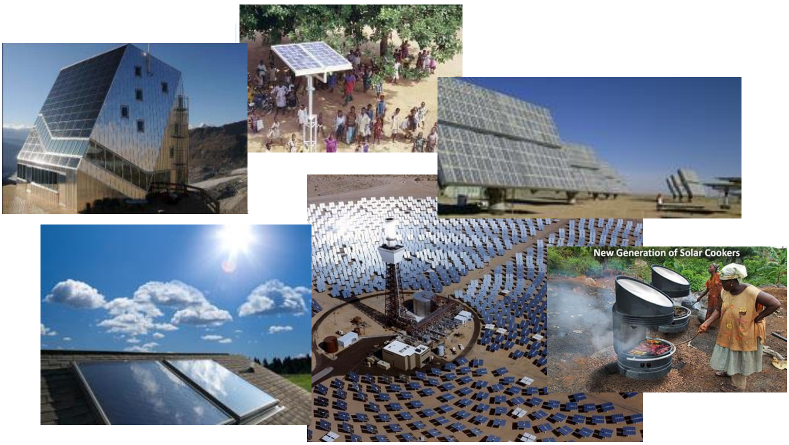
World Federation of Engineering Organisations

WFEO

Standing Committee Energy

Task Group Solar Energy

Study on Solar Energy



Lima 2016

FOREWORD WFEO President

The WFEO Standing Energy Committee responds to the need of engineering solutions in the energy sector with the mission to provide the engineer with updated, unbiased and reliable information on the feasibility of different energy technologies based on scientific principles, engineering criteria and demonstrated technological development.

In response to such assignment, the WFEO Energy Committee set up a Task Group led by Prof. Dr. Carsten D. Ahrens to develop this Report on the

STUDY ON SOLAR ENERGY – 2016

Members of the Task Group were appointed by WFEO Member Organisations.

This Report, being presented as a publication of the WFEO Energy Committee, gathers information on current sustainable energy proposals and the engineering views relating to the conditions of their applicability. It aims at providing the engineer and decision-making officers with up to date information regarding the different proposals that are being used, or are under consideration, for the implementation of sustainable energy policies.

Jorge Spitalnik
President, World Federation of Engineering Organisations
December 2016

FOREWORD Chairman SC Energy

Solar Energy is a proven renewable energy source and an ever-evolving technology. Cost declines and technological advances are contributing to increases in distributed solar power production and multi megawatt field installations that can provide a source of energy to the World.

Cost of Solar Energy systems have significantly dropped over the past few years giving families and businesses access to clean affordable energy.

In response to the importance of Solar Energy technology, the World Federation of Engineering Organization's (WFEO) Energy Standing Technical Committee Task Force created a STUDY ON SOLAR ENERGY. This study discusses types of Solar Energy, Production, Economics, Influence on Climate Change and Storage.

Members of the Task Force were led by Dr. Carsten Ahrens from the Jade University of Applied Sciences, Germany. Dr. Ahrens knowledge and passion for Solar Energy is clearly represented in this Study.

This Study is presented as a publication by the Energy Standing Technical Committee as a Series on Feasibility of Current Energy Options. The Series is intended to give the viewpoint of the Engineer on questions related to technical and economic feasibility of energy issues of significance to Society. It aims to provide the Engineer and decision makers with updated information on state-of-the-art technologies being used for the supply of energy.

WFEO hopes this Study will assist the engineering community, policy and decision makers, and the public to be aware of the conditions that make Solar Energy utilization a feasible option for assuring sustainable development and potential mitigation of climate change effects.

Samuel W. Grossman, PE
Vice President, World Federation of Engineering Organizations
Chairman of Energy Standing Technical Committee
December 2016

FOREWORD Chairman Task Group Solar Energy

The study as it is available now has a relatively long history. It started some years ago, but must be stopped due to private rationales. So it needed some helpful "pressure" from the WFEO president to restart and finish the study in due time.

As the author I am happy and a little bit proud to have finished this study now and finding it agreed by the SC Energy and its Chairman, and especially the president of WFEO. At the WFEO meeting in Lima, Peru, it is now published as an electronic version on the WFEO website.

The study is not a too academic and investigational work, and therefore no learning book. But all data, figures and tables are chosen and collected carefully, and their sources are described in detail and placed according to normal and generally accepted scientific citation rules.

The aim of this study is to give the interested person a comprehensive overlook over the "solar energy world". The person may be an engineer, a scientist, the normal technician, a student or at what is of most wanted interest the "man and women of society". The text is written in English by a non-native English speaker, and thus could make it more easily to understand. The content of the chapters tackle different topics, but sometimes there is a small overlap and rerun.

More than 100 figures illustrate the content of the chapters, and about 70 sources are cited. To make the research and deepening of the topic easier the citation numbers are directly linked to the respective source. Because of the quick changes in the fields of solar energy use and due to the lack of adequate home libraries, all (nearly) sources are to be found in the internet. So the reader can evaluate the data in a quick and comfortable way. Even if the exact address is no longer valid, it is relatively simple to find the information on the general websites of the distinct citation by using the additional information of the bibliography.

Carsten D. Ahrens
Chairman Solar Task Group
WFEO SC Energy
December 2016

Solar Energy

Forewords

WFEO-president
WFEO-chairman Standing Committee Energy
Chairman Task Group Solar Energy

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1. Introduction

Solar energy is availably without energetic limits and without any boundaries worldwide. It can be harvested everywhere, in developed as well as in non-developed countries.

The proposed climate change and the connected efforts in reducing the carbon dioxide emission into the atmosphere result in a number of activities worldwide to reduce the consumption of fossil energy and to – partly - replace them by installing various kinds of renewable energy sources. This repertoire also includes nuclear power stations, which in the opinion of many experts are a suspicious "green" alternative.

The earth's most powerful and sustainable energy source was, is and will be the sun irradiating parts of its energy day by day onto the earth. As figure 1 [1] shows the amount of energy the sun irradiates in one hour onto the earth is sufficient to power the earth's population for an entire year, and this year by year.

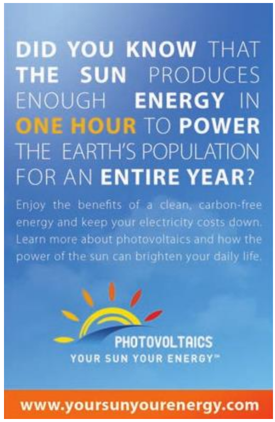


Fig. 1: Summed sun's irradiation

There is a great variety of photovoltaic and heat production solutions; the small ones for home installations and that of extremely powerful solar plants. As these plants have to be installed where the irradiation is extremely high, thus in the deserts, which are some thousand kilometres apart from the consumers, intelligent and efficient electrical current nets with low voltage losses on their way have to be developed. Solar energy is a highly volatile energy source. It is available only

during the daily sunshine time, but not during night. So, very effective and huge energy storage systems have to be developed, to deliver a continuous energy supply. The aim of sustainable energy supply still is a self-consistent sustainable power plant.

2. Solar Energy (general overview)

2.1 Amount of Solar Radiation

The sun offers on average a radiation flux density of 343 W/m2 of which about 70 percentages is absorbed by the Earth system. These remaining 237 W/m2 reach to a large part the surface, namely 165 W/m2. In comparison to mankind's energy flux density of about 0.03 W/m2 the sun's offers at the surface is by a factor of more than 5000 higher.

2.2 Solar Irradiance on the Surface of the Earth

Figure 2 [2] shows the solar thermal potential for electricity generation around the world. Obviously the largest accessible but least tapped form of energy on earth is solar radiation on deserts. Its capacity, i.e. the annually received amount can be estimated in a rather straightforward way, since radiation is quite uniform across the desert regions.

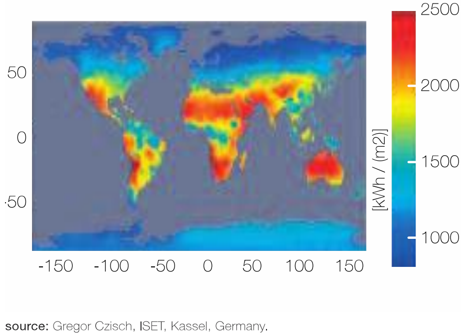


Fig. 2: Solar irradiation around the world

The regions where to harvest sun energy are distributed differently around the earth. There is an obvious belt around the world, where the sun's irradiation is most powerful and which is shown in figure 2 [2].

The hot deserts (red areas) cover around 36 Million km² (UNEP, 2006 [3]) of the 149 Million km² of the Earth's land surface. The solar energy arriving per 1 year on 1 km² desert is on average 2.2 Terawatt hours (TWh), yielding 80 Mio Terawatt hours/year. This is a factor of 750 more than the fossil energy consumption of 2005, and there is still a factor of 250 if this demand would triple until 2050. One conclusion that can be made is to use as much as possible solar energy radiation from the most plentiful deserts. But, the transport of the solar electric energy over very long distances to consumption areas is quite costly and power transmission technology for such distance conditions still needs to be developed.

2.3 Potential of Solar Energy compared to other Energy Resources

Compared to all other global energy resources, especially fossil resources, solar energy overwhelms them manifold as figure 3 is showing in a very comparative way [4].

Fossil fuels are expressed with regard to their total reserves. The renewable energy data describe their **yearly** potential. The energy in the sun's rays that reach the earth's surface could meet global energy consumption 10,000 times over. If only 0.34 % of the European land mass was covered by photovoltaic modules (area of the Netherlands) this would meet Europe's entirely electricity consumption.

The developing and in particular the developed world depend crucially on the continuous supply of energy. The actual world's primary fossil fuel consumption is about 107.000 Tera-Watthours (1 TWh = 1 10^{12} Wh) per year. The world's demand on electrical power with about 18.000 TWh per year sums up to about 17 %. Up to now about 85% of the global demands are covered by fossil energy sources.

So, the global energy supply system of today is mainly built on stored, non-renewable fossil fuels. Nuclear energy still belongs to the fossil energy production line even if some experts call it clean or even "green".

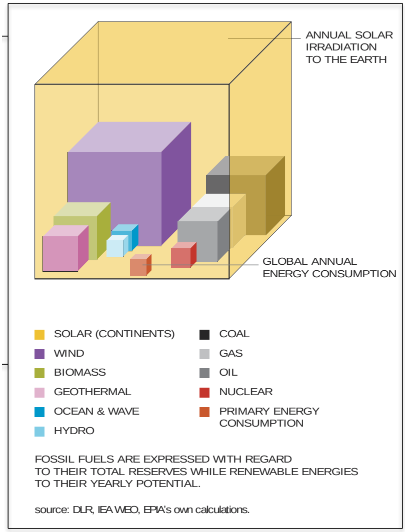


Fig. 3: Annual radiation versus fossil energy [4]

3. Solar Energy Technologies

3.1 Photovoltaic Energy (plane PV)

Photovoltaics (PV) is a method of generating electricity by sun light. The photons of the light exit electrons into a higher energy state. This conversion of light into electric energy appears best in a solar cell of special semiconducting materials. The used material is normally doted mono- or polycrystalline silicon. Small solar cells are connected to solar panels. Such panels can supply different small electric devices. The electric output is direct current. The physical principal of photovoltaic energy production (plane PV) is given in figure 4 [10]. Figure 5 shows an industrially produced PV cell [10].

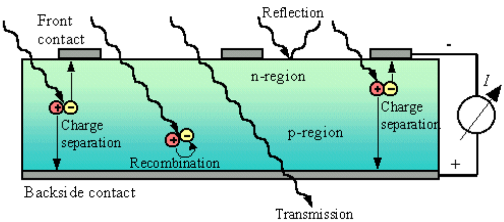


Fig. 4: Principle of PV cell electricity by light [10]   Fig. 5: PV cell

Solar cells are not normally operated on an individual basis, due to their low voltage, and in PV modules, cells are mostly connected in series. Single, unprotected crystalline silicon solar cells can also be damaged rapidly, due to climatic influences. So to avoid this, several crystalline cells of edge length 10–15 cm (4–6 inches) are combined in the form of a solar module for protection. The front cover of this is formed by glass with a low iron content, and the back cover consists of glass or plastic. Between the front and back covers, the solar cells are embedded within plastic,

The following examples of solar panels as stand alone models shall make its enormous variety of application easier to understand:

Fig. 6 – 9: PV on roofs (city and rural area) and on signal devices (6); at facades of mountain buildings, (BIPV, Building Integrated PV), Zermatt [57](7); CIS tower, Manchester [61](8); Solar Vineyard House, California, USA [5](9)

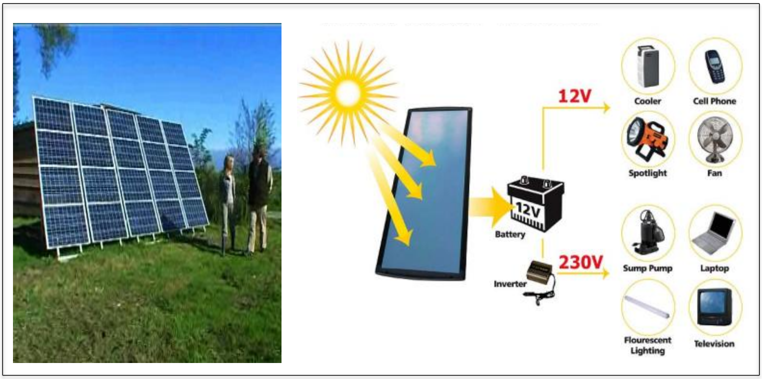


Fig. 10: Extended solar home system for rural areas [6]

Fig. 11: Solar energy field as industrial application [3]

The electrical energy capacity of PV devices is described by "Wp", which is Watts peak. This is the maximum power output under standardized test conditions. In reality the value is much lower, depending on geographical location, time of day, weather conditions and other factors. The range is from < 1 Wp for single cells up to > 500 MWp.

Areas of application for photovoltaics can be expanded in the future through progress in organic PV (OPV), based on organic LEDs. They are flexible and wafer thin and could be used on windows, building facades, mobile phones etc.

3.2 High Concentrating Photovoltaic Energy (HCPV)

When discussing PV use for electricity production normally it concerns the “classic” mono- and poly-crystalline types and thin-bedded (amorphous) modules. All these modules suffer a great because of their relatively poor 10% efficiency to transform sunlight into electricity.

The new type of low/medium/high concentrating photovoltaics may become an outstanding challenge in PV use in countries of the sun-belt regions or at least there, where high direct normal irradiance is available. Figure 12 [7] shows such an ideal region in one of the deserts (in China), which are sketched in the sun-belt region of figure 13 [4].

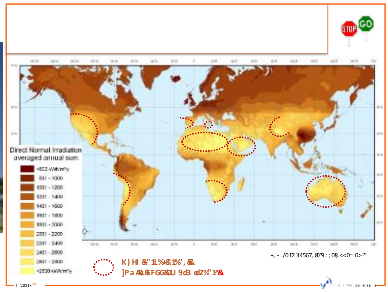
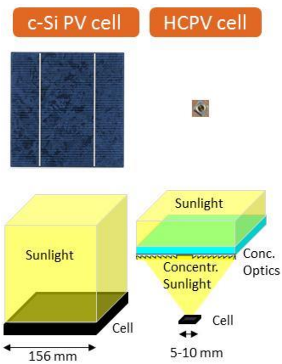


Fig. 12: HCPV place in the desert [7] Fig. 13: Earth’s sun-belt region[4]

As shown in figure 14 concentrating optics are used to focus the light on small but very effective solar cells, which receive the sun summed up to “400 till 1.000 suns” and reduces the costs of PV cells. The efficiency of such cells is about 40% for commercial use [9].



