Chapter 1.

INTRODUCTION TO PHOTOVOLTAIC SOLAR ENERGY

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1.1 Introduction to energy consumption and production

Any change that takes place in the universe is accompanied by a change in a quantity that we name ***energy***. We do not know what energy exactly is, we use this term to describe a capacity of a physical or biological system for movement or change. 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. Human being is a greedy consumer of energy. 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.

The mankind has witnessed an enormous increase in energy consumption during last 100 years. While in 1890 the energy use per inhabitant per year was around 5800 kWh it reached 20200 kWh in 1970. Since 1970 the energy use has dropped to the present level of 19000 kWh per inhabitant per year. The increase in energy use in the 20th century can be related to an evolution process that has started about five centuries ago. The underlying motivation of this process was formulated during the Enlightenment period in the 18th century as the philosophy of human progress. The aim of the process was an examination of the surrounding world and its adaptation to the needs of people whose life would become more secure and comfortable. This process was accompanied by growing industrialization and mass production, which were demanding more and more energy. At the end of the 19th century coal was the main source of energy. In this period electricity was introduced in the industrialized countries as a new and elegant form of energy. This form of energy was quickly applied on a large scale. The widespread growth of electricity use led to construction of hydroelectric plants and hydropower became an important source of energy in the first half of the 20th century.

In the period after the World War II much effort was put into the reconstruction of the society. The emphasis was directed on the growth and efficiency of the mass production. New technologies and new materials, such as plastic, were applied in the production. The energy demand was tremendously growing in this period. Oil and gas started to play an important role as energy sources in the second half of the 20th century. Coal, oil, and gas form today dominant sources of energy. These three energy sources, also known as ***fossil fuels***, are called the ***traditional energy sources***. In this period nuclear energy was introduced as a new source of energy. Increasing and more efficient mass production resulted in the low price of many household products. The consumption of the products grew enormously and therefore it is not surprising that we characterise today society as a consumption society.

Nevertheless, it has become evident at the end of the 20th century that the philosophy of human progress that has manifested itself in a huge production and consumption of goods has a negative side too. It has been recognized that a massive consumption of fossil fuels in order to fulfil the present energy demands has a negative impact on the environment. The deterioration of environment is a clear warning that the present realization of human progress has its limitations. The emerging international environmental consciousness was formulated in a concept of a ***sustainable human progress***. The sustainable human progress is defined as: "… to ensure that it (sustainable development) meets the needs of the present without compromising the ability of future generations to meet their own needs"[1]. 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. 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***.

Energy is an essence of any human activity. When we are interested in how the human civilization has been producing and using energy, we can describe it in terms of an ***energy system***. The main characteristics of the energy system are: the population, the total consumption of energy, and the sources and forms of energy that people use. The energy system at the beginning of the 21st century is characterised by six billion people that live on the Earth and the total energy consumption of approximately 1.3×10^{10} kW.

[1] World Commission on Environment and Development (WCED), *Our Common Future*, Oxford/New York: Oxford University Press (1987).

1.2 Primary energy sources

Figure 1.1 presents an overview of the present ***primary energy sources*** [2]. The primary energy sources can be divided in two groups. The first group includes those energy sources that will be exhausted by exploiting them. These energy sources are called the ***depleting energy sources*** and they are the fossil fuels and nuclear energy. The fossil fuels and nuclear power are the main source of energy in today's energy system and they supply 78% of the energy demand. Under the assumption that the population of mankind does not change drastically and it consumes energy at the current level, the fossil fuel reserves will be exhausted within 320 years and the nuclear energy within 260 years. This can seem a very long time for us. However, when we compare this period of time to the time span of existence of the Earth or the human civilisation, it is a negligible fraction of time. We have to be aware that the reserves of fossil fuels on the Earth are limited and will be exhausted.

