ENE425 Sustainable Energy and App Development

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Contents

Chapter 6

Sustainable energy. Solar Energy

6.1 Introduction

In this chapter we study the main characteristics of solar energy. We study the main features of solar energy and solar panels, and we analyze the future development of this technology. The chapter is organized as follows:

1. Watch a video to **discuss** some important aspects of wind energy.
2. Review the **history**, **evolution** and **types** of solar energy.
3. Study solar panels **technology**, solar cell efficiency and the architecture of solar panels at home.
4. Analyze the **key trends** in solar energy: Materials and modules; applications; operation and maintenance; end-of-life management.
5. **Questions** to summarize the chapter

6.2 Discussion

To motivate the chapter, we start by watching the video The Rise Of Solar Power

Based on that video, we discuss the next questions:

1. Which has been the **main driver** of the increase of solar energy in the last decade?
2. The video proposes **three sizes of solar installations**: Solar installations in houses, big-size installations and mid-size installations. Can you explain some of the advantages and disadvantages of each type of installation?
3. According with the video **big companies as Facebook or Apple** could play a crucial role fostering the investments in solar energy. Could you explain why?
4. According with the video, solar energy + storage could be more profitable than gas power plants. Which should be the **proportion of storage capacity over solar production** to make that solar energy becomes more profitable than gas power plants?

6.3 Solar Energy

This section is based in the information from three main sources:

- Solar Energy Industries Association.
- National Renewable Energy Laboratory (NREL).
- Solar Energy (wikipedia).

6.3.1 Introduction

Solar energy is radiant light and heat from the sun that is harnessed using a range of ever-evolving technologies such as **solar heating**, **photovoltaics**, **solar thermal energy**, **solar architecture**, **molten salt power plants** and **artificial photosynthesis**.

It is an essential source of renewable energy, and its technologies are broadly characterized as either **passive solar** or **active solar** depending on how they capture and distribute solar energy or convert it into solar power.

- **Active solar** techniques include the use of photovoltaic systems, concentrated solar power, and solar water heating to harness the energy.
- **Passive solar** techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air.

6.3.2 History

In 1878, at the Universal Exposition in Paris, Augustin Mouchot successfully demonstrated a **solar steam engine**, but couldn't continue development because of cheap coal and other factors.

In 1897, Frank Shuman, a US inventor, engineer and solar energy pioneer built a small demonstration solar engine that worked by reflecting solar energy onto square boxes filled with **ether**, which has a lower boiling point than water and were fitted internally with black pipes which in turn powered a steam engine. In 1908 Shuman formed the Sun Power Company with the intent of building larger solar power plants. He, along with his technical advisor A.S.E. Ackermann and British physicist Sir Charles Vernon Boys, developed an improved system using mirrors to reflect solar energy upon collector boxes, increasing heating capacity to the extent that water could now be used instead of ether. Shuman then constructed a full-scale steam engine powered by **low-pressure water**, enabling him to patent the entire solar engine system by 1912.

Shuman built the world's first solar thermal power station in Maadi, Egypt, between 1912 and 1913. His plant used parabolic troughs to power a 45–52 kilowatts engine that pumped more than 22,000 litres of water per minute from the Nile River to adjacent cotton fields. Although the outbreak of World War I and the discovery of cheap oil in the 1930s discouraged the advancement of solar energy, Shuman's vision, and basic design were resurrected in the 1970s with a new wave of interest in solar thermal energy.

6.3.3 Potential. Global Solar Atlas

The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere.Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. Most of the world's population live in areas with **insolation levels** of 150–300 watts/m2, or 3.5–7.0 kWh/m2 per day.

The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. This is more energy in **one hour** than the world used in one year.

Photosynthesis captures approximately 3,000 EJ per year in biomass. The amount of solar energy reaching the surface of the planet is so vast that in **one year** it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined.

The potential solar energy that could be used by humans differs from the amount of solar energy present near the surface of the planet because factors such as geography, time variation, cloud cover, and the land available to humans limit the amount of solar energy that we can acquire.

The World Bank and the International Finance Corporation, collectively The World Bank Group, have provided the **Global Solar Atlas** in addition to a series of global, regional and country data layers and poster maps, to support the scale-up of solar power in their client countries. This work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank and supported by 13 official bilateral donors. It is part of a global ESMAP initiative on Renewable Energy Resource Mapping that includes **biomass**, **small hydro**, **solar** and **wind**.

More information about Global Solar Atlas in their official webpage (link)

In World Bank (2020) can be found complete report about solar energy at a country level.

6.3.4 Solar energy production technologies

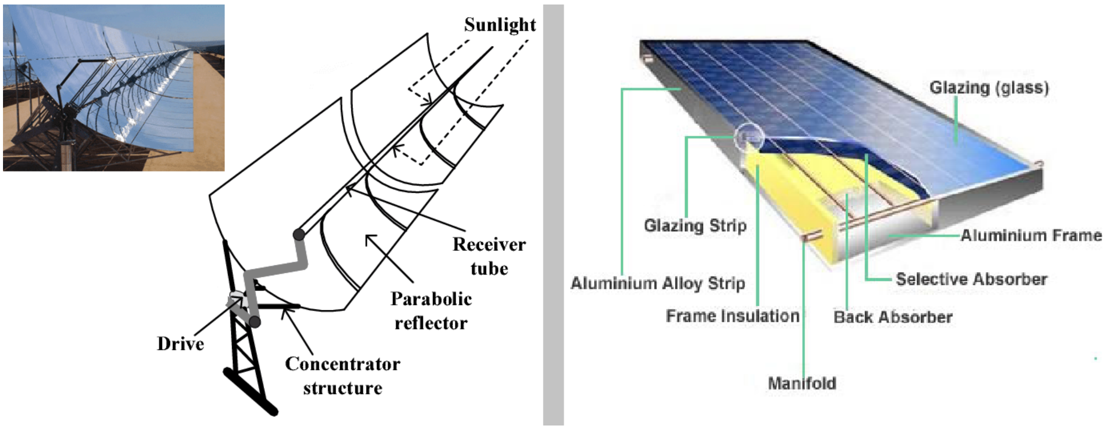
Solar thermal collector

A solar thermal collector collects heat by absorbing sunlight. The term "solar collector" commonly refers to a device for solar **hot water heating**, but may refer to large power generating installations such as solar parabolic troughs and solar towers or non water heating devices such as solar air heaters.

Solar thermal collectors are either **non-concentrating** or **concentrating**.

- In **non-concentrating collectors**, the aperture area (i.e., the area that receives the solar radiation) is roughly the same as the absorber area (i.e., the area absorbing the radiation). A common example of such a system is a metal plate that is painted a dark color to maximize the absorption of sunlight. The energy is then collected by cooling the plate with a working fluid, often water or glycol running in pipes attached to the plate (right-hand side, figure 6.1).
- **Concentrating collectors** have a much larger aperture than the absorber area. The aperture is typically in the form of a mirror that is focussed on the absorber, which in most cases are the pipes carrying the working fluid. Due to the movement of the sun during the day, concentrating collectors often require some form of solar tracking system, and are sometimes referred to "active" collectors for this reason (left-hand side, figure 6.1).

Figure 6.1: Solar thermal collectors



Non-concentrating collectors are typically used in residential and commercial buildings for space heating, while **concentrating collectors** in concentrated solar power plants generate electricity by heating a heat-transfer fluid to drive a turbine connected to an electrical generator.

More information about solar thermal collectors in the **solar thermal collector web-page** (wikipedia).

Photovoltaics

Photovoltaics (PV) is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. The photovoltaic effect is commercially utilized for electricity generation and as photosensors.

A photovoltaic system employs solar modules, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop mounted, wall mounted or floating. The mount may be fixed or use a solar tracker to follow the sun across the sky.

PV has become the cheapest source of electrical power in regions with a high solar potential, with price bids as low as 0.01567 US/kWh in 2020. Panel prices have dropped by the factor of 10 within a decade.

