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Photovoltaic Power Systems (611422)

أنظمة الطاقة الكهروضوئية

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Chapter 1: Introduction

<u>Energy:</u> Any change that takes place in the universe is accompanied by a change in a quantity that we name energy. Energy comes in many forms, such as: electrical energy, chemical energy, or mechanical energy, and it can be used to realize many forms of change, such as movement, heating, or chemical change. **Any activity, and human activity as well, requires energy.**

Human beings need it to move their bodies, to cook, to heat and light houses, or to drive vehicles. An active young man needs about 2500 kcal (2.9 kWh) per day to fulfil his daily energy requirements. This means the energy of about 1060 kWh per year. The present global energy consumption is around 19 000 kWh per inhabitant per year. It means that on average a man consumes about 19 times more energy than is needed for his survival and satisfactory health.

<u>Energy</u>

We will now state some basic physical connections between the three very important physical quantities of: **Force, Energy and power**. These connections are taken from classical mechanics but generally valid.

We start with the force F, which is any influence on an object that changes its motion. According to Newton's second law, the **force F is related to the acceleration (a)** of a body via

$$\mathbf{F} = m * \mathbf{a}$$

where m is the mass of the body. The **bold** characters denote that **F** and **a** are vectors. The unit of force is Newton (N). **It is defined as the force required to accelerate the mass of 1 kg at an acceleration rate of 1 m/s2, hence 1 N = 1 kg m/s^2**

In mechanics, **energy E**, is given as **the product of force times distance,**

$$E = \int F(s)\, ds$$

where s denotes distance.

Energy is usually measured in the unit of **Joule (J), which it defined as the amount of energy required applying the force of 1 Newton through the distance of 1 m,**

1 J = 1 N m = 1 kg. m^2/ sec^2.

Another important physical quantity is the **power (P)**, which tells us **the rate of doing work**, or, which is equivalent, **the amount of energy consumed per time unit**. It is related to energy via:

$$E = \int P(t)\, dt,$$

$$P(t) = E / t$$ where t denotes the time.

The power is usually measured in **Watt (W). 1 W is defined as one Joule per second, 1 W = 1 J/s and 1 J = 1 W. s.** 1 J is a very small amount of energy compared to the human energy consumption. Therefore, in the energy markets, such as the electricity market, often use the unit **Kilowatt hour**

(kWh) is used. It is given as:

$$1\,\text{kWh} = 1000\,\text{Wh} \times 3600\,\frac{\text{s}}{\text{h}} = 3\,600\,000\,\text{Ws}$$

EX1: A 5kW electric motor which runs 2h, consume, 5kWx2h=10kWh of energy.
EX2: Eight 100W light bulbs that are left on all day will consume, 8x100x24=19200Wh=19.2kWh.

Electrical Energy- Electron Volt (eV) Unit

On the other hand, the amounts of energy in solid state physics, the branch of physics that we will use to explain how solar cells work, are very small. Therefore, we will use the unit of electron volt (eV), which is **the energy a body with a charge of one elementary charge (e = 1.602 x 10-19 C) gains or losses when it is moved across electric potential difference of 1 Volt (V),**
E (in eV) = Q x V, where Q is the electronic charge (1.602 x 10-19 C) and V is the voltage
1 eV is equal to 1.602 x 10-19 Joule.

Energy Sources

There is a growing need for energy in the world and since the traditional energy sources based on the fossil fuels are limited and will be exhausted in future, and not clean (polluted), renewable energy is considered a promising energy source candidate. Large-scale application of Photovoltaic (PV) solar energy will also contribute to the diversification of energy sources resulting in more equal distribution of energy sources in the world.

Sustainability

The deterioration of environment is a clear warning that the present realization of human progress has its limitations was formulated in a concept of a sustainable human progress. The sustainable human progress is defined as: **"To ensure that sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs".** A new challenge has emerged at the end of the 20th century that represents a search for and a utilization of new and sustainable energy sources.