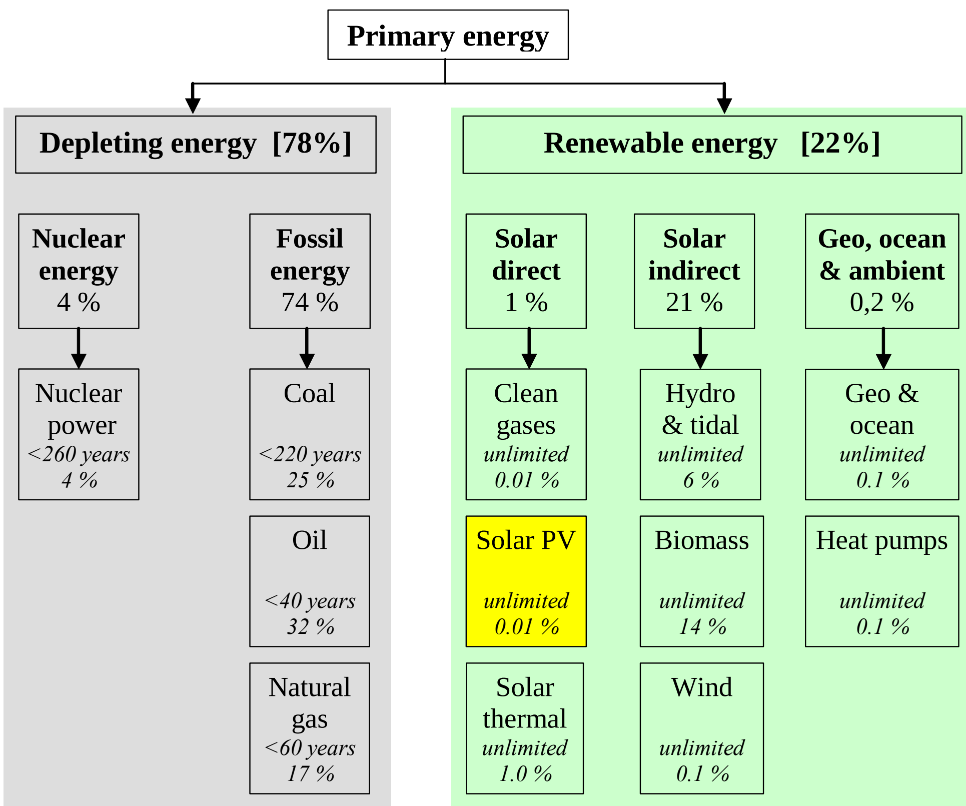


Figure 1.1. An overview of today's energy sources.

[2] D.A. Horazak and J.S. Brushwood, Renewables prospects in today's conventional power generation market, Renewable Energy World, Vol. 2, No. 4, July 1999, p.36.

It is expected that the world population will grow and will reach 10 billion in 2050. In order to provide the growing population with high living standards, further economic development is essential. The further economic development requires more energy than we use today. The extra energy has to come from additional sources than only the traditional ones. Furthermore when we want to take the concept of sustainable development into account, we have to look for environmentally friendly energy sources. These sources are known as ***renewable*** or ***sustainable energy*** sources. The renewable energy sources form the second group of the primary energy sources and today they contribute with 22% to the total energy production. By renewable energy we understand energy that is obtained from the continuing flows of energy occurring in the natural environment, such as solar energy, hydropower and energy from biomass.

About one third of the primary energy is used to generate electric power. This form of energy has become very popular and is widely used for industrial and household applications. The electrical energy represents about 12% of all energy consumed worldwide. Figure 1.2 shows the present distribution of primary energy sources, their contribution to the production of electricity, and the use of electricity.

Since most of the energy production is based on the fossil fuels, these have become a global strategic material. Fossil fuels are not equally distributed over the world and the countries that enjoy huge reserves of fossil fuels can influence the world's economy. The decisions of these countries concerning production levels and price of the fuels have strong effects on the energy production and can result in social tensions. Further, the energy consumption of primary energy is not equal per inhabitant in the world. About ¼ of the world population uses ¾ of the primary energy. For comparison: an inhabitant of the U.S.A. uses on