We analyze in detail photovoltaic energy in section 6.4.

Solar thermal energy

Solar thermal energy (STE) is a form of energy and a technology for harnessing solar energy to generate thermal energy for use in industry, and in the residential and commercial sectors.

Solar thermal collectors are classified by the United States Energy Information Administration as low-, medium-, or high-temperature collectors. Low-temperature collectors are generally unglazed and used to heat swimming pools or to heat ventilation air. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use.

High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric

Figure 6.2: Concentrated Solar Power

power production. Two categories include Concentrated Solar Thermal (CST) for fulfilling heat requirements in industries, and Concentrated Solar Power (CSP) when the heat collected is used for power generation (figure 6.2).

> More information about solar thermal energy in the **Concentrating Solar Power webpage** (The National Renewable Energy Laboratory (NREL)).

Solar architecture

Solar architecture is an architectural approach that takes in account the Sun to harness clean and renewable solar power. It is related to the fields of optics, thermics, electronics and materials science. Both active and passive solar housing skills are involved in solar architecture.

The use of flexible thin-film photovoltaic modules provides fluid integration with steel roofing profiles, enhancing the building's design. Orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air also constitute solar architecture.

Initial development of solar architecture has been limited by the rigidity and weight of standard solar power panels. The continued development of photovoltaic (PV) thin film solar has provided a lightweight yet robust vehicle to harness solar energy to reduce a building's impact on the environment.

> More information about solar architecture in the **solar architecture webpage** (wikipedia)

6.4 Solar panels

6.4.1 History solar cells.

In **1839**, the ability of some materials to create an electrical charge from light exposure was first observed by Alexandre-Edmond Becquerel. Though the premiere solar panels were too inefficient for even simple electric devices they were used as an instrument to measure light. The observation by Becquerel was not replicated again until **1873**, when Willoughby Smith discovered that the charge could be caused by light hitting selenium. After this discovery, William Grylls Adams and Richard Evans Day published "The action of light on selenium" in **1876**, describing the experiment they used to replicate Smith's results.

In **1881**, Charles Fritts created the first commercial solar panel, which was reported by Fritts as "continuous, constant and of considerable force not only by exposure to sunlight but also to dim, diffused daylight." However, these solar panels were very inefficient, especially compared to coal-fired power plants. In **1939**, Russell Ohl created the solar cell design that is used in many modern solar panels. He patented his design in 1941. In **1954**, this design was first used by Bell Labs to create the first commercially viable silicon solar cell. In **1957**, Mohamed M. Atalla developed the process of silicon surface passivation by thermal oxidation at Bell Labs. The surface passivation process has since been critical to solar cell efficiency.

6.4.2 How does solar energy work?

Photovoltaic modules use light energy (photons) from the Sun to generate electricity through the photovoltaic effect. Most modules use wafer-based crystalline silicon cells or thin-film cells. The structural (load carrying) member of a module can be either the top layer or the back layer. Cells must be protected from mechanical damage and moisture. Most modules are rigid, but semi-flexible ones based on thin-film cells are also available. The cells are connected electrically in series, one to another to the desired voltage, and then in parallel to increase amperage. The wattage of the module is the mathematical product of the voltage and the amperage of the module. The manufacture specifications on solar panels are obtained under standard condition which is not the real operating condition the solar panels are exposed to on the installation site.

A PV junction box is attached to the back of the solar panel and functions as its output interface. External connections for most photovoltaic modules use MC4 connectors to facilitate easy weatherproof connections to the rest of the system. A USB power interface can also be used.

Module electrical connections are made in series to achieve a desired output voltage or in parallel to provide a desired current capability (amperes) of the solar panel or the PV system. The conducting wires that take the current off the modules are sized according to the ampacity and may contain silver, copper or other non-magnetic conductive transition metals.

To understand how solar panels (and batteries) work, it is important to understand how electricity works, and to be familiar with the concepts of volts, amperes and watts. We explain both concepts in the next box:

1. **What is electricity?** For more information about electricity in the video (What is electricity? - Electricity Explained - (1)).

Based on the video, answer the next questions:

1. Can you explain which particles are in the **nucleus** of an element? An in the **orbit**?
2. Can the same element have a different number of **neutrons**? And **electrons**?
3. What does mean that an atom is **positively charged**? and **negatively charged**? How this is related to **electricity**?

2. To complete our understanding about how does electricity work, it is important to be familiar with the concepts of **volts, amperes and watts**. The next three videos provide intuitive explanations of those concepts:

- Electricity Explained: Volts, Amps, Watts, Fuse Sizing, Wire Gauge, AC/DC, Solar Power and more!
- What are VOLTs, OHMs and AMPs?
- What is an amp? - Electricity Explained - (2)

Based on the videos, answer the next questions:

1. Can you define the concept of **volt**? This is related with the concept of **pressure**
2. Can you define the concept of **ampere**? This is related with the concept of **wideness** of the wire
3. Can you define the concept of **watt**? This is related with the concept of **volume** of electricity
4. Can you define the concept of **ohm**? This is related with the concept of **resistance** of an electricity system
5. Why these concepts are **important**? these concepts are related to the **transport** of electricity (DC/AC); the **compatibility** of different systems; the **structure** of solar plants, wind farms...

3. How is electricity **transported**? Difference between Direct Current and Alternate Current (**DC/AC**). Edison vs. Tesla: link.

Based in the information from the previous box, we can explain how do **solar cells** and **solar panels** work:

4. To understand how **solar cells** and **solar panels** works, we use the next two videos:

- How do Solar cells work?
- How do solar panels work? - Richard Komp

Based on the previous videos and boxes, we explain the **photovoltaic process**:

1. Initially, the silicon atoms are in balance.

2. Electrons are injected in one layer of the silicon cell (**N-type doping**). some electrons are free to move (randomly).
3. Boron with three valance electrons are injected in the opposite layer of the silicon cell (**P-type doping**). There will be a free hole for each atom.
4. By placing together the N-type and the P-type layers is generated a **depletion region** with no free electrons.
5. **Photons enter in the depletion region** making that electrons move to the N-type layer and holes move to the P-type region. An electric field is created.
6. By **connecting the extremes of the two layers** by using a wire, an electric current is formed.
7. The **performance** of the electric cell **can be increased** by:
    a. Making the N-layer thin and heavily doped.
    b. Making the P-layer thick and poorly doped.
    c. The depletion region becomes thicker and that increase the electron-hole pairs increasing the electric field.
8. Solar panels can be connected by suing **parallel or series circuits**. This is related to the concepts of volts, amps, and watts and have important implications in the design of solar farms.
9. There are two types of solar cells depending on the alignment of silicon atoms: **Polycrystalline** and **monocrystalline**. Monocrystalline silicon cells perform better, but are more expensive.

6.4.3 Solar cell efficiency

Solar cell efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell.

The efficiency of the solar cells used in a photovoltaic system, in combination with latitude and climate, determines the annual energy output of the system. For example, a solar panel with 20% efficiency and an area of 1 m2 will produce 200 kWh/yr at Standard Test Conditions if exposed to the Standard Test Condition solar irradiance value of 1000 W/m2 for 2.74 hours a day. Usually solar panels are exposed to sunlight for longer than this in a given day, but the solar irradiance is less than 1000 W/m2 for most of the day. A solar panel can produce more when the sun is high in the sky and will produce less in cloudy conditions or when the sun is low in the sky. The sun is lower in the sky in the winter. In a high yield solar area like central Colorado, which receives annual insolation of 2000 kWh/m2/year, such a panel can be expected to produce 400 kWh of energy per year. However, in Michigan, which receives only 1400 kWh/m2/year, annual energy yield will drop to 280 kWh for the same panel. At more northerly European latitudes, yields are significantly lower: 175 kWh annual energy yield in southern England under the same conditions. Schematic of charge collection by solar cells. Light transmits through transparent conducting electrode creating electron hole pairs, which are collected by both the electrodes. The absorption and collection efficiencies of a solar cell depend on the design of transparent conductors and active layer thickness.