Renewable Energy Sources

The urge of this challenge is underlined by limited resources of the fossil fuels on the Earth and increasing demand for energy production. This is the reason why the attention is turning to the renewable energy sources. In contrast**, renewable energy sources are energy sources that are replenished by natural processes at a rate comparable or faster than its rate of consumption by humans**. Most of the energy carriers used now are either fossil or nuclear fuels. They are not renewable because they are not "refilled" by nature, at least not in a useful amount of time. Consequently, **hydro, wind and solar energy are renewable energy sources. Wood and biomass also could be considered as a renewable energy sources**.

The energy contained in sunlight, **called solar energy**, can be converted into heat and electricity as well. If this energy is converted into electricity directly using devices based on semiconductor materials, we call it **photovoltaics (PV).** Solar light can also be converted into heat. This application is called **solar thermal energy**. Examples are the heating of water flow through a black absorber material that is heated in the sunlight. Next to generating heat and electricity, **solar energy can be converted in to chemical energy as well**. This is what we refer to as **solar fuels.** For producing solar fuels, photovoltaics and regenerative fuel cells can be combined. In addition, sunlight can also be directly converted into **fuels** using photo electrochemical devices. We thus see that solar energy can be converted into electricity, heat and chemical energy.

The sun is the energy source for almost all the processes that happen on the surface of our planet. **Wind** is a result of temperature difference in the atmosphere induced by solar irradiation. **Waves** are generated by the wind. **Clouds and Rain** are initially formed by the evaporation of water due to sun light.

The aim of this course

As the sun is the only real energy source in the universe, we should start to utilize the energy provided by the sun directly to satisfy our energy needs. The aim of this course is to **teach the reader how solar energy can be converted to electricity and utilized directly. And study the technologies and materials available with electrical components to have maximum and stabilized outputs power.**

Photovoltaic solar energy (solar electricity)

The energy of solar radiation is directly utilized in mainly two forms:

i) Direct conversion into electricity that takes place in semiconductor devices called **photovoltaic solar cells.**

ii) Accumulation of heat in **solar collectors.**

iii)Solar energy can be converted in to chemical energy as well by **fuel cell**s.

The direct conversion of solar radiation into electricity is often described as a **photovoltaic (PV) energy conversion,** because it is based on the **photovoltaic effect**. In general, the photovoltaic effect means the generation of a potential difference at the junction of two different materials in response to visible or other radiation. The whole field of solar energy conversion into electricity is therefore denoted as the **" photovoltaics".** Photovoltaics literally means **"light-electricity".**

The motifs of the PV solar energy development

The motifs that were behind the development and application of the PV solar energy were in general the same as for all renewable energy sources. The motifs were based on the prevention of climate and environment harms and providing clean, cheap and renewable (sustainable) energy for all people. The current motifs can be divided into **three categories: Energy, Ecology and Economy.**

Energy

There is a growing need for energy in the world and since the traditional energy sources based on the fossil fuels are limited and will be exhausted in future. PV solar energy is considered a promising energy source candidate. Large-scale application of PV solar energy will also contribute to the diversification of energy sources resulting in more equal distribution of energy sources in the world.

Ecology

Large-scale use of PV solar energy, which is considered environmentally friendly source of energy, Can lead to a substantial decrease in the emission of gases such as CO_2, NO_x and SO_x, that pollute the atmosphere during burning of the fossil fuels. **At present, the total energy production is estimated to be 1.6x 10^{10} kW compared to 1.0 × 10^{6} KW_P that can be delivered by all solar cells installed worldwide.** When PV starts to make a substantial contribution to the energy production and consequently to **the decrease in the gas emissions depends on the growth rate of the PV solar energy production.** If the annual growth of PV solar energy production is **15% then in year 2050 solar cells will produce 2.0 × 10^{8} kW_P.** The annual growth of **25% will result in the solar electricity power production of 7.5 × 10^{9} kW_P in 2040.** The annual growth of **40% will lead to power production of 2.4 × 10^{10} kW_p in 2030.** This demonstrates that **there must be a steady growth in solar cells production so that PV solar energy becomes a significant energy source after a period of 10 years.**

