Renewable and Alternative Energies

Topic 2. Solar energy (II)

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Topic 2. Solar energy

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- **2.5. Solar panels**.
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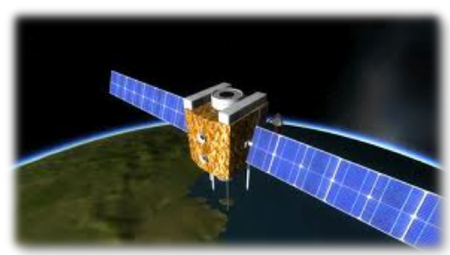
2.5. Solar panels

- **Photovoltaic (PV)** cells **convert** the **solar energy** directly **into electricity**.
- PV based systems are commonly known as "solar cells," and are **currently used** in a number of devices including calculators, watches, and emergency radios. Large scale units can be used to provide power for pumping water, communications equipment, satellites, and lighting homes.
- **PV applications** can be divided into the following **categories:**
  - Simple or "stand alone" PV systems.
  - PV with battery storage.
  - PV with backup power generator.
  - PV connected to the local utility.
  - Utility-scale power production.
  - Hybrid power systems.



2.5. Solar panels

PV Theory

- Photovoltaic cells use **semiconducting materials to capture the energy** of sunlight, which is composed of photons. These **photons contain an energy** corresponding to their wavelengths in the solar spectrum.

- **When** sunlight or **photons strike a PV cell, three events occur:**
  1) **Photons pass straight through the cell.** This depends on the band gap energy of the material. Photons with energy less than the band gap energy pass through the PV cells.
  2) **Photons reflect off the surface.** This depends on the surface characteristics of the material.

2.5. Solar panels

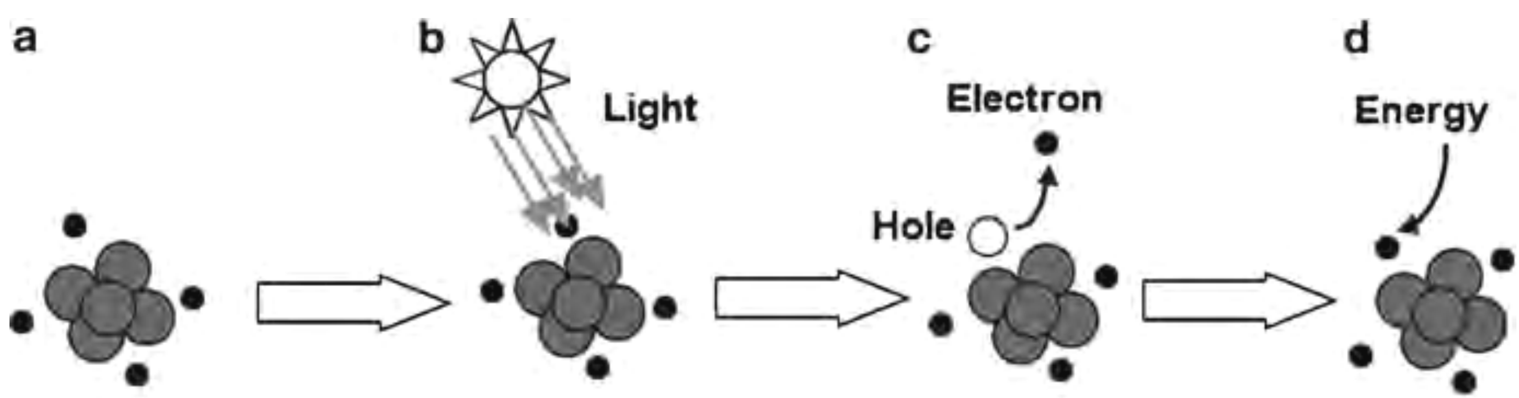
PV Theory

3) **Photons are absorbed by the PV cell.** Only photons with a certain level of energy are able to free electrons from their atomic bonds.

   By leaving this position, the electron causes a “hole” to form.

   The electrons from nearby atoms will move into this hole, and the process will continue until it reaches the external electrical circuit.

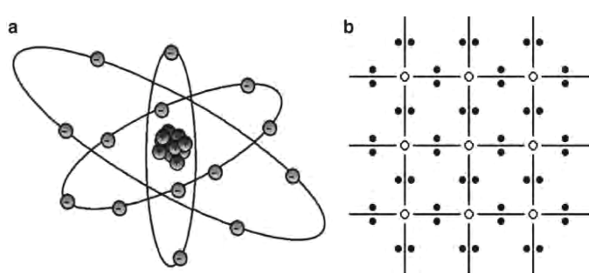
   If the energy of the absorbed photons is higher than the band gap energy, sometimes heat is generated, depending on the band structure.

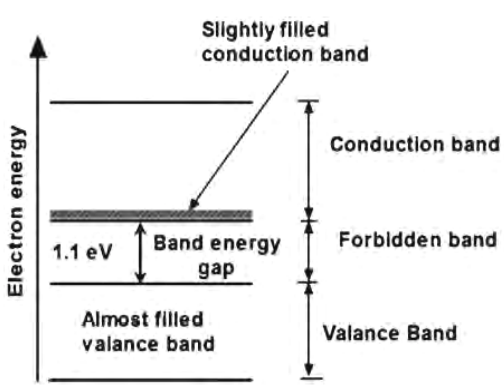


2.5. Solar panels

PV Theory

- Although **silicon (a) is most widely used for making PV cells, pure silicon is nearly an insulator**. Silicon has four electrons in its outer shell. The atoms in crystalline solids are held together by covalent bonds (b).
- For silicon, four outer shell electrons of each atom are shared by neighboring atoms. As a result, **silicon crystals have no free electrons** to make it a conducting metal.
- However, **silicon can be made a semi-conductor by doping it** with another element (called dopant), such as boron or phosphorous. Depending on the dopant, silicon can **become** either **p-type or n-type semi-conducto**r.





