VRE II: Solar Energy (PV & Thermal)

Sheila Tobing, S.T., M.Eng, Ph.D.

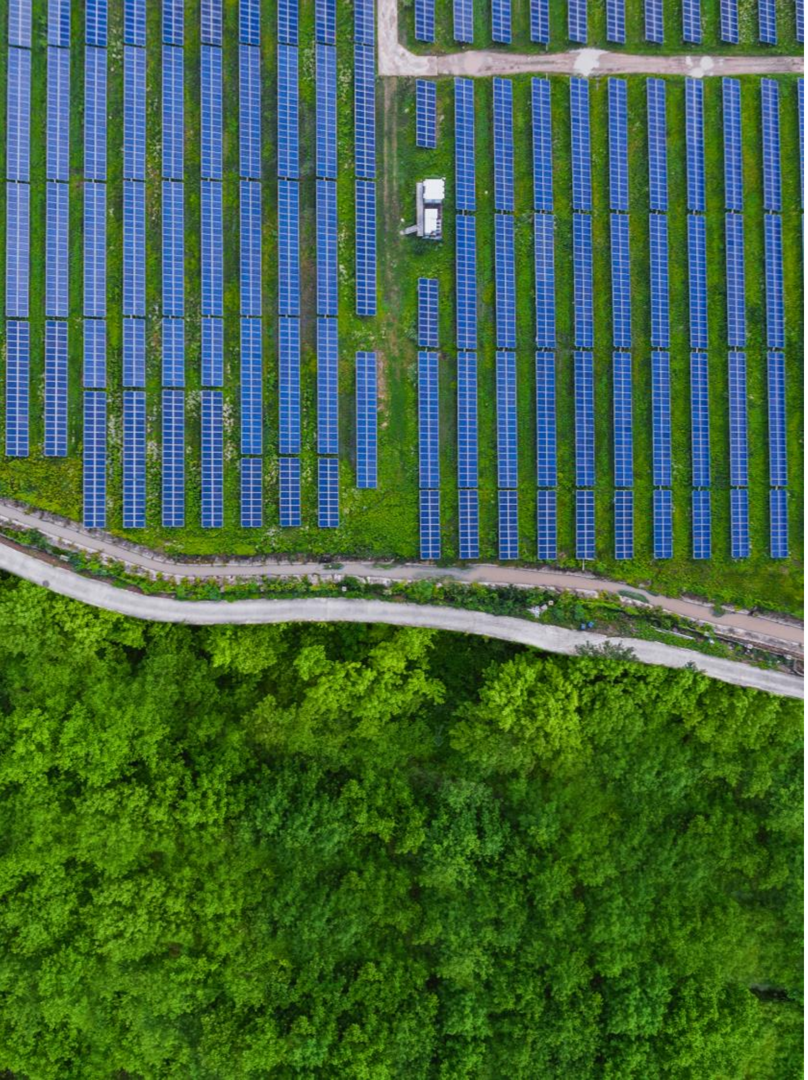
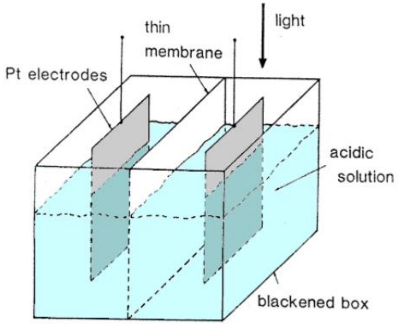
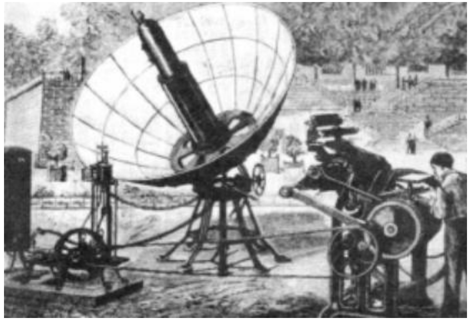


Table of contents

History of Solar Energy



1839 → Edmond Becquerel Discovered photovoltaic effect in 1839 during an experiment with electrolytic cells



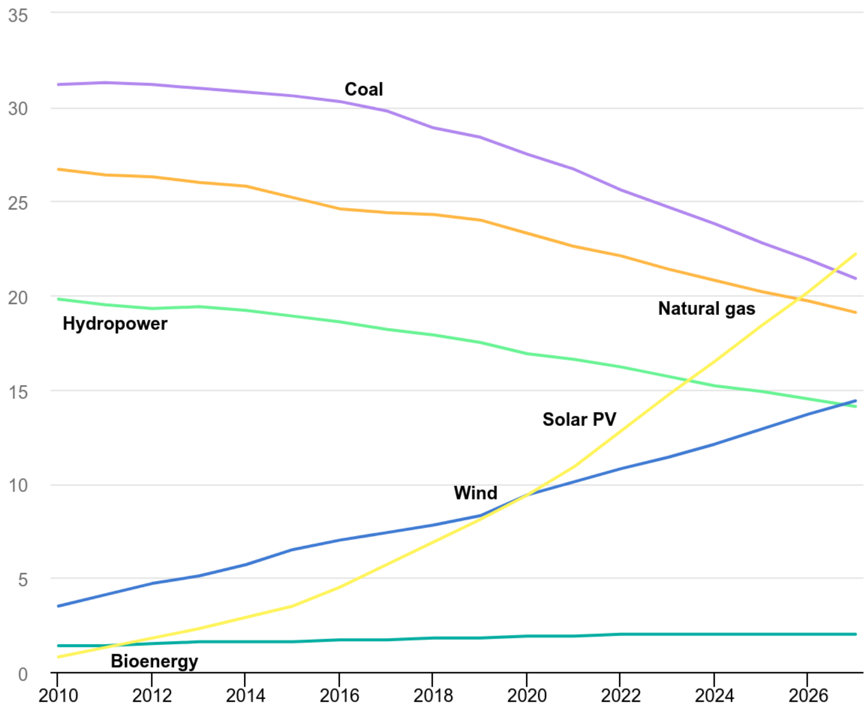
1878 → Augustin Mouchot used solar-powered machine to produce steam to drive a printing machine

1954 → Daryl M. Chapin, Calvin S. Fuller, and Gerald L. Pearson, the developers of the first modern solar cell

Source: Soteris A. Kalogirou (2014)
https://www.nrel.gov/docs/fy04osti/33947.pdf

Current status: Capacity status

Solar energy dominates RE capacity additions (IEA, 2021)

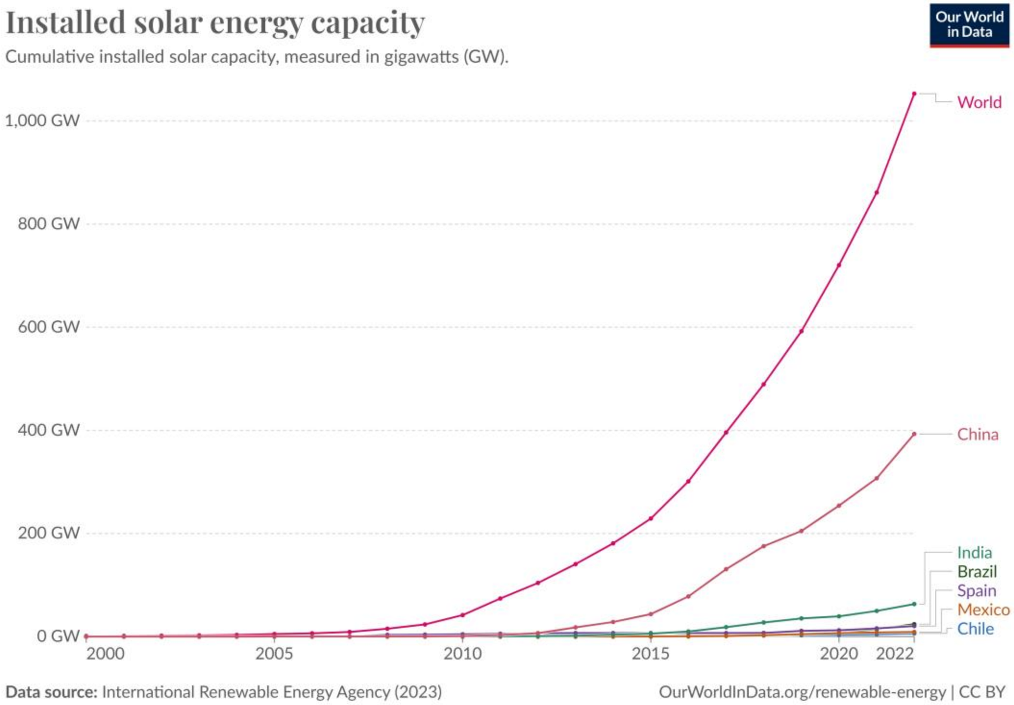


Top 10 PV Market for 10 years

RANKING	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
1	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA	CHINA
2	JAPAN	JAPAN	JAPAN	USA	INDIA	INDIA	USA	USA	USA	USA	USA
3	USA	USA	USA	JAPAN	USA	USA	INDIA	VIETNAM	INDIA	INDIA	GERMANY
4	GERMANY	UK	UK	INDIA	JAPAN	JAPAN	JAPAN	JAPAN	JAPAN	BRAZIL	INDIA
5	ITALY	GERMANY	INDIA	UK	TÜRKIYE	AUSTRALIA	VIETNAM	GERMANY	GERMANY	SPAIN	BRAZIL
6	UK	SOUTH AFRICA	GERMANY	GERMANY	GERMANY	TÜRKIYE	AUSTRALIA	AUSTRALIA	BRAZIL	GERMANY	SPAIN
7	ROMANIA	FRANCE	SOUTH KOREA	THAILAND	SOUTH KOREA	GERMANY	SPAIN	SOUTH KOREA	SPAIN	JAPAN	JAPAN
8	INDIA	SOUTH KOREA	AUSTRALIA	SOUTH KOREA	AUSTRALIA	MEXICO	GERMANY	INDIA	AUSTRALIA	POLAND	ITALY
9	GREECE	AUSTRALIA	FRANCE	AUSTRALIA	BRAZIL	SOUTH KOREA	UKRAINE	SPAIN	SOUTH KOREA	AUSTRALIA	POLAND
10	AUSTRALIA	INDIA	CANADA	TÜRKIYE	UK	NETHERLANDS	SOUTH KOREA	NETHERLANDS	POLAND	NETHERLANDS	NETHERLANDS
RANKING EU	2	3	3	4	5	4	2	2	2	2	2
MARKET LEVEL TO ACCESS THE TOP 10											
	792 MW	779 MW	675 MW	818 MW	944 MW	1 621 MW	3 130 MW	3 492 MW	3 710 MW	4 200 MW	4 788 MW