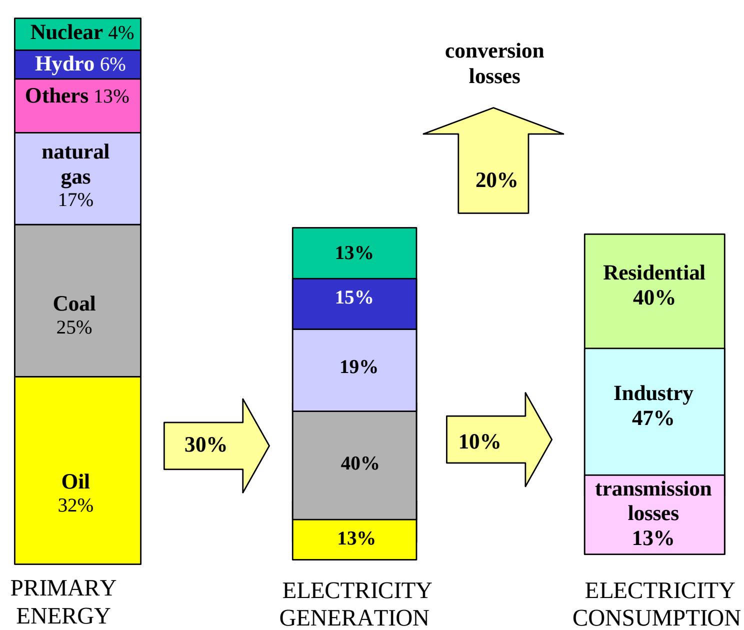


Figure 1.2. Electricity generation and consumption in today's energy system.

average 10 kW of power produced from fossil fuels, while an inhabitant of the Central Africa uses 0.1 kW of power produced from wood. This discrepancy is even more pronounced in the use of electricity. There is no electricity available in most of the rural areas in the developing countries. It is estimated that about 2 billion people have no access to electricity.

It has been recognized that a massive consumption of fossil fuels has a negative impact on the environment. Gases such as CO_2 and SO_X and NO_X are produced as the by-products during burning of the fossil fuels. Enormous quantities of these gases are emitted into the atmosphere, where they change the natural concentrations. The ecological problems, such as the greenhouse effect and acid rains, are caused by the increase of these gases in the atmosphere. The greenhouse effect is linked to the increase of CO_2 in the atmosphere. The CO_2 molecules are transparent to solar radiation but are opaque to heat, which is the radiation in the infrared wavelength region. The concentration of CO_2 in the atmosphere has increased in the 20th century from 280 ppm to 350 ppm. Scientists expect that when this trend continues, the temperature will rise from 3 ºC to 5 ºC in 2030-2050. In order to avoid this situation, in which the climate change, known also as the global warning, can lead to undesired ecological changes a reduction in CO_2 emission is essential.

1.3 Renewable energy sources

The negative aspects of today's energy system have led to the formulation of sustainable human development. The realization of the sustainable development requires an alternative energy system that is based on:
i) policies for efficient energy use and
ii) renewable energy sources.

The world's largest oil company Shell has published recently a vision on future energy consumption and potential energy sources[3]. One of the largest energy producers in the world expects that the restructuring of power industry will take place in near future. The Shell's scenario that is called the "Sustained Growth" is presented in Figure 1.3. The company has concluded that the fossil fuels are still important, but they reach a plateau by 2020. At this time, renewable energy will become a significant source of energy. At first, renewable energy will grow in niche markets rather than compete with traditional sources of energy. The market will decide a share of different forms of renewable energy. In future, the energy supply will become more diversified and hence more robust. It is interesting to notice that Shell expects the photovoltaic (PV) solar energy to become a major energy source within fifty years.

Renewable energy sources are based on the continuing flows of energy that is considered inexhaustible from the point of view of human civilisation. Solar radiation represents such an infinite source of energy for the Earth. The sun delivers 1.2×10^{14} kW energy on the Earth, which is about 10.000 times more than the present energy consumption. The energy that the Earth receives from the sun in just one hour is equal to the total amount of energy consumed by humans in one year.

[3] J. van der Veer and J. Dawson. Shell International Renewables. Web page: http:/www.shell.com, 1997, Transcript of a Press conference in London, 6 October 1997.

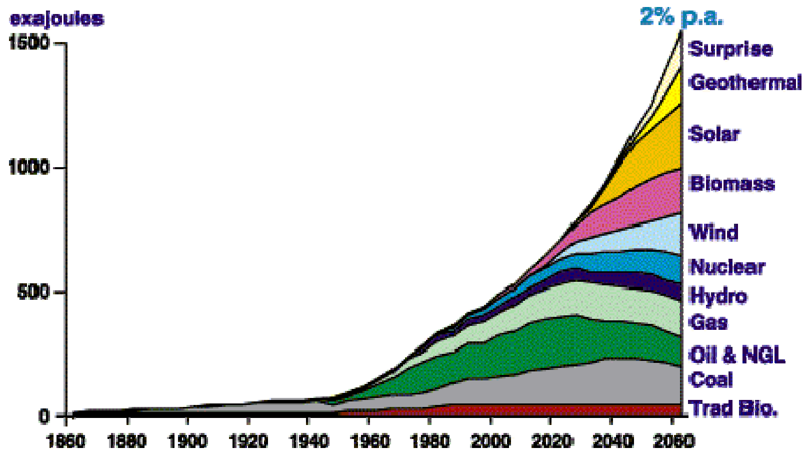


Figure 1.3. Shell's scenario of diversification of energy sources in the 21st century[3].