2.5. Solar panels

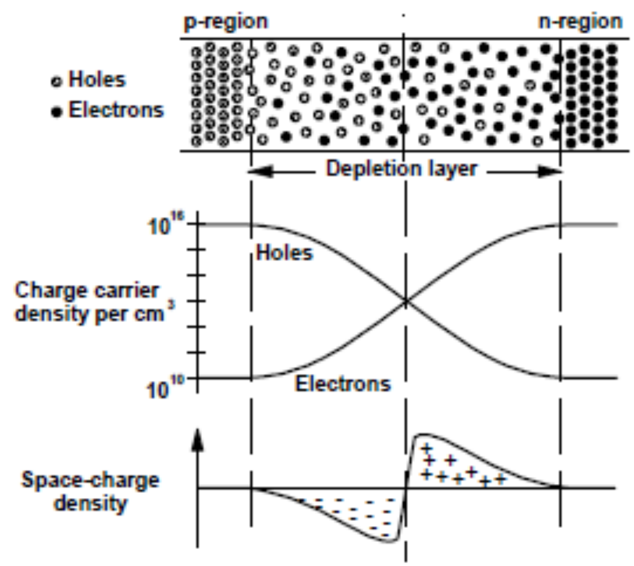
PV Theory

- If **an impurity atom is substituted in place of a silicon atom**, the subtraction or addition of electron in **the crystal matrix changes** the nature of the local covalent bond.
- **This leads to the formation of a p-type** center when there is an absence of an electron **(hole) or an n-type** center if there is an addition of an electron **(free electron)**.
- An **n-type** silicon semiconductor **is obtained by doping pure silicon with Group V elements** of the periodic table: phosphorous (P), arsenic (As), or antimony (Sb). Among these elements, **phosphorous is most widely used**. The purpose of n-type doping is to produce an abundance of mobile or "carrier" electrons in the material.
- The purpose of **p-type** doping is to create an abundance of holes. This is done **by doping silicon with a group III element** of the periodic table, such as boron or aluminum, which is substituted into the crystal lattice.

2.5. Solar panels

PV Theory

- Other important aspects of creating PV cells are the **formation of a p-n junction**.
- A **p-n junction in silicon is created** from a single crystal **with different dopant concentrations diffused across it**. If p- and n-doped materials are brought into contact, holes from the p-doped side diffuse into the n-type region and vice versa.
- **As a result** of the equilibrated concentration of free charge carriers **an electrical field is built up across the** border interface **(p-n-junction)**.



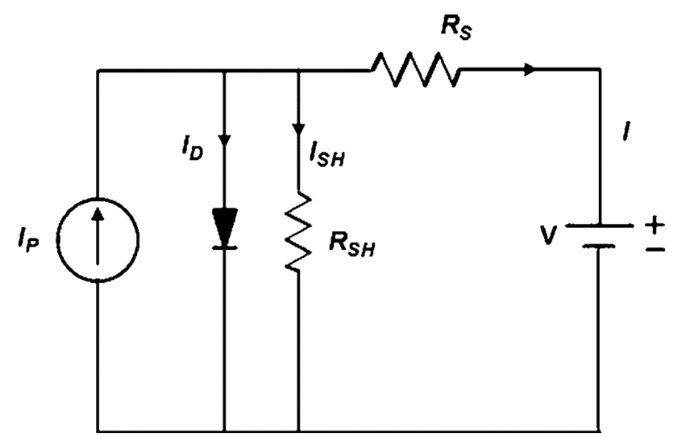
2.5. Solar panels

PV Theory

- The current and voltage generated in a solar cell depend on a host of factors.
- **To calculate the current and voltage** from solar cells, **an equivalent electrical circuit may be considered**.
- The **output current**, **I**, from a solar cell is given by: $\mathbf{I = I_P - I_D - I_{SH}}$ where, $\mathbf{I_P}$ **is the photon generated current** due to photoelectric effect, I_D **the diode current** and $\mathbf{I_{SH}}$ **the shunt current**.
- The diode current, assuming an ideal, can be expressed by the Shockley diode equation as:

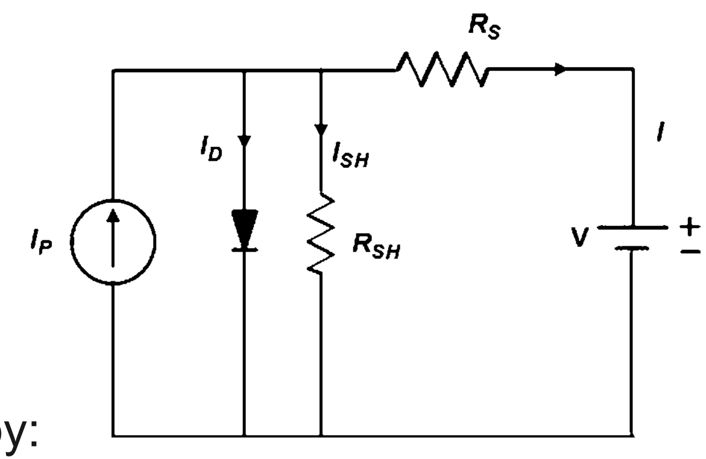
$$I_D = I_0\left(e^{\frac{q*V_D}{k*T}} - 1\right)$$

Where $\mathbf{I_0}$ is the saturation **current of the diode**, **q** is the **elementary charge** ($1.6 \cdot 10^{-9}$ C), **k** is the **Boltzmann constant** ($1.38 \cdot 10^{-23}$ J/K), **T** is the **cell temperature** in Kelvin, and $\mathbf{V_D}$ is the measured **cell voltage**.



2.5. Solar panels

PV Theory



- The **shunt current** is given by:

$$I_{SH} = \frac{V_D}{R_{SH}}$$

Where, R_{SH} is shunt resistance.

- The **output voltage (V)** from the cell is given by:

$$V = V_D - I \cdot R_S$$

Where, **V_D is voltage across** both **the diode and the shunt resistor**, and **R_S is the load**.

