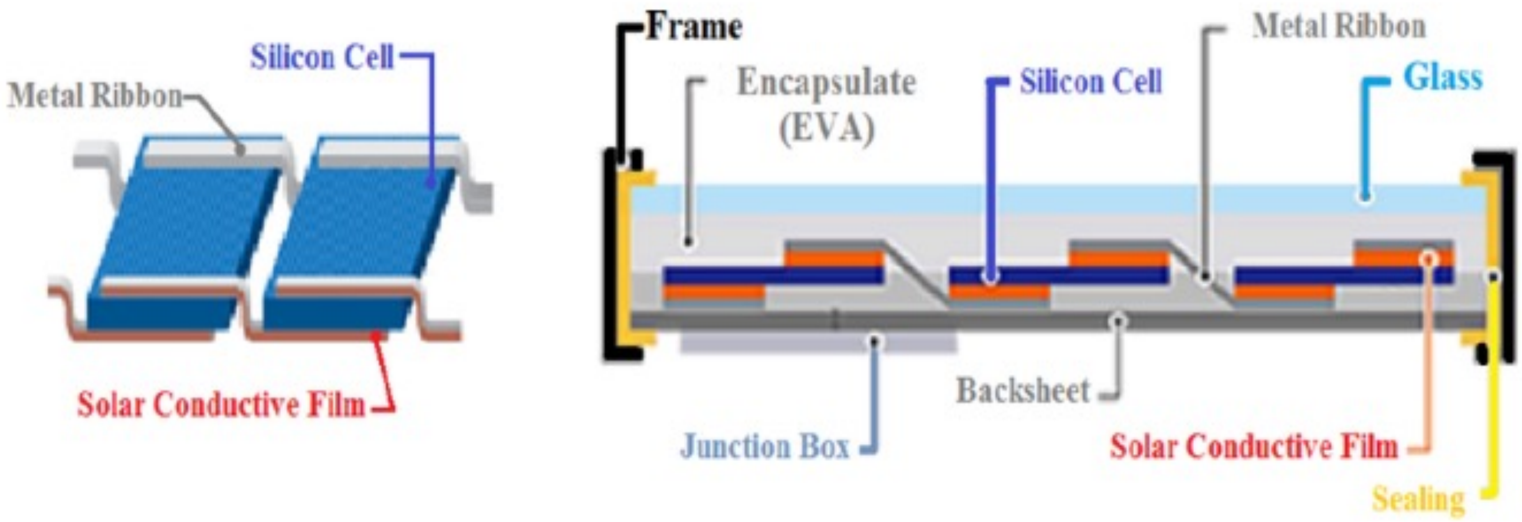
Fundamentals of PV system - Fabrication

- Tempered Glass also known as Superstrate (3.2mm low iron tempered glass).
- Back sheet is made of Polyester/PVF. Polyamide is getting popular as alternative.
- Front glass gives mechanical stability and good light coupling. Regular tempered glass allows approximately 91.5% of light to pass through whereas specially made tempered glass allows about 94% of light to pass through to reach solar cells. Hence, efficiency increases. It also captures light effectively from 380nm to 1100nm, harnessing the primary energy bands of sunlight. Furthermore, it helps to reflect wavelengths exceeding 1200nm, which means it reflects the infrared light reducing the heat generation.

- Encapsulants: Made from ethylene-vinyl acetate (EVA) copolymer. Main component is acetic acid ethenyl ester (40-70%). Encapsulation films stabilize solar cells, preventing movement or breakage, thus ensuring the structural stability and long-term operational efficiency of the panel. High-quality encapsulation films possess excellent transparency, minimizing loss of solar energy. They are also required to be weather-resistant, withstanding the impacts of UV rays, high temperatures, and other harsh environmental conditions. These films provide insulation for the panel, preventing moisture and other environmental elements from penetrating, thus protecting the solar cells from corrosion and damage. The material of the encapsulation film must be capable of enduring prolonged exposure to sunlight and various climatic changes, maintaining its performance over time.

Fundamentals of PV system - Fabrication

- Solar Cells: Solar cells convert light energy into electrical energy. There are two types of solar cells namely – P-type and N-type. In P-type, impurities such as trivalent elements Boron is used which creates positively charged “holes”. P-type materials are commonly used in Mult crystalline silicon solar cells and some mono crystalline silicon solar cells. They are cost-effective and easy to make. On the other hand, N-type solar cells are made by doping silicon with pentavalent elements like Phosphorous. This adds more electrons to valance band. For the proper performance of the module, it is vital that the conducting path in the cells should have low resistance to reduce power loss or i2r loss. It is also vital that there



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