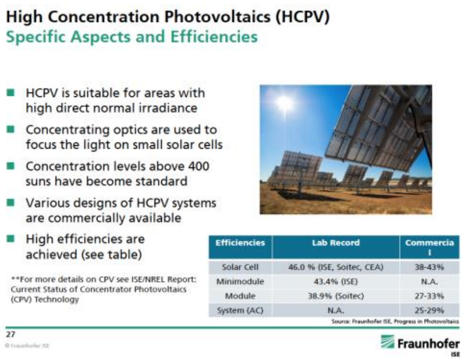


Fig. 14: 1.000 sun cell [9] Fig. 15: Specific aspects and efficiencies [9]

3.3 Solar Thermal Energy (Non-concentrating)

Solar thermal devices use the heat content of the sun's radiation. At the heart of a solar thermal (heating) system is the solar collector. It absorbs solar radiation, converts it into heat, and transfers heat to the system.

There are a number of different design concepts for collectors: besides simple absorbers used for swimming pool heating, more sophisticated systems have also been developed for higher temperatures, such as flat-plate collectors as shown in figures 16 and 17, and evacuated-tube collectors, see figure 18 [all 10]. Both, direct and diffuse irradiance of the sun produce heat by absorption. The absorption takes place in – normally - dark absorbing tubes filled with water. They are installed mostly on the roofs of houses.

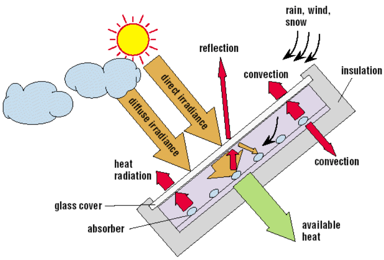


Fig. 16: Plane collector physics [10]

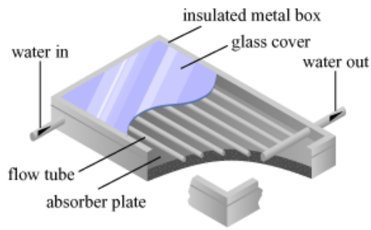


Fig. 17: Plane collector technical

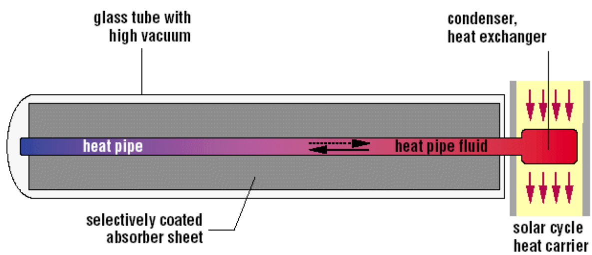


Fig.18: Evacuated-tube collector [10]

The warm water is usually used for heating water for showers and washing and for supporting space heat. The conversion to usable water takes place through a heat exchanger. In simple systems like thermo-syphon, see figure 19 [11], the water is driven by gravity, whereas family houses integrate it into the heating system with a pump as figure 20 shows it [10]. Most systems are mounted on dwelling roofs.

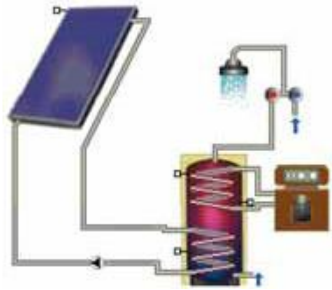


Fig. 19: Thermo-syphon system on roof   Fig. 20: Pump driven system

A new application is conversion of sun heat into air-conditioning and, thus, cooling houses and rooms. The latter is particularly of interest to countries in southern latitudes, which consume up to 80% of power for air-conditioning in the hot summer months. Solar heat can also be used to produce process heat and steam. Worldwide, around 75% of all solar thermal systems installed are thermo-siphon systems and 25% are pumped solar heating systems.

3.4 Concentrating Solar Thermal Energy (CSP)

Concentrating solar power (CSP) plants use the sun's energy to generate electricity in industrial-scale systems. They use mirrors to concentrate the energy from the sun to drive traditional steam turbines or engines that create electricity. The thermal energy concentrated in a CSP plant can be stored and used to produce electricity when it is needed, day or night.

Parabolic Trough

Parabolic trough systems use curved mirrors to focus the sun's energy onto a receiver tube that runs down the center of a trough. In the receiver tube, a high-temperature heat transfer fluid (such as a synthetic oil) absorbs the sun's energy, reaching temperatures of 750°F or even higher, and passes through a heat exchanger to heat water and produce steam. The steam drives a conventional steam turbine power system to generate electricity. A typical solar collector field contains hundreds of parallel rows of troughs, see figure 21 [12], connected as a series of loops, which are placed on a north-south axis so the troughs can track the sun from east to west.

Fig. 21: Parabolic trough [12]

Individual collector modules are typically 15-20 feet tall and 300-450 feet long.

Altogether, there are four types of CSPs: Linear concentrating systems like parabolic trough (see above) or Fresnel collectors, and point focus concentrating systems like solar towers and (parabolic) dishes. All systems must track the sun in order to be able to concentrate the direct radiation. All CSP plants can be used for electricity generation, seawater desalination, industrial drying processes and cooling of large stores or production of hydrogen.

Power Tower

Power tower systems use a central receiver system, which allow for higher operating temperatures and, thus, greater efficiencies. Computer-controlled flat mirrors (called heliostats) track the sun along two axes and focus solar energy on a receiver at the top of a high tower. The focused energy is used to heat a transfer fluid (over 1.000° F) to produce steam and run a central power station.

Fig. 22: CSP as solar power tower [13]

Dish-Engine

With the so-called Dish Stirling system a parabolic reflector mirror concentrates the solar radiation onto the receiver of a connected Stirling engine. The engine then converts the thermal energy directly into mechanical work or electricity. These systems can achieve a degree of efficiency in excess of 30%. Interconnecting several such individual and stand-alone systems offers the creation of a solar farm with production of electric energy in the region of several MWatt. The temperature can reach up to 1.200o F in the focal point of the mirror [13].

Fig. 23: Dish system with stirling motor [13]

4. Solar Energy Production (Capacity)

4.1 General Remarks

Compared with other forms of renewable energy, solar heating's (and cooling) contribution in meeting global energy demand is, besides the traditional renewable energies like biomass and hydropower, second only to wind power as figure 24 shows it [14]. And in installed capacity, solar thermal is the leader. Photovoltaics and concentrated power generation are rather small energy contributors. – The data as reported in 2015 are in general more than 10% higher, in the case of PV even more, compared to the data of 2014. - The picture changes however dramatically when the energy conversion to electricity is discussed.

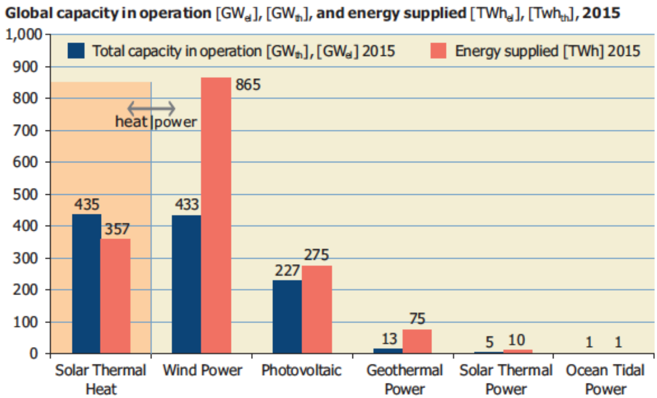


Figure 3: Global capacity in operation [GW_{el}], [GW_{th}] 2014 and annual energy yields [TWh_{el}], [TWh_{th}]
(Sources: AEE INTEC, Global Wind Energy Council (GWEC), European PV Industry Association (EPIA), REN21 - Global Status Reports 2015)

Fig. 24: Total capacity in operation and produced energy in 2014 [14]

The development of global installed capacity of solar thermal heat wind and photo voltaic since 2010 is shown in figure 25. Obviously all three mentioned renewable technologies show positive growth rates in terms of cumulative installed capacities, whereas the annual growth rates tend to decline.

The data as given in this chapter are showing the actual status or forecasted values based on different more or less optimistic scenarios. As the "solar history" is telling these data will vary year for year, and others will replace market leaders. There may come a shift to countries within the sun-belt region, where the sun irradiation is highest.

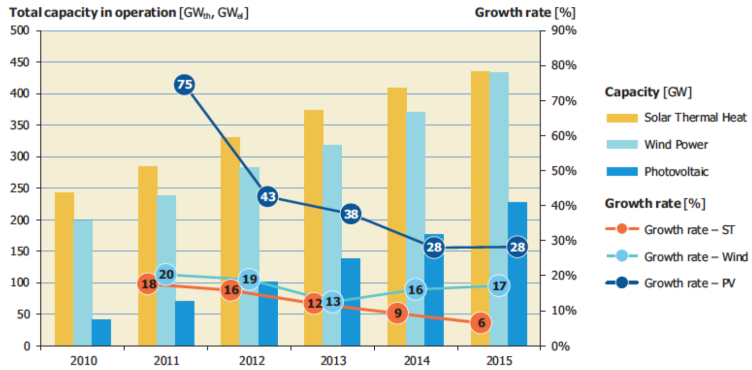


Figure 4: Global solar thermal heat, wind power and photovoltaic capacity in operation and market growth rates between 2010 and 2015 *(Sources: AEE INTEC, Global Wind Energy Council (GWEC), European PV Industry Association (EPIA), REN21 - Global Status Reports 2011-2015)*

Fig. 25: Development of 3 global renewable energies since 2010 [14]

This is the case for the production markets for solar technical equipment, as well as for the consumer countries. Changes are led by technical improvements, possibilities to store solar energy, to distribute solar electricity in smart grids etc. The developments are also strongly directed by governmental influences e.g. through instalment of feed-in tariffs, investment support etc.

In summary it is necessary to have knowledge about the actual status to understand changes, possibilities for improvements and develop-ments. Actual data can be collected by visiting the cited pages in the bibliographic chapter.

4.2 Photovoltaic Energy (Electricity)

Cumulated more than 225 GW of solar power are now installed in the world as figure 26 [16][17] is showing it. The amount of PV electricity generated during the year 2015 is more than 170 TWh, over 100 times more than in 2009. The curve is increasing steeply since 2005. Europe became the first region to pass the 100 GW mark.

The future perspectives are incredible good, as Oliver Schafer, President of SolarPower Europe [16] says as follows:

"Solar is booming and continues to break records in many parts of the world which gives us reasons to believe 700 GW globally installed solar power is possible by 2020"

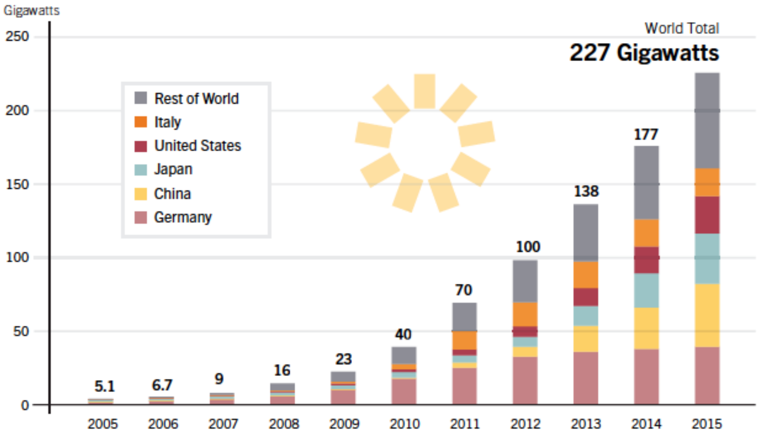


Fig. 26: Solar PV global capacity by country/region (2005 – 2015) [16]

The global rate of annual new-built capacities, which was 7 GW in 2009, was more than seven times higher in 2015 [16] to reach 50 GW, as figure 27 is showing this progress. This number accounts for about 100 billion USD. Europe's market has progressed rapidly over the last decade, with Germany leading it through 7 years. But China became the top PV market in the world in 2013 and achieved the world's largest installation figure.

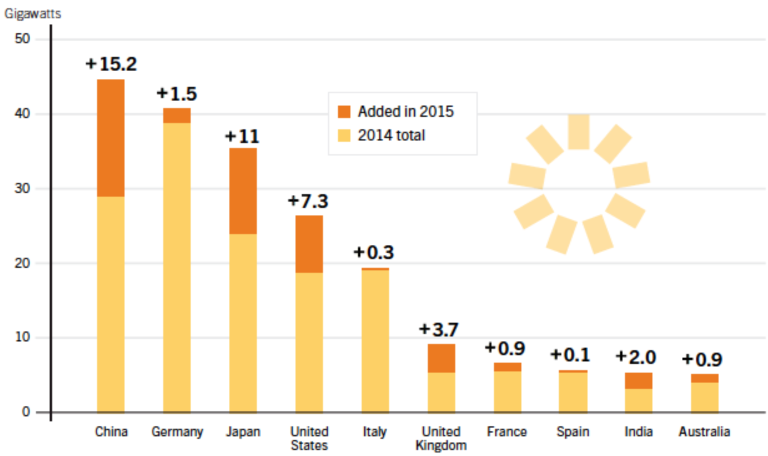


Fig. 27: Solar PV capacity and additions, top ten countries [17]

Figure 27 [17] shows the respective shares of newly installed, as well as cumulative capacities for the top 10 countries. Germany as a country, which is not so much favoured by solar irradiation, is still second, with respect to the cumulative data; leading position is obviously occupied by China.

Concerning newly added capacity China, Japan and the US again lead the world's solar market in 2015, with China and Japan alone responsible for 50% of newly installed capacity. 2015 also marked a growth year for the European solar market with 8.2 GW of grid-connected solar power, the market grew by 15% year-on-year.

Europe is still the predominant player with more than 108 GW installed capacity at the end of the year 2015. By this Europe covers about 40% of the world cumulative PV installations. In addition Europe covers 2.6% of its electricity demand by PV, worldwide it is 1%. This seems to be a small figure but this power is equivalent to at least 32 large coal fired power plants of 1 GW each [16]. Leading countries producing electricity by PV are Italy with 7% and Germany with 5.3%.

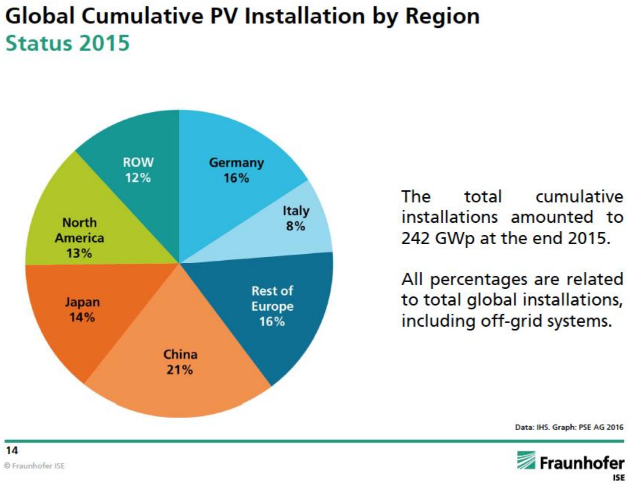


Fig. 28: Percentage of global PV cumulative installed capacity 2000 – 2015 by region [9]

The **outlook**:

Almost 200 GW of solar power could be installed over the next three years, depending on the assumption of the high scenario, leading to a cumulative market of optimistically 540 GW, see figure 29 [17]. The highest probability scenario leads to a value of around 450 GW.

The high scenario counts on favourable environment, accompanied by strong political will. It then depends also on the development of the rooftop, industrial and utility PV market. – Together, wind and solar, will form the new basis of our world energy system [17].

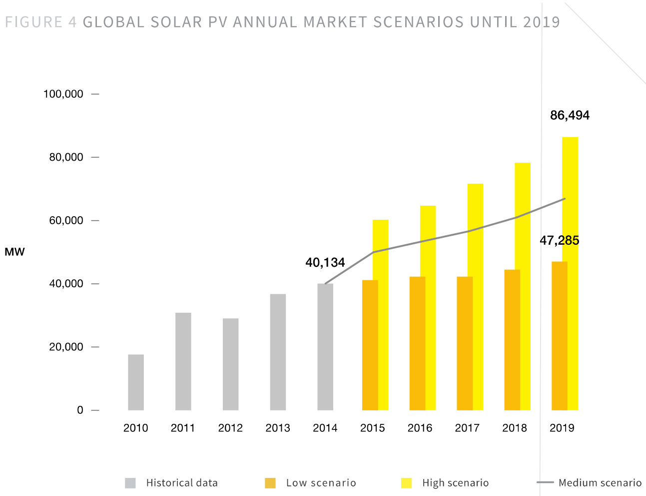


Fig. 29: Global PV scenario till 2019 [17]

A longer prognosis draws an even more optimistic picture, shown in figure 30 [18]. This roadmap envisages a PV share of global electricity of 16% by 2050, which is a significant increase compared to the 2010 roadmap.

