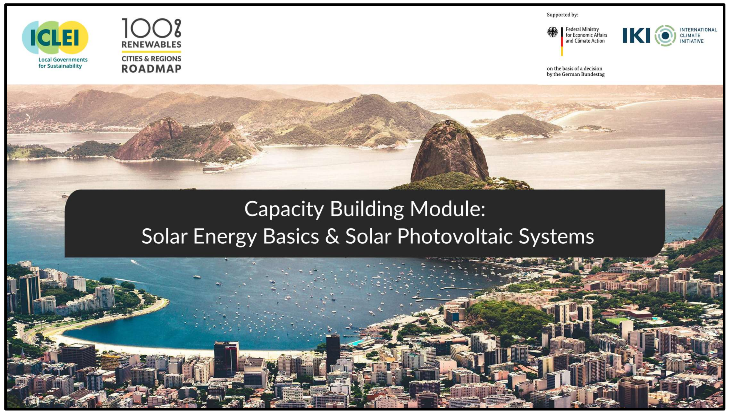
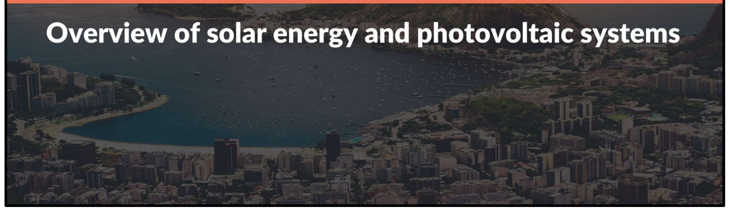
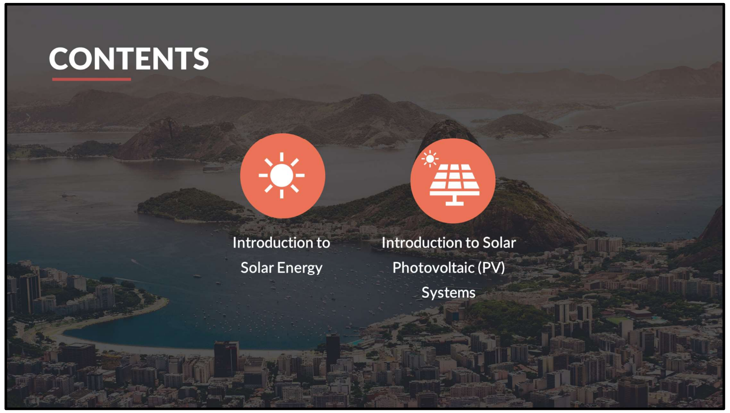

ICLEI
RENEWABLES
CITIES & REGIONS
ROADMAP
IKI
Capacity Building Module:
Solar Energy Basics & Solar Photovoltaic Systems

CHAPTER 1:

Overview of solar energy and photovoltaic systems



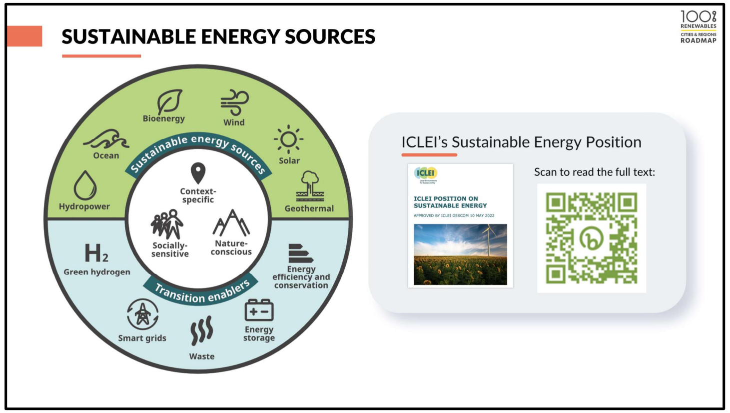


Introduction to 100 % Renewables Cities & Regions, ICLEI's Sustainable energy position
Why renewables, Global status of renewables in power capacity growth & power capacity expansion

Introduction to the solar energy:
Energy from the sun, Solar energy received on earth, sun path geometry, radiation distribution on earth surface, peak sun hours, global horizontal irradiation

Introduction to solar photovoltaic (PV) systems: Solar PV cell operation, key milestones in history of PV technology, Solar PV cell current voltage characteristics, solar cell parameters, solar cell – module – PV panel – PV array, available technologies, linear vs non-linear PV module, area required by technology, technical specifications of PV module, standard test conditions and normal operating cell temperature, working of PV module with varied radiation and temperature.


INTRODUCTION
SUSTAINABLE ENERGY &
100 % RENEWABLES



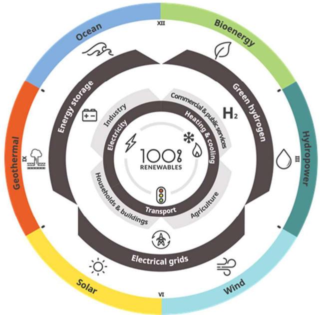
Energy sources can be harnessed without depletion, ensuring a continuous supply of energy meeting our energy needs with minimum (no) environmental impact – Sustainable energy sources.