Several factors affect a cell's conversion efficiency value, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values. Because these parameters can be difficult to measure directly, other parameters are measured instead, including **quantum efficiency**, **open-circuit voltage (V_{OC}) ratio**, and **fill factor**. Reflectance losses are accounted for by the quantum efficiency value, as they affect "external quantum efficiency." Recombination losses are accounted for by the quantum efficiency, V_{OC} ratio, and fill factor values. Resistive losses are predominantly accounted for by the fill factor value, but also contribute to the quantum efficiency and V_{OC} ratio values. In 2019, the world record for solar cell efficiency at 47.1% was achieved by using multi-junction concentrator solar cells, developed at National Renewable Energy Laboratory, Golden, Colorado, USA. This is above the standard rating of 37.0% for polycrystalline photovoltaic or thin-film solar cells

For more information about **solar cell efficiency** visit:

- Solar cell efficiency (wikipedia)
- NREL cell efficiency

For more information about **panel efficiency** visit: NREL panel efficiency

Quantum efficiency:

The term quantum efficiency (QE) may apply to incident photon to converted electron (IPCE) ratio of a photosensitive device.

For more information about quantum efficiency visit: (Quantum efficiency (wikipedia)).

Open-circuit voltage (V_{OC}):

Open-circuit voltage (V_{OC}) is the difference of electrical potential between two terminals of a device when disconnected from any circuit. There is no external load connected. No external electric current flows between the terminals. Alternatively, the open-circuit voltage may be thought of as the voltage that must be applied to a solar cell or a battery to stop the current. It is sometimes given the symbol V_{OC}. In network analysis this voltage is also known as the Thévenin voltage.

For more information about open-circuit voltage (V_{OC}) visit: Open-circuit voltage (wikipedia).

Fill factor (FF):

The fill factor is the available power at the **maximum power point** (P_m) divided by the **open circuit voltage** (V_{OC}) and the **short circuit current** (I_{SC}):

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

For more information about fill factor (FF) visit: Solar cell efficiency (wikipedia).

6.4.4 Solar panels at home (hybrid solar system)

In hybrid solar systems, rooftop solar panels are connected to both a solar battery and the electric grid. This reduces your reliance on the utility while also providing backup power when needed. The architecture of an hybrid solar system is represented in figure 6.3. In the previous sections

Figure 6.3: Solar panels at home (hybrid solar system architecture)

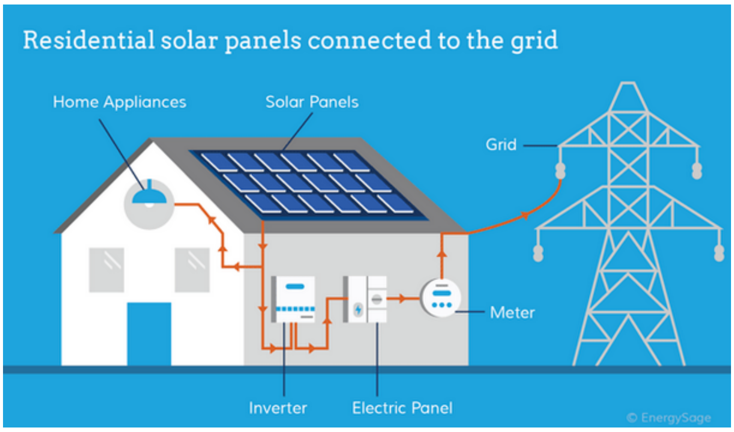
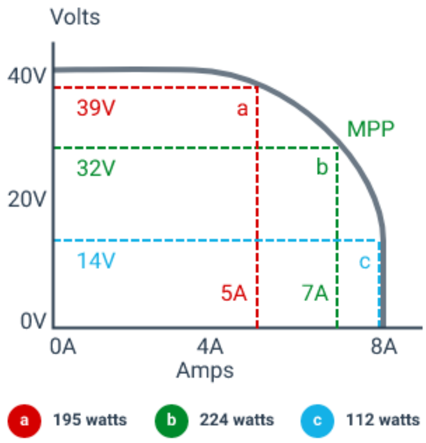


Figure 6.4: Maximum Power Point (MPP) curve



we have studied the main features of solar panels. In this section, we study the role of inverters, since they play an important role in hybrid solar systems.

Solar inverters are an integral part of every solar power system. They perform two key functions:

1. **DC to AC conversion:** All solar panels generate Direct Current (DC); a solar inverter is required to convert this into Alternating Current (AC), the form of electricity usable by your home.

2. **MPP tracking:** The operating conditions of solar panels - sunlight intensity and panel temperature - fluctuate throughout the day. This means that the possible solar panel voltage and current are always changing as well. In a process called Maximum Power Point (MPP) tracking, the solar inverter dynamically selects the exact combination of the two that will produce the most power (figure 6.4).

Types of solar inverter.

There are two categories to consider when deciding on the right solar inverter type: **the solar inverter technology**, and **the type of solar power system the inverter is for**.

1. **Solar inverter technology.**

- **String inverter:** A string inverter is a single, standalone unit that converts power from a whole string (or strings) of solar panels. String inverters are cheap and convenient, but tend to be the least efficient.
- **String inverter + power optimizer:** Power optimizers are attached to each individual panel. They perform MPP tracking at the module level; the optimized DC power is then sent to the string inverter for conversion into AC power. Combining string inverters with power optimizers will increase your cost but allow your system to handle issues like shading better.
- **Microinverter:** Microinverters are also attached to individual panels. They perform both MPP tracking and power conversion at the module level, allowing each panel to output usable AC power. They're good at dealing with shade (like power optimizers), and have the additional advantage of making your solar system easy to expand. They are, however, the most expensive type of inverter.

2. **The type of solar power system the inverter is for**. The solar inverter will need to be compatible with the solar system:

   - **Grid-tied inverters** are meant for grid-tied solar systems, the most common system type. They manage a two-way relationship with the grid, exporting solar power to it, and importing utility power from it as required.
   - **Hybrid inverters** are designed to work with hybrid solar systems (aka solar-plus-storage systems). They have the same functionality as a grid-tie inverter, but can also charge and draw power from a battery setup.
   - **Off-grid inverters** are used in off-grid solar systems, i.e. fully independent solar power systems, giving you back up power when the grid is down. An off-grid inverter requires a battery backup to function, and cannot be connected to the grid.

For a complete video that illustrates how **solar hybrid systems** work visit: Hybrid solar systems

For more information about **solar inverters** visit:

- Power inverter (wikipedia).
- Solar Reviews.

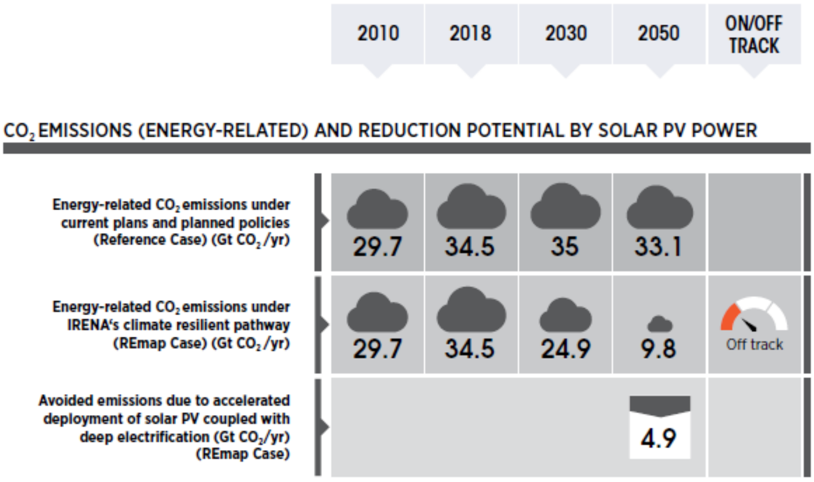
6.5 Future of solar photovoltaic. Deployment, investment, technology, grid integration and socio-economic aspects

6.5.1 Key findings

1. Accelerated deployment of renewables, combined with deep electrification and increased energy efficiency, can achieve over 90% of the energy-related **carbon dioxide (CO2) emission reductions** needed by 2050 to set the world on an energy pathway towards meeting the Paris climate targets. Among all low-carbon technology options, accelerated deployment of solar PV alone can lead to significant emission reductions of 4.9 gigatonnes of carbon dioxide (Gt CO2) in 2050, representing 21% of the total emission mitigation potential in the energy sector (figure 6.5).