- So the **output current, I**, can be expressed as:

$$I = I_P - I_0\left(e^{\frac{q*(V+I*R_S)}{k*T}} - 1\right) - \frac{V + I * R_S}{R_{SH}}$$

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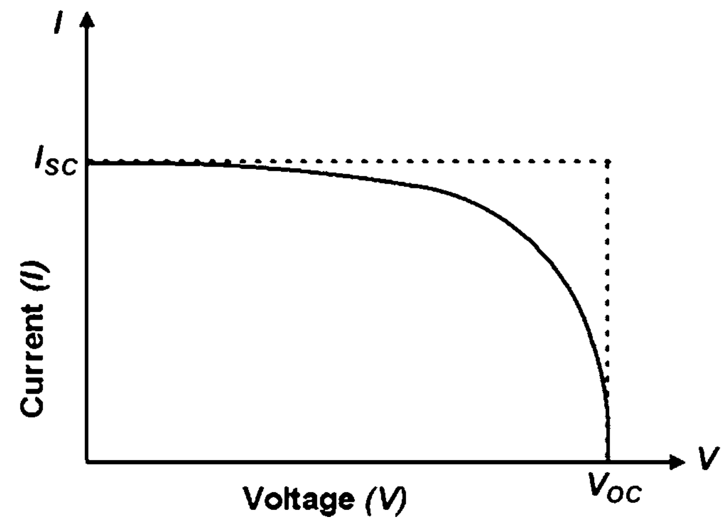
PV Theory

- A **typical I-V curve** represented by the previous equation for a semiconductor when illuminated is:



- I_{SC} **Short Circuit Current:** this refers to the current from a solar cell when the top and the bottom (negative and positive leads) leads are connected in a short circuit. In this situation, the impedance is low and the voltage equals zero.

- V_{OC} **Open Circuit Voltage:** occurs when there is no current passing through the cell.

2.5. Solar panels

PV Theory

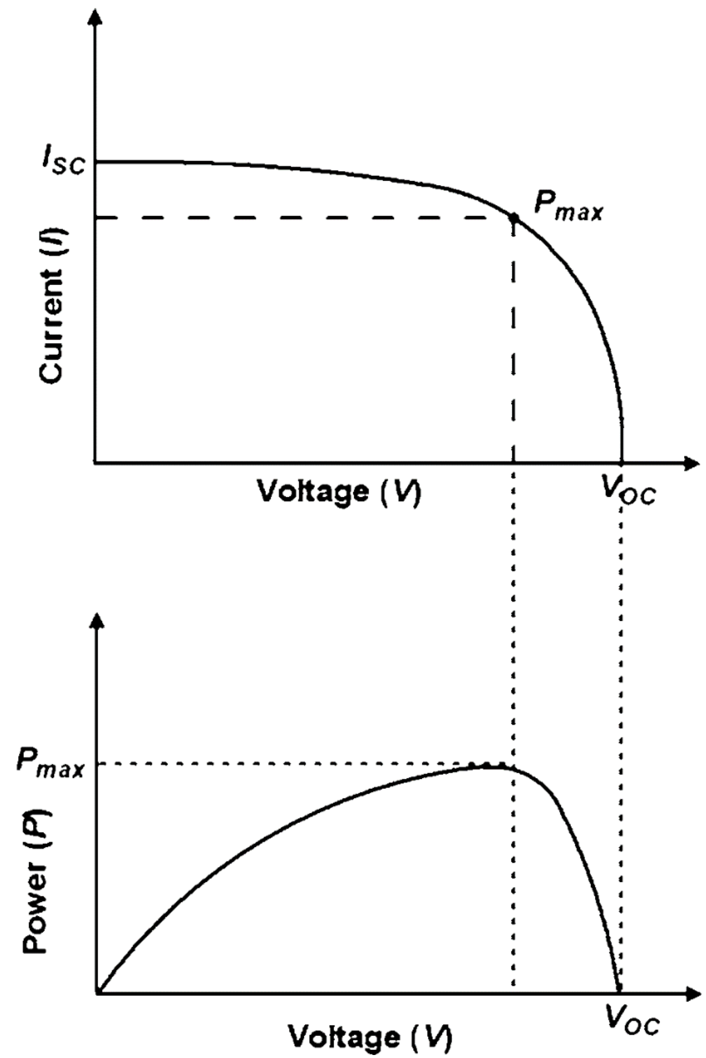
- **P_{max} Maximum Power:** the power is calculated from P = I · V. Therefore, at I_{SC} and V_{OC}, the power will be zero, and the maximum value for power will occur between these values. The voltage and current at this maximum power point are denoted as V_{MP} and I_{MP}, respectively.

- **V_{MP}:** voltage at maximum power.

$$e^{\left(\frac{q*V_{MP}}{k*T}\right)}*\left(1+\frac{q*V_{MP}}{k*T}\right)=1+\frac{I_{sc}}{I_o}$$

- **I_{MP}:** current at maximum power.

$$I_{MP}=\frac{q*V_{MP}}{k*T+q*V_{MP}}*(Isc+Io)$$



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PV Theory

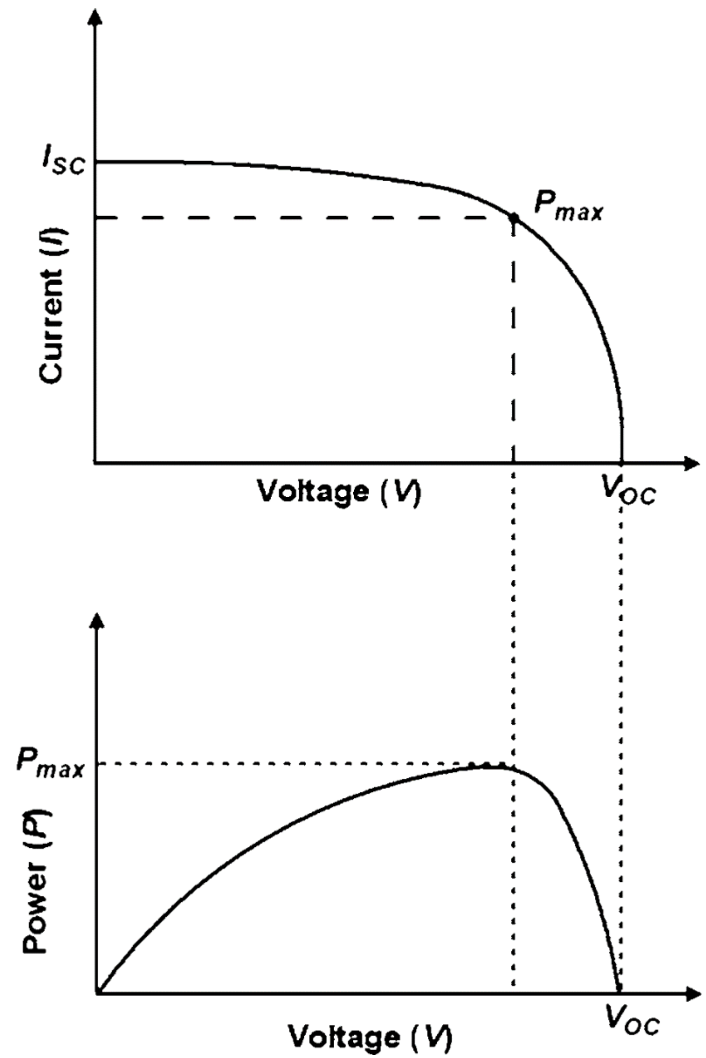
- **FF Fill Factor:** ratio of the maximum power (P_{max}) to the theoretical power (P_T):

$$FF = \frac{P_{max}}{P_T} = \frac{I_{MP} * V_{MP}}{I_{SC} * V_{OC}}$$

The theoretical power is given by the product of the open circuit voltage and short circuit current. The **fill factor (FF)** is considered to be a measure of the **quality of a solar cell**.

