Ch6. Sustainable Energy: Solar Energy

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Spring 2022 - NHH

Chapter outline

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

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, which should be the **proportion of storage capacity over solar production** to make that solar energy becomes more profitable than gas power plants?

Solar energy. History

In 1878, at the Universal Exposition in Paris, Augustin Mouchot successfully demonstrated a **solar steam engine**

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

In 1912 Frank Shuman created the same steam engine with **water**

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

Solar energy. Potential

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

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

Solar energy. Global Solar Atlas

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.

Solar energy. Technologies

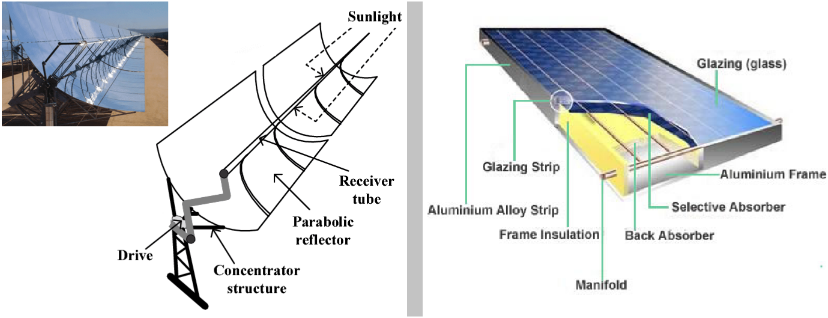
1. **Solar thermal collector**

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)

Solar energy. Technologies

Figure: Solar thermal collectors



Solar energy. Technologies

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**

We analyze in detail photovoltaic energy in the **solar panel section**, and in the **future of solar photovoltaic section**

Solar energy. Technologies

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 (figure below)

Solar energy. Technologies

Figure: Solar thermal energy

Solar panels. History

In **1839**, the ability of **some materials to create an electrical charge from light exposure** was first observed by Alexandre-Edmond Becquerel

The observation by Becquerel was not replicated again until **1873**, when Willoughby Smith discovered that **the charge could be caused by light hitting selenium**

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"

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**, Russell's 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

Solar panels. How does solar energy work?

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**?

Solar panels. How does solar energy work?

2. The next three videos provide intuitive explanations of the concepts of **volts, amperes and watts**:

- 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

Solar panels. How does solar energy work?

Based on the videos, answer the next questions:

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.

Solar panels. How does solar energy work?

Based in the information from the previous boxes, 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

Solar panels. How does solar energy work?

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.

Solar panels. How does solar energy work?

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.

Solar panels. 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

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

In **Michigan**, which receives only 1400 kWh/m2/year, annual energy yield will drop to 280 kWh for the same panel

Solar panels. Solar cell efficiency

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**

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))

Solar panels. Solar cell efficiency

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. 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).

Solar panels. Hybrid solar system (Inverters)

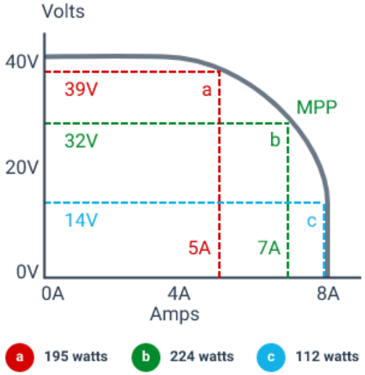
The architecture of an hybrid solar system is represented in the figure below. Above, we have studied the main features of solar panels. Therefore, we study the role of **inverters**, since they play an important role in hybrid solar systems

Solar inverters 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**

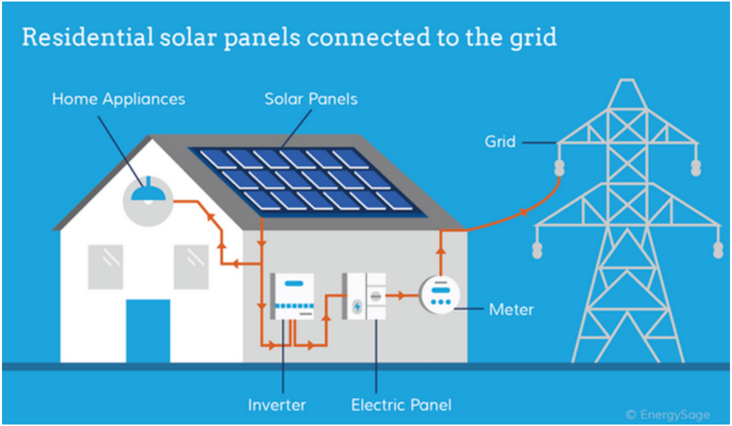
Solar panels. Hybrid solar system

Figure: Maximum Power Point (MPP) curve



Solar panels. Hybrid solar system

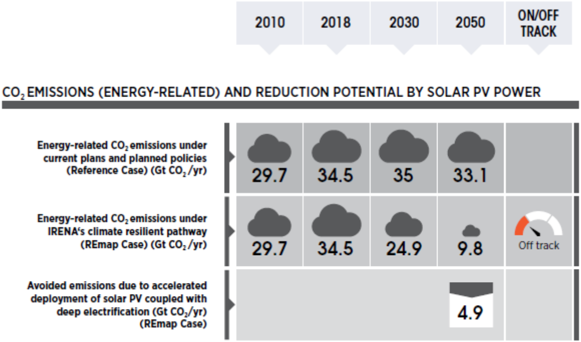
Figure: Solar panels at home (hybrid solar system architecture)