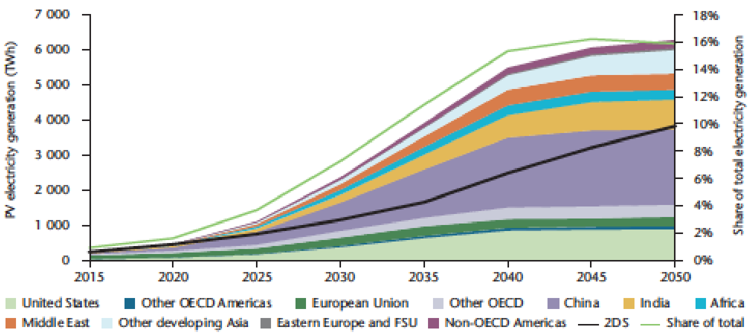


Fig. 30: Road map for global PV electricity by regions till 2050 [18]

PV would then contribute 20% of all renewable electricity. As can be seen China is expected to continue leading the global market, accounting for about 37% of global capacity by 2050. Utility scale and rooftop PV will each have roughly half of the global market.

4.3 High (and Low) Concentrating Photovoltaic Systems Energy

The HCPV technology is relatively new, but its development seems to increase rapidly as figure 31 shows. Starting in 2008/09 it grew by a factor of ten during the recent five years. High CPV uses lenses or other systems like mirrors to concentrate the sun light by a factor from 300 up to 1.000. Low CPV has concentration factors below 100.

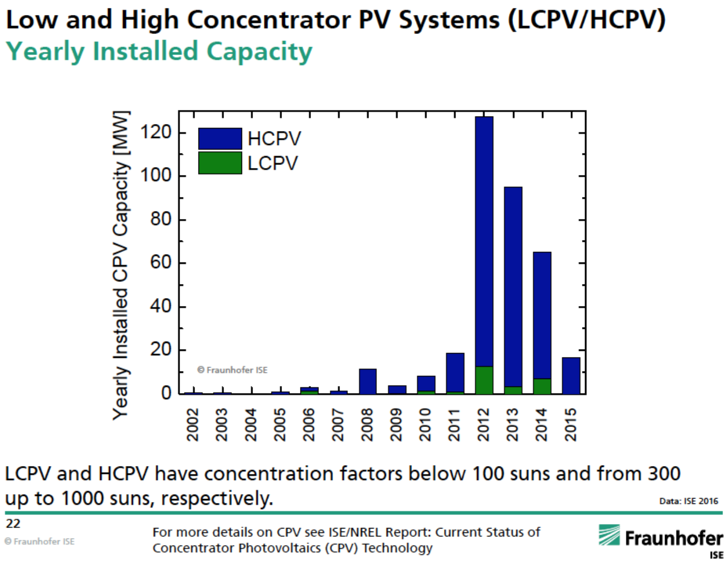


Fig. 31: Yearly installed CPV capacity worldwide [9]

The development of this system depends on the combination of an investment's planning security with its costs per watt peak (Wp), the geographical setting and another significant factor as with political conditions, which play a vital role. A solid database about the total installed capacity is not available up to now.

High concentrated PV installations cover still only a small portion of the PV market. The actual cumulative HCPV power is given in figure 32. China obviously is leading with about 150 MW, second is USA with about 80 MW. South Africa is third, followed by Italy and Spain. All others are negligible, and nearly part of the "rest of the world".

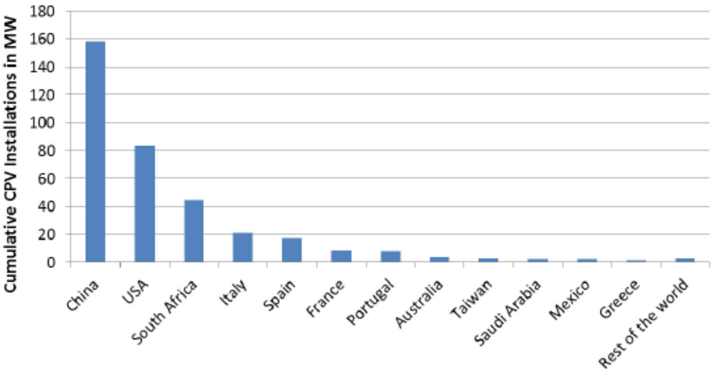
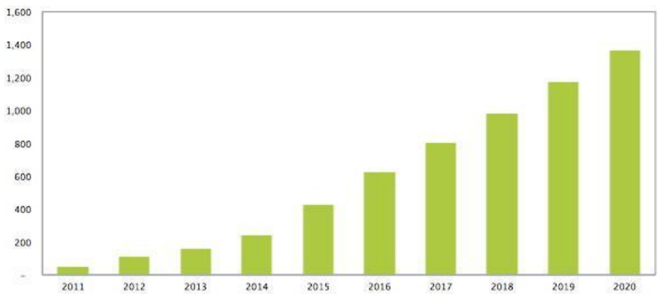


Figure 4: Grid-connected CPV capacity by country through end of 2015. All countries with a total installation of 1 MWp or more are shown separately.

Fig. 32: Grid-connected cumulative HCPV by countries [9]

The overall development of HCPV is sketched in figure 33 [9], which shows the yearly installed capacity. The table gives the actual data by numbers directly.



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
MW	46	108	160	240	425	622	804	982	1,172	1,362
%	—	235%	148%	150%	177%	146%	129%	122%	119%	116%

Fig. 33: Yearly installed capacity of high concentration PV systems [9]

The German Fraunhofer Institute [9] recently has produced a four layer cell, which uses four different wavelengths intervals of the sun light to produce electric energy with an efficiency of more than 50% in the laboratory, which up to now means the world record.

HCPV power plants are installed in sunny regions, which are often characterized by hot and arid climates. The modules have to be cooled normally by water. But water must be saved in these regions. So HCPV systems e.g. from Soitec [19] then use metal heat sinks for passive cooling of the solar cells. No cooling water is needed. Water is only used for regular cleaning of the (H)CPV modules.

Nevertheless the demand for HCPV by itself is lower than it was for PV in the late 2000s, of course. But e.g. IHS sees (H)CPV installations soaring over the next few years, from just 160 MW in 2013 to more than 1.3 GW in 2020, and more than doubling every year. HCPV is increasing its presence mainly in the **utility-scale solar** market, but its growth has been partially stunted by falling prices for less efficient PV options and due to the relatively expensive tracking systems.
Up to now HCPV electricity production is restricted to arid regions mostly situated in the sun-belt region, thus, connected to utility scale electricity production areas.

4.4 Solar Thermal Energy

The estimated total capacity of solar thermal collectors in operation worldwide is about 430 GW_{th} - or about 610 million square meters of collector area -, see figure 36 [14]. This corresponds to an annual collector yield of about 365 TWh, wich is equivalent to savings of more than 40 million tons of CO_2.

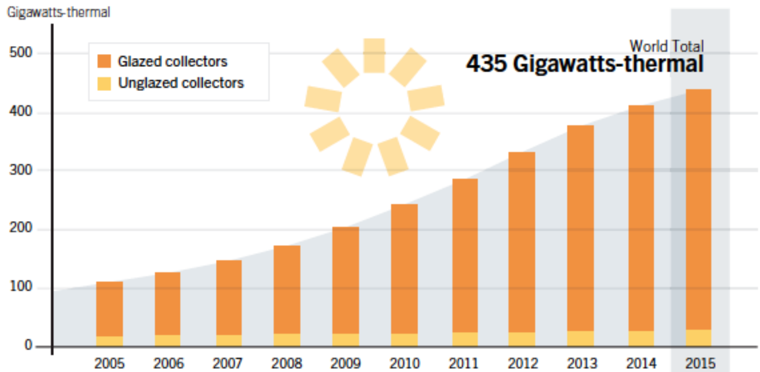


Fig. 36: Solar water heating collectors global capacity till 2015 [17]

The vast majority of the total installed capacity in operation was installed mostly in China, but also in Europe, which together accounted to 82% in 2013. This and the other shares can be seen in figure 37, which does not distinguish between the different types of collectors (glazed and unglazed water and air collectors).

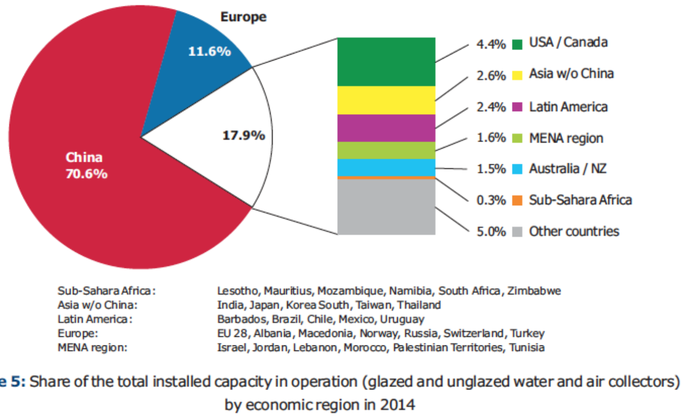


Fig. 37: Share of total installed capacity of solar heat in operation [16]

The added capacity distribution by countries in the year 2015 can be seen in figure 38 [66]. Obviously China is again by far the leading country in using solar energy for heating, followed by USA, Germany, Turkey and Brazil.

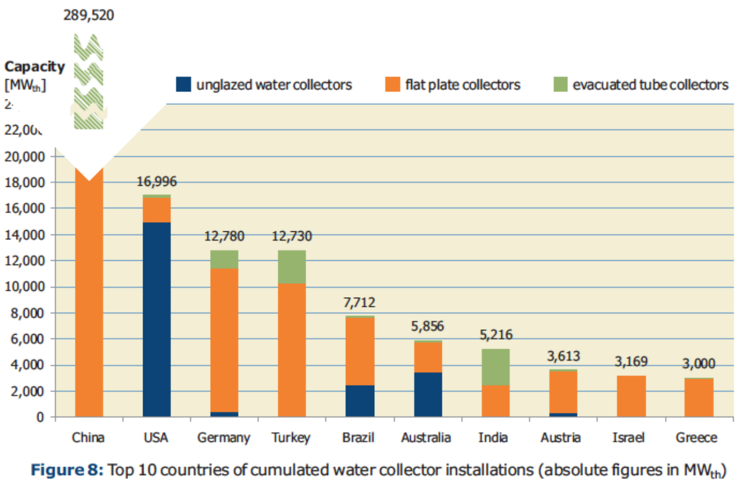


Fig. 38: Cumulated solar water heating collectors capacity [66]

The percentage of shares of new solar heating capacity installed in geographic regions in 2015 is given in figure 39 [62].

It is interesting and somewhat astonishing that the "rest of the world" with so many and so sunny countries like those in the MENA region or across the so-called sunbelt do not contribute remarkably to these figures. Their total share in 2013 was just 18%.

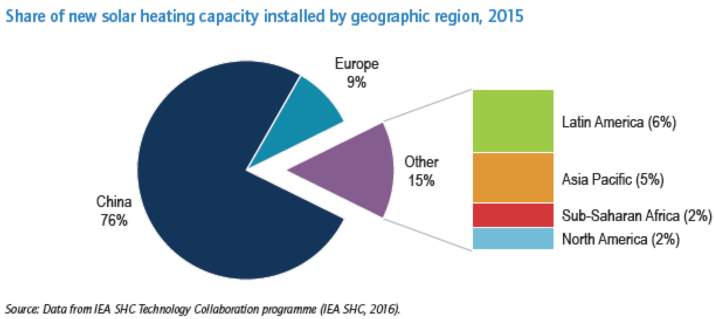


Fig. 39: Share of newly installed solar heating capacity by region [62]

- More than 90% are used for water heating; only a small amount is used for space heating in houses. The share for swimming pool water heating is about 6%!!!

The **outlook/roadmap** in general is quite emphasizing as figure 40 is showing [14].

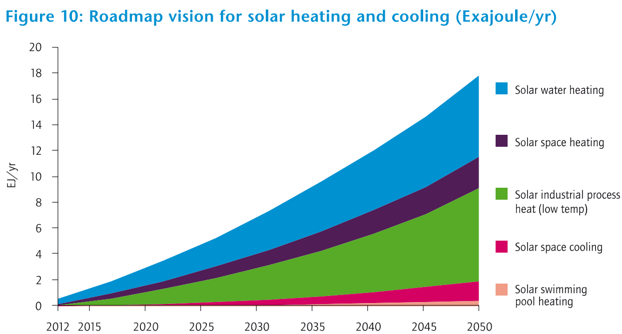


Fig. 40: Roadmap vision for solar heat and cooling energy [14]

Many intelligent application techniques will be developed, including use of process heat and installations of huge district heating water reservoirs, and so will help to come up with this visionary outlook.

4.5 Concentrated Solar Power Energy

The Concentrated Solar Power (CSP) market remains less established than most other renewable energy markets. Nonetheless, in 2014 the sector continued nearly a decade of strong growth. Four new projects totalling over 900 MW increased the total global capacity by 27% to reach nearly 4.4 GW as can be seen in figure 41 [17]. The commercial deployment of CSP plants started by 1984 in the US with the SEGS plants. From 1991 to 2005 no CSP plants were built anywhere in the world.

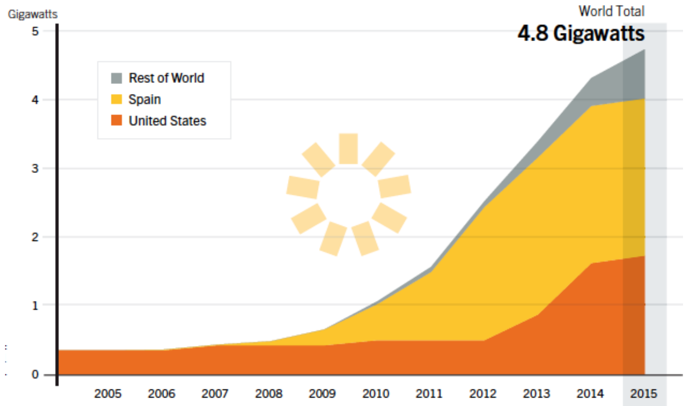


Fig. 41: Concentrating solar thermal power global capacity [17]

Global installed CSP-capacity has increased nearly tenfold since 2004 and grew at an average of 50% per year during the last five years. In the longer outlook Spain and the United States remain the global leaders, while the number of countries with installed CSP is growing. There is a notable trend towards developing countries and regions with high solar radiation, see figures 42 and 43 [18]

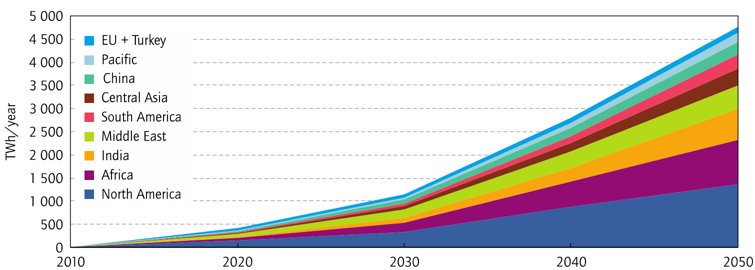


Fig. 42: Growth of CSP production by region (TWh/y) [18]

CSP can also produce significant amounts of high-temperature heat for industrial processes, and in particular can help meet growing demand for water desalination in arid countries.