And **increase** in the shunt resistance $\mathbf{R_{SH}}$ **or a decrease** in the series resistance $\mathbf{R_S}$ has a positive effect on the fill factor, resulting in a **greater efficiency**.

Typical fill factors range from **0.5 to 0.82**.



2.5. Solar panels

Experimental determination of PV efficiency

- Given the variety of solar cells and production methods, the **efficiency** of a cell **is classified by standard methods**.
- A **number of instruments are available** commercially for testing of PV cells.
- A **major factor** when determining the efficiency **is the maintenance of a constant intensity of the light** to which the cells are exposed. The irradiance intensity is often **expressed by the unit, sun value**.

The Sun Value:

- The solar irradiance measurement unit, **One Sun, is defined as equivalent to the irradiance of one solar constant**. The solar constant is **defined as the irradiance of the sun on the outer atmosphere at a distance of 1AU** (AU refers to Astronomical Unit which is the mean distance between the sun and the earth, 149,597,870.66 km).

2.5. Solar panels

Experimental determination of PV efficiency

- Generally, a solar cell, known as the **"reference solar cell" is calibrated** under predetermined conditions. **Other cells can be compared** against the reference cell to determine the efficiency and other cell characteristics.

- **Efficiency (η)** is the **ratio** of the electrical **power output P_{out}**, compared **to the solar power input, P_{in}**, into the PV cell. P_{in} can be taken as the product of the irradiance of the incident light (E), measured in W/m^2 or in suns (1000 W/m^2) under standard test conditions multiplied by the surface area of the solar cell A (m^2).

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{E * A}$$

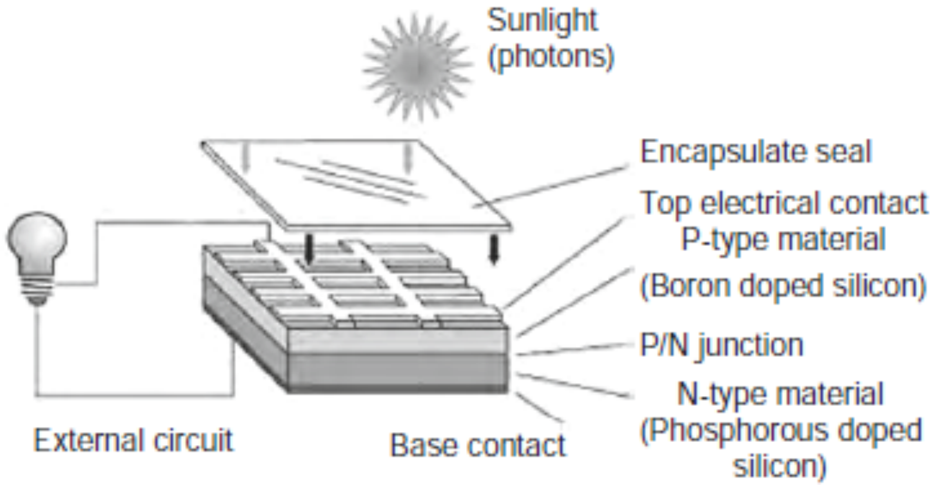
- **Conventional** silicon PV **cells have efficiencies between 5% and 15%** for conversion of solar energy to usable energy. A number of experimental cells have achieved higher efficiencies, **but** only under carefully controlled laboratory conditions and with more expensive materials and higher production cost. Efficiency **is** constantly **increasing with** various **new materials**.

2.5. Solar panels

Effect of thickness of the cell

- Once the sunlight strikes a PV cell, **photons must be absorbed** by the cell material before the electron excitation takes place. **The light of a particular wavelength must penetrate** certain depth **before it is absorbed**.

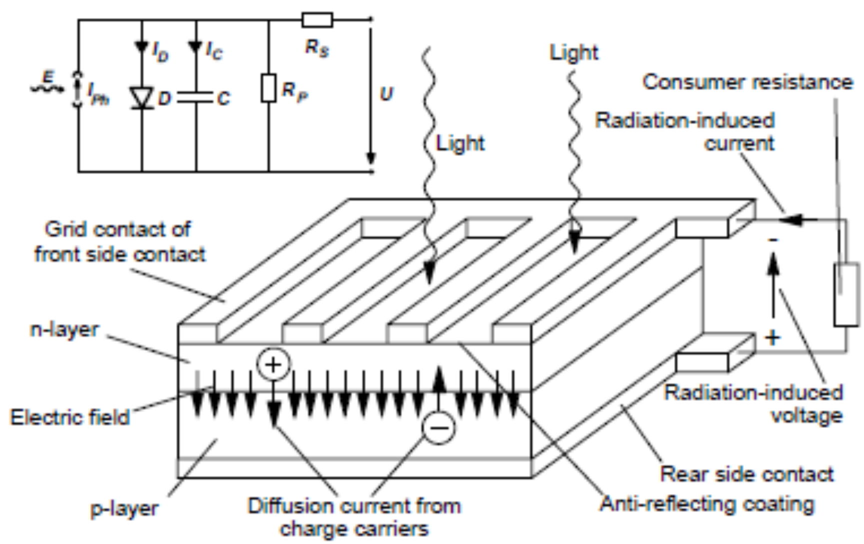
- The **absorption coefficient determines this depth**. The absorption coefficient **depends** both **on the material and the wavelength** of light which is being absorbed.



2.5. Solar panels

Effect of thickness of the cell

- As long as light is shining on the cell, the process is repeated:
  1) Energy from the light is absorbed by electrons and the electrons escape from their orbits.
  2) Electrons are drawn across the junction in the cell which only permits movement in one direction.
  3) Electrons move through an externally-connected load to recombine with the holes, providing an energy device.