Economy

There are **around two billion people** in mostly rural parts of the world who have no access to electricity and solar electricity is already today the most cost effective solution. Bringing solar electricity to these people represents an enormous market. **driving force to a widespread development and deployment of the PV solar** energy. The total production of solar cells has achieved more than **1200 MW_p.** An average cost-prize of 1 W_P was approximately 1$ (0.06 $ for users). This means that the money involved in production of solar cells reached **2 Trillion $.** Assuming that a complete PV system is roughly two times the cost of the cells, a total money involved **PV in 2018 can be estimated to 4 Trillion $.**

Advantages of the PV

The advantages of the PV solar energy, as seen today, are summarized:

- Environmentally friendly.
- No noise, no moving parts, no emissions and no use of fuels and water.
- Minimal maintenance requirements.
- L lifetime, up to 30 years.
- Electricity is generated wherever there is light, solar or artificial.
- PV operates even in cloudy weather conditions.
- Modular or "custom-made" energy, can be designed for any application from watch to a multi-megawatt power plant.

Drawbacks of PV

- PV cannot operate without light or operate with very low efficiency.
- High initial costs that overshadow the low maintenance costs and lack of fuel costs.
- Large area needed for large scale applications.
- PV generates direct current: special DC appliances or inverters are needed in *off-grid* applications energy.
- Storage is needed, such as batteries.

Solar Cell

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. **A solar cell is an electronic unit (pn junction) fabricated**

from semiconductor materials that delivers a certain amount of electrical power characterized by an output voltage and current when it is exposed to solar radiation.

A simple structure of solar cell is shown here in figure 4.

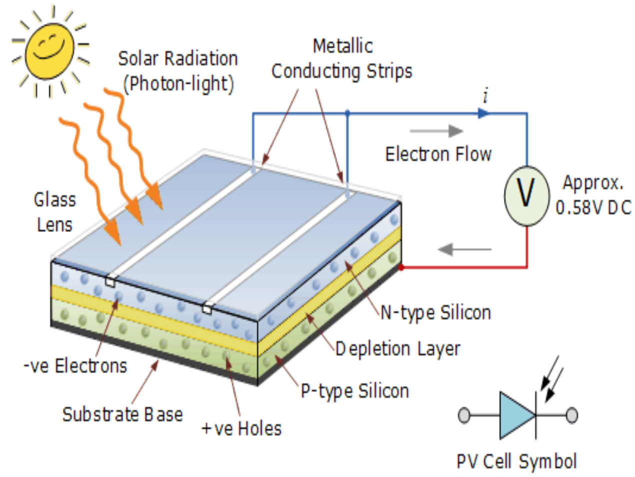


figure 4: A simple structure of solar cell

Solar cell consists of two different layers of Silicon deliberately doped with small quantities of impurities atoms (n-type and p-type) joined together to form a p-n junction. Top has several metallic contact fingers forming cell's negative terminal. Back has metal contact form the cell's positive terminal. Total thickness is ~ 0.3 mm. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells are connected together to form a solar panel, also called a PV module. For large scale generation of solar electricity the solar panels are connected together into a solar array.

<u>Photovoltaic (PV) Power System</u>

The solar panels are part of a complete **PV solar system, which, depending on the** application, comprises:

1. Batteries for electricity storage.
2. dc/ac inverters that connect a PV solar system to the electrical grid.
3. Other miscellaneous electrical components or mounting elements.