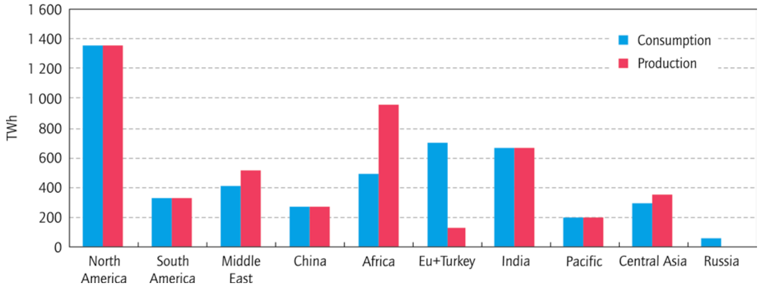


Fig. 43: Production and consumption of CSP electricity by 2050 (TWh)

Globally rapid development can currently be observed in the construction of solar thermal power plants, which means that market cost reductions in the electricity generation price of these systems can be expected.

This is music for the future, but not many valid data exist up to now, even if there is a rather large number of existing CSP plants, especially in USA and in Spain. A list of plants can be found under different addresses e.g. [19] and [20].

4.6 Hurdles in Development

Many hurdles exist on the way to a sustainable/green/clean energy future and, thus, spoil the sometimes optimistic picture as given above. This hurdle race is driven by a number of obstacles like leakages in

- know-how and perception;
- policy support;
- finance;
- grid infrastructure and
- implementation and service.
-

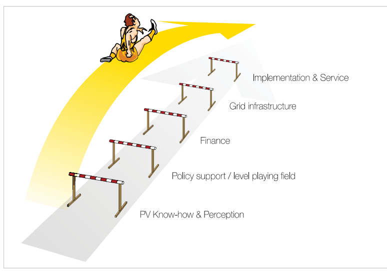
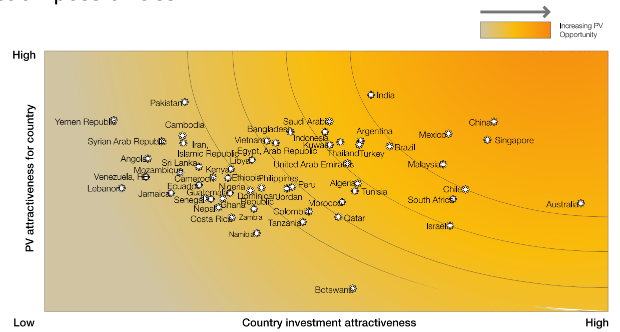


Fig. 44: Renewables' hurdles

In addition the actual prizes for oil and gas do not support investments in renewable energy production techniques. Therefore, the progress of renewables in the heating sector, which comprises almost half of the total final energy consumption (and transport, accounting for a quarter of consumption) has been slower than in electricity [21].

Especially the potential of the sun-belt regions has to be unlocked as figure 45 gives the imagination for [22]. Even if this figure concerns PV energy only, it is transferable to the other three solar energy production possibilities.



* Following countries are not shown on the mapping due to poor availability of data: Chad, Côte d'Ivoire, Congo Democratic Republic, Cuba, Iraq, Madagascar, Mali, Myanmar, Somalia, Sudan, Uganda.

Source: EPIA, Unlocking the Sunbelt Potential of Photovoltaics, 2010

Fig. 45: Unlocking the sun-belt potential of photovoltaic [22]

Concerning just PV sun-belt regions would then represent 27% to 58% of the forecasted global PV installed capacity by 2030. PV electricity in the sun-belt region today is comparable with diesel generators. China is one of the sun-belt countries, and the only one, which developed its potential to a worldwide visible market.

5. Solar Energy Manufacturing and Costs

5.1 General remarks

Solar energy can be used in different ways. The most attractive and therefore mostly used ways are heating up water directly and producing electricity in PV-systems. Due to the technical development both can be combined also to make up cooling systems. As a result of this even PV-systems may become a cheaper way for heating water.

The actual production market for solar energy use therefore is big, very big, and - dependent of the actual demands – in general internationally distributed. According to the needs of the single user the variety in technical devices and, thus, in costs is also very vast.

The demand starts from single rooftop PV-modules or heating water tubes and ends with vast utility plane PV-fields, huge concentrated solar power plants (CSP) and high concentrating PV-fields. Hand in hand go the financial investments. Figure 46 [63] is showing the range of use. Depending on the annual irradiance specific applications are possible and economically interesting. The single personal user is to be placed at the far left.

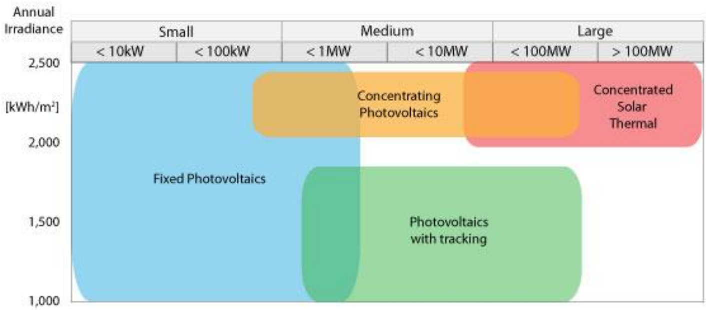


Fig. 46: Range of solar energy use as of the annual irradiance [63]

Concerning the levelized cost range of all electricity production paths figure 47 [67] gives an overview. - This figure is not the most actual one, but still shows the data in a comparing way. Actual data would shift the bars towards lower costs, somewhat downwards.

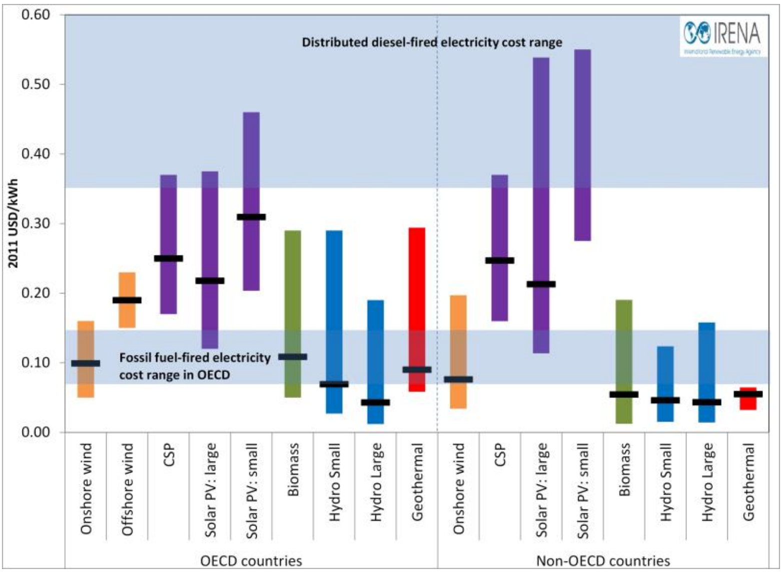


Fig. 47: Levelized costs for different electricity production paths [67]

5.2 PV Plane

The PV industry has undergone a “sea change” in only five years, with considerable increases in manufacturing capacities, and a move of module manufacturing from European countries and the United States to Asia, notably China and Chinese Taipei, as figure 48 shows it [15].

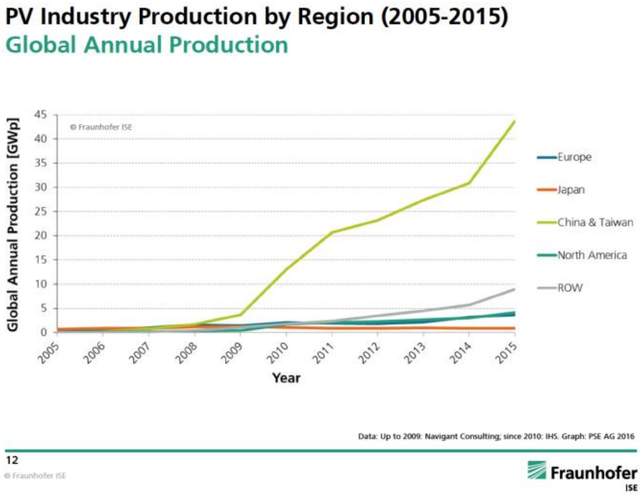


Fig. 48: PV industry manufacturing by countries (data in GWp) [9]

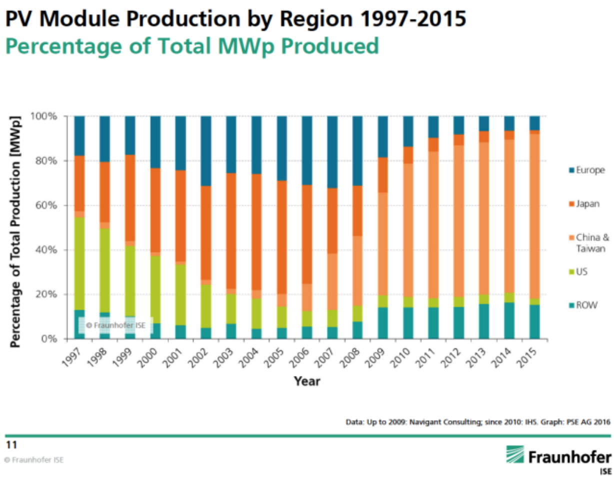


Fig. 49: PV module production by region 1997 – 2015 [9]

Figure 49 [9] illustrates this drastic development in an even more visible way. In the beginning it was the USA, which has lead the development.

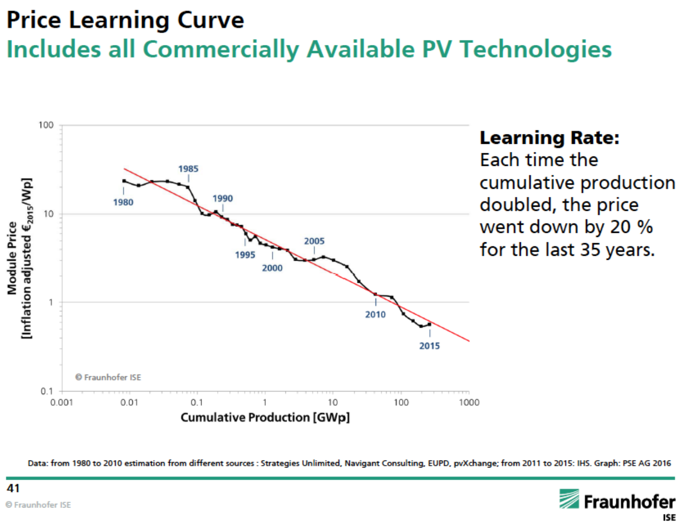


Fig. 50: Price learning curve for PV technologies [9]

In the early 2000s Japan and Europe were leading and from 2010 on China is the champion of module producing countries. Under the first ten solar module producers one can find seven Chinese and two US companies.

Market prices have been drastically reduced, by a factor of five for modules and by a factor of almost three for systems, which is a reduction of 75% within 10 years. Low product prices are the basis, of course, for lower electricity prices, thus to replace fossil (black or brown) electricity and therefore reduce also CO_2 emission.

The corresponding price learning curve, which includes all commercially available technologies, can be seen in figure 50 [9]. It clearly shows that especially PV electricity becomes one of the cheapest production paths.

Hand in hand with the decrease of solar module prices goes the energy pay-back time of rooftop PV systems. Figure 51 [9] is showing the data graphically for Europe. As the data uses the physical parameter of irradiation only the data can be transferred in general to other regions of the world, but being aware of the different installation costs. The Energy Pay-Back Time (EPBT) runs linearly with the irradiation data on the right side of the figure.

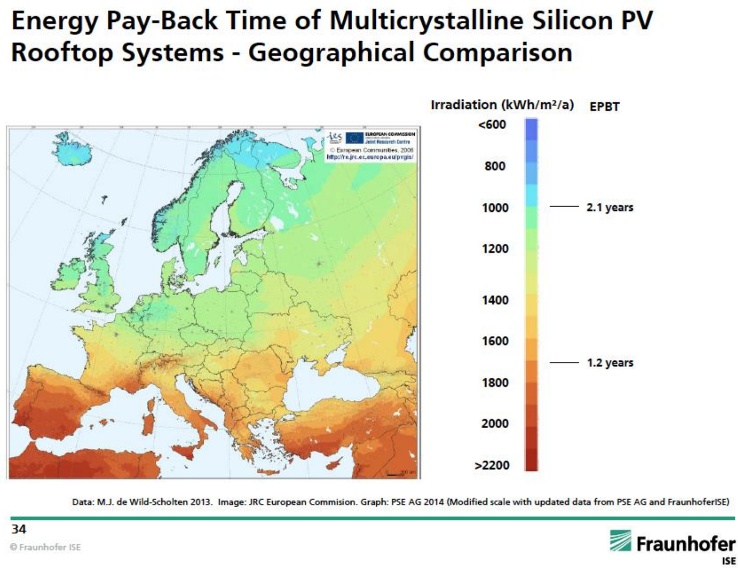


Fig. 51: Energy pay-back time for PV systems in Europe [9]

5.3 Concentrating Solar PV (Low and High)

Concentrating solar power plants need extremely high investments due to size and technology. On the other hand the costs for PV-systems are dropping relatively fast. Nevertheless "CSP-fans" state: "However, the ability of CSP to use thermal energy storage – and thus provide continuous power for long periods when the sun is not shining – could give CSP a vital role in evolving electricity systems [67]."

CSP plants need areas of high direct normal solar irradiation, measured as DNI, direct normal intensity. In addition CSP plants must be sited on land suitable for power generation with adequate access to an increasingly stressed and out-dated transmission grid. Access to high-voltage transmission lines is key for the development of utility-scale solar power projects to move electricity from the solar plant to end users [13]. Very often new transmission lines have to be installed.

Even if the costs differ from country to country figure 52 [67] may give a glance on how much to invest in two different types of SCP plants. Obviously the size of these plants increase with time. But since 2013 the prices decrease, independent whether it is a Trough or Tower type. On the basis of installed prices for 2014 as given in $\$/W_{AC}$ in 2015 prices of around 5 $\$/W_{AC}$ can be achieved in the USA. In OECD countries parabolic trough plants without thermal energy storage systems (TES) have capital costs as low as 4.6 USD/MWh, whereas the prices in developing countries may be as low as 3.5 USD/MWh [68].

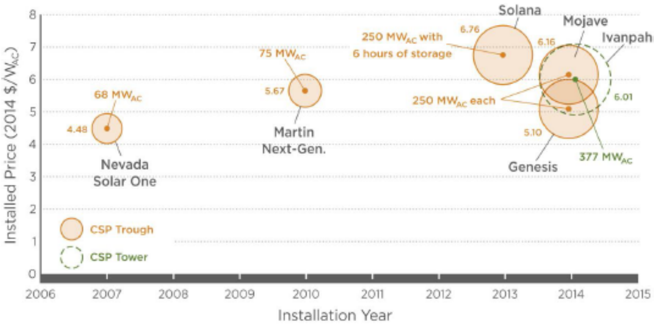


Figure 13. Historic installed costs for CSP projects in the U.S. from 2007 to 2014

Source: Bolinger and Seel 2015
Installed price does not account for differences in capacity factor, so comparisons between technologies with and without storage or versus PV installed price are not representative of LCOE differences.

Fig. 52: Installing costs for CSP projects in the U.S. [67]

The lifespan of CPS plants is expected to be around 30 years. Taking into account normal running and maintenance costs of the plant a price for the electricity per kWh can be calculated.