Source: IEAPVPS, 2024

Global Installed Capacity

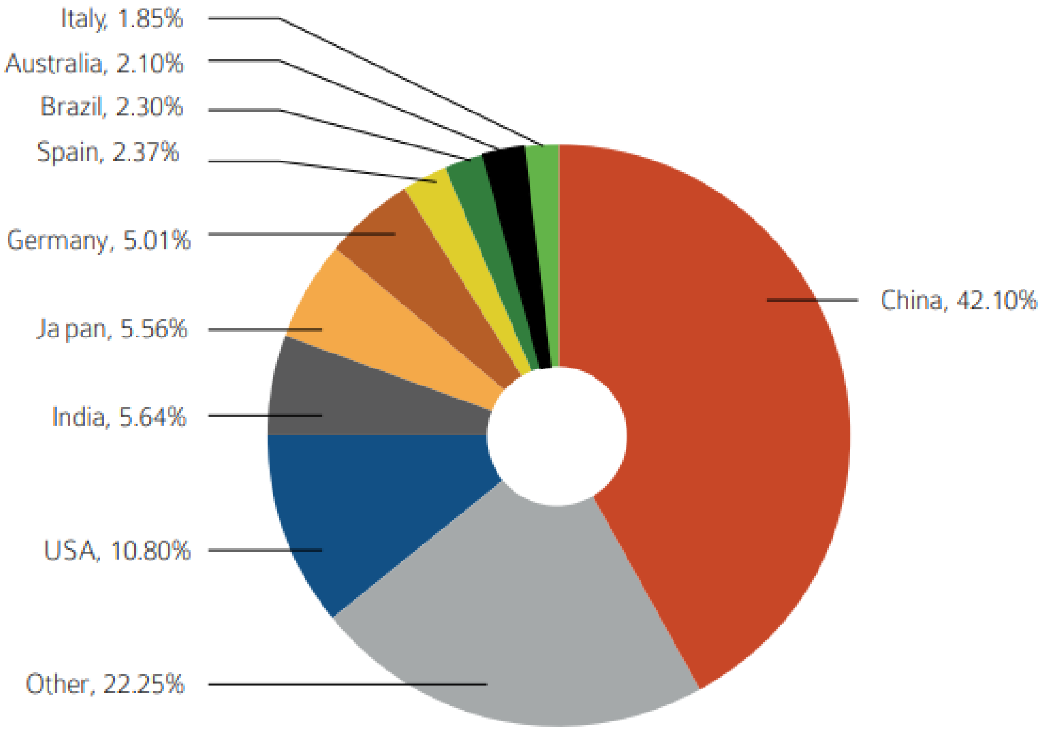


2021 in gigawatts	
World	861.54 GW
China	306.97 GW
India	49.68 GW
Spain	16.02 GW
Brazil	14.20 GW
Mexico	8.17 GW
Chile	4.47 GW

2022 in gigawatts	
World	1,053.12 GW
China	393.03 GW
India	63.15 GW
Brazil	24.08 GW
Spain	20.52 GW
Mexico	9.03 GW
Chile	6.25 GW

https://ourworldindata.org/grapher/installed-solar-pv-capacity

Cumulative PV Capacity



Source: IEAPVPS, 2024

Global Manufacturer of PV

TABLE 4.2: GLOBAL TOP FIVE MANUFACTURERS IN TERMS OF PV CELL/MODULE PRODUCTION AND SHIPMENT VOLUME (2023))

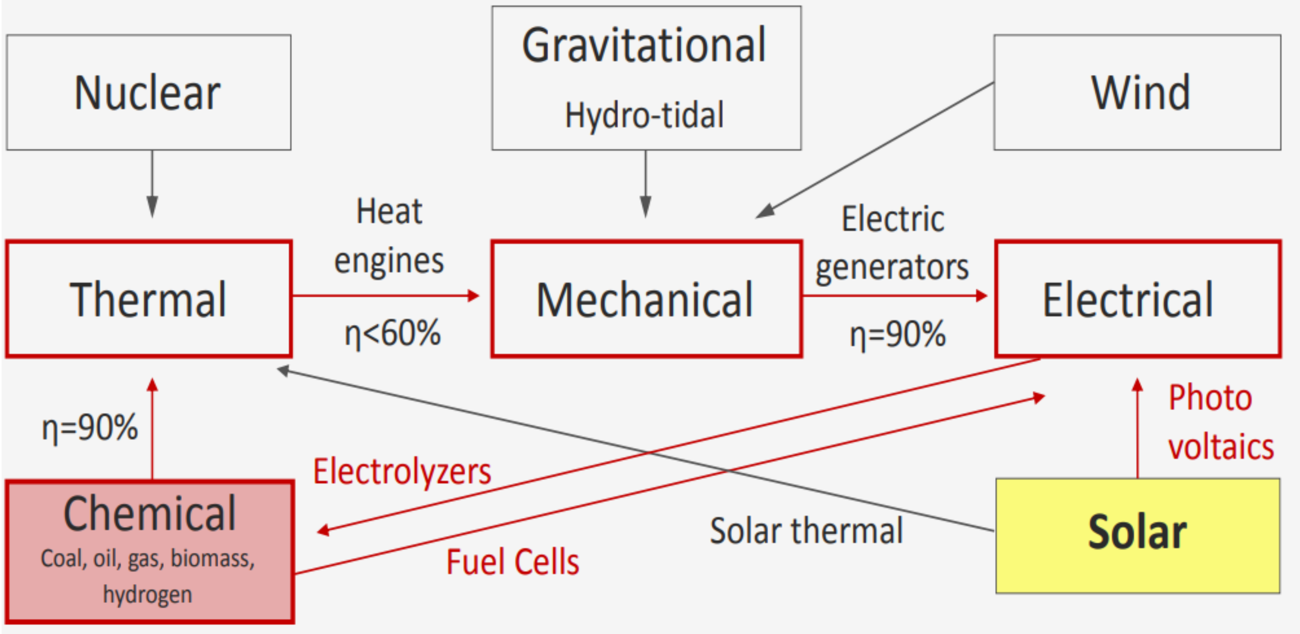
RANK	SOLAR CELL PRODUCTION (GW)		PV MODULE PRODUCTION (GW)		PV MODULE SHIPMENT (GW)	
1	TONGWEI SOLAR	80.8	JINKOSOLAR	83.5	JINKOSOLAR	78.5
2	JINKOSOLAR	63.9	LONGI GREEN ENERGY TECHNOLOGY	72.8	LONGI GREEN ENERGY TECHNOLOGY	67.5
3	LONGI GREEN ENERGY TECHNOLOGY	62.3	JA SOLAR TECHNOLOGY	60	TRINA SOLAR	65.2
4	JA SOLAR TECHNOLOGY	45.5	TRINA SOLAR	58.9	JA SOLAR TECHNOLOGY	55.3
5	TRINA SOLAR	44.3	CANADIAN SOLAR	31.4	TONGWEI GROUP	31.1

NOTE: PRODUCTION VOLUMES ARE MANUFACTURERS' OWN PRODUCTION, WHEREAS SHIPMENT VOLUMES INCLUDE COMMISSIONED PRODUCTION AND OEM PROCUREMENT

SOURCE IEA PVPS, RTS CORPORATION

Solar resources & Potential

Energy conversion



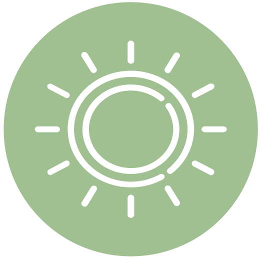
(Source: L. Freris, D. Infield, Renewable Energy in power Systems, Wiley 2008)

What is solar sources?

Solar resource (physical term solar radiation) **is fuel to solar energy systems.** The solar radiation available for solar energy systems at the ground level **depends on processes in the atmosphere**. This leads to **a high spatial and temporal variability at the Earth's** surface.
The **interactions of extra-terrestrial solar radiation with the Earth's atmosphere, surface and objects** are divided into four groups:

1. Solar geometry, trajectory around the sun and Earth's rotation (declination, latitude, solar angle)

2. Atmospheric attenuation (scattering and absorption)



3. Topography (elevation, surface inclination and orientation, horizon)

4. Shadows, reflections from surface or local obstacles (trees, buildings, etc.) and re-diffusion by atmosphere.

What is solar irradiation?

Radiation is the emission or transmission of energy in the form of waves through space or through a material medium (Radiation -- from Eric Weisstein's World of Physics).

Solar irradiance is the **power per unit area** received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument.

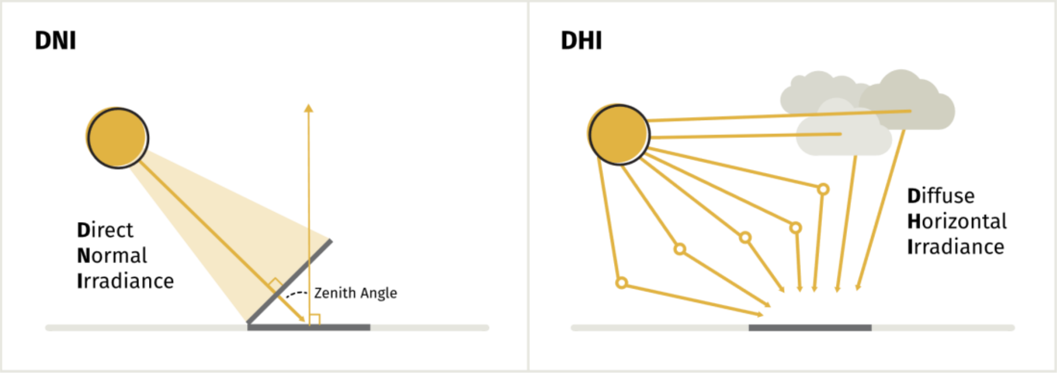
The solar irradiance integrated over time is called **solar irradiation**, insolation, or solar exposure. However, insolation is often used interchangeably with irradiance in practice.

Irradiance refers to the amount of solar radiation received per unit area by a given surface, expressed in **kW/m^2**

Irradiation/Insolation refers to the quantity solar radiation energy received on a surface during an amount of time, expressed in **$kWh/\ m^2$**.

Terminology in Solar Irradiation

- **Direct Normal Irradiance (DNI):** the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky..
- **Diffuse Horizontal Irradiance (DHI or DIF):** the portion of solar radiation that reaches the earth indirectly. Water vapor, aerosols and clouds reflect and absorb solar radiation, diffusing it throughout the atmosphere.
- **Global Horizontal Irradiance (GHI):** sum of direct and diffuse radiation received on a horizontal plane.
- **Global Tilted Irradiance (GTI):** irradiation that falls on an inclined surface.