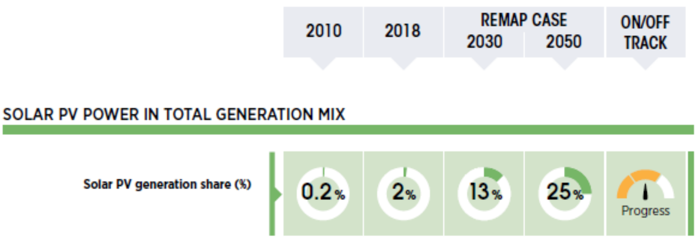
2. Achieving the Paris climate goals would require significant acceleration across a range of sectors and technologies. By 2050 solar PV would represent the second-largest power generation source, just behind wind power and lead the way for the transformation of the global electricity sector. **Solar PV would generate a quarter** (25%) **of total**

Figure 6.5: CO2 emissions (energy-related) and reduction potential by wind power



Source: IRENA (2019a)

Figure 6.6: Solar power in total generation mix



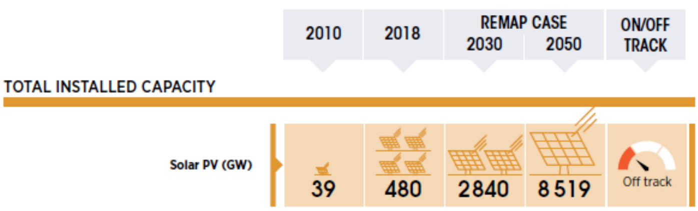
Source: IRENA (2019a)

electricity needs globally, becoming one of prominent generations source by 2050 (figure 6.6).

3. Such a transformation is only possible by significantly **scaling up solar PV capacity in next three decades**. This entails increasing total solar PV capacity almost sixfold over the next ten years, from a global total of 480 GW in 2018 to 2 840 GW by 2030, and to 8 519 GW by 2050 – an increase of almost eighteen times 2018 levels (figure 6.7).

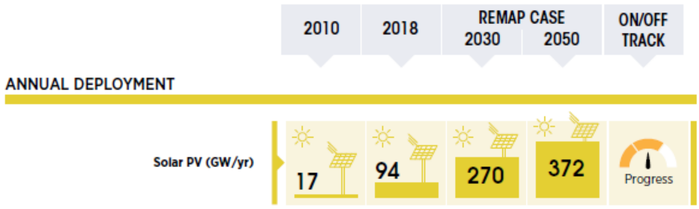
4. The solar PV industry would need to be prepared for such a significant growth in the market over the next three decades. In annual growth terms, an almost threefold rise in yearly solar PV **capacity additions** is needed by 2030 (to 270 GW per year) and a fourfold rise by

Figure 6.7: Solar total installed capacity



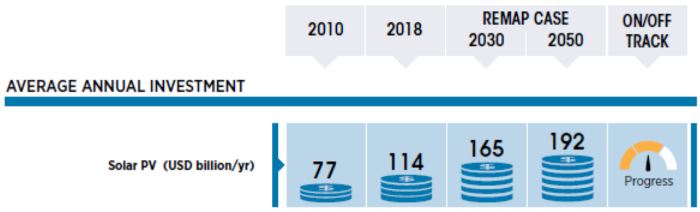
Source: IRENA (2019a)

Figure 6.8: Solar annual deployment



Source: IRENA (2019a)

Figure 6.9: Solar average annual investment



Source: IRENA (2019a)

2050 (to 372 GW per year), compared to current levels (94 GW added in 2018) (figure 6.8).

Thanks to its modular and distributed nature, solar PV technology is being adapted to a wide range of off-grid applications and to local conditions. In the last decade (2008–18), the globally installed capacity of off-grid solar PV has grown more than tenfold, from roughly 0.25 GW in 2008, to almost 3 GW in 2018. Off-grid solar PV is a key technology for achieving full energy access and achieving the Sustainable Development Goals.

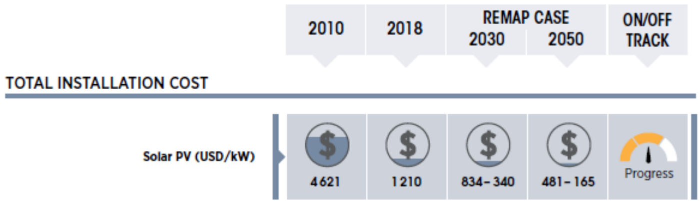
5. At a regional level, Asia is expected to drive the wave of solar PV capacity installations, being the world leaders in solar PV energy. Asia (mostly China) would continue to dominate solar PV power in terms of total installed capacity, with a share of more than 50% by 2050, followed by North America (20%) and Europe (10%).

6. Scaling up solar PV energy investment is critical to accelerating the growth of installations over the coming decades. Globally this would imply a 68% increase in **average annual solar PV investment** from now until 2050 (to USD 192 billion/yr). Solar PV investment stood at USD 114 billion/yr in 2018 (figure 6.9).

7. Increasing economies of scale and further technological improvements will continue to reduce the costs of solar PV. Globally, the **total installation cost of solar PV projects** would continue to decline in the next three decades. This would make solar PV highly competitive in many markets, with the average falling in the range of USD 340 to 834 per kilowatt (kW) by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018 (figure 6.10).

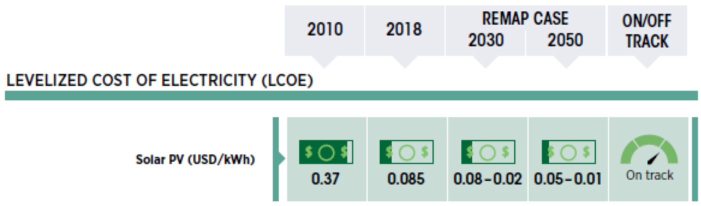
The **levelised cost of electricity (LCOE) for solar PV** is already competitive compared to all fossil fuel generation sources and is set to decline further as installed costs and performance continue to improve. Globally, the LCOE for solar PV will continue to fall from an average of USD 0.085 per kilowatt-hour (kWh) in 2018 to between USD 0.02 to 0.08/kWh by 2030 and between USD 0.014 to 0.05/kWh by 2050 (figure 6.11).

Figure 6.10: Solar total installation cost



Source: IRENA (2019a)

Figure 6.11: Solar levelised cost of electricity (LCOE)



Source: IRENA (2019a)

8. The solar PV industry is a fast-evolving industry, changing rapidly thanks to **innovations along the entire value chain** and further rapids reductions in costs are foreseen.

9. Taking advantage of the fast-growing solar PV capacity across the globe, several research projects and prototypes are ongoing to stimulate future market growth by exploring **innovative solar technologies at the application level**.

10. **Technological solutions** as well as enabling **market conditions** are essential to prepare future power grids to integrate rising shares of solar PV. To effectively manage large-scale variable renewable energy sources:

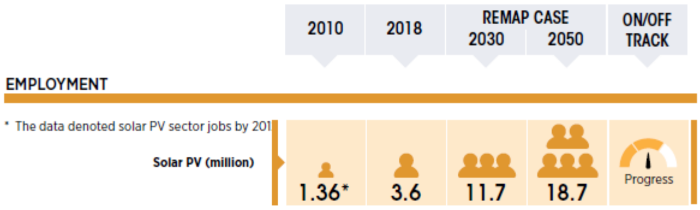
    - **Flexibility** must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems.
    - **Storage** (both electrical and thermal)
    - Increasingly, **flexible demand** (demand-side management and sector coupling).