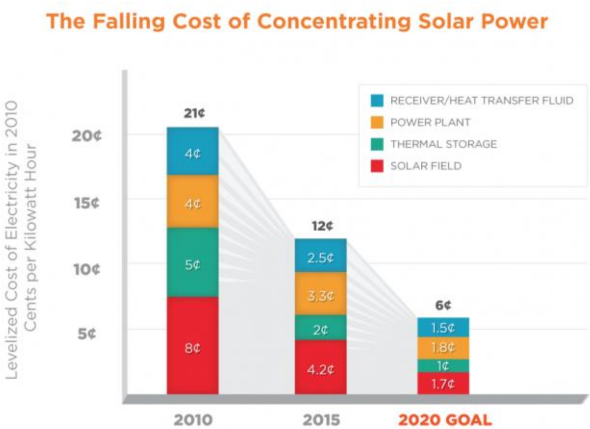


Fig. 53: Levelized costs for electricity by CSP plants in U.S. [69]

The most reliable data about such levelized costs for electricity from CSP plants in the USA are given in figure 53 [69]. Even starting in 2010 the data are recalculated for 2015 and extrapolated for the year 2020 as the goal. This is the goal of the US SunShot Initiative to reduce the costs by a factor of two.

5.4 Solar Thermal

Solar thermal is by far the mostly used sun energy harvesting method in the world (see chapter 4.4). Considering typical solar thermal systems sizes for the different applications in all countries around the world the number of systems in operation is calculated to be around 101 million. All together in 2014 they need about 584 million square meters, corresponding to a thermal peak capacity of 409 GWth [66].

Compared with this number of heating systems the number of its "opposite" systems is rather small. When using the phrase solar thermal energy normally this means that the energy is used for heating purposes. With the aid of thermal cooling machines driven with the sun's solar energy another aspect of using thermal energy is evident. Even if the number of such cooling systems is increasing since 2004 till 2014, the respective numbers are relatively small. This is shown by figure 54, which distinguishes between the data for Europe and the World. Most of the cooling systems are produced in Europe [66].

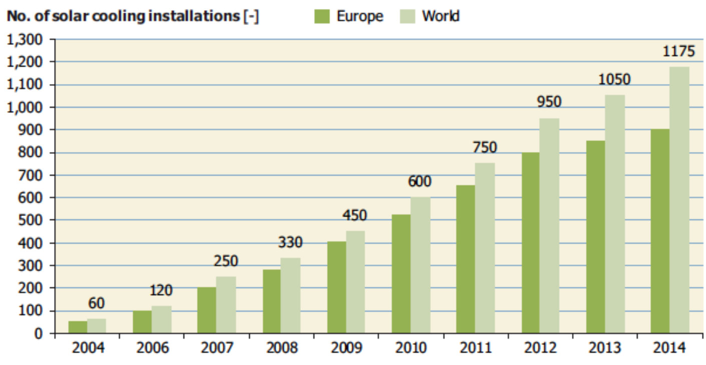


Fig. 54: Market development of solar cooling installations [66]

This small number of solar cooling systems is insofar astonishing as there are so many "hot" countries, which have installed millions of electricity driven air condition systems for cooling down the rooms to nearly freezing temperatures - and then to "convert" them to heaters in winter times. What a misuse and what a waste of electric energy.

5.5 Concentrated Solar Thermal

Solar thermal technology is large-scale by comparison. One big difference from PV is that solar thermal power plants generate electricity indirectly. Heat from the sun's rays is collected and used to heat a fluid. The steam produced from the heated fluid powers a generator that produces electricity. It's similar to the way fossil fuel-burning power plants work except the steam is produced by the collected heat rather than from the combustion of fossil fuels [65].

This technology is rather expensive and its power plants mostly often are very remote from the customers. The technology started in the 1980s. Its application lost interest in the 1990s due to the dropping gas prices. It seems that with the huge CSP-plants as built recently in China and Morocco this technology regains and could become a market player with comparative production costs of electricity. As figures 47 and 86 show it the levelized costs of electricity are becoming cheaper in the near future, not only for CSP but also for all others.

6. Influence on Climate Change, CO2 Reduction

6.1 General Remarks

Solar energy production in principal and in general is free of green house gas emissions and especially helps to avoid CO_2 emission. Energy production and use accounts for two-thirds of global greenhouse-gas emission. As shown in figure 55 [10] it is time to immediately stop CO_2 emission, if the 2-degree target shall be reached.

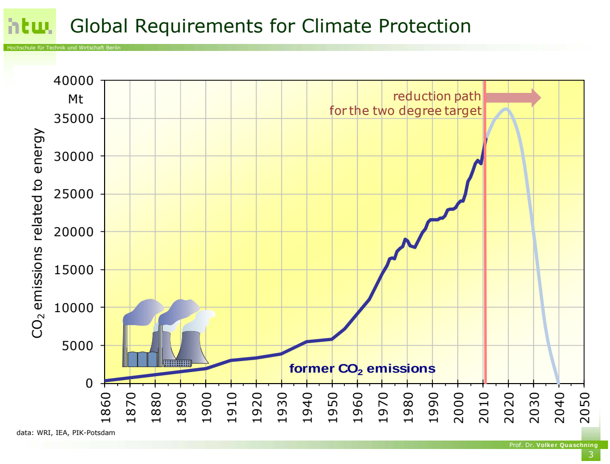


Fig. 55: Global requirements for climate protection [10]

Therefore, the crossroads have to be followed - figure 56 shows it [10].

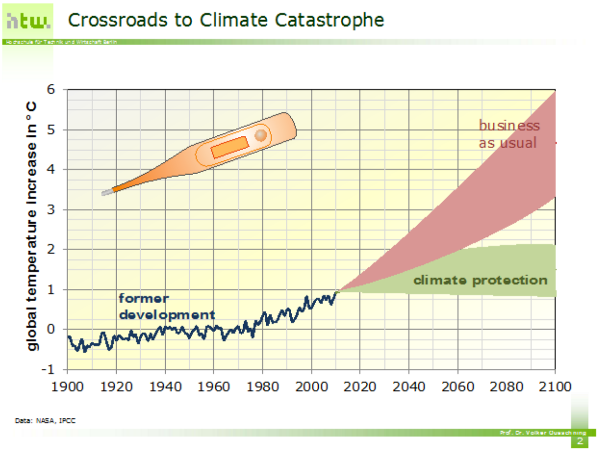


Fig. 56: Crossroads to climate catastrophe [10]

The placement of PV carbon intensity within other key electricity generation systems is given in figure 57 [24]. The values for PV refer to manufacturing in Europe (UK Climate Change Committee targets are included for comparison).

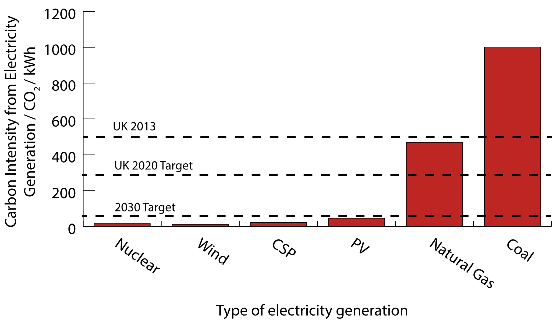


Fig. 57: Carbon intensity from electricity generation [24]

In figure 57 there is missing the contribution of normal thermal solar heat. Even in 2013 the CO_2 reduction by water collectors worldwide was more than 100 million tons – see figure 58 [64]- and nowadays would reach an even higher value. China is leading by far, but on the other hand is producing a much higher amount by other means.

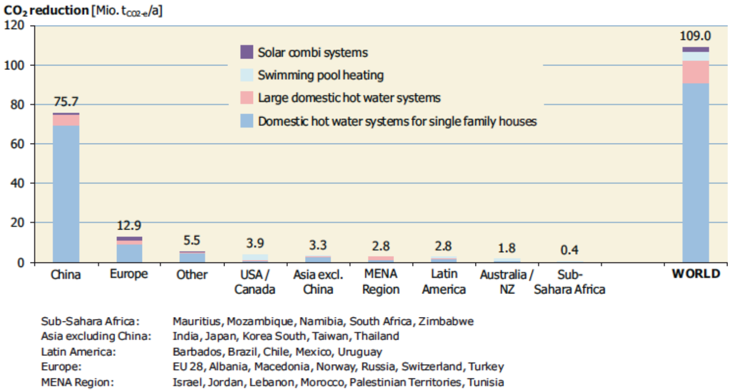


Figure 33: Contribution to CO_2 reduction by unglazed and glazed water collectors in operation by end of 2013

Fig. 58: CO2 reduction by water collectors by end of 2013 [64]

Obviously solar energy production, whether it is heat or electricity, is environmentally friendly. It does not need remarkable amounts of water for the production process. Other materials and procedures can do even the cooling process. So, solar energy production is a strong player in the water-energy nexus discussion, which becomes more and more important worldwide. More and more often it is the ultimate decision point whether to build a fossil thermal power plant fossil thermal power plant with water-cooling.

Fig. 59: Water-energy nexus candle [23]

6.2 PV and its Contribution to CO2 Reduction

Solar PV entails no greenhouse gas (GHG) emissions during operation and does not emit other pollutants (such as oxides of sulphur and nitrogen); additionally, it consumes no or little water. As local air pollution and extensive use of fresh water for cooling of thermal power plants are becoming serious concerns in hot or dry regions, these benefits of solar PV become increasingly important.

Figure 50 is showing how rapidly the CO_2 savings increased from 2000 till 2014 [18] to values of nearly 25 Mio tons. This growth, of course, is connected with the growth of installed PV systems.

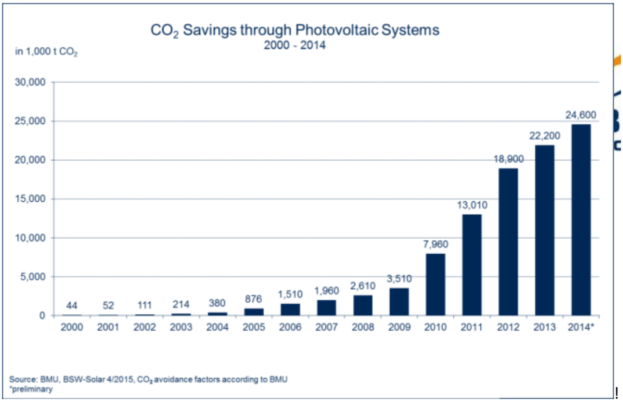
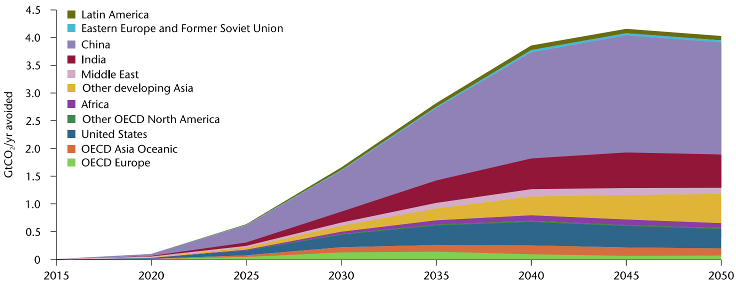


Fig. 60: CO_2 savings through PV systems [18]

The IEA roadmap vision from 2014 [18] calculates a value of 4.600 GW of installed PV capacity by 2050, which would avoid the emission of up to 4 gigatons (Gt) of carbon dioxide (CO_2) annually. The development till 2050 is sketched in figures 61 [17] and 62 [19]. There will be a rapid increase till 2040 and a flattened plateau afterwards. China obviously shows the biggest amount in CO_2 reduction through PV energy, which is shown in figure 46 as impressive relative shares [18].

CO_2 emission reductions from solar photovoltaic energy

CO_2 abatement through PV in this roadmap over the 6DS, 2015-50



KEY POINT: China delivers one-half of the CO_2 emission abatement through PV over the 6DS.

Fig. 61: CO2 reductions from PV energy [18]

The calculated reductions in general and for some countries are rather impressive, but use the 6°C Scenario (6DS), which is largely an extension of current trends. By 2050, primary energy use grows by almost two-thirds (compared with 2012) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentration of GHGs, average global temperature rise above pre-

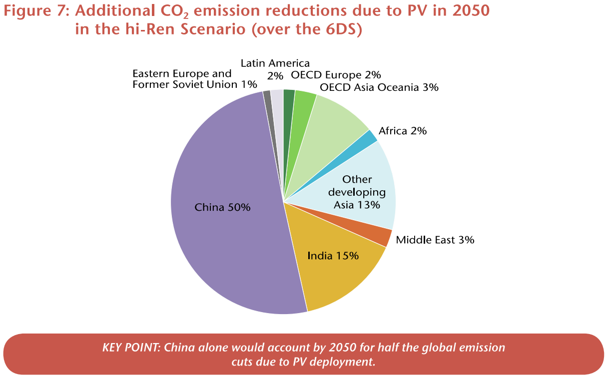


Fig. 62: Additional CO2 reductions due to PV in 2059 [19]

industrial levels is projected to reach almost 5.5°C in the long term (i.e. after 2100) and almost 4°C by the end of this century. Already, a 4°C increase within this century is likely to stimulate severe impacts, such as sea level rise, reduced crop yields, stressed water resources or disease outbreaks in new areas. The 6DS is broadly consistent with the WEO Current Policy Scenario through 2040. The 4DS takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency.

6.3 HCPV

No actual data are available. It is assumed that data for reduction of CO2 emission by HCPV are included in the general PV reduction rates.

6.4 Solar Heat Contribution

The annual collector yield of all water-based solar thermal systems in operation by the end of 2013 in the 60 recorded countries was 314 TWh (= 1,129 PJ) [15]. This corresponds to an energy savings equivalent of 33.7 million tons of oil and 109 million tons of CO_2. The calculated number of different types of solar thermal systems in operation was around 111 million.

In 2013, 94% of the energy provided by solar thermal systems worldwide was used for heating domestic hot water, mainly by small-scale systems in single family houses (84%) and larger applications attached to multi-family houses, hotels, schools, etc. (10%), see figure 63. Swimming pool heating helds a share of 4% in the contribution to the energy supply and CO_2 reduction and the remaining 2% was met by solar combi-systems.

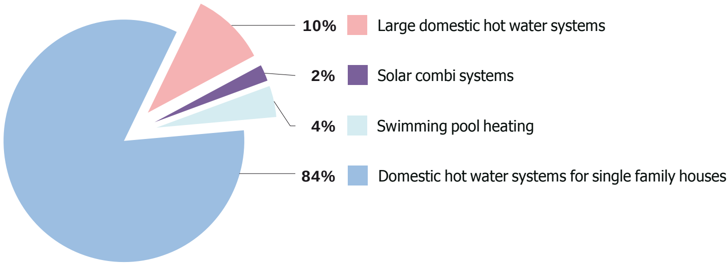


Fig. 63: Share of contribution to both heat and CO2 savings [15]

6.5 CSP and CO2 Emission Reduction

In 2050 around 4.000 TWh of solar electricity are generated by CSP plants. It is expected that this amount would reduce CO_2 emission by around 2.5 gigatonnes (Gt) per year. Together with savings of natural gas another 0.5 Gt may be gained, depending of the respective scenario [25].

7. Storage – and use - of Solar Energy

7.1 General Remarks

As solar energy – like wind power – is a very volatile energy, the development of renewable energy as the future backbone of electricity and heat production is very much dependent on the possibility of storage and thus continuous availability. There are a number of single storage devices, but they all lack on storage capacity and availability when heat or electricity is needed.

According to the three different varieties of solar energy conversion.

- solar thermal, where energy is converted to heat;
- solar photovoltaic, where light energy is converted to electrical work and
- solar chemical, where light energy is converted to stored chemical potential energy,

storing systems can use these conversion processes, too. The scale is as different as that of the production, from small private to huge industrial power/storage plants.Storage possibilities and their actual and future realisation are described in this chapter to give a practice-oriented overview.

Heat Storage

Heat can be stored in the form of heated water or other fluids, by production of water vapour, through crystallisation processes etc. Losses through heat transfer processes reduce the efficiency of these storage procedures, even when very effective insulation capsules are used.

Storage of Electricity

The use and storage of volatile electricity is somewhat more complex and a worldwide problem for scientists and engineers.

The simplest way to store electricity seems to use hydropower in the way that a surplus of electricity is used to pump water "uphill" into a water reservoir and release it through a hydro power station downhill at times when electricity is used.