Energy from sun – solar energy
Kinetic energy from wind – wind energy
Potential energy from water – hydro energy
Steam present at the underground – geothermal energy
Decomposition of bio-materials – bioenergy
Continuous movement from tides – ocean energy

100% RENEWABLES CITIES AND REGIONS

" Renewable energy encompasses all renewable resources, including bioenergy, geothermal, hydropower, ocean, solar and wind energy. One hundred percent renewable energy means that all sources of energy to meet all end-use energy needs in a certain location, region or country are derived from renewable energy resources 24 hours per day, every day of the year. Renewable energy can either be produced locally to meet all local end-use energy needs (power, heating and cooling, and transport) or can be imported from outside of the region using supportive technologies and installations such as electrical grids, hydrogen or heated water. Any storage facilities to help balance the energy supply must also use energy derived only from renewable resources.

-IRENA Coalition for Action

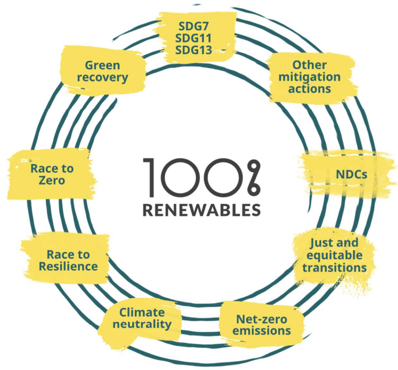


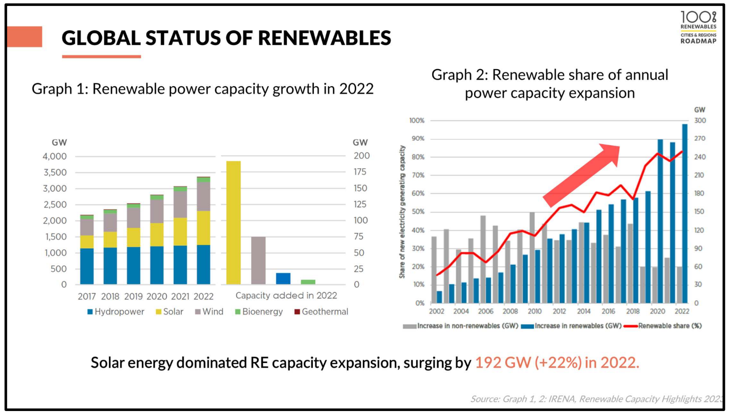
Graphical representation of 100% renewable energy by ICLEI - Local Governments for Sustainability

100% RENEWABLES AS A CORNERSTONE

Decarbonizing energy supply through renewable energy sources, deployed in a socially- and environmentally-conscious way, is key to achieving various climate and socio-economic goals:

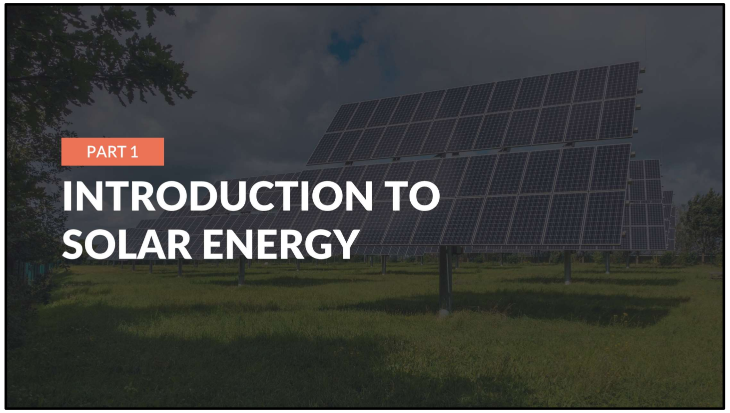
- Transitioning towards a renewables-based energy system is a cornerstone on the way to net-zero emissions and a ensuring a just transition
- Renewable energy can help enhance climate adaptation and resilience efforts
- Improved access to clean and modern energy and associated welfare benefits
- Use of SE sources will improve energy security and independence at local and national levels
- Zero operational emissions from SE (incl. pollutants) brings additional health benefits compared to fossil fuels

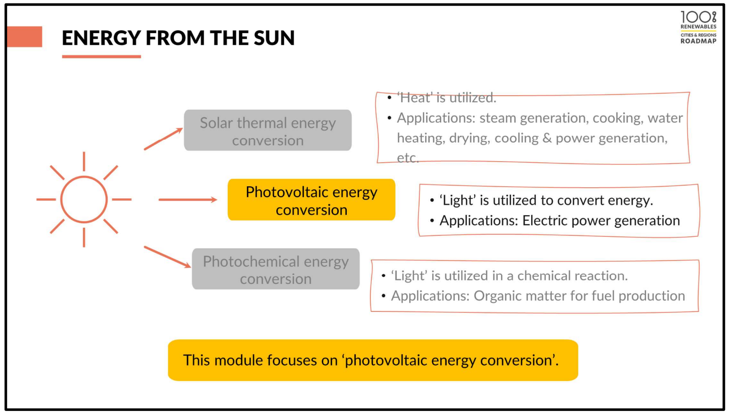




At the end of 2022, global renewable generation capacity amounted to 3372 GW. Solar and wind energy accounted for most of the remainder, with total capacities of 1053 GW and 899 GW respectively.