11. **Innovative business models** and cost competitiveness of solar PV are driving the reductions in system prices. The deployment of **rooftop solar PV systems** has increased significantly in recent years, in great measure thanks to supporting policies, such as net metering and fiscal incentives which in some markets make PV more attractive from an economic point of view than buying electricity from the **grid-PV-hybrid minigrid**, **virtual power plants** and **utility Power Purchase Agreement (PPA)**.

A **virtual power plant (VPP)** is a cloud-based distributed power plant that aggregates the capacities of heterogeneous distributed energy resources (DER) for the purposes of enhancing power generation, as well as trading or selling power on the electricity market.

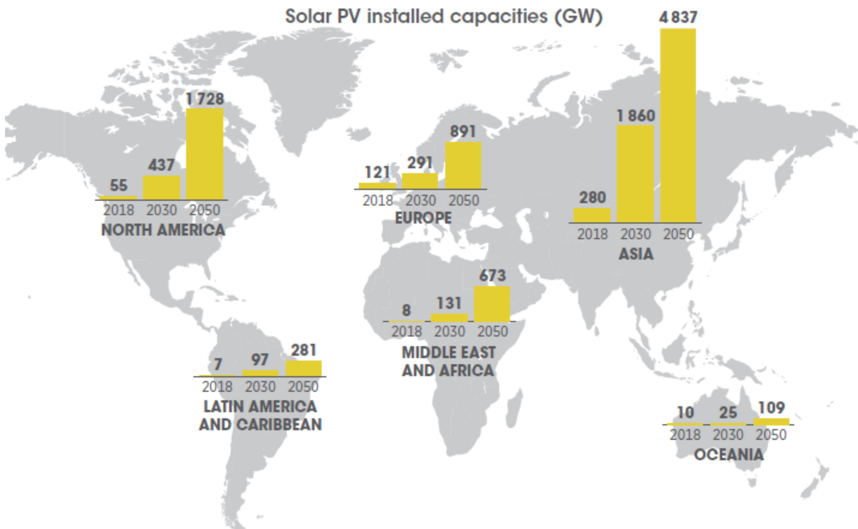
For more information about virtual power plants visit **(virtual power plant (wikipedia))**.

Figure 6.12: Solar employment



Source: IRENA (2019a)

Figure 6.13: Solar installed capacities by region



Source: IRENA (2019a)

12. If accompanied by sound policies, the transformation can bring **socio-economic benefits**. The solar PV industry would employ more than 18 million people by 2050, five times more than the 2018 jobs total of 3.6 million (figure 6.12).

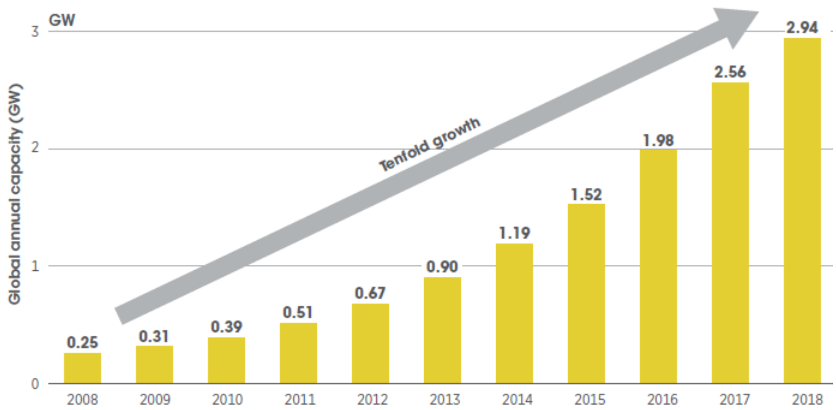
6.5.2 The evolution and future of solar PV markets

The global installed capacity of solar PV would rise six-fold by 2030 (2 840 GW) and reach 8 519 GW by 2050 compared to installations in 2018 (480 GW) (figure 6.7). To achieve the global installed capacity objectives, the global average annual solar PV investment needs to scale up by 68% until 2050 (USD 192billion/year) compared to 2018 investment (USD 114 billion/year) (figure 6.9).

Solar energy by region

The global solar market in 2018 was dominated by Asia, accounting for over half of the world's addition of solar capacity. The region's installed solar capacity reached 280 GW by the end of 2018, dominated by China with 175 GW. The European Union represented the world's second-largest solar PV market, mainly driven by Germany with 45 GW cumulative installed capacity by the end of 2018, followed by North America with 55 GW (figure 6.13), of which the United States accounted for 90%.

Figure 6.14: Solar global power capacity, off-grid solar PV, 2008–18



Source: IRENA (2019a)

Under the REmap scenario Asia would continue to lead global solar PV installations, with 65% of the total capacity installed by 2030 (figure 6.13). Within Asia significant deployment would be seen in China, where installed capacity is projected to reach around 1 412 GW by 2030. North America would have the second-highest installed solar PV capacity, reaching 437 GW by 2030, with more than 90% of these installations in the United States.

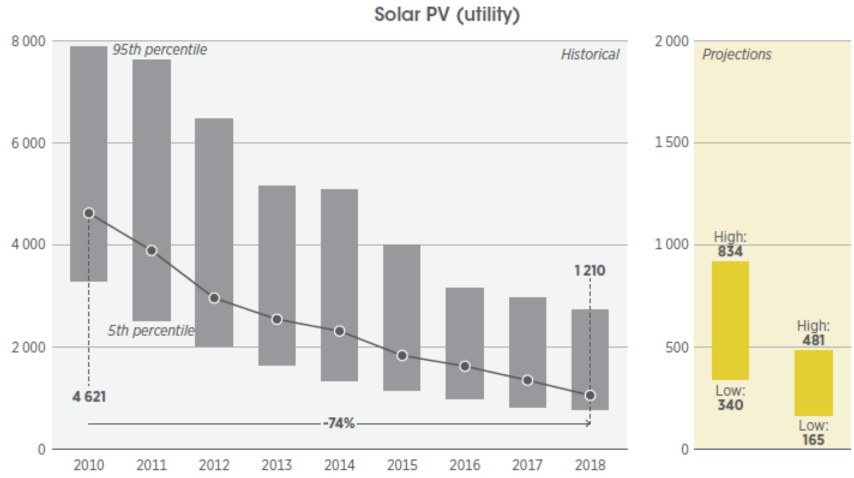
Europe would represent the third-highest region by 2030, with 291 GW of solar PV capacity installed. A similar picture is expected on a 2050 horizon, when Asia would still dominate the scene at almost half of the cumulative global capacity installed (4 837 GW). Within Asia, China would dominate the scene, with a compound annual growth rate (CAGR) of 9% after 2018 leading to projected capacity of around 2 803 GW by 2050. North America would still have the second-largest installed capacity, reaching 1 728 GW by 2050, with the United States still dominating the region. Europe could still hold the third place among regions in 2050, with 891 GW of total solar PV capacity installed. More than 22% of these installations would be in Germany, where the installed capacity is projected to reach around 200 GW by 2050. Even though installed capacity may remain highest in Asia, North America and Europe, market growth seems likely to shift to other regions, with large markets also expected to emerge in South America and Africa.

Solar PV for off-grid solutions

Off-grid (or stand-alone) applications are typically used where there is no electric grid or when the cost of connecting to the grid is high. Applications are normally smaller than other system types and are often used for small-scale projects in rural areas, as a solution in developing countries, as well as for residential households willing to disconnect from the grid (typically not the most economic or efficient option) (IRENA, 2017).