These additional parts of the PV solar system form a second part of the system that is called **balance of system (BOS).**

Finally, the solar system includes products such as household appliances; radio or TV set that use the solar electricity for their operation. We refer to these products as a load. In summary, the PV solar system consists of three parts:

i) **solar panels or solar arrays,**

ii) **balance of system,**

iii) **load.**

<u>Photovoltaic technologies</u>

The first practical use of solar cells was the generation of electricity on the **orbiting satellite Vanguard 1 in 1958**. These first solar cells were made from **single crystal silicon wafers and had efficiency of 6 %.** The space application was for some time the only application of solar cells. The major obstacle of using solar cells for terrestrial electric generation has been **a** much higher price of the solar electricity when compared to the price electricity generated from the traditional sources.

i. First generation: The single crystal silicon wafer-based solar cells that had been used in space became also the first solar cells to be used for terrestrial generation of electricity. Crystalline silicon solar cell technology represents today not only single crystal silicon wafer-based solar cells, but also multicrystalline silicon solar cells. Both technologies that deal with " bulk" crystalline silicon are considered the **first generation solar cells for terrestrial applications.** As this technology has matured, costs have become increasingly dominated by material costs, namely those of the silicon wafer, the glass cover sheet, and encapsulates.

ii. Second generation: In order to decrease the material costs of crystalline silicon solar cells, research has been directed to develop. **low cost thin-film solar cells, which represent a second generation solar cells** for terrestrial application. There are several semiconductor materials that are potential candidates for thin-film solar cells, namely:

- Copper indium gallium diselenide ($CuInGaSe_2$=CIGS),
- Cadmium telluride (CdTe),
- Hydrogenated amorphous silicon (*a-Si:H),*

iii. The third generation photovoltaics refer to all novel approaches that aim to overcome the single bandgap limit, preferably at a low cost. This means that all energy absorbed by the solar cell can escape the solar cell by either the generated current density or by radiative recombination of charge carriers. Under these assumptions the efficiency limit is around 33% in the band gap range from 1.0 eV up to 1.8 eV. There are several third generation concepts:

- **Multi-junction solar cells.**
- **Concentrator photovoltaics.**
- **Spectral up and down conversion. ($\eta \sim 33\%$)**
- **Multi-exciton generation.**
- **Intermediate band-gap solar cells.**
- **Hot carrier solar cells.**

Photovoltaic applications and market

Figure 5 below presents an overview of the different solar cell technologies that are used or being developed for two main solar cell applications, namely space and terrestrial applications.