Renewable generation capacity increased by 295 GW (+9.6%) in 2022. Solar energy continued to lead capacity expansion, with a massive increase of 192 GW (+22%), followed by wind energy with 75 GW (+9%). Renewable hydropower capacity increased by 21 GW (+2%) and bioenergy by 8 GW (+5%). Geothermal energy increased by a very modest 181 MW.

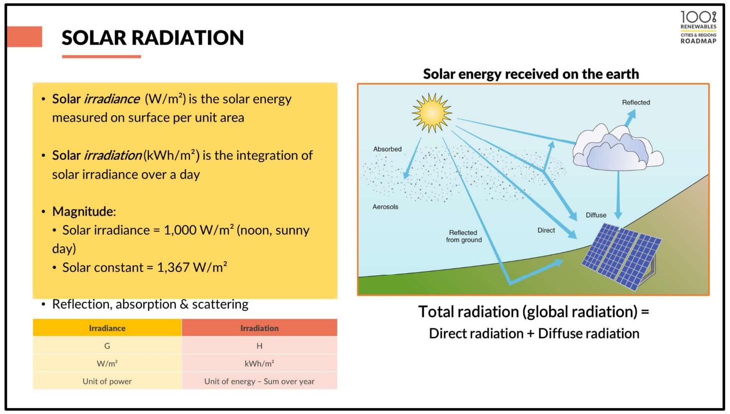

PART 1
INTRODUCTION TO
SOLAR ENERGY



1) Solar Thermal Energy conversion: Solar thermal energy conversion involves using sunlight to heat a fluid, such as water or air, which then transfers the heat to a working fluid to produce steam. This steam drives a turbine connected to a generator, producing electricity. The sun's energy is concentrated to raise the temperature of the fluid, thus harnessing its thermal energy for power generation.

2) Photovoltaic Energy conversion: In photovoltaic energy conversion, sunlight is directly converted into electricity using photovoltaic cells made of semiconductor materials, usually silicon. When sunlight strikes the cells, it excites electrons, creating a flow of electric current. This phenomenon is known as the photovoltaic effect. The cells are connected in arrays to generate usable electric power from the absorbed sunlight.

3) Photochemical Energy conversion: Photochemical energy conversion utilizes sunlight to initiate chemical reactions. This process is often seen in artificial photosynthesis, where light energy is used to split water into oxygen and hydrogen, producing clean fuels. It involves capturing solar energy and transforming it into chemical energy that can be stored and used for various applications.



Sun is a continuous source emits the packets of energy called photons. Every place on earth receives same amount of heat, but not the same number of hours of sunlight. Amount of irradiation depends upon the distance between the sun and the earth.

Irradiance (measure of power density of sunlight falling per unit area and time)

It is the rate at which radiant energy is incident on a unit surface area. Units: W/m^2

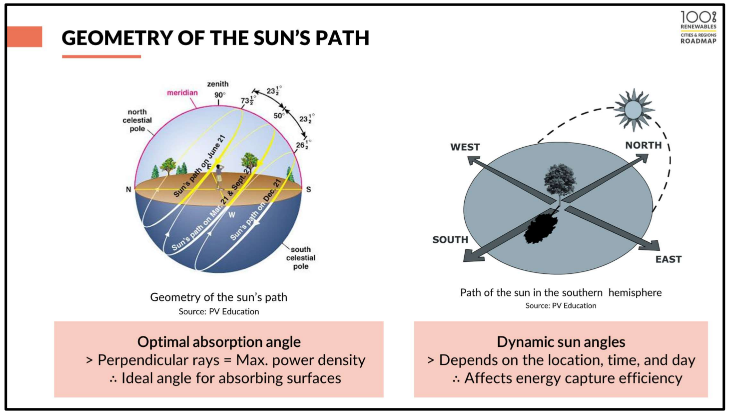
Irradiation

The integration of solar illumination or irradiance over a specified time (usually an hour or kilowatt a day). It is solar energy per unit surface area which is striking a body over a specified time. Units: kWh or kWh/m^2

For example, if irradiance is 20 kW/m2 for 5 h, irradiation is 20 × 5 = l00 kWh/m^2

On a clear sunny day, amount of the solar irradiance at noon = 1,000 W/m^2.

The solar constant refers to the amount of energy received from the sun per unit time on a unit surface area at the top of Earth's atmosphere when Earth is at its mean distance from the sun. Solar radiation enters to earth’s surface – Reflection, absorption and scattering. Hence, reduced. Depending upon the cloud conditions and the time of the day (both), Irradiation power and proportion of direct and diffuse radiation can vary greatly.