Thanks to its modular and distributed nature, solar PV can be adapted to a wide range of off-grid applications and to local conditions, ranging from lanterns to household systems to village-powering mini-grids. In the last decade (2008–18), the global installed capacity of off-grid solar PV has grown more than ten times, from roughly 0.25 GW in 2008, to 2.94 GW in 2018 (figure 6.14). Currently, off-grid solar solutions constitute about 85% of all off-grid energy installations, comprising of solar home systems (about 50%) and solar lanterns/solar lighting systems (about 35%). This is followed by rechargeable batteries (10%) and mini-grids (2%) (World Bank, 2020a).

Figure 6.15: Solar PV cost evolution



Source: IRENA (2019a)

Strong business case for a significant future solar PV market

The breakthrough in renewables capacity additions over past few years has largely been achieved due to significant cost reductions driven by enabling government policies, including deployment policies, research and development funding, and other policies that have supported the development of the industry in leading countries.

Solar PV is emerging as one of the most competitive sources of new power generation capacity after a decade of dramatic cost declines. A decline of 74% in total installed costs was observed between 2010 and 2018 (figures 6.10 and 6.15).

The levelized cost of electricity for solar PV is already competitive now compared to all generation sources (including fossil fuels) and is expected to decline further in the coming decades, falling within the range of USD 0.02 and 0.08/kWh by 2030 and USD 0.014 0.05/kWh (figure 6.11).

6.5.3 Technological solutions and innovations to integrate rising shares of solar PV power generation

The variable nature of the solar and wind resources will require significant changes to the way the power system operates as the share of variable renewable energy (VRE) reaches high levels in different markets. We have studied those changes in sections **??** and **??**.

6.5.4 Future solar PV trends

Overview

The main **components** of a solar plant that decision makers may consider manufacturing domestically are the solar cells, solar modules, inverters, trackers, mounting structures and general electrical components (IRENA, 2017).

<u>Solar modules.</u>

The global market for solar module production is highly diversified, although some consolidation among manufacturers is taking place. The majority of the market is held by **crystalline**

Figure 6.16: Solar value chain

Source: IRENA (2019a)

silicon (c-Si) module manufacturers, thanks to the maturity of the technology and the lower investment costs due to the fall in the price of polysilicon – its raw material. The **thin-film market**, by comparison, has fewer manufacturers and relatively few players have been able to consistently commercialise these products.

Solar inverters.

The market for solar inverters is currently in a growth phase, the rising demand for power together and various global initiatives to encourage the implementation of renewable smart grids being the main drivers behind this development.

In 2018 the Asia-Pacific region dominated the market for solar inverters, accounting for 71% of new installations globally. At a country level, China, the United States and India were the top countries, collectively accounting for approximately 70% of global PV inverter installations in 2018.

The next subsections explore the innovation progress in the solar PV industry in materials, module manufacturing, applications, operation and maintenance, and in ways of decommissioning panels and managing their end of- life stage (figure 6.16).

Materials and module manufacturing

Materials.

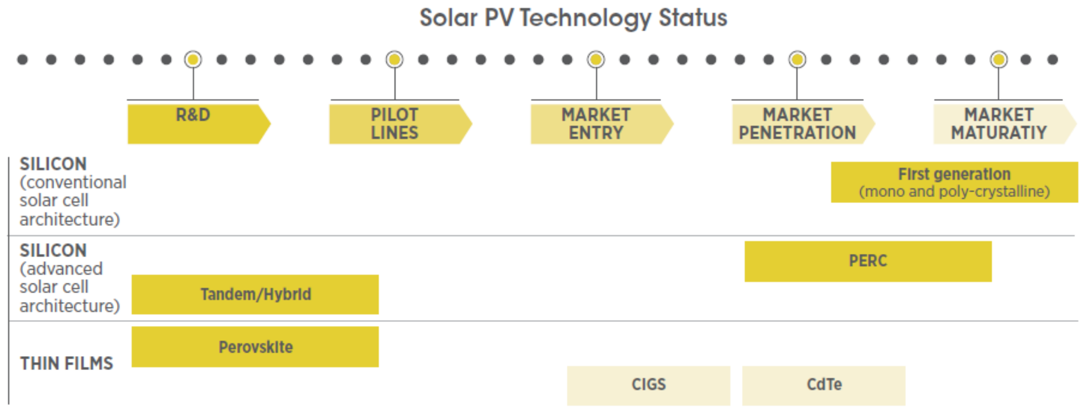
First-generation technologies, which have been evolving along the whole PV value chain, still account for the majority of global annual production (Fraunhofer ISE, 2019). **Tandem and perovskite technologies** also offer interesting perspectives, but in the longer term due to barriers that still need to be addressed and overcome (durability, price).

The figure 6.17 gives an overview of the PV technologies and concepts under development.

1. **Silicon – conventional solar architecture**. Crystalline silicon (c-Si) panels belong to the first generation solar PV panels and they hold 95% share of worldwide PV production (Fraunhofer ISE, 2019). The economies of scale of its main material, silicon, make c-Si more affordable and highly efficient compared to other materials.

   The average module efficiency in 2006 was 13.2% for multi crystalline PV panels and 14.7% for mono crystalline PV panels and since then has increased steadily, reaching 17% and 18% respectively.

Figure 6.17: Solar PV technology status



Notes: CIGS = copper-indium-gallium-diselenide; CdTe = cadmium telluride. PERC = passivated emitter and rear cell/contact

Source: IRENA (2019a)

However, despite the high-efficiency level of this first-generation PV technology, there remains a lot of **scope for improvement**, including:

- Lowering the cost of c-Si modules for better profit margins.
- Reducing metallic impurities, grain boundaries, and dislocations.
- Mitigating environmental effects by reducing waste.
- Yielding thinner wafers through improved material properties.

2. **Silicon - advanced solar architecture.**

   (a) **PERC.** A PERC cell uses advanced silicon cell architecture. PERC cells are not much different in construction from a typical monocrystalline PV cell; however, the **key improvement is the integration of a back-surface passivation layer**, which is a layer of material on the back of the cells that is able to improve the cell's efficiency. In fact, the passivation layer **increases the overall cell efficiency** in three key ways:

   - It reduces electron recombination.
   - It increases absorption of light.
   - It enables higher internal reflectivity.

   The efficiency gain of implementing PERC architecture for monocrystalline cells is about 0.8% to 1% absolute, while the boost for multicrystalline cells is a little lower, at 0.4% to 0.8%.

   (b) **Tandem/hybrid cells. Tandem solar cells are stacks of individual cells, one on top of the other**, that each selectively convert a specific band of light into electrical energy, leaving the remaining light to be absorbed and converted to electricity in the cell below. Emerging PV technologies comprise several types of tandem cells that can be grouped mainly depending on materials used (e.g. organic, inorganic, hybrid) as well as on the kind of connection used. The tandem cell approach has been used to fabricate the world's most efficient solar cells that can convert 46% of sunlight into electricity.

3. **Thin-film.** Thin film technologies are often referred to as second-generation solar PV. The semiconducting materials used to produce thin-film cells are only a few micrometres

thick (IRENA, 2016).

These technologies generally include **two main families**:

- **Silicon-based thin film** (amorphous [a-Si] and micromorph silicon [a-Si/c-Si].
- **Non-silicon based** (perovskites, cadmium telluride [CdTe] and copper-indium-gallium diselenide [CIGS]).

These technologies can be cheaper to produce, as such they are being deployed on a commercial scale, but they have historically had lower efficiency levels.

(a) **Perovskites.** Currently most solar cells are made from silicon; however, an area to watch is the development of new materials for solar cells. In particular, one of the most promising material is perovskites, a type of mineral very good at absorbing light. The first perovskite PV devices in 2009 converted just 3.8% of the energy contained in sunlight into electricity. However, because crystals are very easy to make in the lab, their performance was quickly improved and by 2018 their efficiency had soared to 24.2%, set by researchers in the United States and the Republic of Korea — close to silicon's lab record of 26.7%. However, perovskite efficiency records have only been set on tiny samples.