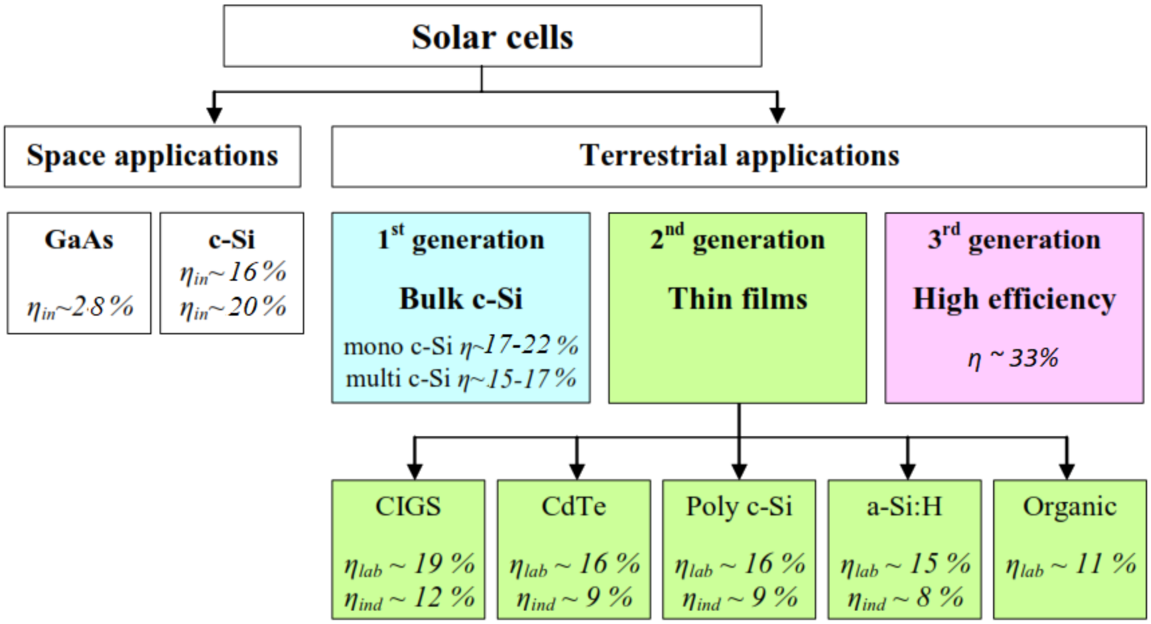


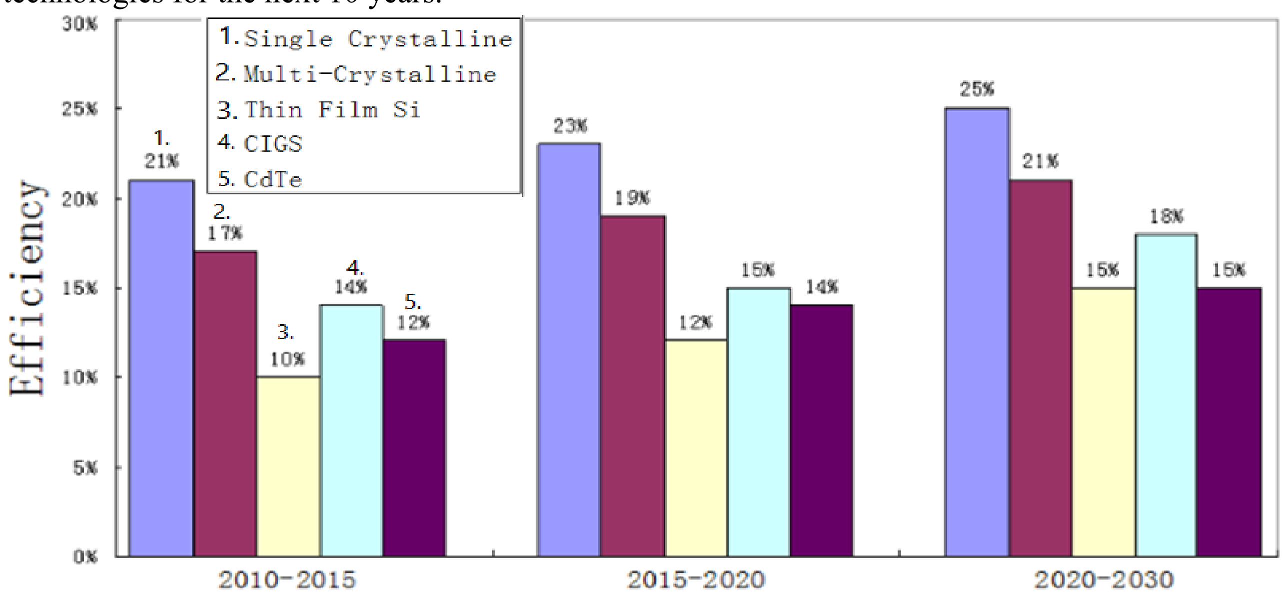
Figure 5; presents an overview of the different solar cell technologies and their efficiencies.

Today's **(2019)** commercial PV systems based crystalline silicon, in terrestrial applications convert sunlight into electricity with efficiency ranging from 7% to 25%. They are highly reliable and most producers give at least 30 years guarantee on module performance.

In case of the **thin-film solar cells** the best conversion efficiency that has been achieved in **laboratory (11-22%)** is shown together with the conversion efficiency that is typical for **commercial solar cells (7-19%).**

Third generation solar cells, the best conversion efficiency that has been achieved in laboratory (~33%).

Figure 6 below forecasts potential efficiency improvements of first and second generation PV technologies for the next 10 years.



Global PV Production

The commercial production of solar cells is steadily increasing and from 1996 as given in figure 7, the average increase is around 30%. In 2017 the PV market broke several records and continued its global expansion, with reaching almost the 100 GW threshold. The main reason is the contribution of the China whose PV development accounts for almost the 54% of the total installed capacity in 2017. Overall, these developments raised the global PV market for the first time to at least 98 GW.