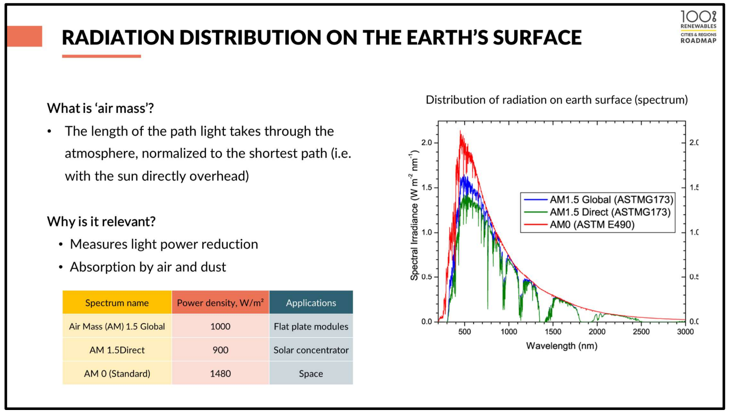


By taking into account the Sun's path and Earth's revolution, PV modules can be strategically placed to harvest the maximum amount of solar energy, increasing the efficiency of the solar energy system and maximizing electricity production.

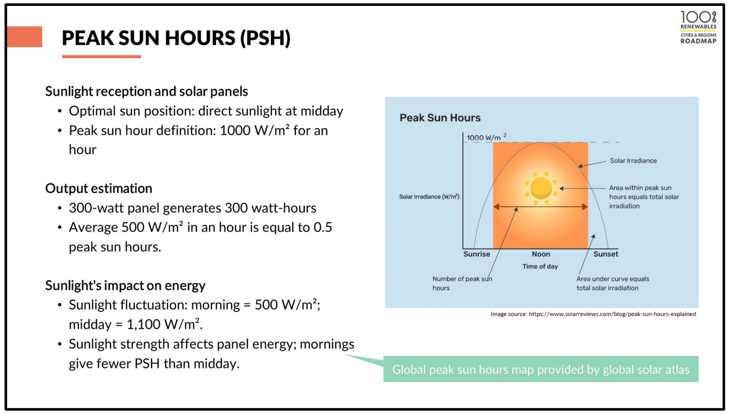
In general, the angle of the noon sun (from the horizon) at the equinoxes equals (90° - latitude). Also note that the angle between the noon sun at the equinox and the noon sun at the (summer and winter) solstice is always 23.5°, whatever the latitude. You can therefore draw a similar diagram for any latitude. (For example, the sun paths at 40°N are as follows.) To utilize maximum amount of irradiation, the solar PV modules are tilted. In general, latitude of the location is considered as the tilt angle against the horizontal. Exact value depends on location.

- This apparent motion of the sun has a major impact on the amount of power received by a solar collector. When the sun's rays are perpendicular to the absorbing surface, the power density on the surface is equal to the incident power density.

- The angle between the sun and a fixed location on Earth depends on the particular location (the longitude of the location), the time of year and the time of day.



The Air Mass (AM) is 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.

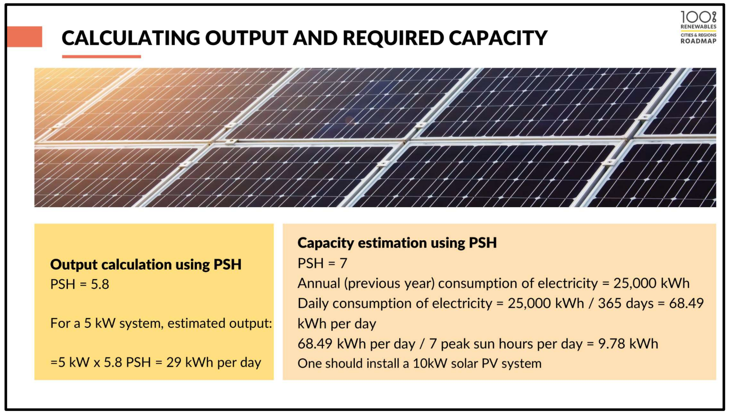


Solar panels are only likely to receive around that much sunlight when facing directly towards the sun when the sun is at its strongest, at midday. A peak sun hour is the equivalent of 1000 W/m² of sunlight for an hour.

That amount of sunlight – 1000 W/m² over an hour – also happens to be the exact amount of sunlight used to test and rate solar panels in the lab. That means that over the course of a peak sun hour, a solar panel should be producing – before system losses due to temperature and other factors – at close to its specified output rating.

In other words, before system losses, during a peak sun hour you can expect a 300-watt solar panel to produce roughly 300 watt–hours of electricity, and a 6 kilowatt system to produce roughly 6 kilowatt–hours of electricity.

An hour in the morning that receives an average of 500 W/m² of sunlight is equal to 0.5 peak sun hours.
An hour at midday that receives an average of 1,100 W/m² of sunlight is equal to 1.1 peak sun hours.



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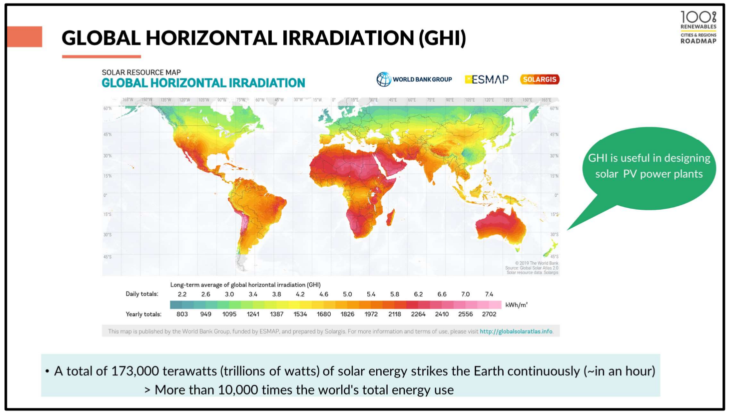


Renewable energy sources can be harnessed without depletion, making them a sustainable and environmentally friendly choice for meeting our energy needs. – That's why they are important.