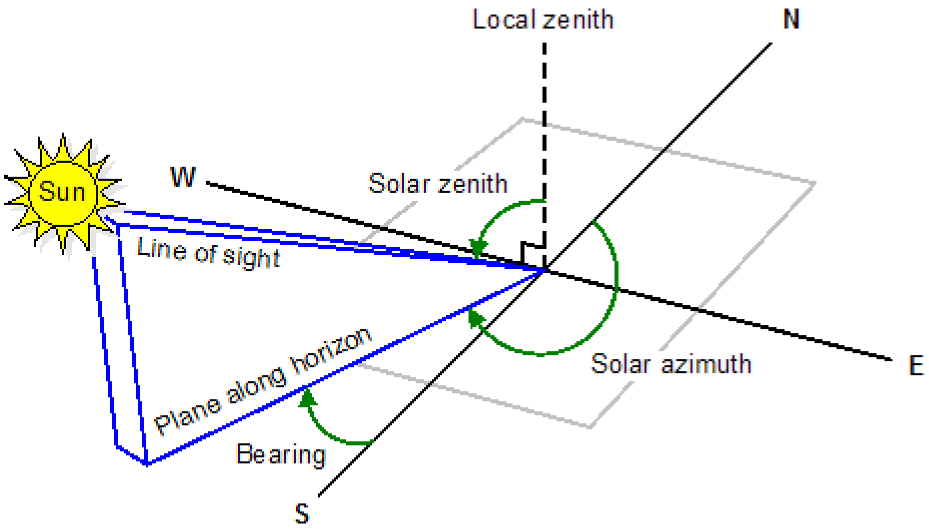


$$GHI = DHI + DNI * cos(\alpha_{zenith})$$

α_{zenith}= solar zenith angle

Source: solaranywhere.com, Direct Normal Irradiation - an overview | ScienceDirect Topics

Solar Zenith and Azimuth Angles



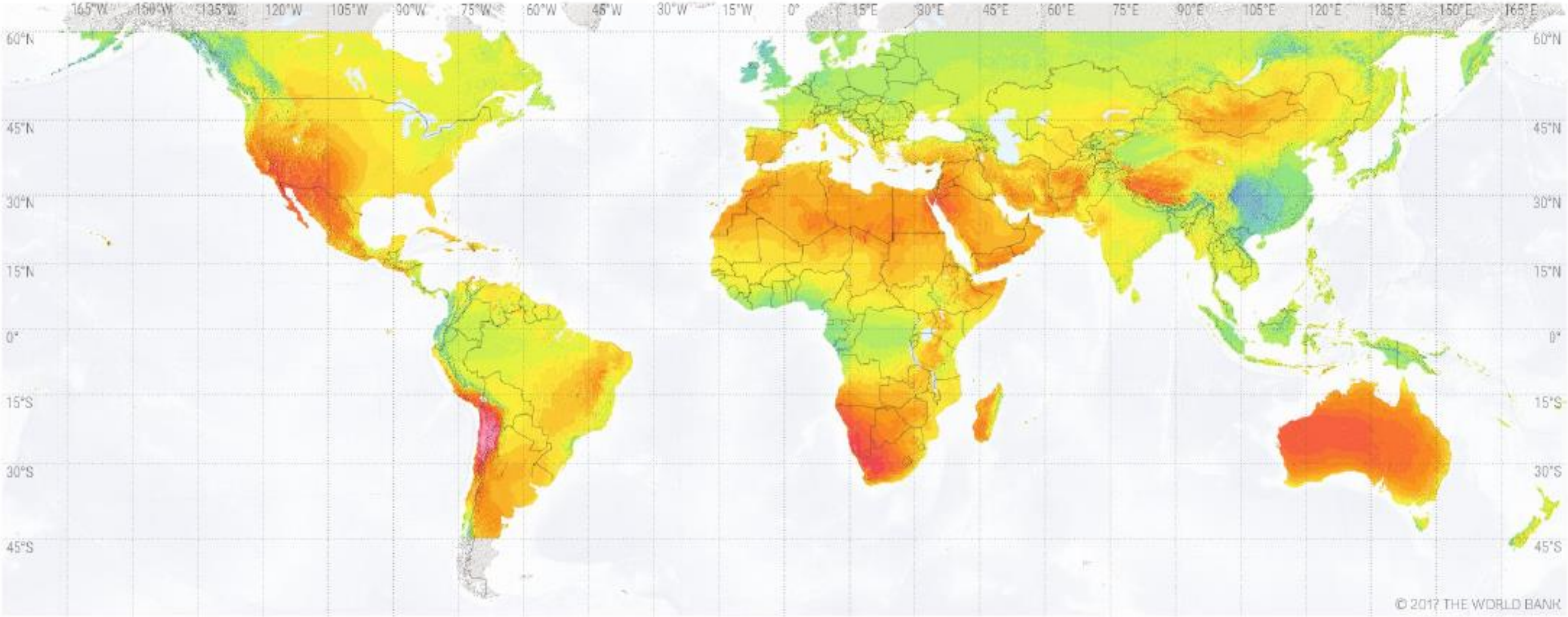
- The solar azimuth and solar zenith express the position of the sun.
- The **solar azimuth** is the angle of the direction of the sun measured clockwise north from the horizon.
- The **solar zenith** is the angle measured from the local zenith and the line of sight of the sun.

https://catalyst.earth/catalyst-system-files/help/concepts/focus_c/atcor_aboutZenithAzimuth.html#:~:text=The%20solar%20azimuth%20and%20solar,of%20sight%20of%20the%20sun.

SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION

WORLD BANK GROUP THE WORLD BANK IFC ESMAP SOLARGIS



Long-term average of daily/yearly sum

Daily sum:	<	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0 >
Yearly sum:	<	365	730	1095	1461	1826	2191	2556	2922	3287	3652 >

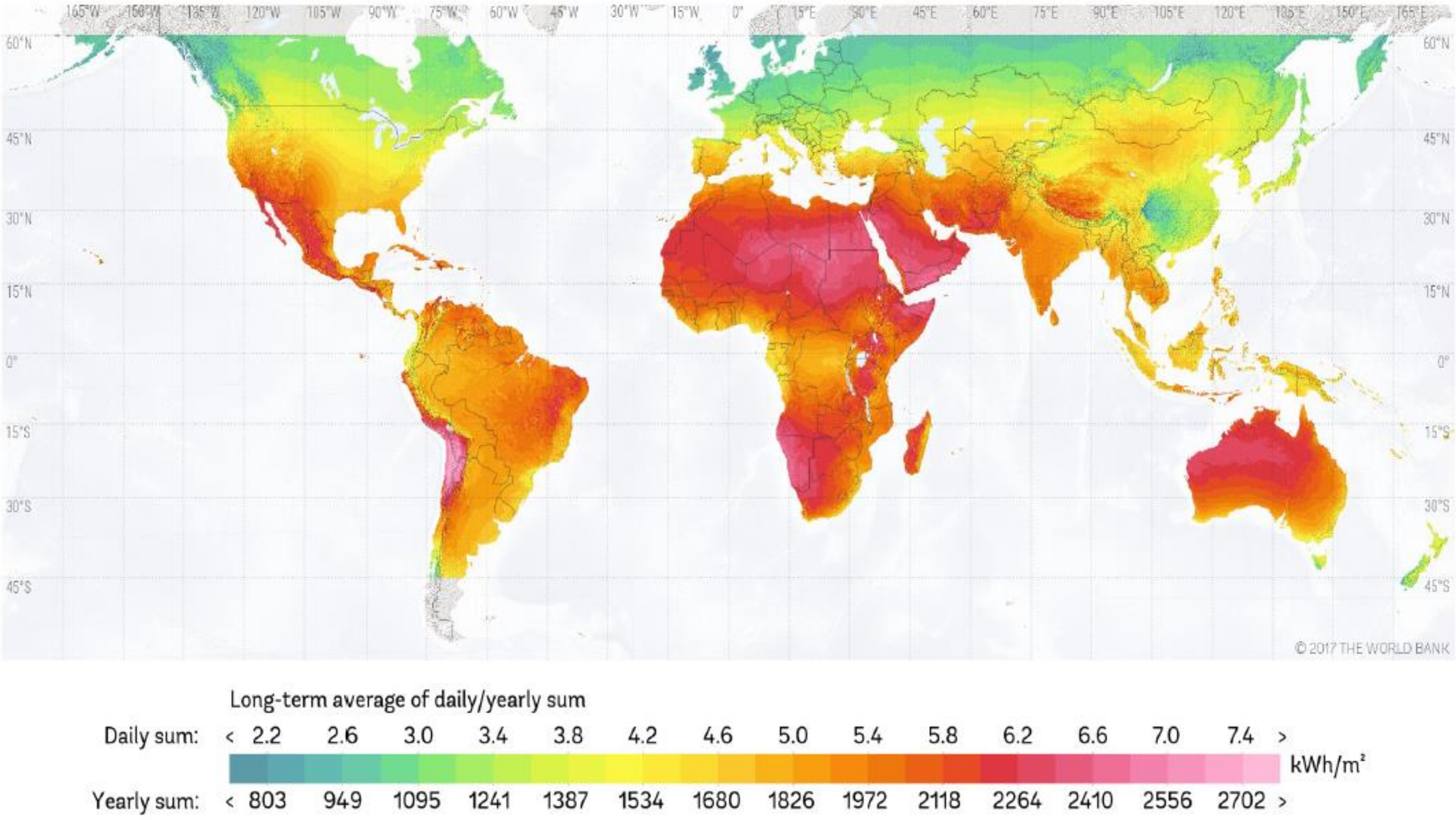
kWh/m²

This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info

SOLAR RESOURCE MAP

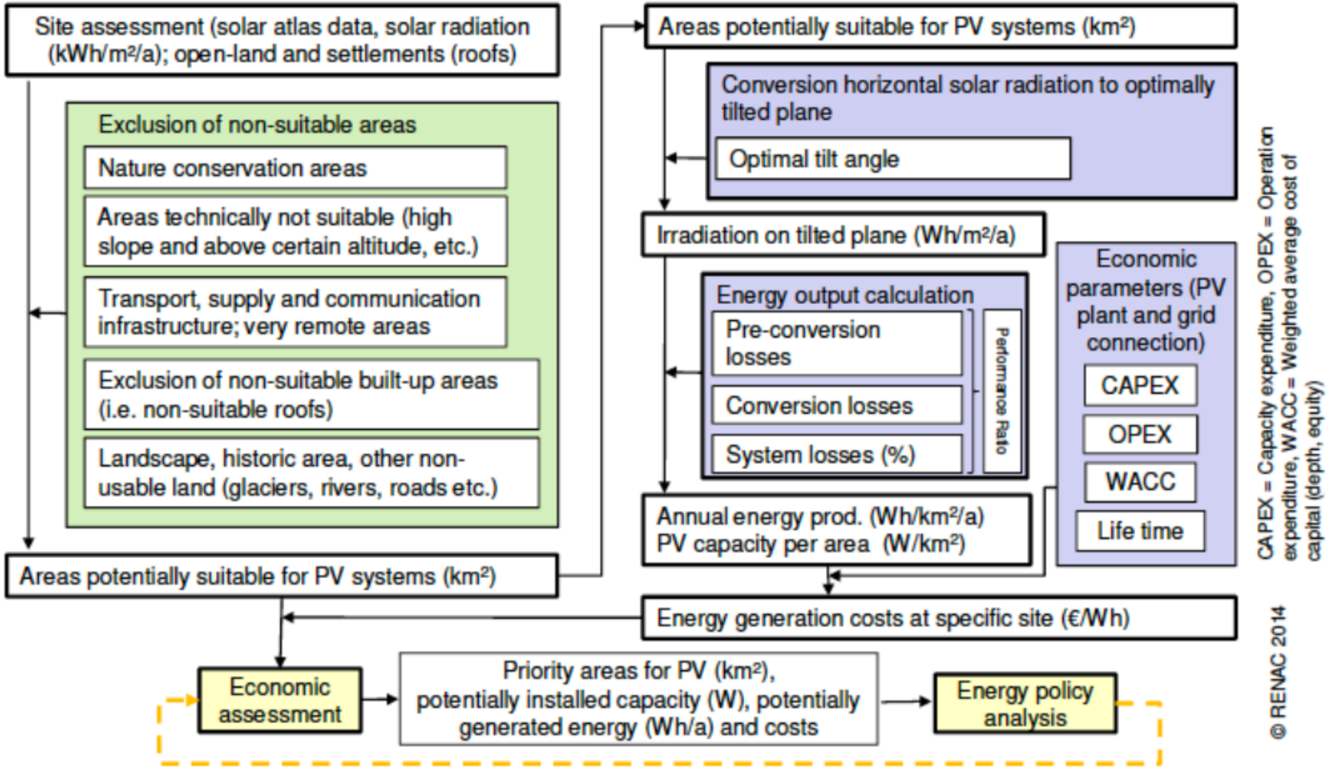
GLOBAL HORIZONTAL IRRADIATION

WORLD BANK GROUP
THE WORLD BANK IFC
ESMAP
SOLARGIS



This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info.