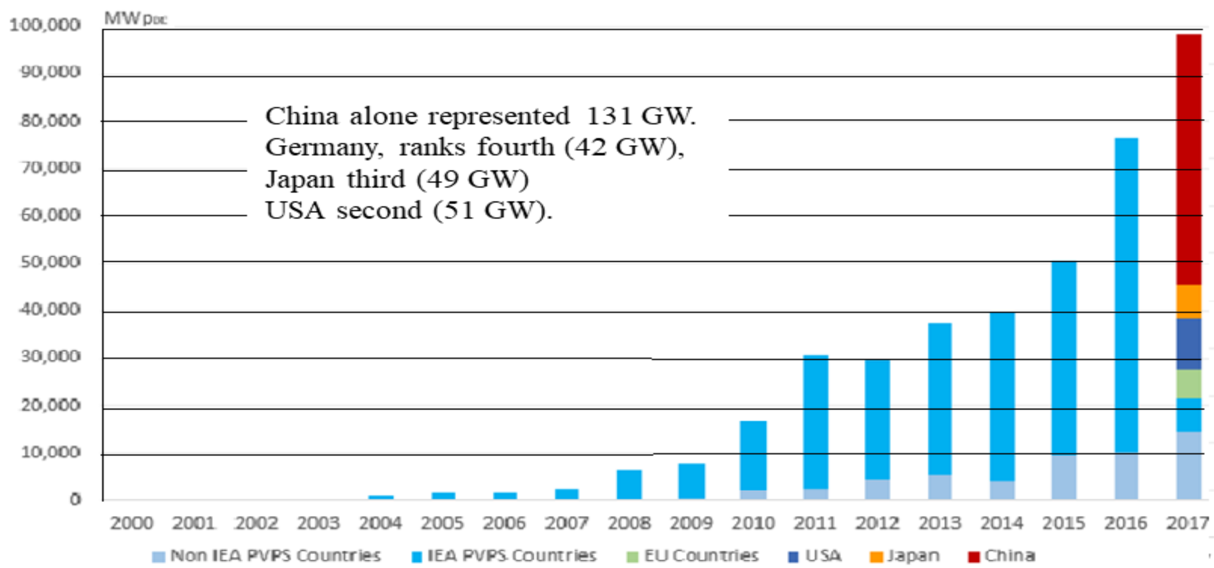


FIGURE 7: EVOLUTION OF ANNUAL PV INSTALLATIONS (MW - DC)

Figure 8: shows the evolution of total installed capacity (GW- DC). At present 397 GW represents the minimum installed by end 2017. Remaining installations account for some additional 5.7 GW installed in the rest of world that could bring the overall installed capacity to around 402.5 GW in total.