Abundant and Free Resources: Renewable energy sources are available in abundant quantities and are free to use, unlike non-renewable energy sources that are limited and will eventually run out.

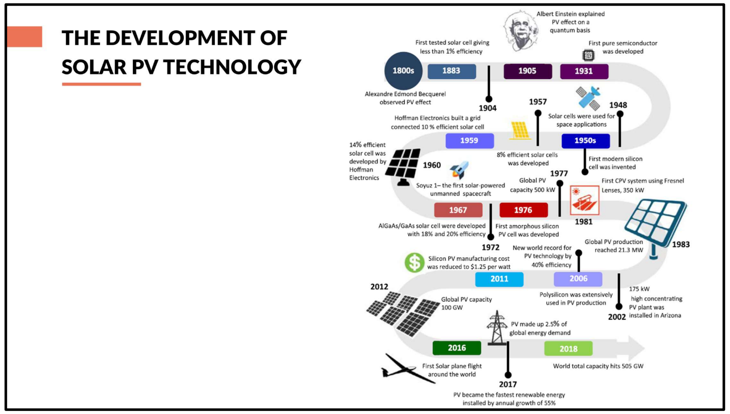
Low Carbon Emissions: Renewable energy sources have low carbon emissions, making them environmentally friendly and helping to mitigate climate change.

Economic Stimulus and Job Creation: The development of renewable energy infrastructure stimulates the economy and creates job opportunities. Building renewable energy plants can provide employment to thousands or even millions of people.

Energy Independence: By relying on renewable energy sources, the dependence on fossil fuels and other countries for energy supply can be minimized.

Cost Efficiency: Advancements in renewable energy technologies have significantly reduced the cost of generation. In some cases, renewable sources are cheaper than consuming electricity from the local electrical grid, leading to potential long-term savings on electricity bills.


PART 2
INTRODUCTION TO
SOLAR PV SYSTEMS

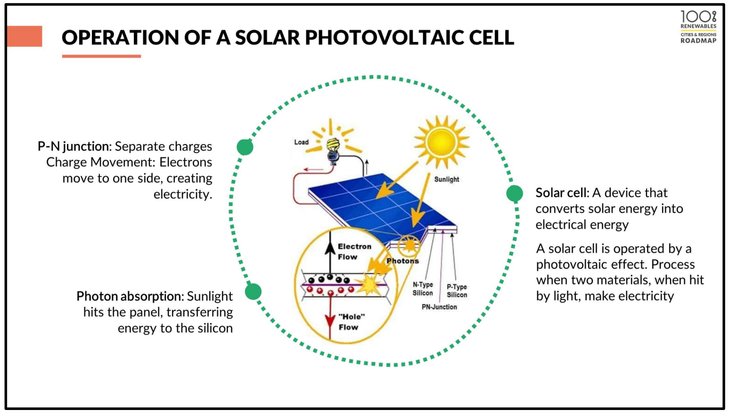


Development history of solar cells

In essence, the study of PV technology began in the 1800s, and research continued until 1904 to complete the discovery phase of PV. In 1905, a scientific foundation was formed for technology development until the 1950s, where Bell labs introduced the first silicon solar cell in 1954.

After this breakthrough, the first practical PV devices emerged drastically for a decade. From 1960 to 1980, PV technology obtained a global scale, and its utilization was extended to the power scale while the number of devices integrated with this technology rose.

PV developments slowed during 1980–2000, which was rooted in the political and energy independence strategies. However, after 2000, the technology accelerated, fueled by the considerable cost reduction and great improvements in the efficiency of commercial cells. This led to the advent of new cell generation and advanced deployment of the technology. Above figure summarizes the historical timeline of the development of PV technology.

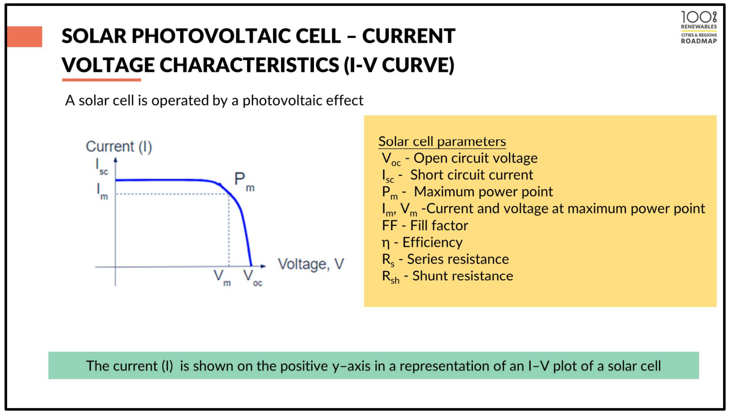


The photovoltaic effect is a process where two different materials in close contact generate an electrical charge when exposed to light or radiant energy. When light strikes crystals like silicon or germanium, it provides the energy to release electrons from their bound condition, creating a flow of free electrons across the junction between the materials. This results in a negative voltage on one side of the junction relative to the other, similar to a battery.