As illustrated in Figure 1.1 solar radiation can be utilised in various forms. The ***direct utilisation*** of solar radiation uses the energy of light (mostly in the visible wavelength region) or heat (infra-red wavelength region). Light is used for the photovoltaic solar power generation, which means the direct conversion of light into electricity in devices called ***solar cells***, or production of photochemical hydrogen. Heat is used mostly as a water heater in ***solar collectors***. Wind, hydroelectric and wave power generation can be considered examples of the ***indirect utilisation*** of solar radiation. For example, mills for grinding grain, water pumping or electricity generation use energy of the wind. The energy carried by the flow of rivers, by water from reservoirs, or by tidal and wave motion is converted into the hydroelectric power using the turbines. The photosynthesis process creates biomass, which is used for the production of ethanol in case of sugar cane or maize, or for the production of biogas in case of organic household waste. The examples of the geothermal energy sources are geysers or terrestrial heat surfaces, such as steam and hot water, for heating applications.

The major advantages of using renewable energy sources over the traditional energy sources are reflected in a cleaner environment, creating employment opportunities, and security of energy supply. The use of renewable energy can reduce the emission of greenhouse gases and other pollutants. The expanded use of renewable sources of energy can have a positive impact on job creation in the technology manufacturing industries and also the agricultural sector, which supplies biomass fuel. Renewable energy can play an important role in increasing security of energy supply by providing domestic resources of energy and avoiding dependence on imported supplies of fossil fuels.

Today, the renewable energy sources contribute around 22% to energy production, with traditional biomass and hydroelectric power as the main contributors. In Europe, the renewable energy's contribution to the primary energy is 5.3% (1994) in the European Union and 1.7% in Eastern Europe. Since 1989, the use of renewable energy in Europe has been growing at a rate of 2.7% per year, 50% faster than the 1.8% annual growth of the overall energy market over the same period. It is likely that renewable energy will, by 2020, be one of the three largest sources of energy in Europe, along with gas and nuclear. At present, the level of renewable energy market penetration strongly depends on policies, particularly policies for environment, research and development (R&D), and market support policies. Europe's renewable energy industry is already leading the world in some areas, notably in wind and PV, and is a world pioneer in advanced biomass.

Electricity from renewable sources is today still more expensive than electricity produced from traditional sources. Therefore, a large-scale application of renewable energy sources as electricity power sources is not yet economically attractive in the industrialised countries. The comparison of electricity generating and investment costs for various energy technologies is presented in Table 1[4]. The environmental benefits of renewable technologies are probably the strongest factor for growing market and national policies to encourage renewable energy sources. However, electricity from renewable energy sources is already today the most effective cost solution for two billion people in many parts of the world who have no access to electricity grid.

Table 1.1 Comparison of investment and electricity generating costs for various energy technologies[4].

Technology	**Generating costs** (US cents/kWh)		**Investment costs** (US $/W)	
	Mean	**Range**	**Mean**	**Range**
Gas combined cycle	3.5	3.0-4.0	0.6	0.5-0.7
Coal	4.8	4.0-5.5	1.2	1.0-1.3
Nuclear	6.0	3.3-8.0	1.6	1.2
Wind	5.5	3.0-8.0	1.4	2.0
Biomass 25 MWe combustion	6.5	4.0-9.0	2.0	1.5-2.5
Small hydro	7.5	5.0-10.0	1.0	0.8-1.2
Solar thermal	15.0	12.0-18.0	5.0	4.0-6.0
Solar PV	55.0	30.0-80.0	7.0	6.0-8.0

[4] P. Langcake, Getting a clear view Strategic perspective for renewable energy companies, Renewable Energy World, Vol. 6, No. 2, Mar-Apr 2003.

1.4 Photovoltaic solar energy (solar electricity)

1.4.1 Introduction to photovoltaic solar energy

The energy of solar radiation is directly utilised in mainly two forms:
i) direct conversion into electricity that takes place in semiconductor devices called ***solar cells***
ii) accumulation of heat in ***solar collectors***.