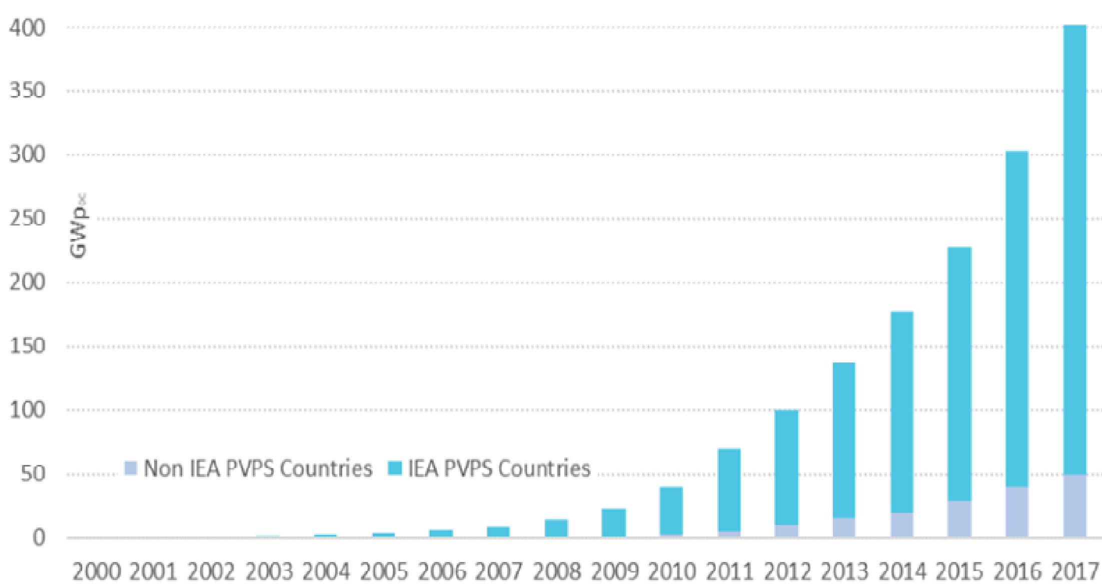


FIGURE 8: EVOLUTION OF TOTAL INSTALLED CAPACITY (GW - DC)

At present, there are four primary market areas for photovoltaic terrestrial applications:
i. Consumer products, such as watches, calculators, and lanterns.
ii. Off-grid, also called stand alone, residential power systems, such as solar home systems for individual households.
iii. Off-grid industrial power systems for water management, lighting, and telecommunication.
iv. Grid connected PV systems that are integrated in roofs and outer walls of buildings or in noise barriers along the motorways.
Figure 9, shows the expectation of photovoltaic capacity growth in the world till 2050.

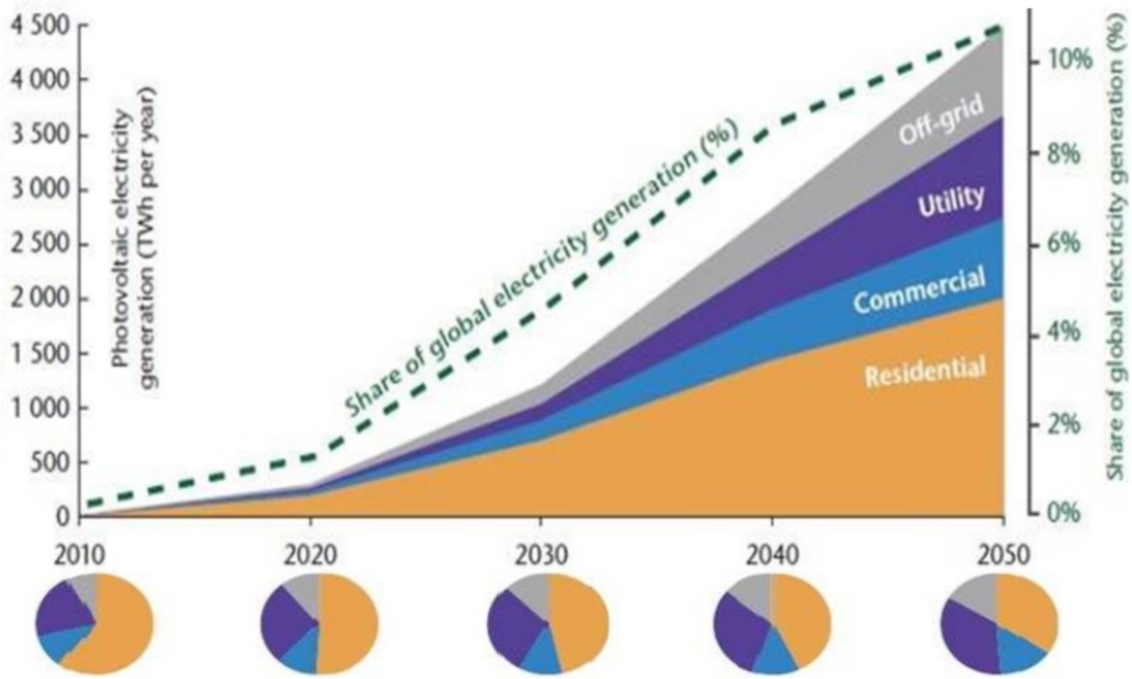


Figure 9: shows the expectation of photovoltaic capacity growth in the world till 2050.