When sunlight hits a solar cell, it excites electrons, causing them to move from one energy level to another, leaving holes behind. These electrons and holes act as negative and positive charge carriers, respectively.

the separated electrons and holes create an electric field within the cell. This electric field drives the electrons towards one side of the cell and the holes towards the other side. As a result, an imbalance of charges is created, generating a potential difference, or voltage, across the cell.

When an external circuit is connected to the solar cell, the flow of electrons and holes within the cell creates a current through the circuit. This current represents the conversion of solar energy into electrical energy, which can then be used to power electrical devices or stored in batteries for later use.



The short-circuit current is the largest current which may be drawn from the solar cell.

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited).

The open-circuit voltage, V_{oc}, is the maximum voltage available from a solar cell, and this occurs at zero current.

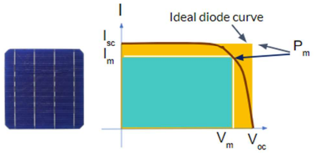
Power out of a solar cell increases with voltage, reaches a maximum (P_m) and then decreases again.

SOLAR CELL PARAMETERS

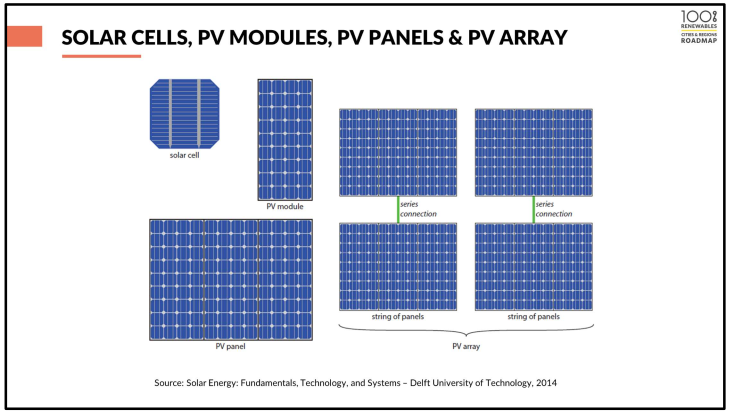
Fill factor (FF) is the measure of the 'squareness' of the solar cell i.e. the ratio of maximum power from the actual solar cell to the maximum power from an ideal solar cell

Efficiency (η) is defined as the ratio of energy output from the solar cell to input energy from the sun.

Solar cell and I–V curve



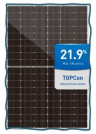
- $Maximum\ power\ point, P_m = I_m \times V_m$
- $FF = \frac{Max\ power\ from\ real\ cell}{Max\ power\ from\ ideal\ cell} = \frac{V_m I_m}{V_{oc} I_{sc}}$
- $\eta = \frac{Max\ cell\ power}{Incident\ light\ intencity} = \frac{V_m I_m}{P_{in}}$
- $\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$



Solar cell is a basic unit of PV system (smallest component, used to convert solar energy into electrical energy).
A PV module, is a larger device in which many solar cells are connected.
The names PV module and solar module are often used interchangeably.
A solar panel, consists of several PV modules that are electrically connected and mounted on a supporting structure.
Finally, a PV array consists of several solar panels.
This array consists of two strings of two solar panels each, where string means that these panels are connected in
series.

AVAILABLE PHOTOVOLTAIC TECHNOLOGIES

Generation	Technology	Efficiency
1st Generation	Silicon based: crystalline silicon, Passivated Emitter and Rear Contact (PERC), etc.	Reasonable efficiency high cost
2nd Generation	Thin film: Amorphous silicon a-Si; Cadmium telluride CdTe; Copper indium gallium selenide CIGS; Polymer solar cell; Organic solar cell	Low efficiency
3rd Generation	Technological combination of thin film & silicon: III junction solar cell for space applications (Gallium arsenide); Nanoparticles; Dye-sensitive solar cell; Perovskite solar cell	High efficiency



N-type bifacial TOPCon solar panel
Source: Sun EVO solar co.


Thin-film cadmium Telluride (CdTe) solar panels
Image: Toledo Solar

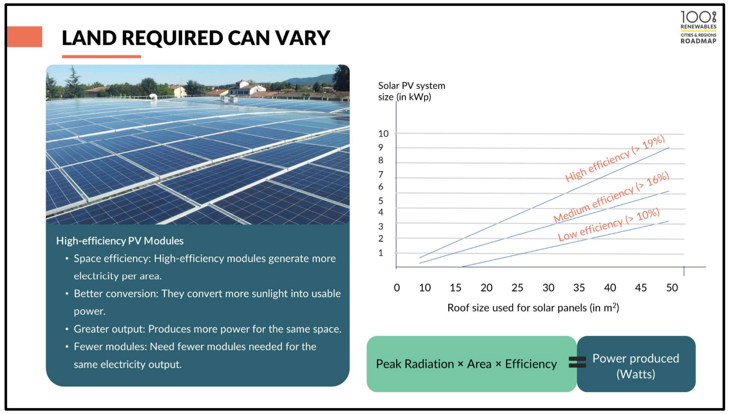

Silicon hetrojunction Thin-film (HJT) modules
Image: Waaree

1.First Generation: First-generation solar cells are made of crystalline silicon wafers and are the most widely used and commercially available solar cells. These cells have a high efficiency and are commonly seen in residential and commercial solar installations.