A very interesting, thrilling and huge storage system with tourist attraction is to be seen in figure 64 [26]. It is called "Ringwallspeicher", a storage system of two lakes, the upper one of which is surrounded by a walling ring. The capacity could reach for a 14-days electricity supply through a 2 GW hydropower station.

Fig. 64: Ringwallspeicher with hydro power station and touristic attractions [26]

Even “simple” storage systems need electricity supply and release of electricity, and, thus, have to be connected to the grid. This connection is “open” into two directions; other electricity producers and users are also “open”. If the connecting grid would not be “smart”, it could happen that two electricity producers come up with zero-electricity, if their electric inputs are not exactly in-phase, as engineers say.

In the future the question of having, implementing, using, optimising a “smart grid” will be crucial for the success of renewable/green/clean electricity supply in the world. Up to now the classical electricity energy supply was one-way-supply: From power station to users. Now there will still be many “old” users but in addition many “new” producers. These producers are both “momentum” producers or “storage” producers, and both at a small scale at home PV or at utility or even industrial scale, at home or far away in the desert.

Smart grids are electricity grids that are more resilient and better able to cope with larger shares of decentralised and intermittent energy sources. Figure 65 gives an illustration what to understand when talking about smart grids.

Obviously, many small, “self-intelligent” in themselves, have to be connected intelligently on urban-scales, country scales, regional scales – and last but not least across national borders worldwide.

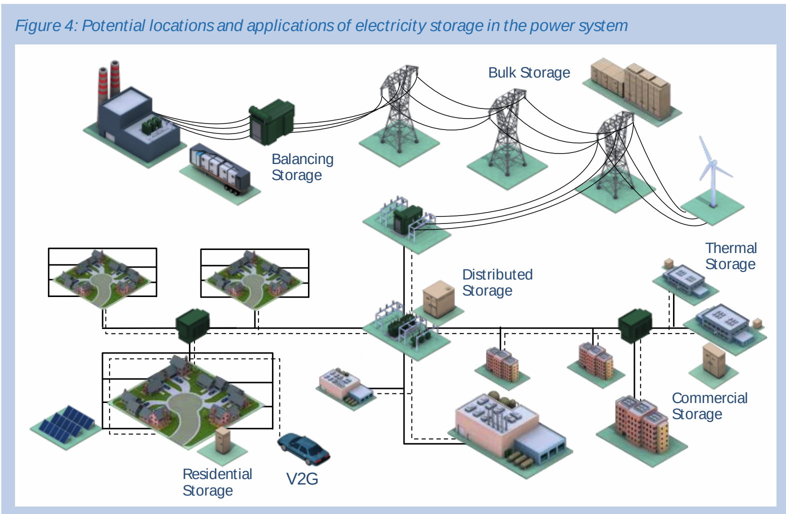


Fig. 65: Example of a smart grid [27]

In figure 65 also wind power generation is included. If it is off-shore wind power then long distance grid line are necessary. Other power generation e.g. from biomass facilities has to added, too.

– In a developed electric-based transport the many small batteries in electric vehicles can act as decentralised storage facilities while they are charged overnight (V2G see figure 65). The user V2G there represents a future scenario of electric traffic, where the electric vehicle charges at home overnight.

7.2 PV Solar Energy Storage Systems

PV solar systems produce electricity directly from sun radiation. So storage of PV energy is a question of storing electricity, in the form of direct and alternating current. PV electricity is also a decentralised production process, and as such requires the decentralisation of energy storage.

Small Scale – at home

In the future small batteries will be used as decentralised storage systems, see figure 66 [10]. Storage of direct PV electricity on a small scale is possible with any type of batteries. So, many small applications include small batteries, which are loaded during sunshine and reloaded when necessary (LED-lights, smart phones, …).

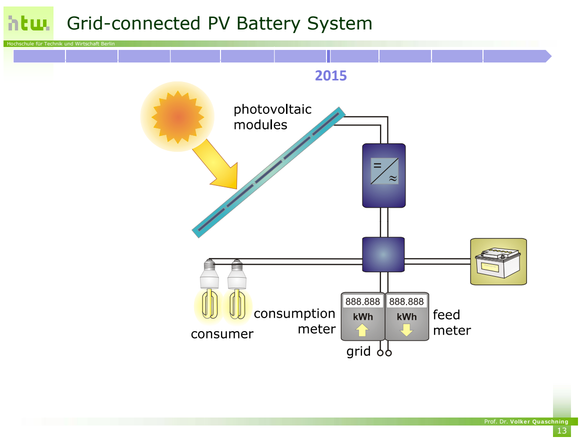


Fig. 66: Grid-connected PV battery system [10]

Dwellings with rooftop PV can be supplied by daytime by "own" electricity and can feed the surplus during peak times into the grid or can feed it in a daily balance into the home storage facility, as figures 67 shows it. The gain relative to "normal" feeding-back into the grid is both 10% when using an intelligent management system and a small storage system (battery).

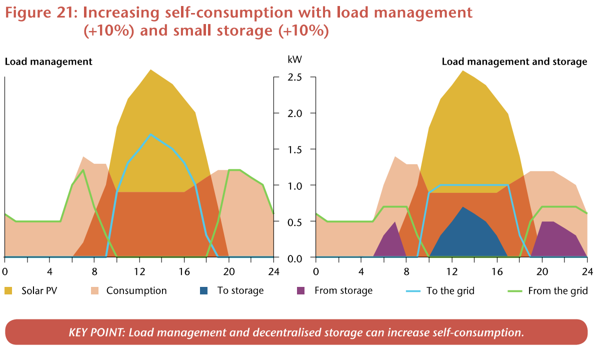


Fig. 67: Peak shaving strategy using and storage system [25]

With such a decentralised intelligent management system plus battery up to 80% of the home-used electricity can be gained on a yearly basis for a dwelling in normal sunny regions. Different management devices are on the market, of which three examples are shown in figure 68 [28]. Their size is small enough to install them on the wall.

Fig. 68: Examples of storage and managing system [28]

Industrial Scale

The "sunny harvest" of large PV plant(ation)s is normally fed into the grid. The enormous amount of surplus cannot be stored in battery packages, but smart grids can guide the surplus to "old fashioned" storage systems in the way that the electricity drives pumps to elevate water into water reservoirs. On demand the water can drive hydro generators to feed electricity into the grid. This possibility of storage is, of course, restricted to the respective regions and landscapes or innovative plants, see figure 64.

As mentioned above today hydro-pump facilities are the major big storage systems. In addition, innovative solutions like flywheels, compressed air storage, hydrogen production etc. will become more attractive and payable. – Besides the technical side the costs always play a crucial role when choosing the appropriate storage systems. Obviously all storage costs will decrease in the coming years, but they contribute to the electricity costs.

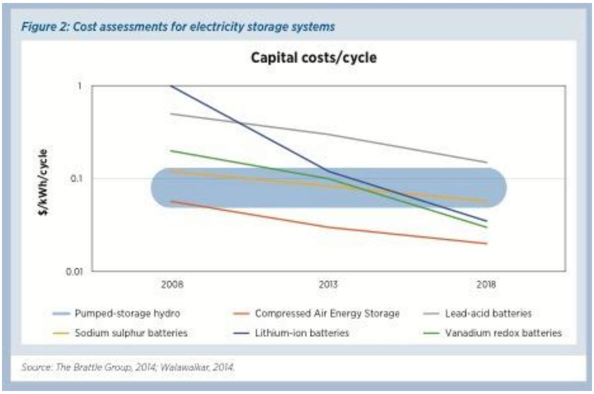


Fig. 69: Electricity storage costs per cycle [29]

As smart grids can work as virtual storage systems, new electricity power plants can be and still are installed in a virtual way as e.g. "SchwarmEnergie" [30] in Germany.

Additional possibilities have to be taken into account for electricity storage systems on islands and in remote areas where the electricity supply is mainly due to diesel generators.

7.3 HCPV Energy Storage

Most of the HCPV installations are utility scale power plants and located almost in remote regions. The surplus in electricity generation can be "stored" only in the normal grid. Depending on the grade of its smartness it can then be stored in the normal way like PV electricity.

Smaller devices produce electricity and heat, which both can be used and stored regularly. New developments to a combined heat and cooling power system (tri-generation) can help to serve industrial plants as well as districts with heat and electricity – and cold water or air.

7.4 Thermal Solar Energy – for Heating and Cooling

Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. TES systems are used particularly in buildings and industrial processes [31].

There are three kinds of ETS systems, namely sensible heat storage, latent heat storage and thermo-chemical storage. The cheapest and, thus, most spread storage system is the sensible heat storage system, which uses liquid or solid storage media like water (the cheapest), sand, molten salt, rocks for heating or cooling. The table in figure 70 gives typical data for theses systems.

Table 1 – Typical Parameters of Thermal Energy Storage Systems [1]

TES System	Capacity (kWh/t)	Power MW)	Efficiency (%)	Storage period (h, d, m)	Cost (€/kWh)
Sensible (hot water)	10-50	0.001-10	50-90	d/m	0.1-10
PCM	50-150	0.001-1	75-90	h/m	10-50
Chemical reactions	120-250	0.01-1	75-100	h/d	8-100

Fig. 70: Table of typical parameters of TES systems [31]

The most widespread TES system in principal is a water tank, because it is cost-effective. In connection with optimal water stratification in the tank and highly effective thermal insulation it is even more cost-effective.

Figure 1 – Large Hot Water Storage (construction and final state) combined with Solar Thermal District Heating "Am Ackermann-bogen" in Munich, Germany

Fig. 71: District Heating TES in Munich, Germany [31]

The type and dimensions of such tanks differ very much depending on their use. In dwellings tanks contain around 500 – 1.000 litres, which is sufficient for intermediate storage times. District heating systems are much bigger as can be seen in figure 71, which shows a tank in a district of München, Germany [31].

Bigger tanks can be built in the earth as borehole, cavern of aquifer storage tanks, which then can be used e.g. for cooling and heating of office buildings or for industrial processes, as figure 72 shows it schematically [31].

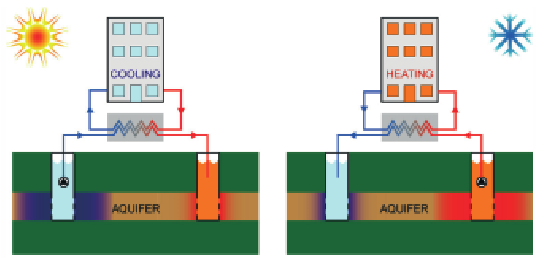


Figure 2 – Layout Scheme of an Aquifer Storage System

Fig. 72: Layout scheme of an aquifer storage system [31]

Addendum to chapter 6.3

The storage of thermal energy (typically from renewable energy sources, waste heat or surplus energy production) can replace heat production from fossil fuels and, thus, reduce CO_2 emission. In Europe, it has been estimated that around 1.4 million GWh per year could be saved, and 400 million tonnes of CO_2 emissions avoided, in the buildings and industrial processes by more extensive use of TES [31].

7.5 CSP Storage Systems

CSP-plants produce heat in a great amount and at high temperatures, which converts water into hot steam to run an electricity generator. Independent whether it is a trough, tower, (linear) Fresnel or dish CSP-system the heat surplus of this industrial plant can be used to heat up molten salt, which is pumped from a cold to the hot salt tank.

If the solar collector field cannot produce enough heat to drive the system, the molten salt is pumped back from the hot into the cold tank, and heats up the heat transfer fluid.

Fig. 73/74: CSP-plants with mirror (left) and trough (right) system and integrated storage tanks using molten salt [32], [33]

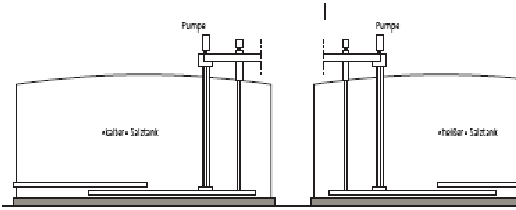
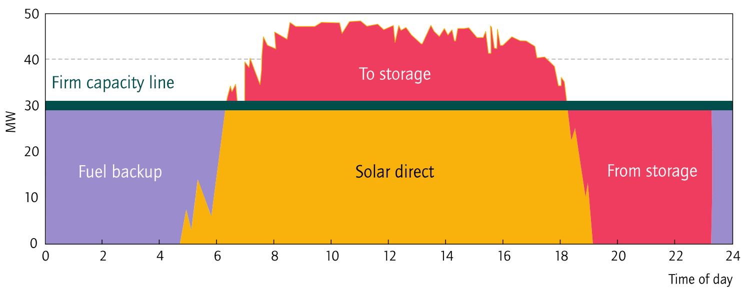


Fig. 75: Principle of molten salt tanks   Fig. 76: Size of field and tanks

So, normally at daytime solar energy produces electricity and heat, whereas at night the re-crystallisation heat of the molten salt runs the steam producer and thus the generator. – If necessary, an external fuel backup can be installed. To have an imagination of the sizes use figure 76, which shows the 110 MW Crescent Dunes Solar Energy Plant in Nevada [34].

The principle of this heat exchange is shown in figure 77 [34]. The plant has 30 MW power capacity line.



Source: Geyer, 2007, *SolarPACES Annual Report*.

Fig. 77: Daily heat production in a CSP plant with salt storage system [34]

At daytime, the direct solar irradiation can feed the storage. After sunset the storage capacity can deliver electricity for another 4 hours. During the last night and the morning hours the generator has to be fed by another fuelled machine.

New developments use great solid concrete blocks, which consist of many individual elements, cassettes and/or modules connected through pipes in series and parallel. Surrounded by concrete a single storage element integrates heat exchanger tubes contained inside a steel casing steel pipes, see figure 78 [36].

Through these pipes the heat transfer fluid (air, gas, water, steam, oil) is flowing to heat up the surrounding concrete during daytime sun radiation. The concrete is heated up to 550° C without any evidence of degradation and can give back the heat when needed.

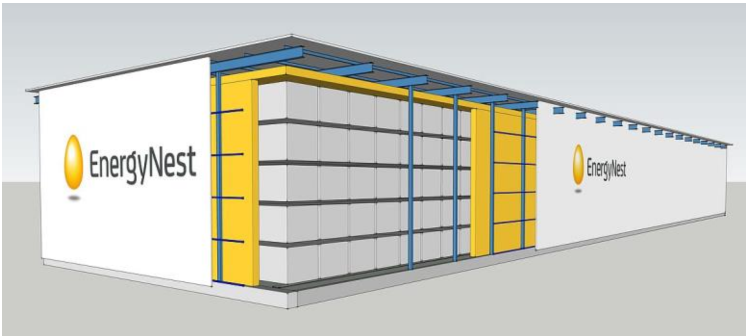


Fig. 78: Solid-state thermal energy storage system with concrete [36]

The blocks can be linked in series and parallel to build up storage systems from 100's kWht to 1.000's of MWht or even more. The costs of this storage system are much less than those using molten salt. A "first of this kind" of new technology has been built recently at Masdar Institute's Solar Platform (MISP) in Abu Dhabi [36].

8. Specific Applications and Benefits – rural and industrial

8.1 General Remarks

The possibilities of application of solar energy to people are non-countable. In this chapter only a few spectacular and/simple-to-use but very efficient solar energy applications for normal, rural and industrial life are sketched. Many of these applications concern PV applications.

8.2 Concentrated and Non-concentrated Solar Heat

Far below the Concentrated Solar Power plants (CSP) solar heat can also be concentrated for individual or home use. So parabolic mirrors or Fresnel lenses can concentrate the sun's irradiation to heat up the food in a pot located in the focal centre of the mirror, see figure 79 [37].

Fig. 79: New generation of solar cooker (Fresnel lens) [37]

This cooker uses a Fresnel lens (could be also a parabolic mirror, but with less efficiency) to concentrate the sun for direct cooking, and also is heating up a Lithium Nitrate container, which can store the solar heat for 25 hours at a time. Thus, this solar oven can work "full-time", the whole daylong. This solar oven can cook at any place with sunshine, in the desert, close to the shore, on high mountains, but not during rain.
This cooker could also alleviate the "fossil" charcoal grill to contribute to a cleaner, greener and more socially sustainable cooking option in the developed or developing world. Of course, more simple cookers for direct cooking help survive without connection to electricity or to use wood for the oven fire. These cookers can serve as survival kid, which also can heat up water or other fluids or meals [38].