    Perovskites still face some significant **challenges** before achieving market maturity.

    - One of the main ones is **durability**. Because the crystals dissolve easily, they are not able to handle humid conditions and need to be protected by moisture through encapsulation, for instance through an aluminium oxide layer or sealed glass plates.
    - Another challenge for scientists is that, whist they have been able to achieve high **efficiency** levels with small perovskites, they have not been able to replicate such effect with **larger cell areas**.

(b) **Copper indium gallium selenide cells (CIGS).** CIGS cells have achieved high efficiency levels (22.9%) comparable to commercial crystalline silicon (Fraunhofer ISE, 2019). However, **manufacturing** CIGS cells can be difficult due to the rarity of indium, as well as to the complex stoichiometry and multiple phases to produce them, restricting large-scale production in the near term.

(c) **Cadmium telluride (CdTe).** Cadmium telluride cells have achieved an efficiency of 21%, very similar to CIGS, and are characterised by good absorption and low energy losses (Fraunhofer ISE, 2019). CdTe solar cells are made through low temperature processes, which makes their production very flexible and affordable. CdTe currently has the largest market share of all thin-film technologies.

Advanced module technologies.

1. **Bifacial solar cells.** Bifacial solar cells have been under development for decades and their manufacturing process can be considered one of the most advanced for solar modules today. **Bifacial cells are capable of generating electricity not only from sunlight received on their front, but also from reflected sunlight received on the reverse side of the cell**.

   Bifacial operation, facilitated by the uptake of PERC (which is driving the bifacial boom), offers a near term effective efficiency increase of $5 - 20\%$ relative by increasing the energy output from a given module area.

2. **Multi-busbars.** Silicon solar cells are metallised with thin strips printed on the front and rear of a solar cell; these are called busbars and have the purpose of conducting the electric direct current (DC) power generated by the cell. Older solar cells typically had two busbars; however, the industry has moved towards **higher efficiencies** and busbars have increased to three (or more) in most solar cells.

   The increased number of busbars has several **advantages**:

   - First is the high potential for cost saving due to a reduction in metal consumption for front facing metallisation (Braun,S., 2013).
   - Second, series resistance losses are reduced by employing thin wires instead of regular ribbon.
   - Third, optimising the width of the busbars leads to an additional rise in efficiency.
   - Finally, multi-busbar design is highly beneficial for bifacial technology, especially for improving the bifaciality for PERC cells of 90%.

3. **Solar shingles.** Solar shingles are a type of solar energy solution where solar panels are designed to look like conventional roofing materials, while also producing electricity.

   Solar shingles have several **advantages**.

   - First, a key advantage is that they eliminate the need for ribbon, connecting cells like roof tiles.
   - Second and related to the removal of the ribbon, module aesthetics are improved, as the panels are homogeneously coloured.
   - Third, unlike a standard cell, cells for shingle modules have busbars at opposite ends and cells are sliced into several strips, which reduces the current and consequently the load on fingers (metallic super-thin grid fingers, perpendicular to the busbar, collecting the generated DC current and delivering it to the busbars).

Applications: Beyond fields and rooftops

Taking advantage of the rapidly growing solar PV capacity across the globe, several research projects or prototypes are underway to stimulate future market growth, exploring innovating solar technologies at the application level. The major developments are as follows.

1. **Floating PV.** Floating PV is an exciting emerging market, with the potential for rapid growth. According to a World Bank report, as of the end of September 2018 the global cumulative installed capacity of floating PV plants was 1.1 GW (World Bank, 2018).

   Demand for floating PV is expanding, especially on islands (and other land-constrained countries), because the cost of water surface is generally lower than the cost of land. Floating solar is particularly well suited to Asia, where land is scarce but there are many hydroelectric dams with existing transmission infrastructure.

2. **Building-integrated PV panels**. Building-integrated PV (BIPV) solar panels are an application also known as solar shingles (see above). BIPV solutions have several **advantages**.

   - First, they are **multifunctional** as they can be adapted to a variety of surfaces (e.g. roofs, windows, walls) as an integrated solution, providing both **passive** and **active** functions. A key passive function is thermal and acoustic insulation, as with any other construction material, which is complemented by a unique active function – the PV component – which generates renewable electricity that can be directly used in the building.

- Other functions, also unique to BIPV systems, include the possibility of **real-time thermal or lighting regulation**.

An EU-funded project, **PVSITES**, is currently developing a new generation of solar panels that can be part of traditional house elements like roofs, windows and glass façades. The project is creating BIPV solar panels alongside building energy management systems and architectural design tools. The aim is to demonstrate the integration of effective energy production with good design to create cost-effective buildings. The project is also developing design software tools for architects to help them better integrate these novel PV products in their designs.

3. **Solar trees.** Solar trees work very much like real ones, as they have leaf-like solar panels connected through metal branches using sunlight to make energy. Solar trees can be seen as complementary to rooftop solar systems.

4. **Solar carports.** Solar carports are ground-mounted solar panels that are installed so that parking lots and home driveways can be laid underneath to form a carport. They have been a very popular alternative or supplement to the classic rooftop systems.

5. **Solar PV-Thermal systems.** Solar PV-T systems combine the production of both kinds of solar energy in one collector. It consists of a solar PV panel combined with a cooling system where cooling agent (water or air) is circulated around the PV panels to cool the solar cells, such that the warm water or air leaving the panels may be used for domestic applications such as domestic heating.

   This cooling system for PV panels has a **twofold benefit**:

   - It significantly increases the efficiency of PV systems in the electricity sector.
   - It also allows for the capture of the heat from the PV system for use in space, water and process heating in a range of industries and applications.

   In fact, PV modules normally use 15˘20% of the incoming solar energy, while the rest is lost in the form of heat. The PV-T technology aims to increase the overall efficiency by using this “lost” energy to heat air or water and at the same time cool the PV cells by taking away the heat from the panel.

6. **Agrophotovoltaic (APV).** Agrophotovoltaic (APV) combines solar PV and agriculture on the same land and consists of growing crops beneath ground-mounted solar panels. Although the concept was proposed long ago, it has received little attention until recently, when several researchers have confirmed the benefits of growing crops beneath the shade provided by the solar panels.

   Cultivating crops underneath reduces the temperature of the panels, as they are cooled down by the fact that the crops below are emitting water through their natural process of transpiration.

Operation and maintenance

<u>Smart PV power plant monitoring.</u>

1. **Drones for intelligent monitoring of solar PV.**

   The exponential growth seen in PV markets has led to the development of large-scale power plants, which has increased demands for better tools for inspection and monitoring. Normally, the process of monitoring is done by conducting manual inspections; however, these can be replaced by intelligent systems, such as drones. Drones are becoming highly suited to the solar industry due to a wide range of surveillance and monitoring capabilities, the possibility of long-range inspection and easy control.

2. **PV plant power output forecasting.**

   Currently simulation models and meteorological forecasting resources for specific PV plants are well proven technologies. Algorithms that are able to match weather forecasts with PV plant characteristics are being used to predict energy production on an hourly basis for at least the next 48 hours.

3. **Smart PV plant monitoring.**

   Innovations in monitoring systems aim to improve the ability to identify the root causes of performance problems that lead to plant underperformance and unavailability.

<u>Retrofit coatings for PV modules.</u>

1. **Solar power coolant.**

   While progress is being made on increasing efficiency and maximising power output of solar PV, difficulties remain in addressing the need to keep solar PV modules cool, because their performance and lifetime are reduced by the heat of the sun.

   PV-Thermal systems are currently one of the most popular methods for cooling PV panels. Other techniques include the use of water.

   Other approaches include applying a **transparent coating of patterned silica** to solar cells to capture and radiate heat from infrared rays back to the atmosphere. This was found to improve absolute cell efficiency by more than 1%.