Steps to Design Solar Energy



Solar Spectrum

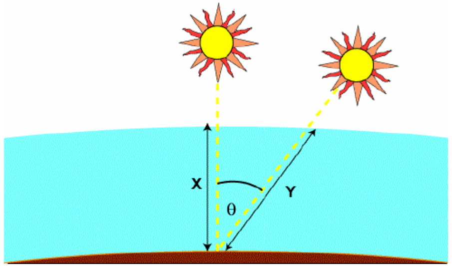
- **<u>The Air Mass is</u>** the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead).
- The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is calculated by:

$$AM = \frac{1}{\cos(\theta)}$$

Valid for small to medium θ

Table 1: AM values versus solar zenith angle.

AM Values	Solar Zenith Angle	Irradiance E in W/m^2
AM 0.0	Irradiance outside the atmosphere	1360
AM 1.0	Sun rays perpendicular to the surface, 0.0°	-
AM 1.5	Industry standard, 48.2°	1000
AM 2.0	60.0°	-
AM 2.5	66.5°	-
AM ∞	After sunset, $\geq$ 90.0°	0



AM1: Sun directly overhead

AM1.5G: “Conventional”
<u>G</u> *(Global): Scattered and direct sunlight*
<u>D</u> *(Direct): Direct sunlight only*

AM0: Just above atmosphere (space applications)

Estimating Land Requirement

How much land is needed

How much energy (kWh) will be produced over the year

$$Land\ requirements\ (m^2) = \frac{Energy\ Burn\ Rate\ (\frac{kWh}{yr})}{Solar\ Resource\ \left(\frac{kWh}{m^2 \times yr}\right) \times Conversion\ efficiency}$$

How much energy from the sun is available

The ability of a given technology to convert sunlight into a usable, **ENTIRE SYSTEM** efficiency

Example: land requirements of a PV project

Q: An area is planned to utilize PV panels to produce 10 MWh annually. The area has a solar resource potential of up to 1800 kWh/m²/year. Estimate the land requirement for this project if the overall efficiency is 10%.

A: $$Land = \frac{10{,}000\,\frac{kWh}{year}}{1{,}800\,\frac{kWh}{m^2.year}\times 10\%} = 55.56\,m^2$$

Solar Power Input

For a given irradiance level ***E*** and a module, calculation of solar (input) power falling on to the module is given by equation:

$$P_{in} = Area\ of\ the\ module\ \times E$$

This is only the input power received by a solar module and hence it is an upper bound on what the module can generate

Estimating System Output from Insolation Maps

$$energy\ output\ estimation = \frac{Array\ Power\ (Wp) \times Insolation(\frac{Wh}{m^2.day})}{A.M.1.5G\ (\frac{Wp}{m^2})}$$

Estimating System Output from Insolation Maps

Q: Estimate energy production in a year with an array of 2.2 kWp if the average location receive 4.0 kWh/m²/day

$$energy\ output = \frac{2200\ W_p \times 4.0 \frac{kWh}{m^2.day}}{1000\ W_p/m^2} = 8.8\frac{kWh}{day} = 3200\frac{kWh}{year}$$

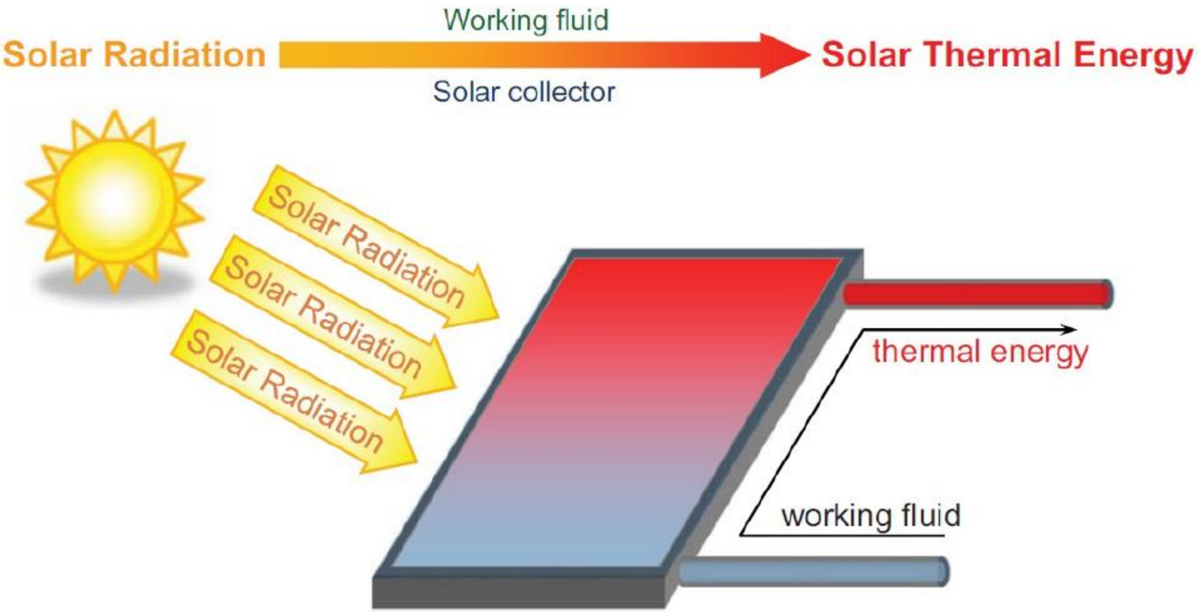
AM 1.5

Solar Thermal

Solar Thermal System

- Solar thermal systems (STS) convert solar radiation into heat. These systems are used to raise the temperature of a heat transfer fluid, which can be air, water or a specially designed fluid.
- The hot fluid can be used directly for hot water needs or space heating/cooling needs, or a heat exchanger can be used to transfer the thermal energy to the final application.
- The heat generated can also be stored in a proper storage tank for use in the hours when the sun is not available. Solar thermal technologies are also used to provide hot water for commercial buildings and industrial process heat.
- The Key component in this system is **Solar collector,** with existing types are **Flat-Plate Solar Collectors (FPC) and Evacuated Tube Solar Collectors (ETC)**

Principle of Solar Thermal Energy

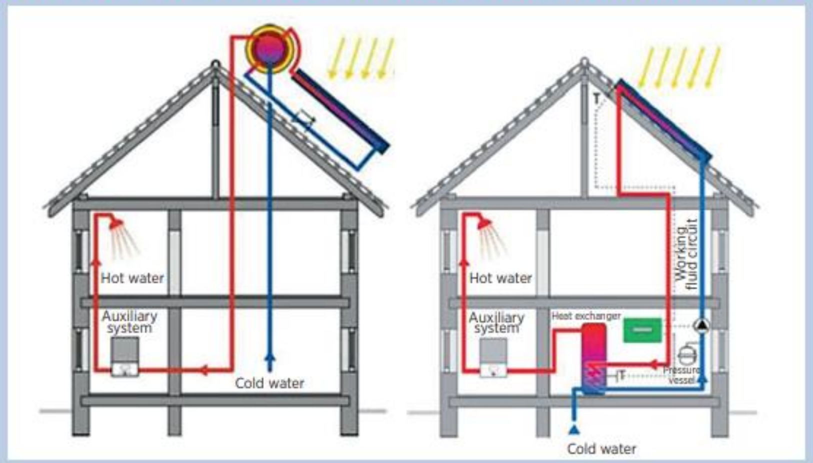


Source: https://www.slideshare.net/slideshow/solar-energy-76441018/76441018#26

Solar Collector

- A solar collector is the key component of a solar thermal system. A distinction can be made between thermo-syphon (or passive) systems and pumped (or active) systems
- **Thermosyphon systems** use natural convection to drive the water from the solar collector unit to the hot water storage tank.
- **Pumped systems** use a pump to circulate the heated fluid from the collector to the storage tank.

Figure 1: Difference between a thermosyphon system used to heat water directly (left) and a pumped indirect solar thermal system (right).

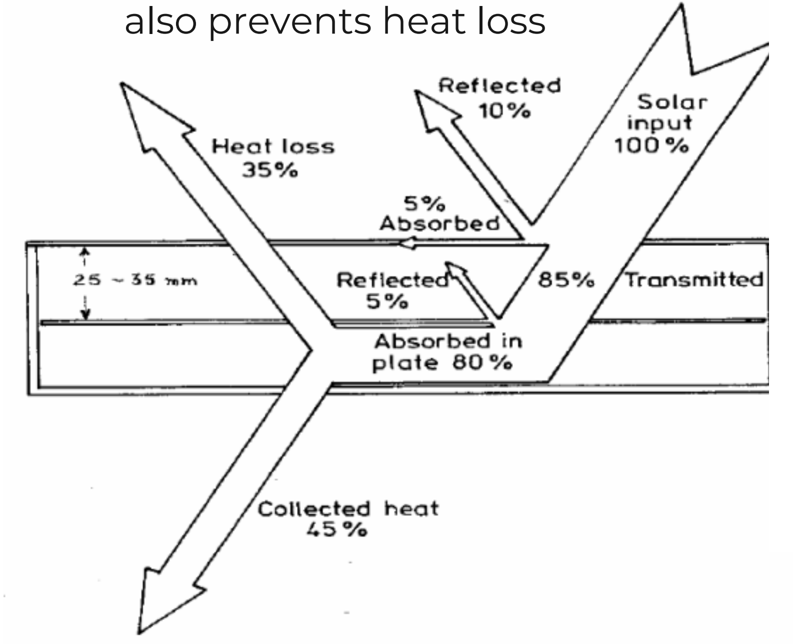


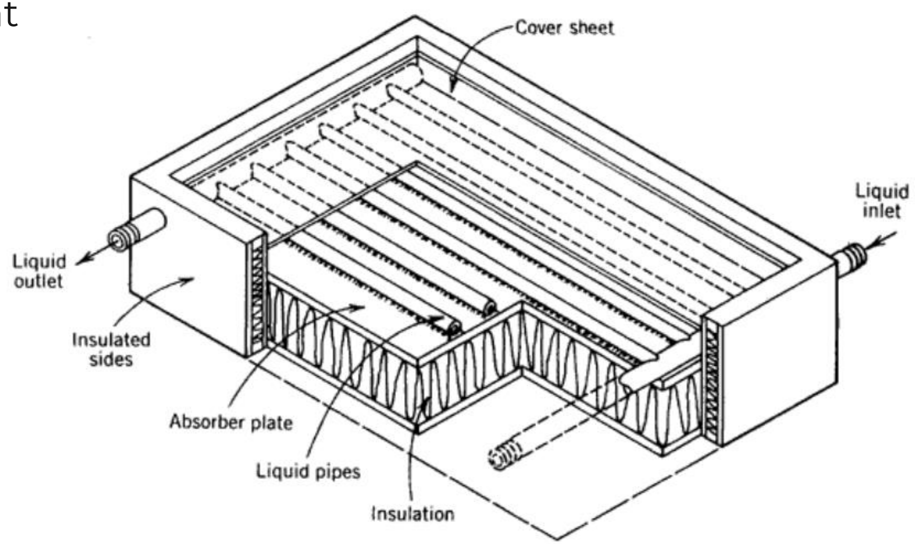
adapted from: Terra (2007)