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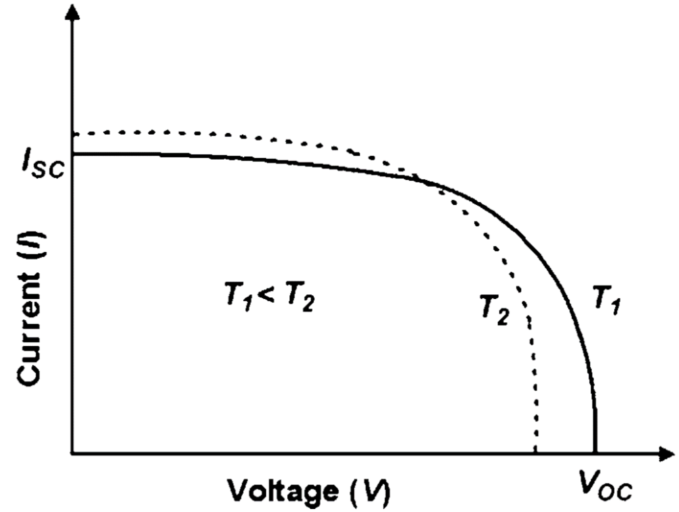
Effect of temperature

- The **efficiency** of PV cells **depends on the temperature** at which they are operating.

- When a PV cell is exposed to **higher temperatures, I_{SC} increases** slightly, while **V_{OC} decreases** more significantly, and the overall effect is the **reduction in efficiency**.

- As a result, **higher temperatures decrease** the maximum power output **P_{max}**.

- As temperature increases, the band gap energy decreases, because the crystal lattice expands and the interatomic bonds are weakened. Therefore, less energy is needed to free an electron and move it to the conduction band.

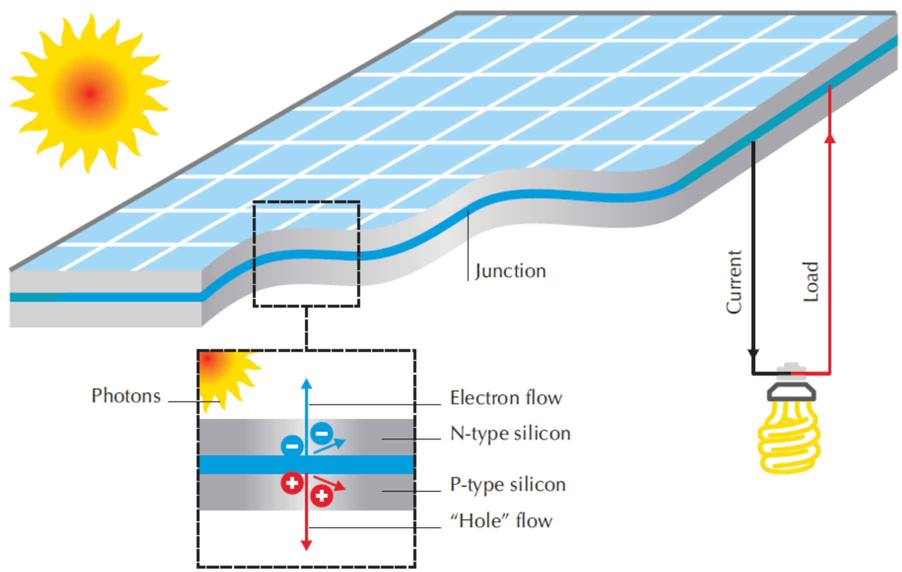


2.5. Solar panels

Effect of dopant concentration

- The concentration of dopant in a semiconductor used for making n- or p- type semiconductors can change the band gap of the material.

- High doping densities reduce the band gap, since the distance between two dopants narrows. This is due to the overlapping of two wave functions that form an energy band, rather than forming a discreet energy level.



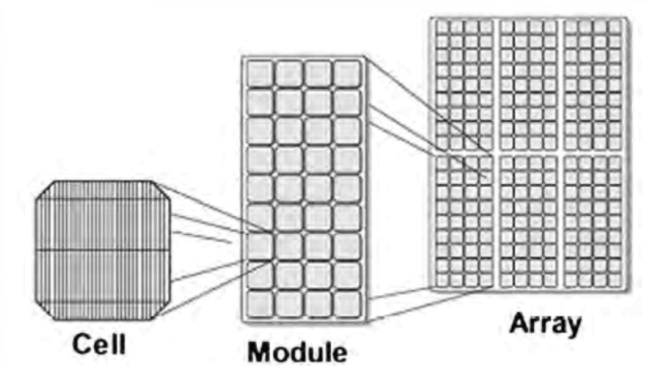
2.5. Solar panels

From cells to arrays

- An individual **PV cell** is the **basic unit** of a PV system. An individual PV cell typically **produces between 1 and 2 W**. Therefore, a number of individual **cells** are **connected** together to form larger units **called modules**. **Modules** are then **connected** to form larger units known **as arrays**. Several arrays are next joined together to produce **large scale power units**.

- **PV systems provide Direct Current (DC)**. For off-grid PV systems, these can be used directly, provided appliances can be run in DC. Generally, few appliances are available that run in DC, and these appliances are also costly. Therefore, **it is necessary to convert the DC into Alternating Current (AC)**.

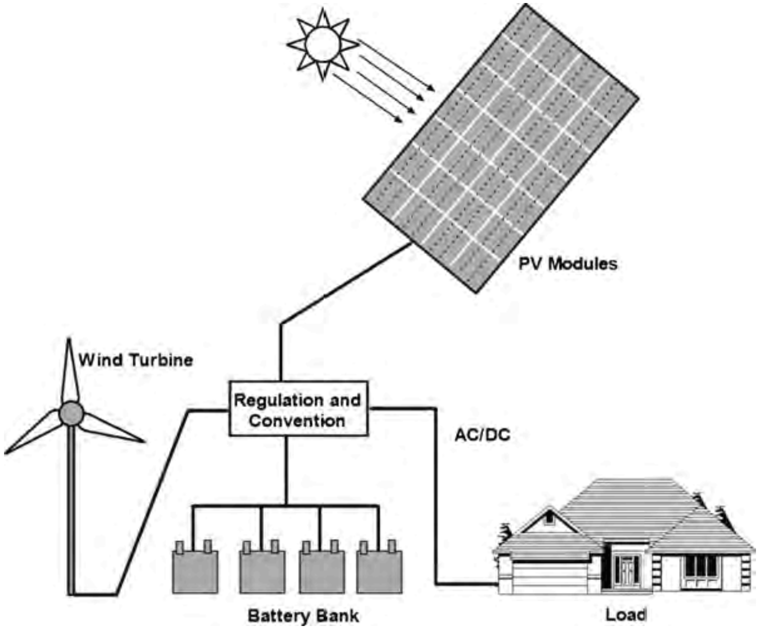
- Appliances and lights running on AC are much more common and are generally cheaper. The conversion of DC into AC is generally 80% efficient, resulting in some loss of power.