2. **Anti-soiling solutions.**

   Regular module washing is common practice in PV plants, as soiling can significantly and negatively impact their performance. For instance, in Europe soiling causes an average 2% power loss with significant rain, which can go as high as 11% in non rainy environments. In this context, **several anti-soiling solutions are being implemented**.

   - First, **robotic panel cleaning technology** consists of robots moving along the array of panels.
   - Second, **sprinkler systems** consist of a water filtration system and a soap dispensing system, mainly used in very dry areas to keep the panels clean with the same cleaning effect as rain.

End-of life management of solar PV

Despite the growth of solar PV and its bright future, the sun sets on even the best panels. As the global PV market increases, so will the need to prevent the degradation of panels and manage the volume of decommissioned PV panels. The sections below explore innovative and alternative ways to reduce material use and module degradation, and opportunities to reuse and recycle PV panels at the end of their lifetime.

The framework of a **circular economy** and the classic waste reduction principles (reduce, reuse and recycle) can also be applied to PV panels.

1. **Reduce: Material savings in PV panels.**

   The best option is to increase the efficiency of panels by reducing the amount of material used. Whilst the mix of materials has not changed significantly, efficient mass production, material substitutions and higher-efficiency technologies are already happening thanks to strong market growth, scarcity of raw materials and reduction of PV panel prices.

2. **Reuse: Repairing PV panels.**

   Most PV systems were installed in the last six years. A six-year-old panel today has aged by an equivalent of 20% of its expected average lifetime of 30 years (IRENA, 2016). If flaws and imperfections are discovered during the early phase of a PV panel's life, customers can claim guarantees for repair or replacement and insurance companies may be involved to compensate for some or all of the repair/replacement costs.

3. **Recycle: Decommissioning and treatment of PV panels.**

   The value creation stemming from end-of-life PV management involves:

   - **Unlocking raw materials and their value.** The extraction of secondary raw materials from end of- life PV panels could create important value for the industry. PV panels have an average lifetime of 30 years, and they build up a large stock of embodied raw materials that will not become available for recovery for some time. As such, recovered raw material can be injected back into the economy and serve to produce new PV panels or other products, thus increasing the security of future PV supply. Rapidly growing panel waste volumes over time will stimulate a market for secondary raw materials originating from end-of-life PV panels.
   - Creating new industries and jobs in the PV sector.

6.6 Solar energy and development

Solar empowerment across countries

United Nations Development Programme. Clean energy

6.7 Some questions to summarize the chapter

1. Which are the main **solar energy production technologies**?

1. **Solar thermal collector**.

A solar thermal collector collects heat by absorbing sunlight. The term "solar collector" commonly refers to a device for solar **hot water heating**.

Solar thermal collectors are either **non-concentrating** or **concentrating**

- In **non-concentrating collectors**, the aperture area (i.e., the area that receives the solar radiation) is roughly the same as the absorber area (i.e., the area absorbing the radiation) (right-hand side, figure below)
- **Concentrating collectors** have a much larger aperture than the absorber area. The aperture is typically in the form of a mirror that is focussed on the absorber, which in most cases are the pipes carrying the working fluid (left-hand side, figure below)

2. **Photovoltaics**.

Photovoltaics (PV) is the **conversion of light into electricity** using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry.

A photovoltaic system employs solar modules, each comprising a number of **solar cells**, which generate electrical power.

PV installations may be ground-mounted, rooftop mounted, wall mounted or floating. The mount may be fixed or use a solar tracker to follow the sun across the sky.

PV has become the **cheapest source of electrical power in regions with a high solar potential**, with price bids as low as 0.01567 US/kWh in 2020. **Panel prices have dropped by the factor of 10 within a decade**.

3. **Solar thermal energy**.

Solar thermal energy (STE) is a form of energy and a technology for harnessing **solar energy to generate thermal energy** for use in industry, and in the residential and commercial sectors.

Solar thermal collectors are classified by the United States Energy Information Administration as **low-**, **medium-**, or **high-temperature collectors**.

Low-temperature collectors are generally unglazed and used to heat swimming pools or to heat ventilation air. **Medium-temperature collectors** are also usually flat plates but are used for heating water or air for residential and commercial use.

High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric power production.

2. Can you define the **concepts** of volts, amps and watts?
   How those concepts can help us to understand **electricity production in solar cells and solar panels**?

To answer this question, it is necessary to watch the video in one of the pink boxes in the chapter.

3. How does the **photovoltaic process work** to produce electricity?

Based on the information from the previous question, the **photovoltaic process works** through the following broad steps:

a. The silicon photovoltaic solar cell **absorbs solar radiation**

b. When the sun's rays interact with the silicon cell, **electrons begin to move**, creating a flow of electric current

c. **Wires** capture and feed this direct current (DC) electricity to a solar **inverter** to be converted to alternating current (AC) electricity

4. Can you explain the concept of **solar efficiency**? Which are the **parameters used to measure solar efficiency**?

Solar cell efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell.

Several factors affect a cell's conversion efficiency value, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values.

Because these parameters can be difficult to measure directly, other parameters are measured instead, including **quantum efficiency**, **open-circuit voltage (V_{OC}) ratio**, and **fill factor**.

The architecture of an hybrid solar system is represented in the figure below. Above, we have studied the main features of solar panels. Therefore, we study the role of **inverters**, since they play an important role in hybrid solar systems

5. In an **hybrid solar system**? Which is the role of the **inverters**?

Solar inverters perform **two key functions**:

a. **DC to AC conversion:** All solar panels generate Direct Current (DC); a solar inverter is required to convert this into Alternating Current (AC), the form of electricity usable by your home.

b. **MPP tracking:** The operating conditions of solar panels - sunlight intensity and panel temperature - fluctuate throughout the day. This means that the possible solar panel voltage and current are always changing as well. In a process called Maximum Power Point (MPP) tracking, the solar inverter dynamically selects the exact combination of the two that will produce the most power

6. Which should be the **PV trends** to achieve the Paris agreement?

a. **Solar PV and CO2**: Deployment of solar PV alone can lead to **significant emission reductions** of 4.9 gigatonnes of carbon dioxide (Gt CO2) in 2050, representing 21% of the total emission mitigation potential in the energy sector.

b. **PV production**: **Solar PV would generate a quarter** (25%) **of total electricity needs globally**, becoming one of prominent generations source by 2050.

c. **PV capacity**: Solar PV capacity should increase almost sixfold over the next ten years, from a global total of 480 GW in 2018 to 2 840 GW by 2030, and to 8 519 GW by 2050 – an increase of almost eighteen times 2018 levels.

d. **Regional highlights**
Asia (mostly China) would continue to dominate solar PV power in terms of total installed capacity, with a share of more than 50% by 2050, followed by **North America** (20%) and **Europe** (10%).

e. **PV investments**: The **average annual solar PV investment** should increase 68% from now until 2050 (to USD 192 billion/yr). Solar PV investment stood at USD 114 billion/yr in 2018.

f. **Installation cost**: The **total installation cost of solar PV projects** would continue to decline in the next three decades. This would make solar PV highly competitive in many markets, with the average falling in the range of USD 340 to 834 per kilowatt (kW) by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018.

g. **Levelised cost**: The **levelised cost of electricity (LCOE) for solar PV** is already competitive compared to all fossil fuel generation sources and is set to decline further as installed costs and performance continue to improve. The LCOE for solar PV will continue to fall from an average of USD 0.085 per kilowatt-hour (kWh) in 2018 to between USD 0.02 to 0.08/kWh by 2030 and between USD 0.014 to 0.05/kWh by 2050.

7. Which are the main innovations in **materials** to manufacture PV?

a. **Silicon – conventional solar architecture**.

b. **Silicon - advanced solar architecture. PERC.**

c. **Silicon - advanced solar architecture. Tandem/hybrid cells.**

d. **Thin-film.**

8. Which are the main innovations in **modules** to manufacture PV?

a. **Bifacial solar cells.**

b. **Multi-busbars.**

c. **Solar shingles.**

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