Source: IRENA, 2015

Flat-Plate Solar Collector

- Consist of tubes carrying a fluid running through an insulated, weather-proof box with a dark absorber material and thermal insulation material on the backside that also prevents heat loss

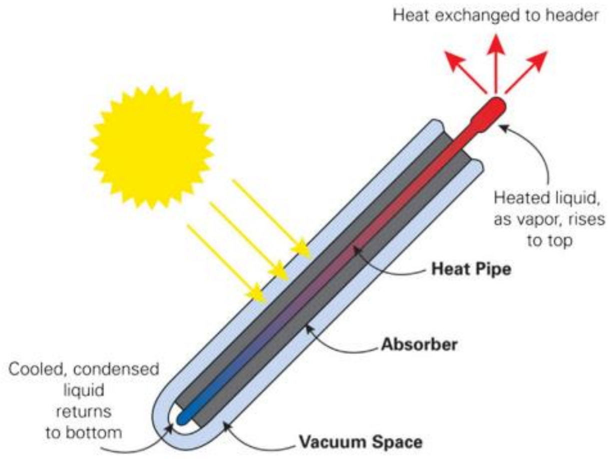


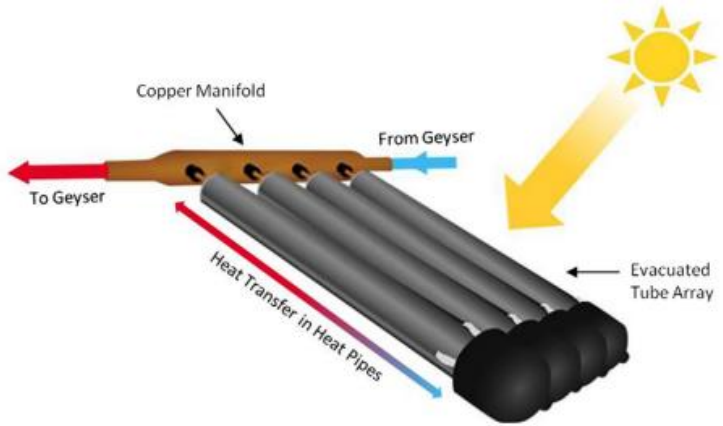


Source: Struckmann, 2008 in Analysis of a Flat-plate Solar Collector

Evacuated Tube Solar Collector

- ETC uses parallel rows of glass tubes, each of which contains either a heat pipe or another type of absorber, surrounded by a vacuum. This greatly reduces heat loss, particularly in cold climates.





Source: Shirazi et. al. , 2018, Solar-powered absorption chillers: A comprehensive and critical review

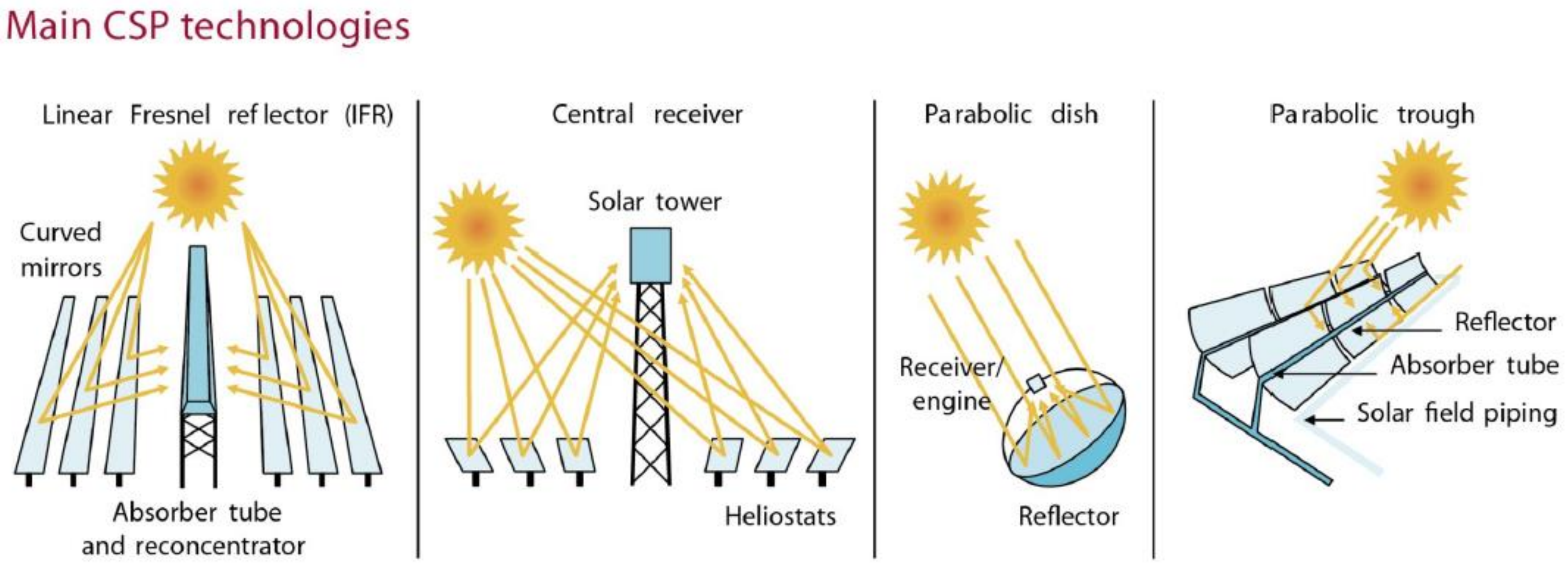
Concentrating Solar Power (CSP)

- Concentrating Solar Power (CSP) plants use mirrors to concentrate the sun's rays and produce heat for electricity generation via a conventional thermodynamic cycle.
- Unlike solar photovoltaics (PV), CSP uses only the direct component of sunlight (DNI) and can provide carbon-free heat and power only in regions with high DNI.

Figure 1 – CSP Parabolic Trough Solar Collectors

Source: IRENA, 2013, CSP Technology Brief

CSP Technologies



IRENA, 2013, CSP Technology Brief

Solar Thermal Cooling

- Solar thermal cooling systems can be used to replace gas-driven or electricity-driven absorption/adsorption chillers or to replace electricity-driven, vapor-compression air conditioning systems.
- Two common systems are: closed absorption chiller systems **with ammonia-water (NH_3 /H_2O**) or **water-lithium-bromide (H_2O/LiBr**) as refrigerant/absorber fluids.

Figure 3: Schema of solar thermal cooling with a ammonia-water Chiller

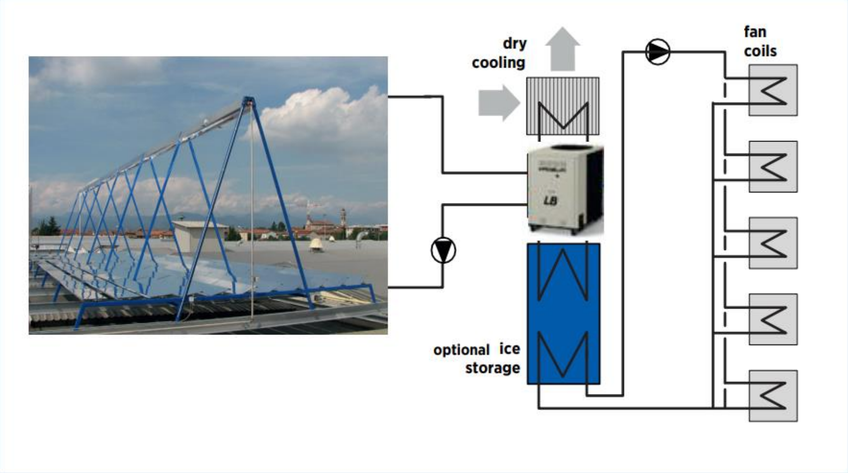
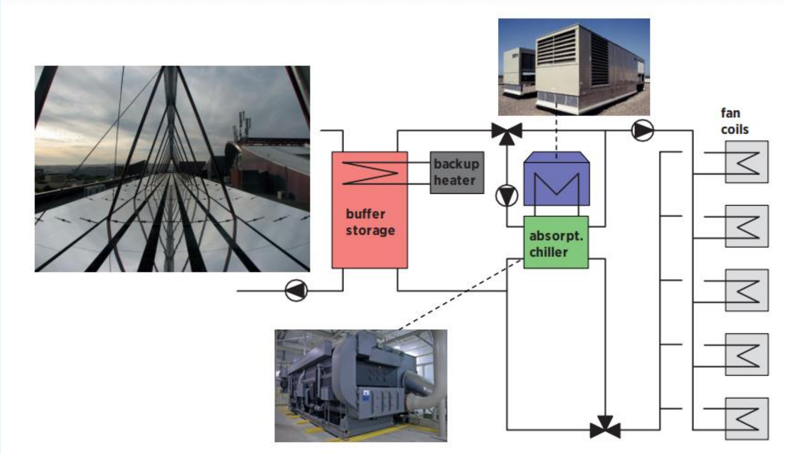


Figure 4: Schema of solar thermal cooling with double-effect water-lithium-bromide Chiller