2.5. Solar panels

Hybrid power systems

- The **PV arrays** can be used **more effectively in a hybrid** power generation **system**.
- A **hybrid power system combines a number of electricity production** and storage units to meet the energy demand of a given facility or community.
- The development of a hybrid electric system **requires the knowledge of the energy demand** to be met and the resources available. This will allow **designing a hybrid system** that best meets the demands of the facility or community.



Topic 2. Solar energy

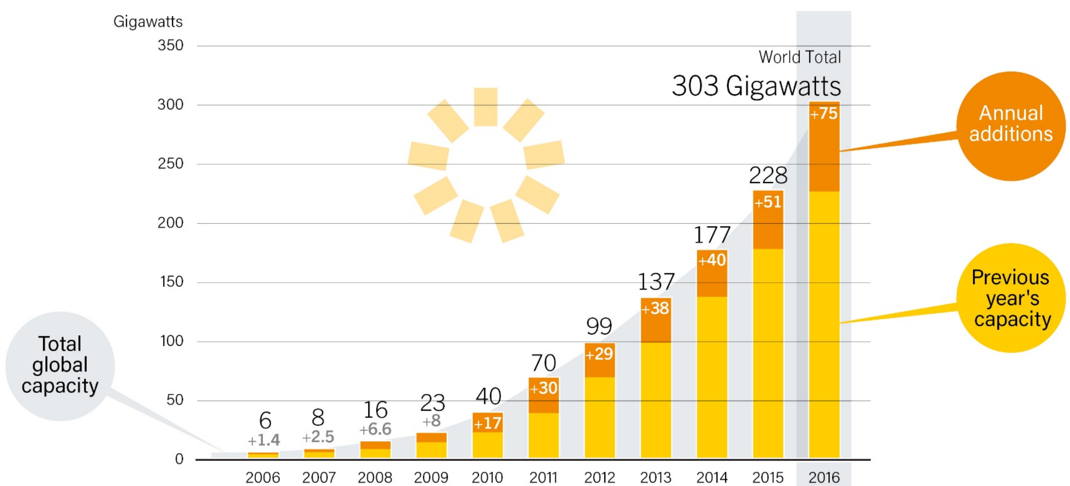
2.6. Photovoltaic applications

Photovoltaic use. Worldwide capacity

- Solar PV experienced another year of record growth in 2016, with the annual market for new capacity up 50% over 2015.

- In 2016 more than 75 GW was added bringing total global capacity to about 303 GW.

Solar PV Global Capacity and Annual Additions, 2006-2016

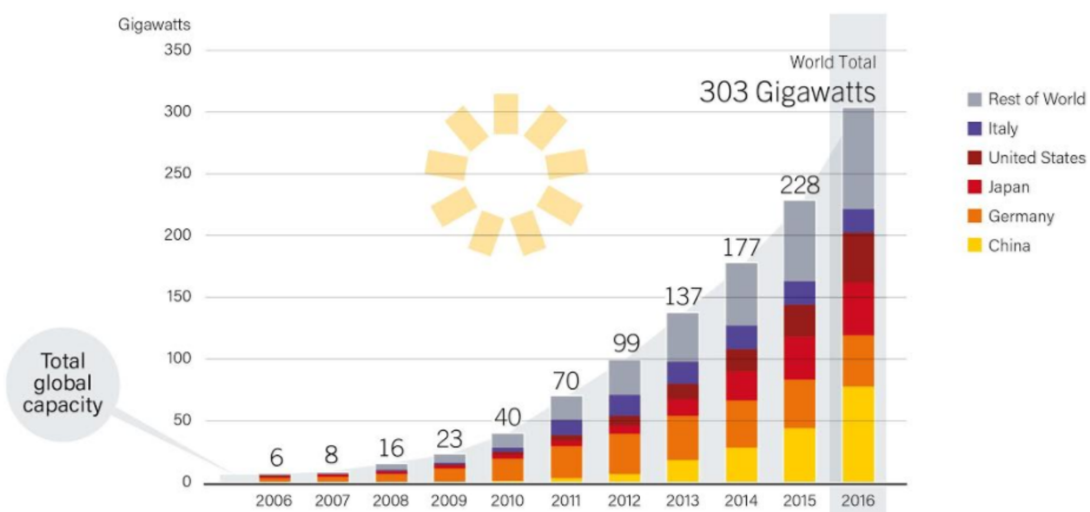


2.6. Photovoltaic applications

Photovoltaic use. Worldwide capacity

- By end-2016, every continent had installed at least 1 GW. At least 24 countries had 1 GW or more of capacity and 114 countries had more than 10 MW.