Therefore, do not confuse solar cells with solar collectors. 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”, because “photo” is a stem from the Greek word “phõs” meaning light and "Volt” is an abbreviation of Alessandro Volta’s (1745-1827) name who was a pioneer in the study of electricity. Since a layman often does not know the meaning of the word photovoltaics, a popular and common term to refer to PV solar energy is ***solar electricity***.

The oil company Shell expects that PV solar energy will become the main energy source for the "post-fossil-era"[3]. Developing the PV solar energy as a clean and environmentally friendly energy source is considered at present noble mission. In this mission, the sun is consciously given an additional function to the one that it has had: to provide energy for life on the Earth. The sun’s additional function will be to provide the Earth with energy for people’s comfort and well being by producing the solar electricity.

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 and providing clean 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 and SO_X and NO_X that pollute the atmosphere during burning of the fossil fuels. When we closely look at the contribution of the PV solar energy to the total energy production in the world we see that the PV solar energy contribution is only a tiny part of the total energy production. At present, the total energy production is estimated to be 1.6×10^{10} kW compared to 1.0×10^{6} kW_p that can be delivered by all solar cells installed worldwide. By W_p (Watt peak) we understand a

unit of power that is delivered by a solar cell under a standard illumination. 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. When 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 and 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 30 years.

Economy

The solar cells and solar panels are already on the market. An advantage of the PV solar energy is that the solar panels are modular and can be combined and connected together in such a way that they deliver exactly the required power. We refer to this feature as "***custom-made***" energy. The reliability and very small operations and maintenance costs, as well as modularity and expandability, are enormous advantages of PV solar energy in many rural applications. There are 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. Some companies and people have realised that solar electricity can make money already now and this fact is probably the real ***driving force*** to a widespread development and deployment of the PV solar energy. We can roughly estimate how much money is already involved in the production of solar cells. The total production of solar cells has achieved more than 1200 MW_p. An average cost-prize of 1 W_p. was approximately 3.5 €. This means that the money involved in production of solar cells reached 4.2 milliard €. Assuming that a complete PV system is roughly two times the cost of the cells, a total money involved PV in 2004 can be estimated to 10 milliard €.

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

Advantages:

- environmentally friendly
- no noise, no moving parts
- no emissions
- no use of fuels and water
- minimal maintenance requirements
- long 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:

- PV cannot operate without light
- 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 neededin *off-grid* applications energy storage is needed, such as batteries

1.4.2 Photovoltaic (PV) system

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers a certain amount of electrical power that is characterised by an output voltage and current. 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***.

The solar panels are part of a complete ***PV solar system***, which, depending on the application, comprises batteries for electricity storage, dc/ac inverters that connect a PV solar system to the electrical grid, and 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.

1.4.3 Photovoltaic technologies

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 energy crisis in the seventies of the 20th century accelerated a search of new energy sources for terrestrial applications. This search resulted in a growing interest for PV solar energy. The major obstacle of using solar cells for terrestrial electricity generation has been a much higher price of the solar electricity when compared to the price of electricity generated from the traditional sources. Therefore, there has been much effort in the field of solar cells to reduce the price of solar electricity to a level that is comparable to the conventional electricity. 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. In order to increase the efficiency of single crystal silicon solar cells and to lower their price, the crystalline silicon solar cell technology has improved dramatically in the past twenty years and today it is the dominant solar cell technology. Crystalline silicon solar cell technology represents today not only single crystal silicon wafer-based solar cells, but also multi-crystalline 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 encapsulants.

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), thin-film polycrystalline silicon (*f*-Si). The titanium oxide nanocrystals covered with organic molecules represent so called dye-sensitized nano-structred solar cells. It is expected that the efficiency of commercial second generation solar modules is likely to reach 15%.

Conversion efficiency has to be increased substantially in order to progress further. Calculations based on thermodynamics demonstrate that the limit on the conversion efficiency of sunlight to electricity is 93% as opposed to the upper limit of 33% for a single junction solar cell, such as a silicon wafer and most present thin-film solar cells. This suggests that the performance of solar cells could be improved 2-3 times when different concepts were used to produce a ***third generation*** of high efficiency, thin-film solar cells.