Source: IRENA, 2015

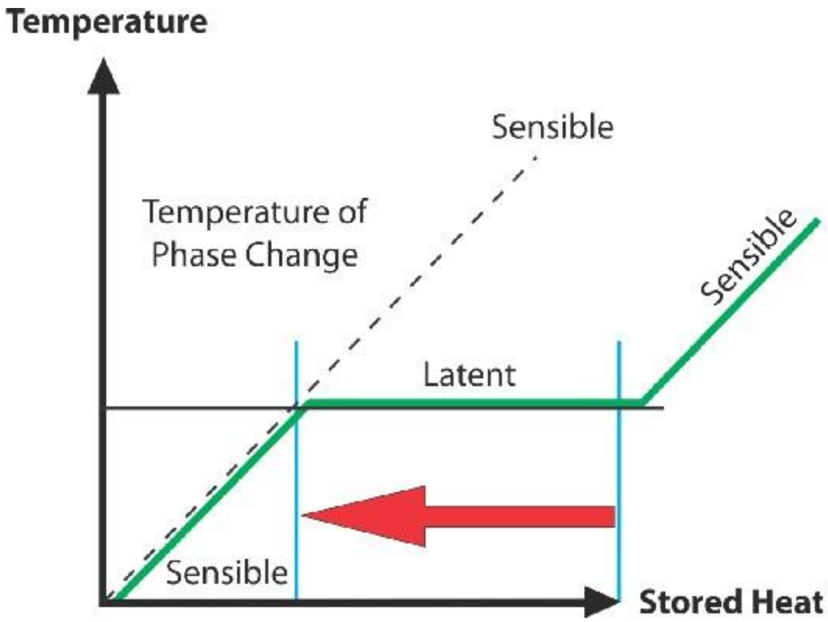
method	closed cycle		open cycle	
refrigerant cycle	closed refrigerant cycle		refrigerant (water) is in contact to the atmosphere	
principle	chilled water		dehumidification of air and evaporative cooling	
phase of sorbent	**solid**	**liquid**	**solid**	**liquid**
				
typical material pairs	water - silica gel	water - water/ lithiumbromide, ammonia/water	water - silica gel, water - lithiumchloride	water - calcium chloride, water - lithium chloride
market available technology	adsorption chiller	absorption chiller	desiccant cooling	close to market introduction
typical cooling capacity [kW cold]	adsorption chiller: 50-430 kW	absorption chiller: 15 kW - 5 MW	20 kW - 350 kW (per Module)	-
typical COP	0.5-0.7	0.6-0.75 (single effect)	0.5->1	>1
driving temperature	60-90°C	80-110°C	45-95°C	45-70°C
solar collectors	vacuum tubes, flat plate collectors	vacuum tubes	flat plate collectors, solar air collectors	flat plate collectors, solar air collectors

"Solar Assisted Cooling – State of the Art –,"ESTIF, 2006.

Solar Cooling Tech Comparison

Solar Thermal Basics: Heat Transfer

$$Q_{sensible} = m\,C_p(T_2 - T_1)$$
$$Q_{Latent} = m\,L$$



Source: https://rgees.com/phase-change-technology/

Solar Thermal Application

Figure 4: Marstal Solar District heating plant (33 360 m²), Denmark

Photograph: AltOmSolvarme

Source: IRENA, 2015

Solar Thermal Application

Figure 9: Application of parabolic trough collector in a dairy processing plant in Mexico

Photograph: Inventive Power A.S.

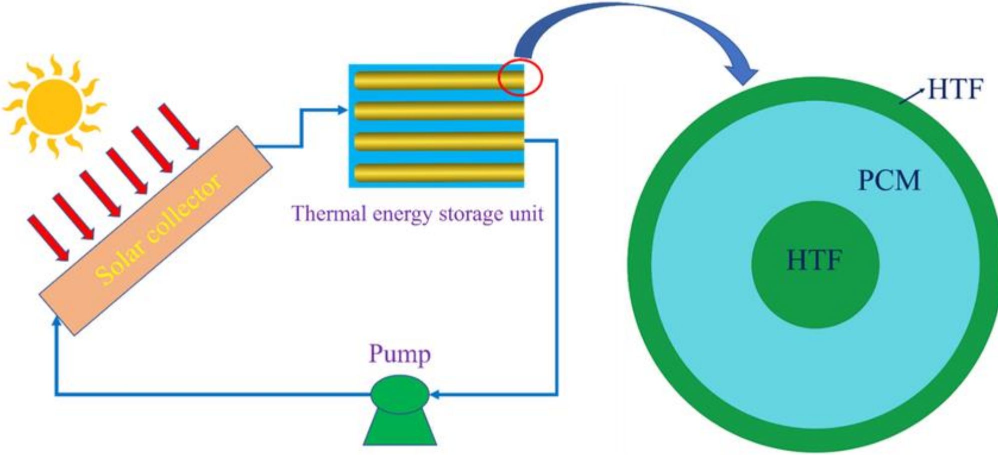
Figure 2: Solar air heating system in textile industry in Vietnam

Photograph: Grammer Solar

Source: IRENA, 2015

Solar Thermal Storage

- Solar energy heating systems must be able to store energy for night time use and for cloudy days. Different materials absorb different amounts of heat.
- Depending on the weather and the amount of thermal energy stored will determine how long a house can continue to be heated by the stored solar energy.
- Phase-change material (PCM) can be used to add additional heat to the living space.



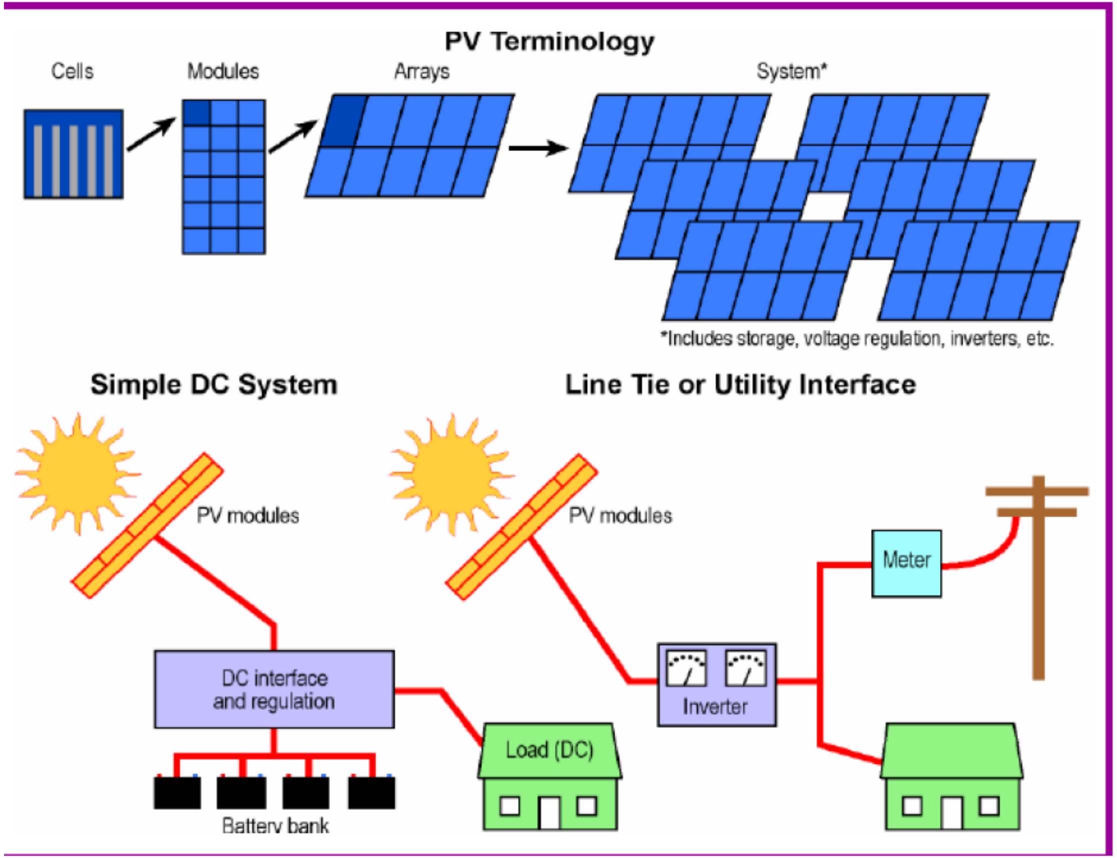
HTF: Heat Transfer Fluid/ Working Fluid
PCM: Phase-Change Material

Source: Han & Yang, 2022, Nanoparticles to Enhance Melting Performance of Phase Change Materials for Thermal Energy Storage

Solar Photovoltaic

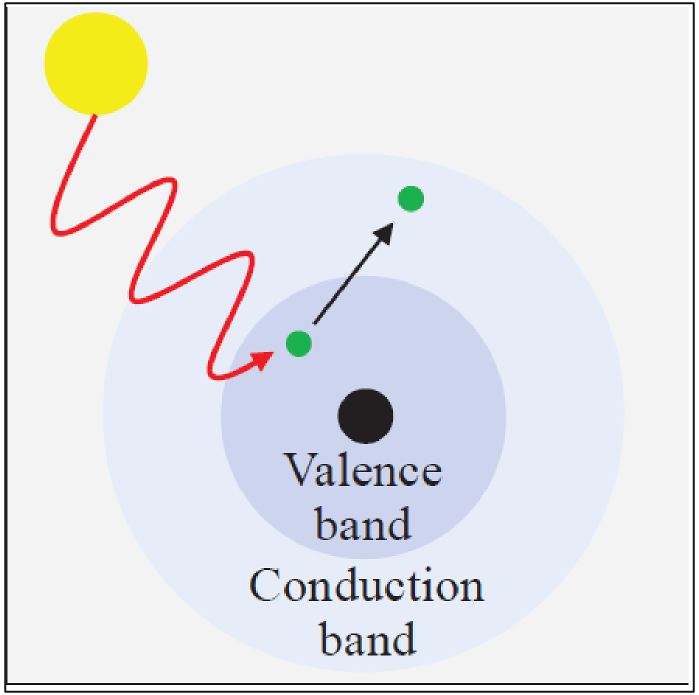
PV Terminology

Source:



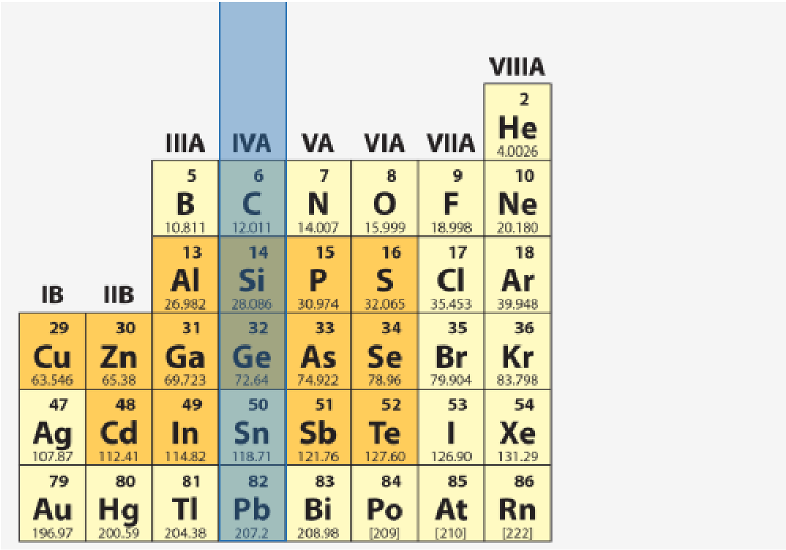
Solar PV Basics

- The energy of an electron increases upon receiving photovoltaic energy through a light photon
- If the energy rises by a large amount, it moves an electron from its valence band to the conduction band
- The conduction band is further away from the nucleus and accommodates electrons that are ready to break away from their nucleus
- An electron in the conduction band is directed through a circuit
- The opposite effect of photovoltaic is fluorescent