Solar PV Global Capacity, by Country and Region, 2006-2016

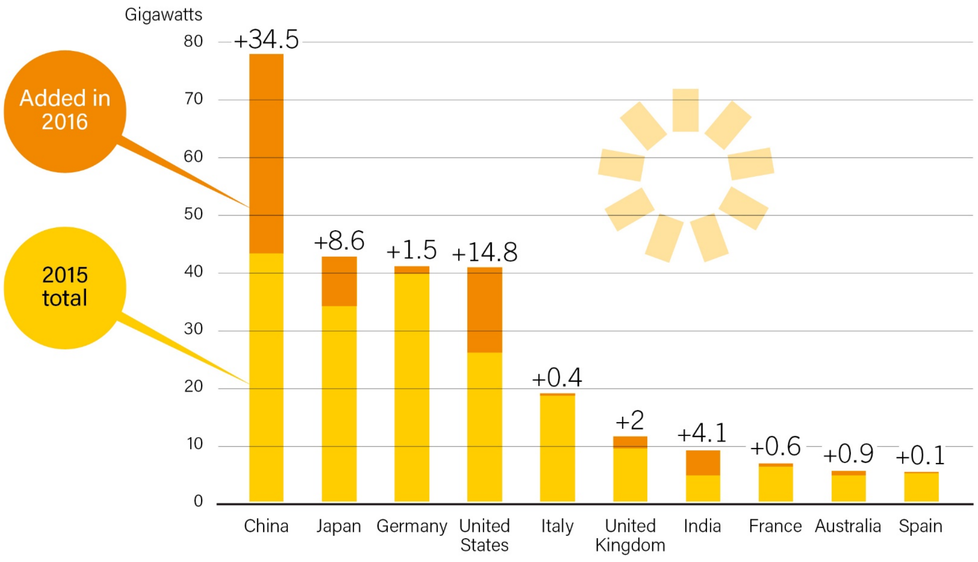


2.6. Photovoltaic applications

Photovoltaic use. Worldwide capacity

- In 2016, China added 34.5 GW (up 126% over 2015), increasing its total solar PV capacity 45% to 77.4 GW, far more than that of any other country.

Solar PV Capacity and Additions, Top 10 Countries, 2016

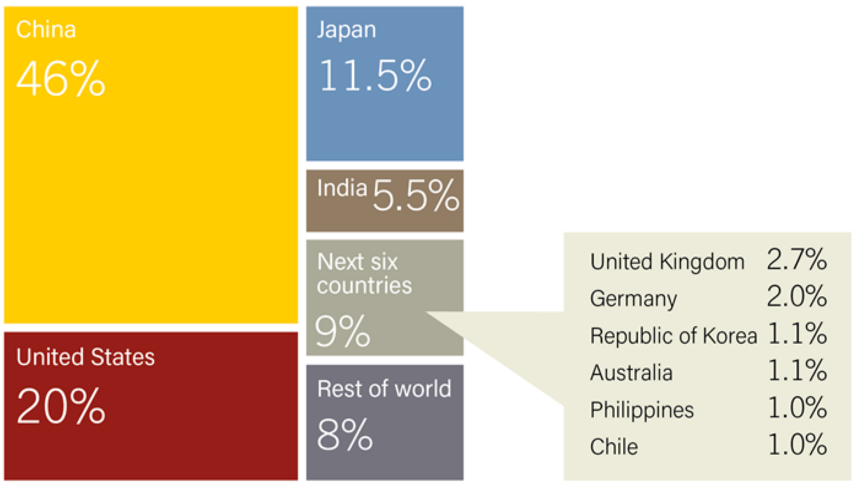


2.6. Photovoltaic applications

Photovoltaic use. Worldwide capacity

- Top 5 markets for solar PV accounted for about 85% of additions: China, United States, Japan, India and United Kingdom.

Solar PV Global Capacity Additions, Shares of Top 10 Countries and Rest of World, 2016

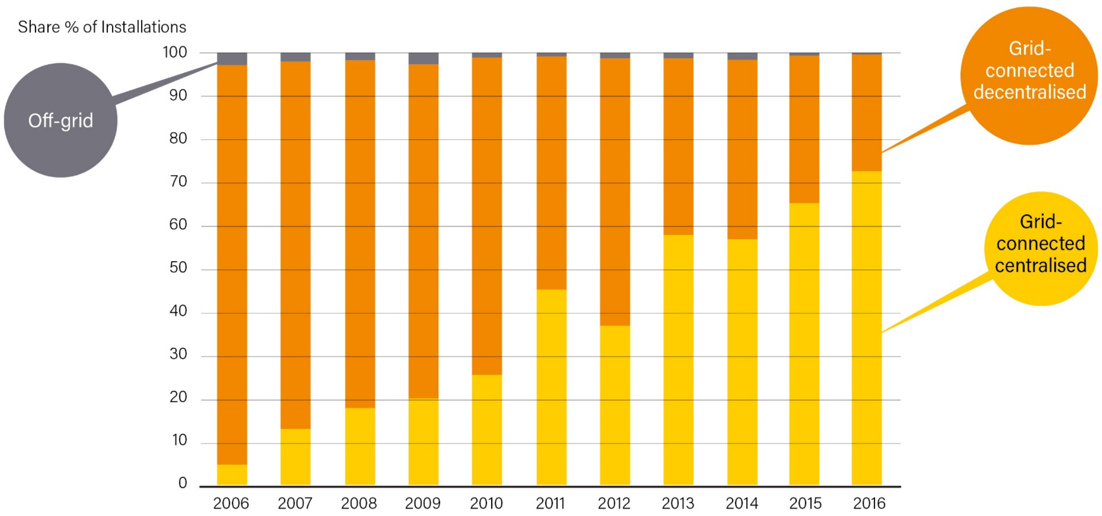


2.6. Photovoltaic applications

Photovoltaic use. Worldwide capacity

- Demand is expanding rapidly for off-grid solar PV, but capacity of grid-connected systems is rising more quickly.

Solar PV Global Additions, Shares of Grid-Connected and Off-Grid Installations, 2006-2016



2.6. Photovoltaic applications

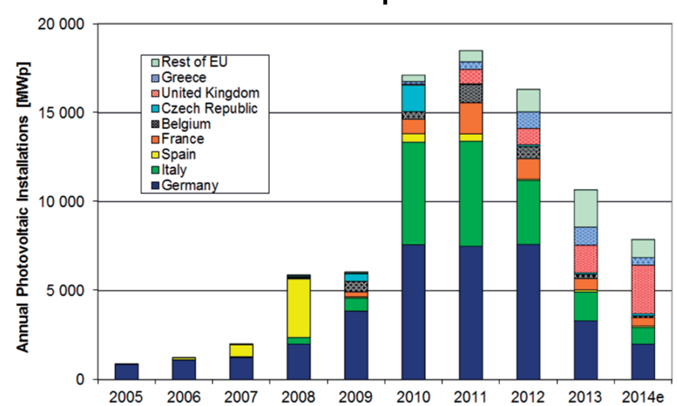
Photovoltaic use. Spain

- **Spain** is the fifth country **in Europe** with regard to the total cumulative installed capacity, at **5.4 GW**.

- Most of this capacity was installed in 2008 when the country was the largest market, with over 3.3 GW. This was more than twice the expected capacity and was due to an exceptional race to install systems before the autumn of 2008, when the Spanish Government introduced a cap of 500 MW on annual installations.