Key trends

1. **Solar PV and CO2**

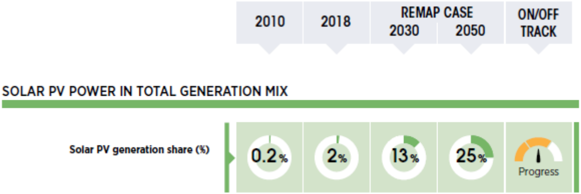
Deployment of solar PV alone can lead to **significant emission reductions** of 4.9 gigatonnes of carbon dioxide (Gt CO2) in 2050, representing 21% of the total emission mitigation potential in the energy sector



Key trends

2. **PV production**

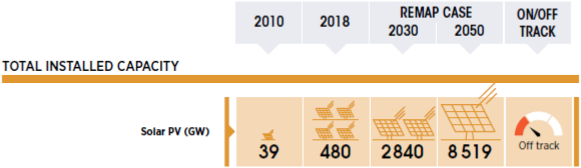
Solar PV would generate a quarter (25%) **of total electricity needs globally**, becoming one of prominent generations source by 2050



Key trends

3. **PV capacity**

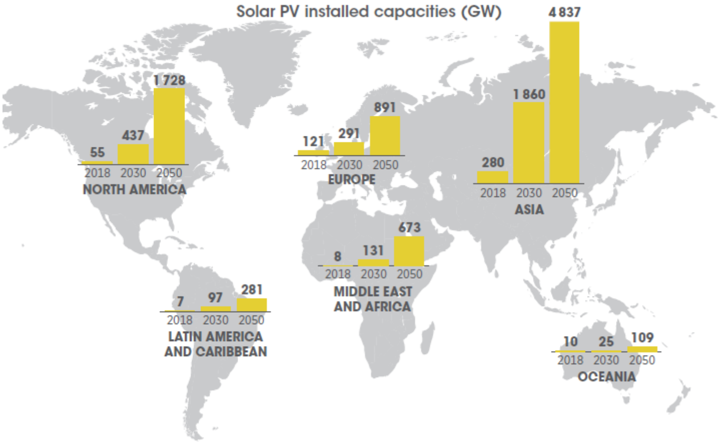
Solar PV capacity should increase almost sixfold over the next ten years, from a global total of 480 GW in 2018 to 2 840 GW by 2030, and to 8 519 GW by 2050 – an increase of almost eighteen times 2018 levels



Key trends

4. **Regional highlights**

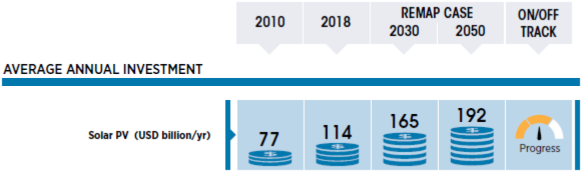
Asia (mostly China) would continue to dominate solar PV power in terms of total installed capacity, with a share of more than 50% by 2050, followed by **North America** (20%) and **Europe** (10%)



Key trends

5. **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

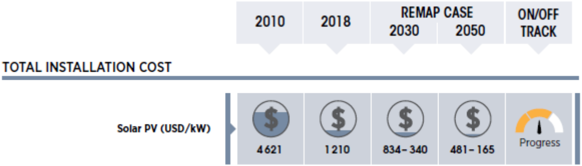


Key trends

6. **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

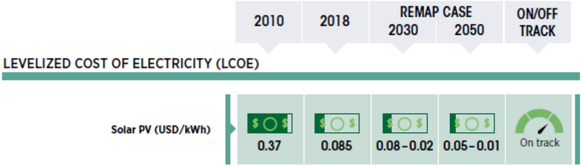


Key trends

7. **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



Future trends. Materials

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

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

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

Future trends. Materials

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

Future trends. Materials

3. **Silicon - advanced solar architecture. Tandem/hybrid cells. Tandem solar cells are stacks of individual cells, one on top of the othe**r, 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

Future trends. Materials

4. **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

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**

Future trends. Modules

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

Future trends. Modules

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
- 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**

Future trends. Modules

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)

Questions to summarize the chapter

Group 1:

1. Which are the main **solar energy production technologies**?
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**?
3. How does the **photovoltaic process work** to produce electricity?
4. Can you explain the concept of **solar efficiency**? Which are the **parameters used to measure solar efficiency**?
5. In an **hybrid solar system**? Which is the role of the **inverters**?

Group 2:

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

Group 3:

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