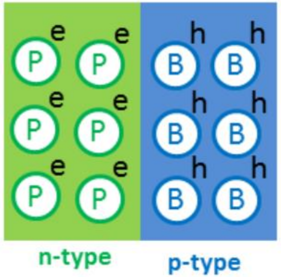
Solar Cell Fundamentals

- A solar cell requires two main ingredients, the **energy gap** of the material which enables the possibility of absorbing photons and excite electrons, and an **internal electric field** to drive the photogenerated electrons out of the device and deliver an electric current (at some voltage) to an external load.
- Semiconductors are required to provide the energy gap, and the combination of a metal/semiconductor interface or a semiconductor with two differently doped regions (homojunction) or two different semiconductors (heterojunction) is required to provide the internal electric field.
- Common materials used as Semiconductor for PV are Silicon and Germanium (Both belongs to the same Group **IVA**

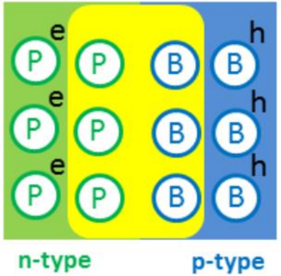


Source: Urbina, 2021, Sustainable Solar Electricity

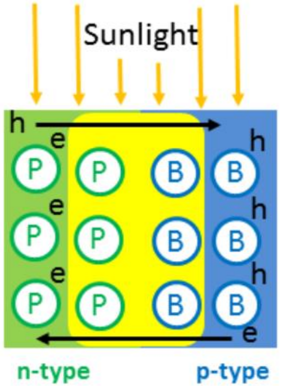
Multistep Physics of Solar Cell Works



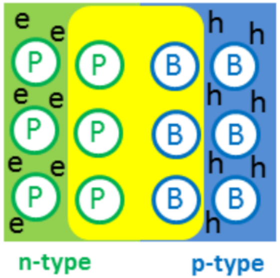
Step 1: p-n junction formation
The p-type silicon semiconductor has excess holes due to the Boron doping and the n-type silicon semiconductor has excess electrons due to Phosphorous doping.



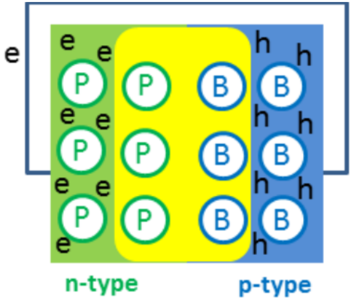
Step 2: Depletion region
In this step due to hole-electron recombination at the interface depletion region a potential difference is created in the p-n junction.



Step 3: Photoelectric effect
In this step, the holes generated in the n type semiconductor are accelerated to the p-type semiconductor and vice versa.



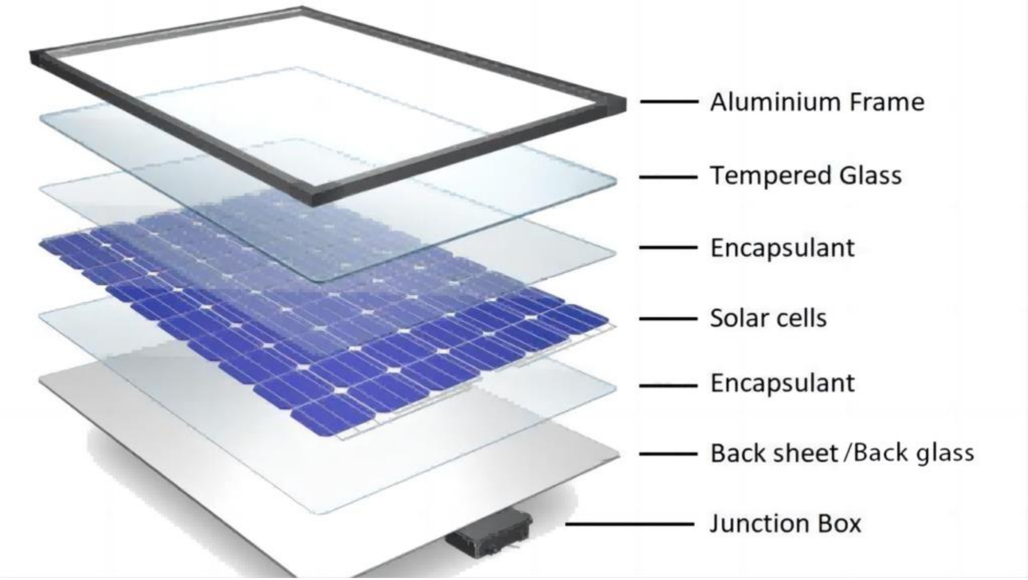
Step 4: Carrier concentration
In this step, the holes are concentrated in the p-type material and the electrons are concentrated in the n-type material.



Step 5: Current flow
In this step, unidirectional flow of electrons is observed when contacts are made on the n and p-type semiconductor.

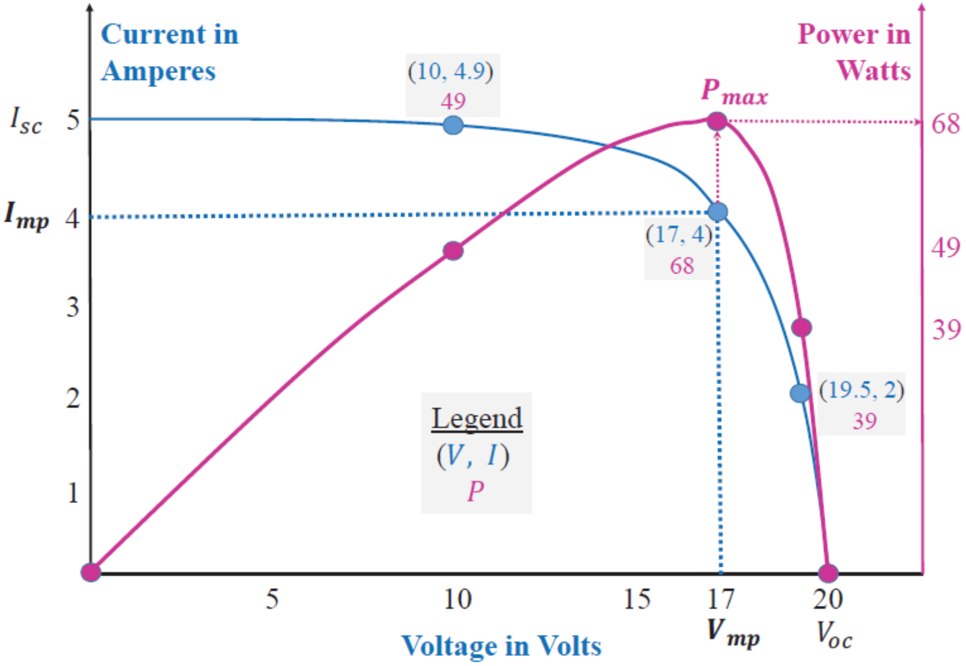
Source: ¸Cakanyıldırım

Solar Cell Structure



Source: Masysunsolar.eu

Power Output



I : Current
P : Power
V: Voltage

subscript:
mp: Max. Power
oc: Open Circuit
sc: Short Circuit

PV efficiency

$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\mathrm{mp}} \cdot I_{\mathrm{mp}}}{P_{in}}$$

$$\text{Fill Factor} \equiv FF = \frac{V_{\mathrm{mp}} \cdot I_{\mathrm{mp}}}{V_{\mathrm{oc}} \cdot I_{\mathrm{sc}}}$$

$$\text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\mathrm{mp}} \cdot I_{\mathrm{mp}}}{P_{in}} = \frac{FF \cdot V_{\mathrm{oc}} \cdot I_{\mathrm{sc}}}{P_{in}}$$

Example: Efficiency of a PV module

A solar module with area of 1.64 m^2 has V_{oc} = 39.4 volts, I_{SC} = 10 ampere, V_{mp} = 34.5 volts and I_{mp} = 8.7 ampere under STC (Standard Temperature Conditions). Calculate the maximum power output P_{max}, fill factor *FF* and efficiency of the module.

$$\begin{aligned} P_{max} &= V_{mp} I_{mp} = (34.5)(8.7) = 300.15\ W; \\ FF &= \frac{V_{mp} I_{mp}}{V_{sc} I_{sc}} = \frac{(34.5)(8.7)}{(39.4)(10.0)} = 0.7618; \\ P_{in} &= [\text{Area of the Module}]\ E = (1.64)(1000) = 1640\ W, \end{aligned}$$

$$\eta = \frac{P_{max}}{P_{in}} = \frac{300.15}{1640} = 0.183 = 18.3\%. \quad \diamond$$

Comparison of Efficiency commercial PV material

Table 2.5 Examples of power conversion efficiency of best research cells and best commercial modules for photovoltaic technologies. Summary of data from the National Renewable Energy Laboratory (NREL) efficiency chart and data published 1st July 2021 [8]

PV technology	Best research cell PCE(%)	Best module PCE(%)
mono-Si (concentrator)	27.6	
mono-Si (non-conc.)	26.1	24.4
multi-Si	23.3	20.4
HIT-Si	26.7	
a-Si	14.0	9.8
CdTe	22.1	19.0
CIGS	23.4	19.6
III-V (4 junction, conc.)	47.1	38.9
III-V (4 junction, non-conc.)	39.2	31.2[a]
Organic	18.2	11.7
Dye-sensitized	13.0	
Perovskite	25	17.9
Perovskite-Si tandem	29.5	
Quantum dot	18.1	
CZTS	12.6	

[a] For non-concentrator triple junction III-V modules

Source: Urbina, 2021, Sustainable Solar Electricity

Comparison of PV cell technologies

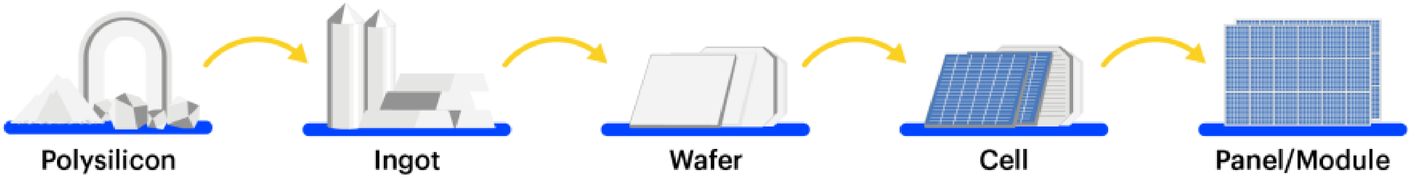
Table 1
Comparison of commercial PV cell materials.