- A revised decree (Royal Decree 1578/2008) set considerably lower fits for new systems and limited the annual market to 500 MW, with the provision that two-thirds are rooftop-mounted and there are no longer any free-field systems. These changes resulted in a sharp fall in new installations.

Global Status Report 2016. REN21



"Spain, which drove the global market in 2008, has virtually disappeared from the solar PV picture due to retroactive policy changes and a new tax on self consumption".

2.6. Photovoltaic applications

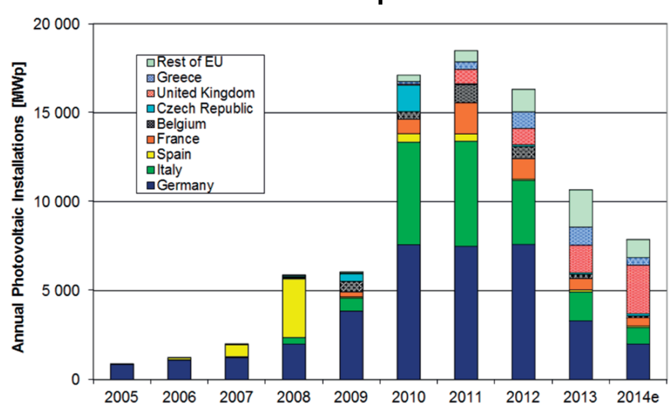
Photovoltaic use. Spain

- In January 2012, the Spanish Government passed Royal Decree 1/12, which suspended the remuneration pre-assignment procedures for new renewable energy power capacity, affecting about 550 MW of planned solar PV installations.

- Despite Royal Decree 1/12 and other measures taken in 2012 and 2013, including the increase in electricity prices and introduction of new taxes on electricity generation from the beginning of 2013, the tariff deficit increased further in 2012 and 2013.

- In 2013, new PV systems were installed with a capacity of 118 MW. In the same year, electricity generated from PV systems contributed 8.3 TWh or 3.2 % of the Spanish demand.

Global Status Report 2016. REN21



"Spain, which drove the global market in 2008, has virtually disappeared from the solar PV picture due to retroactive policy changes and a new tax on self consumption".

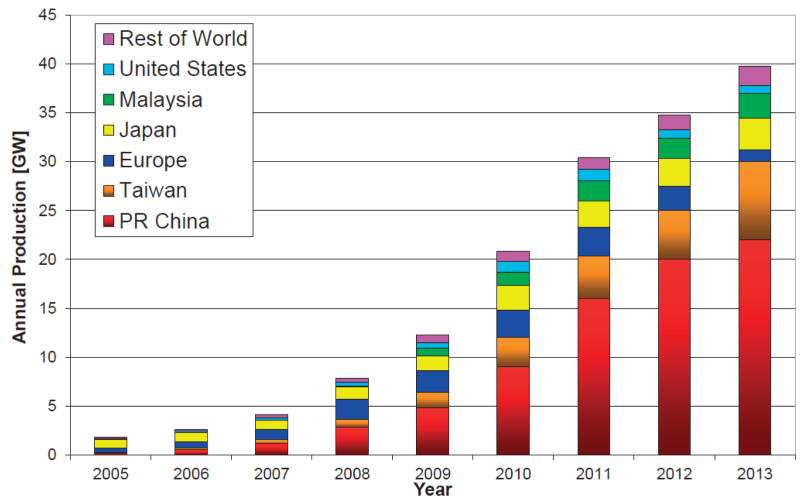
2.6. Photovoltaic applications

Photovoltaic use. Worldwide production

- Production data for **global cell production in 2013** was around **39.8 GW** representing a moderate increase of about 14% compared to 2012.

- Since 2000, total PV production has increased by almost two orders of magnitude, and over the last decade the compound annual growth rate has been about 55%.

- The **most rapid growth** in annual production over the last five years has been observed **in Asia**, where China and Taiwan together now account for more than 70% of worldwide production.



2.6. Photovoltaic applications

Photovoltaic use. Costs

- Over the last four decades, solar module **prices have fallen** following a price-experience or "learning" curve with an average learning rate of about 80%, i.e. the average selling price (ASP) of solar modules fell by 20% for each doubling of production volume.

- Between 2008 and the end of 2012, there was a **massive 80% drop in the price** of modules, with 20% in 2012 alone, creating serious financing problems for all companies and leading to the closure of a significant number of them.

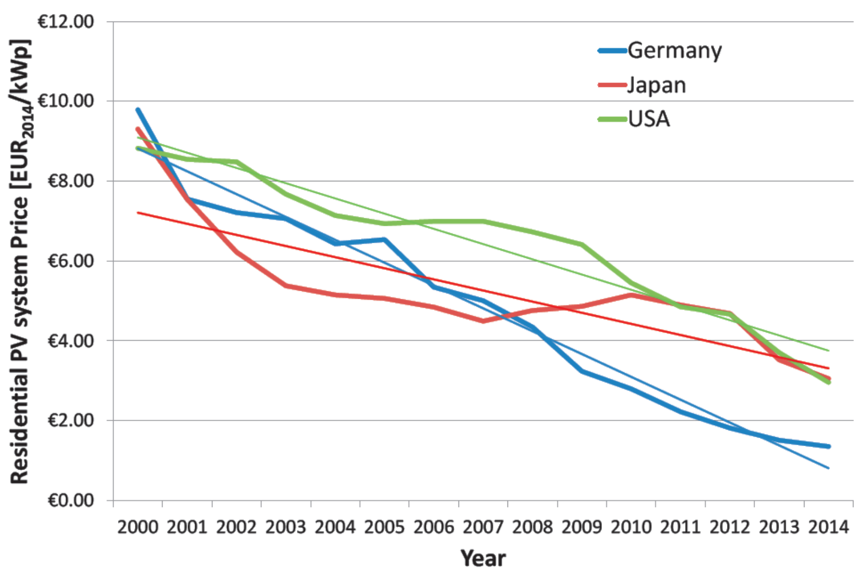
- PV system **prices are changing rapidly**, –not only in Europe– this opens up new opportunities for photovoltaics in a growing number of countries to become one of the major electricity providers in the near future.

2.6. Photovoltaic applications

Photovoltaic use. Costs

- Over the last decade, **prices for residential grid-connected** PV systems have **decreased** significantly.

- As shown in a growing number of countries, electricity production from residential PV solar systems can be cheaper than residential electricity prices, depending on the actual electricity price and the local solar radiation.



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