On an industrial scale solar heat can drive a solar tower plant using the air updraft technology within a chimney as figure 80 schematically shows it [39]. Figure 81 shows a not yet working plant, but an artist's impression of a 5 MW solar chimney power plant [39].

Air under a plane roof of about 150 m in diameter is heated by normal sun irradiation on the "roof". Through a chimney of some 100 meters (up to 1.000 m) in height the hot air rushes upwards and drives an electricity generator.

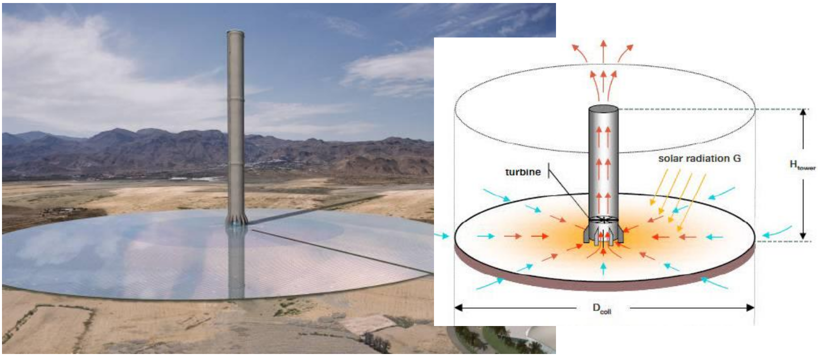


Fig. 80: Solar chimney power plant (artist’s impression)

and Fig. 81: principle of updraft technology [39]

8.3 PV Applications

Many simple but effective PV tools are possible and offered on respective markets, as figures 82 and 83 show it, practically as women do it and demonstrate it on their homepage for rural developments, see [40].

Fig. 82 and 83: Simple rural PV applications [40]

However, the possibilities using PV solar energy are huge and of a great variety as figure 83 is partly showing it [41]. Also small desalination systems can be realized [42].

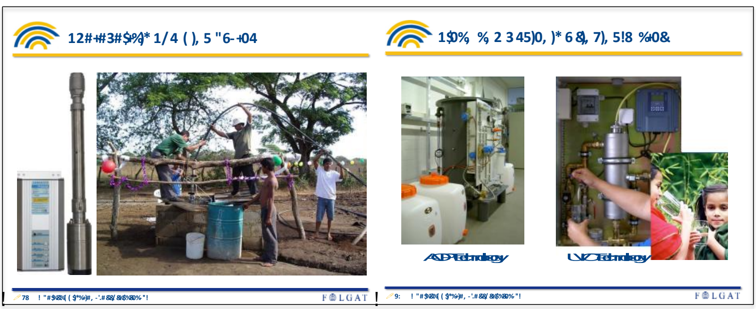


Fig. 84: PV pumping and water cleaning systems [42]

Many other applications for non-electrified (rural) regions are available and applicable as can be seen in figure 85 [41].

Fig. 85: PV applications for non-electrified (rural) areas [41]

If PV stations are not existing or available or if they erected as fixed stations elsewhere one can hire a sun-trolley, which is the Greenpeace price winner [43] in its class, and consists of a 1200W solar PV array, electronic controller - and additionally a 1HP pump. If one prefers to own his or her own small PV-set there is a great market, which sells complete PV packages for just a few 100 $ for a 100 Wp 12 V device [44].

Fig. 86: PV sun-trolley (Greenpeace price winner) [43]

More advanced and useful are extended solar home systems, which need solar panels and rechargeable battery, see figure 87. With an inverter it can be extended to feed more attractive and educationally helpful devices, like TV and computer [6].

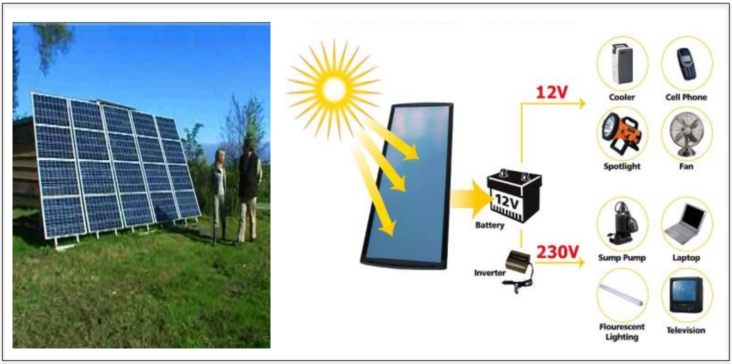


Fig. 87: Extended PV solar home system [6]

Worldwide numerous small PV applications are working, the realisation of specific needs and wishes is obvious. Worldwide many universities offer PV courses at the campuses but also on-line [45].

Fig. 88: PV applications worldwide in remote areas [45]

Worldwide the most ambitious solar energy project - including also other renewable energy sources like wind, biomass and hydro – is the DESERTEC-EUMENA project, see figure 89 [46]. The realisation is now open, on the other hand Morocco is on the best way to become a strong "solar player" with its new CSP-plants.

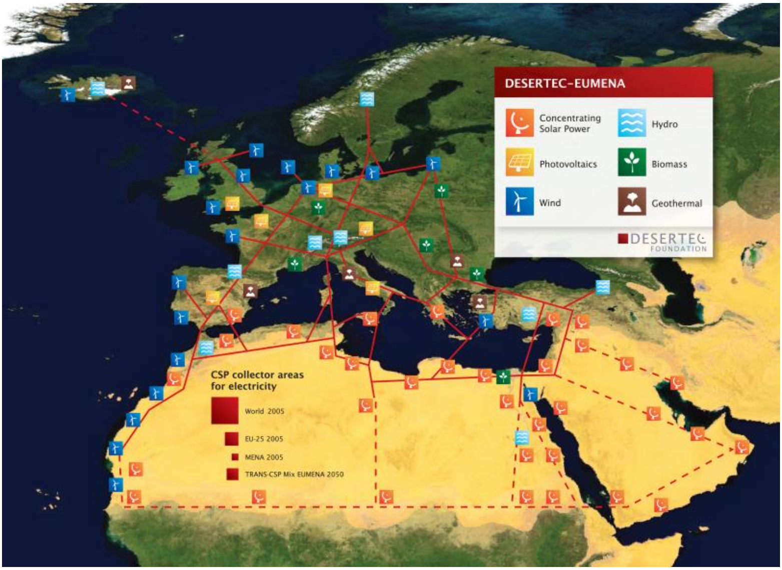


Fig. 89: DESERTEC project in the EUMENA region [46]

This project is – or better to say – was planned to supply **EU**rope and the **ME**ditteranian region and **N**orth **A**frica with electricity. The backbone of the electricity production is thought to be mainly the CSP electricity located in the hot and sunny regions of the Sahara desert. – The red cubes indicate the size/area of land, which is necessary to produce the electricity for the given region.

Even the world (in 2005) could be served theoretically with electricity by the bigger "hot spot". – Despite the tremendous capital investment also the technical demands like the electricity distribution by DC-cables of thousands of kilometres in length seem to bring to an end this ambitious plan.

The use of solar energy as heat or electricity is worldwide accepted and implemented in the nations' energy supply systems. The global solar power map in figure 90 [16] gives an actual overview about the solar data for chosen countries:

Upper data: Cumulative installed capacity in 2019
Middle data: Cumulative installed capacity in 2014 and
PV penetration in 2014
Lower data: Number of people powered by solar in 2014.

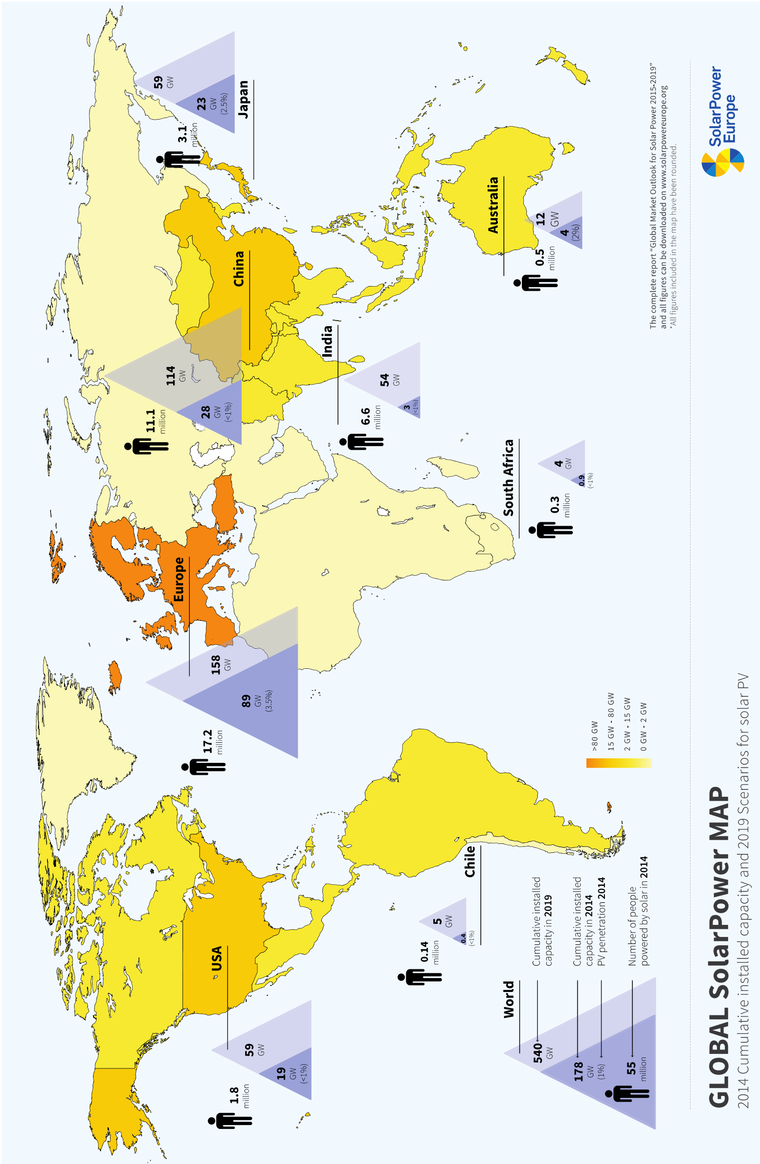


Fig. 90: Global solar power map for selected countries [16]

9. Recycling

9.1 General Remarks

The use of solar energy is a sustainable solution to the energy challenges of today. Not only do solar energy systems generate energy with zero greenhouse gas emissions, but the solar industry has also taken on the responsibility to mitigate and manage the full range of social and environmental impacts during the entire lifecycle of the solar energy system. These social and environmental impacts include respecting the human rights of workers, ensuring the rights of communities and other stakeholders are respected, and making business operations safe and environmentally responsible.

Solar energy production by "classical" heat production does not affect environmental aspects or climate change arguments with respect to waste and reuse of material. All involved components, including molten salt, are more or less made of "clean" or renewable materials. So, it is only PV and HCPV, which have a remarkable impact onto the environment as the cells, modules, panels and fields contain some different and toxic material. This impact becomes more and more visible and technically important, because the PV market is worldwide expanding to a great solar energy heating, cooling and electricity production industry.

9.2 PV

Solar photovoltaic systems, solar thermal and concentrating solar power technologies have a life expectancy of 20 - 30 years. Many manufacturers back their products with performance guarantees backed by warranties. As the volume of solar installations worldwide grows, the industry has to think not only but to plan ahead to create PV panel recycling programs [47].

The Silicon Valley Toxics Coalition (SVTC), a San Francisco-based non-profit organisation, has tracked the environmental impact of the high-tech industry since 1982 [48]. It takes action to reduce the use toxic chemicals in PV, develop responsible recycling systems, and protect workers throughout the global PV supply chain. The solar scorecard 2014 lists more than 30 manufacturers from all over the world [49]. Five companies are leaders, and still nine are above average as SVTC has set it.

Worldwide PV now is under critical supervision concerning the toxicity of the panels. In the US the end-of-life disposal of solar products is governed by the Federal Resource Conservation and Recovery Act (RCRA), and state policies that govern waste [50]. This act gives the United States Environmental Protection Agency (EPA) the authority to control hazardous waste from the "cradle-to-grave".

In Europe, the EU has introduced the so-called WEEE directive for recycling since 2014, which compels manufacturers to account for their stock. One company, PV Cycle, has been providing recycling and consultation services since 2007 in Europe. It was set up as a voluntary initiative by a group of companies in the solar industry. PV Cycle says it has already recycled 12,000 tonnes of PV module waste to date [51].
Also Japan supports recycling of PV modules and panels [52].

Currently, toxic materials like cadmium, silicon tetrachloride, tellurium and indium are used in solar panels. Recycling materials, even rare ones such as cadmium and tellurium, can be an expensive process. In fact, at the present time it is cheaper to use new materials, but as this is in part due to the lack of large-scale recycling programs. As more solar panels need to be recycled, the costs may decrease.

A very informative picture of a solar panel and its single components is given in figure 91 [53]. As can be seen a number of rare metals are part of the module, too.

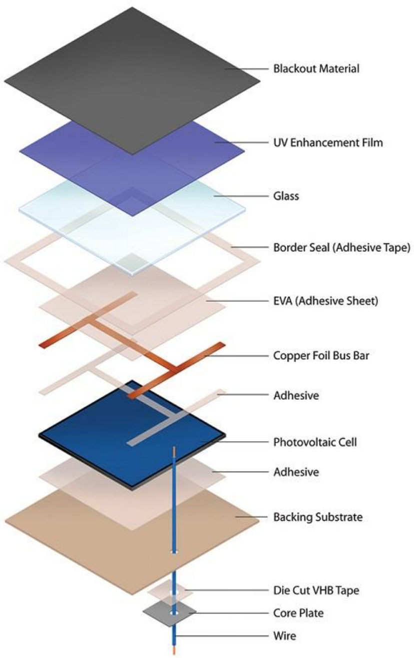


Fig. 91: Components of a solar panel [53]

The industrial recycling process is sketched in figure 92 [54]. Most parts of a solar module can be recycled including up to 97% of certain semiconductor materials or the glass as well as large amounts of ferrous and non-ferrous metals. As mentioned above, some private companies and non-profit organizations are currently engaged in take-back and recycling operations for end-of-life modules.

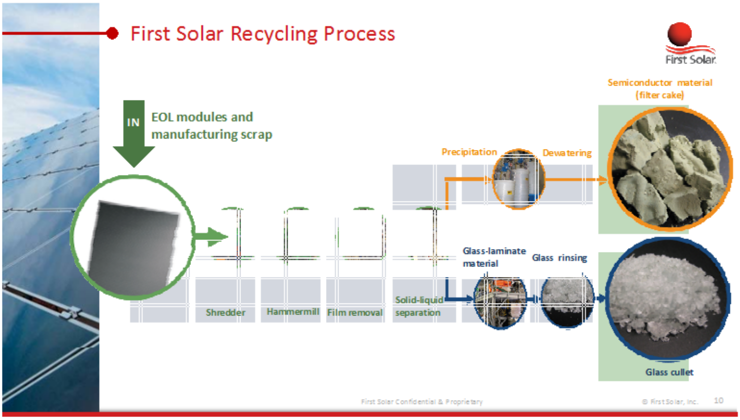


Fig. 92: First Solar recycling process [53], [54]

Recycling possibilities depend on the kind of technology used in the modules [53], [54]:

- Silicon based modules: aluminium frames and junction boxes are dismantled manually at the beginning of the process. The module is then crushed in a mill and the different fractions are separated - glass, plastics and metals. It is possible to recover more than 80% of the incoming weight. This process can be performed by flat glass recyclers since morphology and composition of a PV module is similar to those flat glasses used in the building and automotive industry. The recovered glass for example is readily accepted by the glass foam and glass insulation industry.