2.Second Generation: Second-generation solar cells include thin-film solar cells. These cells are typically thinner, lighter and cost-effective than first-generation cells, allowing for flexibility and different form factors. Second-generation solar cells offer advantages in manufacturing cost and adaptability to various applications.

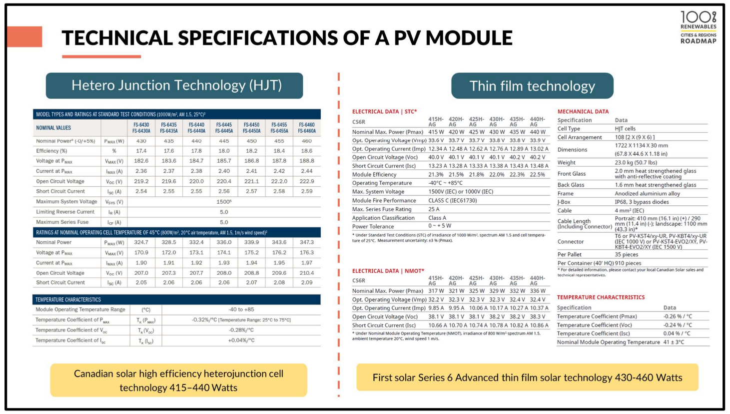
3.Third Generation: Third-generation solar cells are still in the research and development phase. They aim to overcome the limitations of first and second-generation cells by using new materials and innovative designs. These cells include technologies such as organic solar cells, dye-sensitized solar cells, and perovskite solar cells. Third-generation solar cells have the potential to achieve higher efficiency, lower production costs, and better integration into various surfaces.

Tunnel oxide passivated contact (TOP Con) solar cell technology is a new development with the potential to replace passivated emitter and rear contact (PERC) and high-efficiency passivated emitter, rear totally-diffused (PERT) solar panels.



High-efficiency modules in PV (photovoltaic) power plant installations require less space due to their ability to generate more electricity per unit of area. This higher efficiency means that these modules can convert a larger portion of the sunlight they receive into usable electricity, resulting in greater power output for a given footprint.

Because high-efficiency modules produce more power for the same amount of space, fewer modules are needed to generate a specific amount of electricity compared to lower-efficiency modules.



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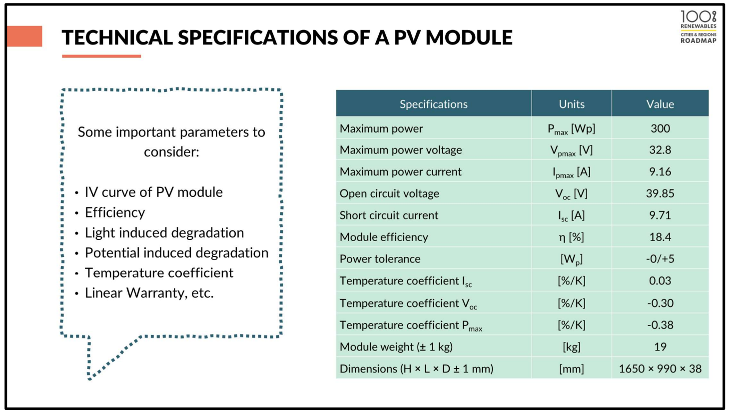

Specifications	Units	Value
Maximum power	P_{max} [Wp]	300
Maximum power voltage	V_{pmax} [V]	32.8
Maximum power current	I_{pmax} [A]	9.16
Open circuit voltage	V_{oc} [V]	39.85
Short circuit current	I_{sc} [A]	9.71
Module efficiency	η [%]	18.4
Power tolerance	[W_p]	-0/+5
Temperature coefficient I_{sc}	[%/K]	0.03
Temperature coefficient V_{oc}	[%/K]	-0.30
Temperature coefficient P_{max}	[%/K]	-0.38
Module weight (± 1 kg)	[kg]	19
Dimensions (H × L × D ± 1 mm)	[mm]	1650 × 990 × 38