Cell Type	Crystalline Silicon		Thin Film		
	Mono-crystalline	Poly-crystalline	Amorphous silicon	Cadmium Telluride	CIGS
Max. Efficiency	25%	20%	13%	21%	20%
High temp. effect on efficiency	15% drop	20% drop	0% drop	0% drop	0% drop
Temperature coefficient PMax	–0.5%	–0.5%	–0.25%	0%	0%
Low irradiance performance	power output reduction	power output reduction	low impact on power output	low impact on power output	low impact on power output
Optimal Performance Temp.	performs well in cool weather but poorly in hot weather	performs well in cool weather but poorly in hot weather	performs well in cool weather, hot weather even in extreme heat	performs well in cool weather, hot weather even in extreme heat	performs well in cool weather, hot weather even in extreme heat
Surface area for 1 kW power	7–9 m^2	8–9 m^2	13–20 m^2	11–13 m^2	9–11 m^2
Cost ($/W)	1.6	1.4	0.8	0.7	0.75
Complexity of Manufacturing process	complicated, sophisticated and expensive	simpler and less expensive than mono crystalline	lower cost than crystalline silicon because less silicon required	lower cost and less sophisticated than crystalline silicon	lower cost and less sophisticated than crystalline silicon
Carbon Footprint (gCO_2-eq/kWh)	45	44	50	35	46
Energy Payback Time (EPBT) (months)	48	36	36	8	12
Market Availability	easily available and dominant	most dominant with largest market share	less dominant than crystalline silicon in the market	largest market for thin film	less dominant than crystalline silicon in the market
Environmental Effects	no known effects	no known effects	no known effects	elemental Cadmium is toxic	no known effects

Source: Ogbomo, et. al., 2017

Solar Economics and Environmental

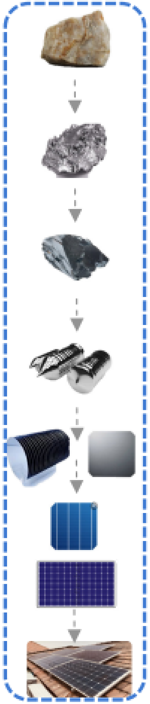
Key stages in the main manufacturing process for solar PV



Source: IEA, 2022

PV supply chain

Simplified manufacturing from raw materials for c-Si and CdTe solar PV systems



Crystalline silicon

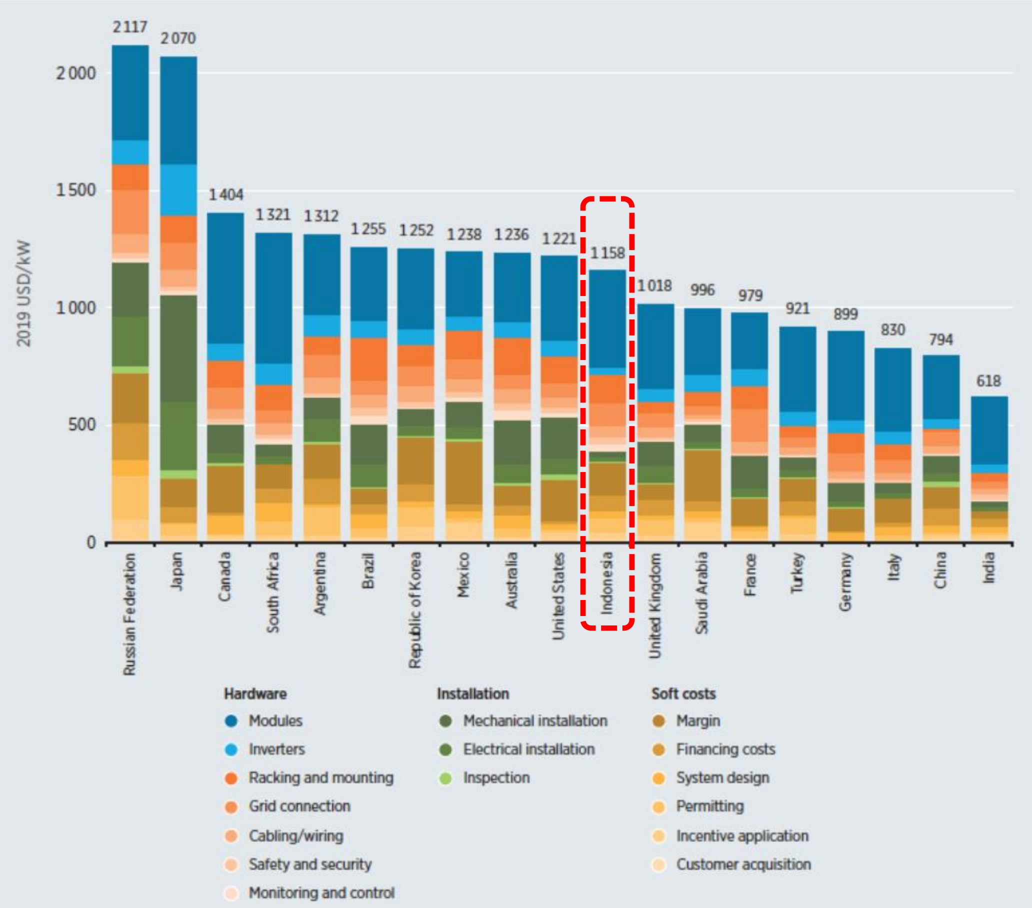
- Mineral extraction
- Silica (SiO2) : quartzite, quartz pebble, quartz vein
- Carbothermic reduction (carbon arc welding [CAW]), removal of impurities
- Metallurgical-grade silicon (MG-Si >98% purity)
- Hydrochloration
- Trichlorosilane gas (HSiCl3) | Silane gas (SiH4)
- Siemens process | Fluidised bed reactor (FBR)
- Polysilicon (6-13N purity)
- Czochralski (CZ) process | Float zone (FZ) technique | Molding (heat exchange method / electro-magneto casting / directional solidification system), doping
- Monocrystalline silicon ingot | Multicrystalline, mono-like or quasi-mono silicon ingot
- Sawing and slicing
- Wafers
- Cleaning, texturing, doping (diffusion), etching, anti-reflective coating deposition, contact printing and sintering, testing
- Cells
- Backsheet, contacts, encapsulation, glass and frame assembly and sealing, junction box connection, testing
- Module
- Mounting, inverter connection, connection to the grid
- PV system

Thin-film (CdTe)

- Mineral extraction and refining
- Cadmium (Cd), Tellurium (Te), etc.
- Deposition of a transparent conducting oxide (TCO) (e.g. fluorine-doped tin oxide or indium-tin oxide) front contact layer on a substrate (e.g. glass, polymer)
- Deposition of a n-type cadmium sulfide (CdS) buffer or window layer
- Deposition of a p-type cadminum telluride (CdTe) absorber layer
- Junction-activation heat treatment
- Deposition of the back contact metal layers (e.g. zinc telluride [ZnTe], molybdenum [Mo])
- Definition of cells by laser scribing, interconnection bussing
- Cells
- Encapsulation, electrical lead attachement, junction box connection, testing
- Module
- Mounting, inverter connection, connection to the grid
- PV system

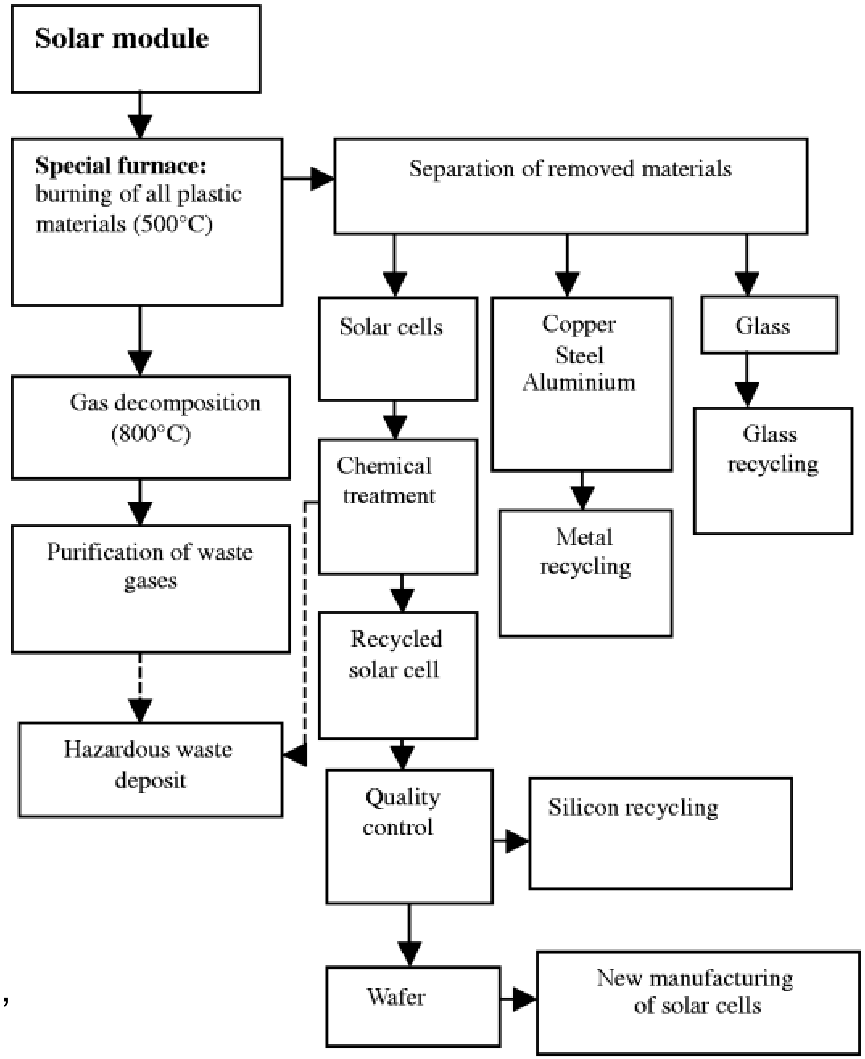
Source: IEA, 2022

CAPEX Breakdown of PV



Source: IRENA, 2019

Recycling PV



Source: Goetzberger & Hoffmann, 2005, Photovoltaic Solar Energy Generation

Land area required for PV

- Recently, large PV plants have been constructed in open countryside areas. Some argue that these plants impact landscapes due to their extensive land usage.
- Example: Solarpark Sonnen near Passau, Germany, operational since August 2002. Power capacity: Approximately 1.7 MWp. It is located in the open countryside, where solar modules are installed.
- The site is also used as a pasture for sheep, demonstrating multi-functional land use. Conclusion: PV plants do not necessarily harm landscapes, as they can coexist with agricultural activities

Fig. 9.1. Detailed view of the Solarpark Sonnen (Germany)

Source: Goetzberger & Hoffmann, 2005, Photovoltaic Solar Energy Generation

Thank You