1.4.4 Photovoltaic applications and market

Figure 1.4 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. The conversion efficiency of solar cells used in space applications is the initial efficiency measured before the solar cells are launched into the space. This conversion efficiency is also referred to as the begin-of-life efficiency. Today's commercial PV systems in terrestrial applications convert sunlight into electricity with efficiency ranging from 7% to 17%. They are highly reliable and most producers give at least 20 years guarantee on module performance. In case of the thin-film solar cells the best conversion efficiency that has been achieved in laboratory is shown together with the conversion efficiency that is typical for commercial solar cells.

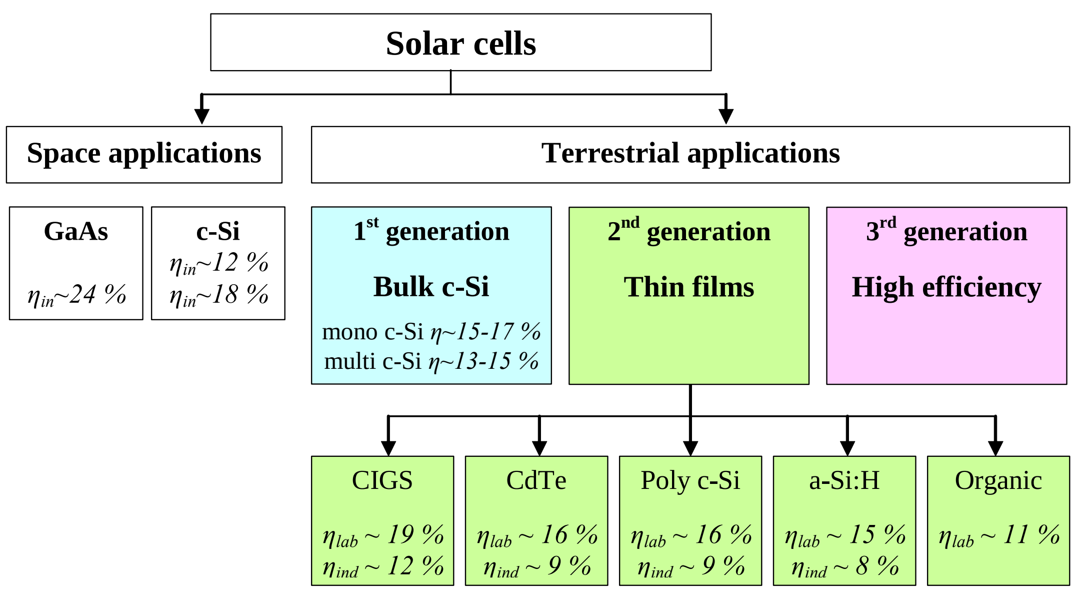


Figure 1.4. Overview of solar cell applications and of several types of solar cells used in different applications.

The commercial production of solar ells is steadily increasing and from 1996, the average increase is around 30%. The growth of the solar cell production is depicted in Figure

1.5 [5,6]. The total commercial production of solar cells in 2004 was $1GW_p$ and was 1250 MW_p. As illustrated in Figure 1.5 almost all commercial solar modules were produced from silicon. Crystalline silicon based solar cells amounted to 95% of the total production and were the dominant solar cell technology. The *a*-Si:H technology contributed with 4% to the total production in 2004. The only non-silicon technology that was delivering commercial modules was the CIS and CdTe technology with almost 1% from the total production. In 2004 most of the solar modules were manufactured in Japan (47%), the USA contributed with 11%, and Europe with 27%, the rest of the solar cells was produced in countries such as China, India and Australia.

The PV solar systems are already an important part of our lives. The simplest PV solar systems power many of the small calculators and wrist watches that we use every day. More complicated systems provide electricity for pumping water, powering communications equipment, and even lighting our homes and running our household appliances.

At present, there are four primary market areas for photovoltaic terrestrial applications:

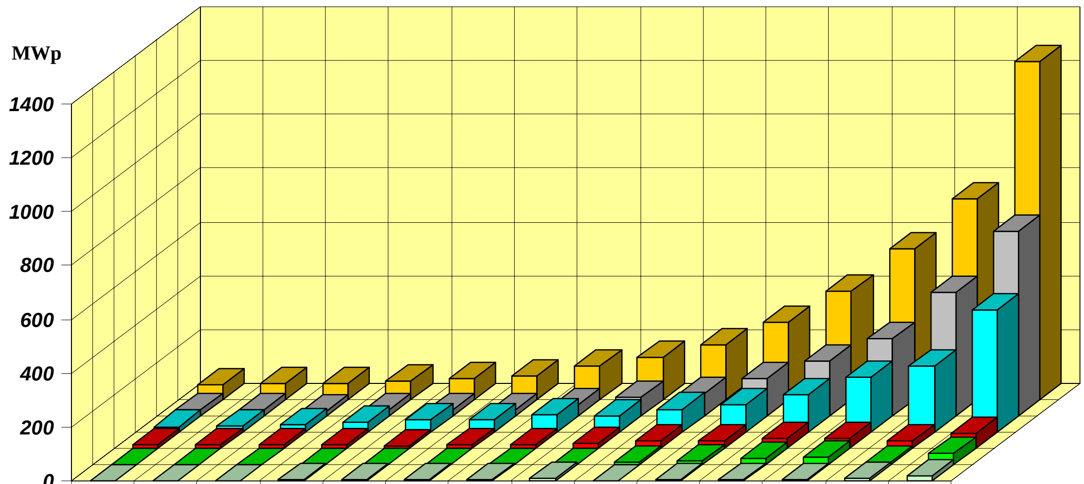
i) Consumer products, such as watches, calculators, and lanterns.
ii) Off-grid, also called stand alone, residential power systems, such as solar home systems for individual households.
iii) Off-grid industrial power systems for water management, lighting, and telecommunication.
iv) Grid connected PV systems that are integrated in roofs and outer walls of buildings or in noise barriers along the motorways.

Table 1.2 demonstrates the evolution of the share of PV modules in different market sectors. It is interesting to note that from 1996 the most growing market for PV modules are the grid connected PV systems that are integrated in roofs and outer walls of buildings.

Table 1.2: The share of PV modules in different market sectors[6].

Market sector	1993	1996	1999	2001	2003
	[MW_p]	[MW_p]	[MW_p]	[MW_p]	[MW_p]
Consumer products	18	22	35	45	65
US off-grid residential	5	8	13	19	30
World off-grid rural	8	15	31	45	70
Communications/signal	18	23	35	46	70
PV/diesel commercial	10	12	25	36	50
Grid connected	2	7	60	199	365
Central power	2	2	2	5	8
Total	**63**	**89**	**201**	**395**	**658**

[5] Photon International No. 3 (2005).
[6] P.D. Maycock, Renewable Energy World, Vol. 2, No. 4, July 1999.



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
rest	1.0	1.0	1.0	2.0	4.0	6.0	6.0	7.0	0.7	3.6	2.8	5.0	7.0	19.0
ribbon Si	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	14.7	22.5	26.3	6.8	41.0
a-Si	14.0	15.0	13.0	11.0	9.0	12.0	15.0	19.0	24.8	27.0	35.8	35.8	25.8	55.2
mono c-Si	20.0	22.0	29.0	36.0	47.0	47.0	62.0	60.0	85.0	102.0	138.7	201.4	244.0	455.0
multi c-Si	21.0	20.0	18.0	21.0	20.0	24.0	43.0	67.0	84.5	140.0	201.6	288.7	459.8	687.0
Total	55.4	57.9	60.1	69.4	77.6	88.6	125.8	154.9	201.3	287.7	401.4	559.6	744.1	1256.8

Figure 1.5. Commercial production of solar cells per technology.

Major national and international investments in research, development, demonstration and dissemination resulted in important technical improvements and a drop of the price of PV modules by a factor of more than 20 over the last two decades. In 1990 PV module costs were in the range US$5-6/$W_p$. This has now decreased to US$3.5-4.00/$W_p$. The cost of a PV system is about twice of PV module. The cost of solar electricity depends on the performance of the PV module. The solar cell performance, which is characterized by the conversion efficiency, has been improved. Commercial PV modules, which are made from crystalline silicon solar cells, have efficiencies of 12 to 17%. Further reductions in the cost of crystalline silicon solar cells are anticipated due to improved production methods, increases in efficiency of solar cells and reductions in the costs of producing modules. These could results in module costs of $2/$W_p$ by 2005. Amorphous silicon technology, which has a potential to become a low cost technology, delivers today modules with efficiencies of 5 to 8 %.

The world sales of PV modules in 1997 were around 0.5 billion US$. As costs decline and technology improves, more markets will be captured, leading to production increase and further cost reduction. Shell has predicted that a successful development of the PV business would involve annual 22% market growth linked to an annual 6% cost reduction in real terms. Current predictions show a 6 billion dollar global market for PV systems by 2010.