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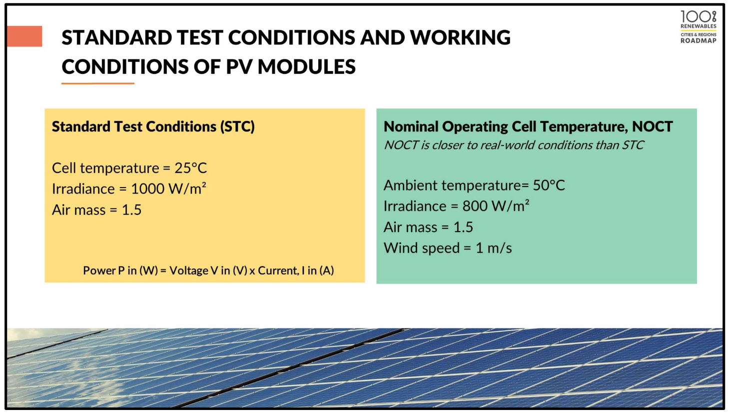
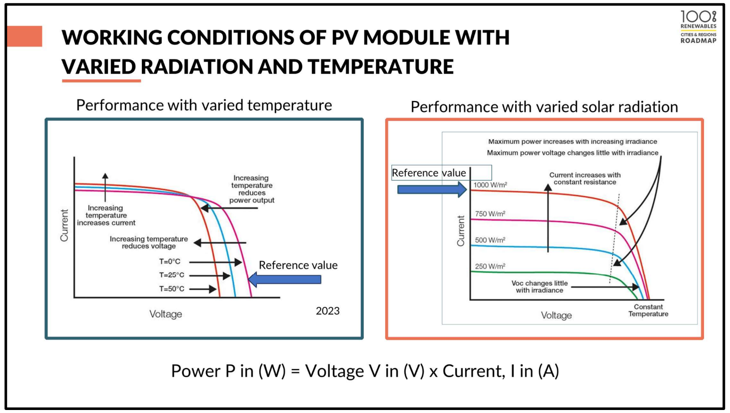


For system design, STC can only be used (not NOCT).
NOCT is useful for comparing two panels, with the same STC rating. A panel with a higher rated power at NOCT for example, will generally result in a higher performing panel.

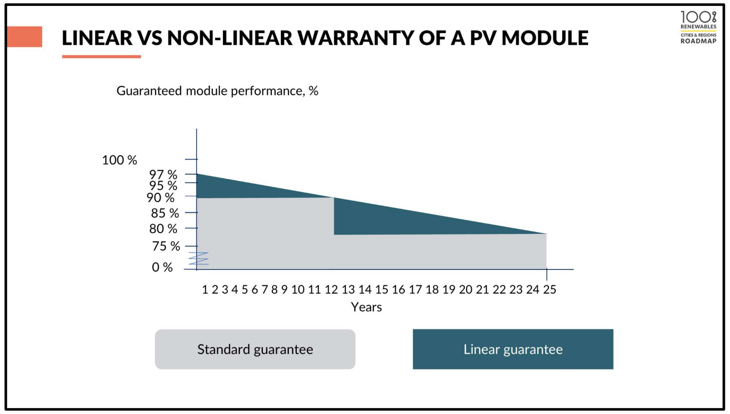
Example: A 100 Wp solar PV module has power tolerance of ±5 %, which means the module can produce 95 W and still be called a 100W module.
Range – 95 to 100 W, consider the lower side.
Similarly, efficiency will also have a tolerance under STC conditions.



There are various factors that can influence the performance of solar PV modules, including temperature and irradiance.

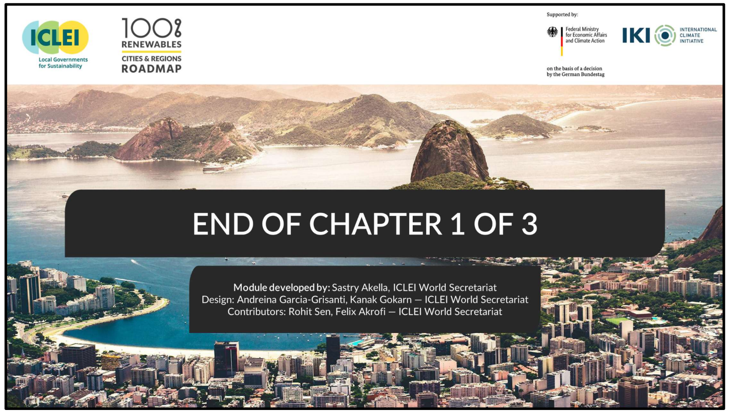
The open circuit voltage of a PV module varies with cell temperature. As the temperature increases, due to environmental changes or heat generated by internal power dissipation during energy production, the open circuit voltage (Voc) decreases. This in turn reduces the power output. The design of a solar PV system must take into account the PV module temperature coefficient, comparing the expected average cell temperature in its operational environment, against the STC data used to calculate the module output. In the same way, irradiance will also affect module performance, with a reduction of sunlight resulting primarily in a reduction in current and consequentially a reduced power output.

When comparing I-V curves measured in the field with predicted profiles, full consideration of these factors needs to be taken into account if the comparison is to produce meaningful results.



Linear Warranty: A linear warranty guarantees a consistent decrease in module performance over the warranty period. For example, if a PV module has a linear warranty of 25 years with a degradation rate of 0.5% per year, it means that the module's efficiency will decrease by 0.5% each year. At the end of the 25-year warranty period, the module's efficiency should not be lower than the specified percentage (e.g., 80% in this case).

Non-Linear Warranty: A non-linear warranty, on the other hand, does not assume a consistent degradation rate. Instead, it often provides a lower degradation rate in the initial years of the warranty period and a higher rate in the later years. For example, a non-linear warranty might offer a 10-year warranty with a lower degradation rate of 0.2% per year, followed by a higher degradation rate of 0.5% per year for the remaining 15 years.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INTERNATIONAL CLIMATE INITIATIVE
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