- Non-silicon based modules: they require specific recycling technologies such as the use of chemical baths in order to separate the different semiconductor materials. For cadmium telluride modules, the recycling process begins by crushing the module and subsequently separating the different fractions. This recycling process is designed to recover up to 90% of the glass and 95% of the semiconductor materials contained Some commercial-scale recycling facilities have been created in recent years by private companies.

The costs for recycling and the benefits of reusable material, as well as the environmental footprints, very much depend on the quality and the respective possibilities and governmental restrictions/advices in the involved nations [55].

10. Advantages and Disadvantages of Solar Energy Use

Comparing plus and minus of the different solar energy production possibilities the following table could help to choose one, depending on use for private or for industrial purposes.

	Plane PV	**HCPV**	**Solar thermal**	**CSP**
availability day/night	day /with batteries	day	day /water tank	day /molten salt, concrete blocks
scale	small utility industry	- utility industry	small utility -	- - industry
electricity	1 Wp - 200 MWp	>1 MWp	-	> 200 MWp
heat	none	None/partially	all	all
tracking systems	none	two axes	none	two axes
Area for use	small - large fields	Small – medium sized	small – medium sized	large fields
costs for maintenance	small	medium- great	small	great
Investment/ kWp	small	great	-	great
recyclability	not yet settled	not yet settled	no problem	no problem
cooling water	no	no	Water as medium	no
ecological impact	small scale no esthetical problems	normally yes esthetical problems	no esthetical problems	yes
land use	yes for big fields	yes for big fields	no	yes for big fields

Table 1: Some characteristic descriptors of solar energy production possibilities

11. Outlook

11.1 General Remarks

The outlook for the development of solar energy production worldwide is as sunny as its source. This concerns the techniques, the political acceptance and regulatory frameworks, the number of jobs in renewable energies – and the people's awareness.

Some of these aspects shall be described in this chapter, even if they partially also could be part of former chapters.

11.2 Policy and Regulatory Framework

The most remarkable and rather early political kick-off for solar energy production and use started in Germany in the year 2000 with the "Erneuerbare Energie Gesetz" (Renewable Energy Act). From this date on the renewables as solar, onshore wind and biomass energy production increased rapidly to set Germany on top of the global players. This was and still is a rather expensive way to increase renewable energy production and, thus, very likely restricted to relatively rich countries. Therefore other nations used other ways.

In general it is consensus that appropriate regulatory frameworks will be critical to achieve the vision of a mainly renewably powered world. At least it is necessary to install a regulatory framework, which has to provide robust long-term price signals. Actual there are four national and/or regional frameworks to investigate and support especially the potential of PV (see the respective webpages):

- The Sun Shot initiative of the US Department of Energy;
- The EU Strategic Energy Technology Plan (SET plan);
- The international Technology Roadmap for PV (ITRPV) and
- The chines 12th Five-year plan for the solar PV industry.

These frameworks are insofar necessary because it is very cost-intensive to build and install many/big solar power plants. On the other hand, afterwards maintenance costs are low and the sun power generation is nearly "for free". Investors need the confidence to be paid back during this time for their financial involvement when building.

On the other hand restrictive market mechanisms would hinder the development. Market-based solutions and the development of new contract and pricing structures should enable long-term investments for market players. Also adequate and structured pricing systems for CO2 emissions would help increase the solar energy market and fulfil the goals of the different roadmaps, especially the PV market [56].

11.3 Future Global Renewable Energy Scenario

The investment basis for renewable energies is existent as figure 93 is showing it.

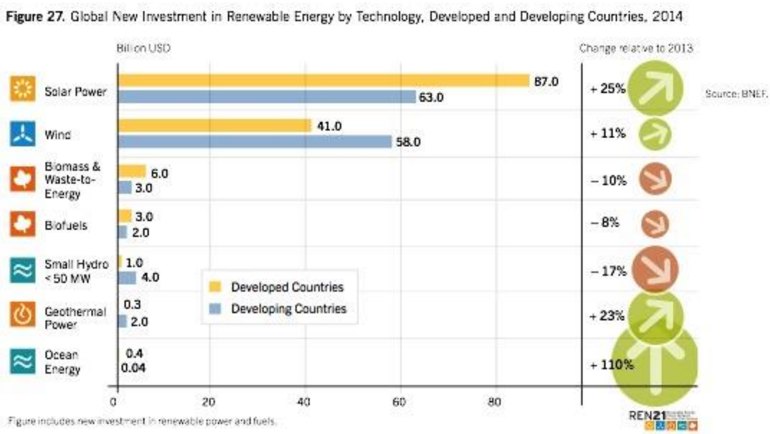


Fig. 93: Global new investment in renewable energy by technology [17]

Obviously solar power is by far the most important technology, followed by wind power generation. It is interesting that solar doubles the value of wind in developed countries, whereas wind power investments are nearly equal in developed and developing countries [17]. It is not clear yet in detail whether or how regulatory frameworks influenced this actual status.

The status as described may be based on regulatory frameworks, and is now the basis for the hi-Ren Scenario at least for PV, as described in figure 94 of the IEA Technology solar PV Roadmap [18].

Table 3: PV capacities by region in 2030 and 2050 in the hi-Ren Scenario (GW)

Year	*US*	*Other OECD Americas*	*EU*	*Other OECD*	*China*	*India*	*Africa*	*Middle East*	*Other developing Asia*	*Eastern Europe and former Soviet Union*	*Non-OECD Americas*	*World*
2013	12.5	1.3	78	18	18	2.3	0.3	0.1	1.4	3	0.2	135
2030	246	29	192	157	634	142	85	94	93	12	38	1721
2050	599	62	229	292	1738	575	169	268	526	67	149	4674

Fig. 94: PV capacities by region today, in 2030 and 2050 [18]

This scenario may give an optimistic view on the development of renewables in general. This view is supported, too, by figure 85 [18], which shows a converted energy situation.

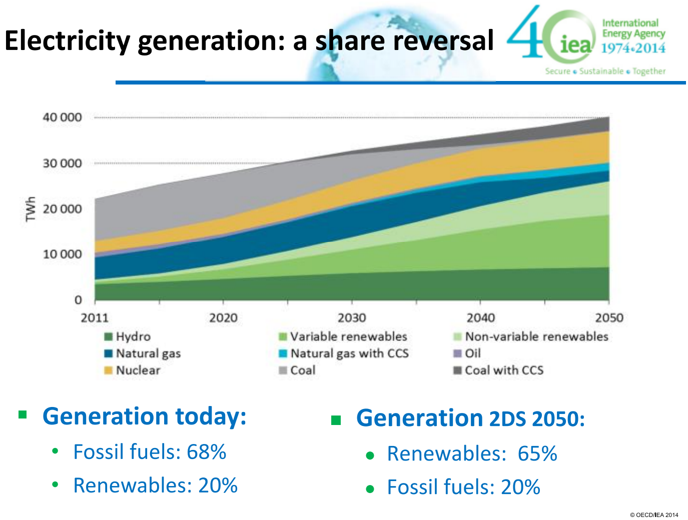


Fig. 95: The share reversal of electricity generation [57]

The electricity generation today depends by 68% on fossil fuels and only 20% is from renewables. According to the 2D2 2050 scenario the picture changes completely as renewables come up with 65% of the electricity generation [57].

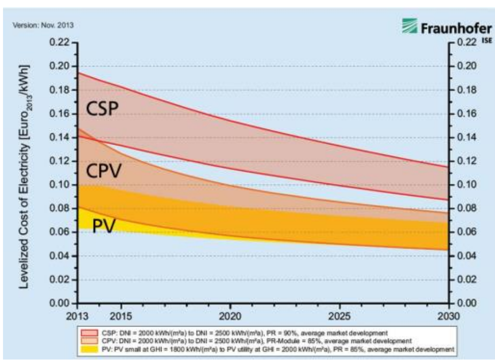


Figure 6: Development of the LCOE of PV, CSP and CPV plants at locations with high solar irradiation of 2000 kWh/(m²a) - 2500 kWh/(m²a). Source: [5].

Fig. 96: Development of levelized costs of electricity [9]

This development goes hand in hand with the decreasing levelized costs for electricity production. Figure 96 shows this development till 2030 for the solar energy production by PV, CPV and CSP [9].

11.4 Roadmap for Electricity Storage

The development of electricity generation as described in the former chapter very much depends on the possibility of technical storage devices and systems for electricity, but additionally, on future oriented "roadmaps". One of these roadmaps is sketched in figure 97, which analyses storage systems necessity and includes policy makers and economic assessments, too [29].

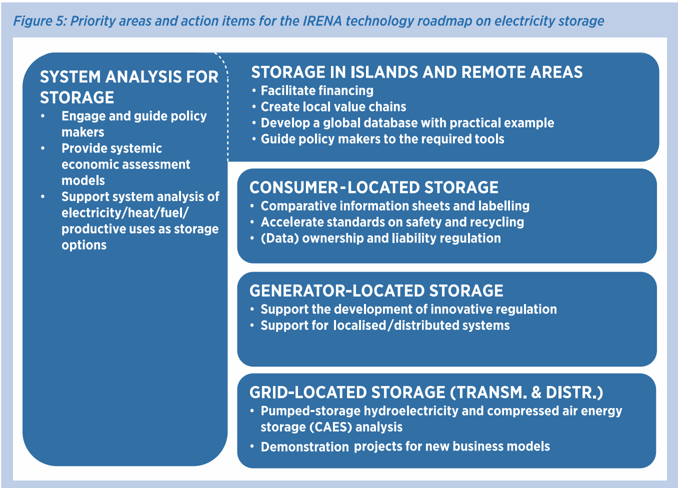


Fig. 97: Areas and actions for IRENA electricity storage roadmap [29]

Some of the technical storage possibilities have been mentioned in the respective chapter 7. What is new and worth considering is the fact that storage possibilities are located to where specific storage needs are existing. The grid as a whole can store electricity, but it could be a better and more effective storage if electricity is stored beforehand at the production place, and later, from the consumer, who himself can also be a producer with his PV-system on the roof. Islands and remote areas are new storage members with specific needs and economic support.

Such storage systems are not a prerequisite for continuous increase in renewable power generation, but they very much facilitate the transition from (island) diesel generators to renewable energy production [29].

11.5 Solar Heating and Cooling

Solar energy is normally connected with heat, not that much with cooling processes. This is an obvious deficit of "solar knowledge". The possibility of using solar energy also for small to large-scale air conditioning and cooling systems offers a new horizon for solar energy applications. Up to now solar cooling is still a niche-market. Only about 1.000 solar cooling systems are installed worldwide in the year 2013, as figure 54 [14] is showing it.The market shows a positive trend since 2014 and is expected to grow even more rapidly. Approximately nearly 80% of the solar cooling installations worldwide were installed in Europe, most notably in Spain, Germany and Italy. The heat is gained from flat plate or evacuated tube collectors and is converted into cold by means of driving a thermal cooling machine.

Since 2007 a cost reduction of such systems of about 50% has been realized, which was supported by further standardisation of the solar cooling kits [14]. These systems are indeed designated to run cooling systems especially in hot regions, where there is abounded solar energy and the daily need of cooling food, rooms, medical storage places, industrial halls etc.

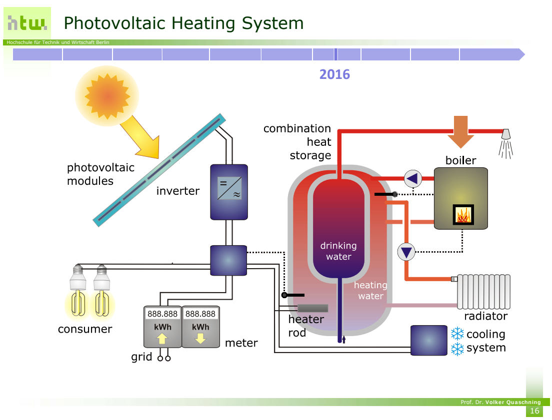


Fig. 98: Dwelling with PV heating, cooling and electricity producing and storing systems [10]

In confortable dwellings even rooftop PV systems can be used to run cooling systems in addition to all other possible features like room heating, water heating, electricity production for home-use, feeding into the grid, and last but not least, for storing it. Figure 98 is showing this constellation [10]. The description should include these possibilities, especially that for cooling.

11.6 Jobs in renewable energy production

Production of energy by renewables generates a huge amount of jobs, see figure 99. The world renewable energy job market is majored by solar, which includes PV, CSP and thermal (heating and cooling).

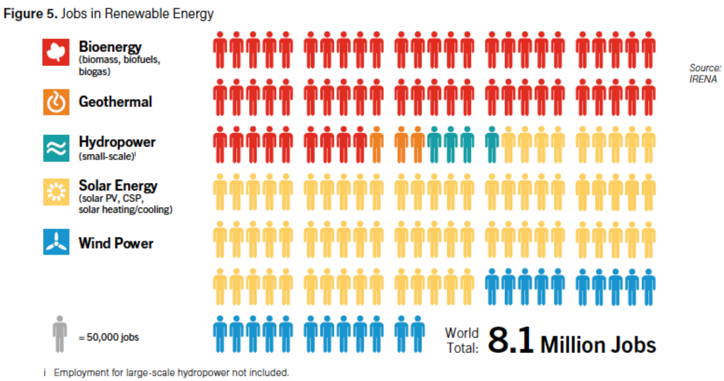


Fig. 99: Jobs in renewable energy production [17]

An overview about the job market by industry in the renewable energy sector is given in figure 100 [70] and shows the regional distribution of these jobs. Most jobs can be found, of course, in the solar market. China is leading, followed by Japan and US.

Table 1. Estimated Direct and Indirect Jobs in Renewable Energy Worldwide, by Industry

	World	China	Brazil	United States	India	Japan	Bang-ladesh	European Union[i] Germany	European Union[i] France	European Union[i] Rest of EU
	THOUSAND JOBS									
Solar PV	**2,772**	1,652	4	194	103	377	127	38	21	84
Liquid biofuels	**1,678**	71	821[c]	277[f]	35	3		23	35	47
Wind power	**1,081**	507	41	88	48	5	0.1	149	20	162
Solar heating/ cooling	**939**	743	41[d]	10	75	0.7		10	6	19
Solid biomass[a,g]	**822**	241		152[e]	58			49	48	214
Biogas	**382**	209			85		9	48	4	14
Hydropower (small-scale)[b]	**204**	100	12	8	12		5	12	4	31
Geothermal energy[a]	**160**			35		2		17	31	55
CSP	**14**			4				0.7		5
Total	**8,052[h]**	**3,523**	**918**	**769**	**416**	**388**	**141**	**355[j]**	**170**	**644[k]**

Fig. 100: Jobs in Renewable Energy by regions [70]

11.7 Building Integrated PV (BIPV)

After several turbulent years, the market for PV now entered a more mature phase. Prices have been stabilized, market volumes show a healthy growth and national support schemes are being reduced or redefined. At the same time we see an interesting market segment emerging: Building integrated PV (BIPV).

It is expected that especially the European market will experience a rapid growth in the years to come. Its key market driver is the European directive 2010/31/EU [58] and [59]. - The BIPV market up to now is relatively small, and is not increasing due to the fascinating possibilities of integration, but needs the change from just technology to an integration in the whole building process.

In BIPV applications PV modules are integrated into any element of the building envelope. These modules can be opaque as thin films or fixed as crystallites on any flat or flexible surface (metal, glass, etc.) as part of the building hull. Due to their features (size, flexibility, shape and appearance) these BIPV modules are suitable for any design of buildings [58]. They can be integrated in tiles (and shingles), curved roofs (skylight, transparent), facades (glass elements, semi-transparent, shading) as warm or cold facades etc.

Fig. 101 - 104: Beautiful BIPV buildings
Mountain house (Zermatt) [58]; IRENA head-quarter (Masdar) [60]; CIS tower (Manchester) [61];
Solar Vineyard House (California) [5]

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Remarks

Notices

Figures on cover page:

[57], [7], [11], [13], [37]

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