Global Energy Network Institute

Review and Comparison of Different Solar Energy Technologies

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Yinghao Chu
Research Associate, Global Energy Network Institute (GENI)
charlie0586@address.com

Under the supervision of and edited by
Peter Meisen
President, Global Energy Network Institute (GENI)
www.geni.org
peter@geni.org (619) 595-0139

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Abstract

Most of the power generated nowadays is produced using fossil fuels, which emit tons of carbon dioxide and other pollution every second. More importantly, fossil fuel will eventually run out. In order to make the development of our civilization sustainable and cause less harm to our environment, people are looking for new source of substitute clean energy.

Because of the increasing demands in clean energy, the solar energy industry is one of the fastest growing forces in the market. Nowadays there are several major directions for solar technology development. For example, photovoltaic systems directly convert the solar energy into electrical energy while concentrated solar power systems first convert the solar energy into thermal energy and then further convert it into electrical energy through a thermal engine.

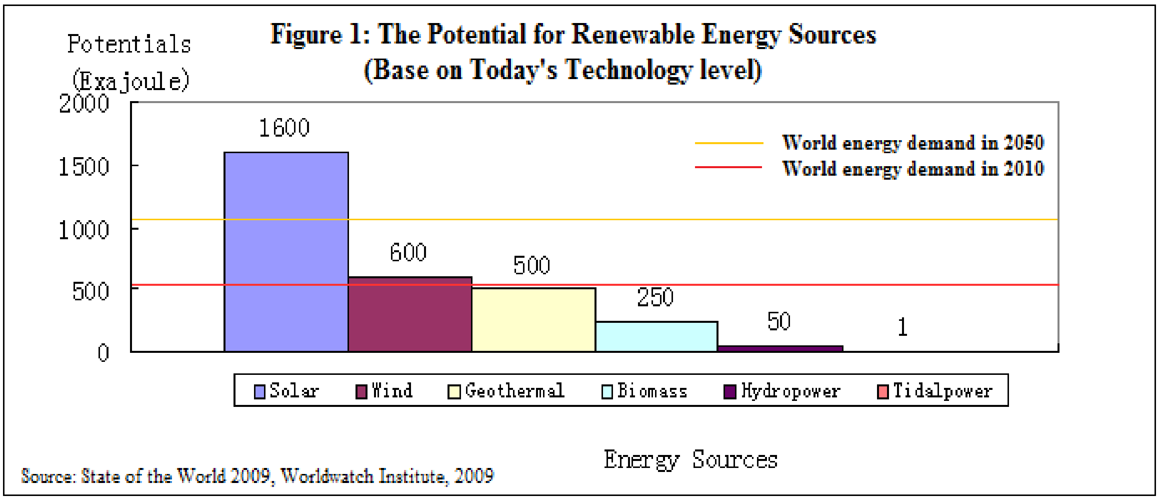
After a system has been established, it will be very difficult to upgrade the systems or change the operation methods. In order to choose the right solar system for a specific geographic location, we want to understand and compare the basic mechanisms and general operation functions of several solar technologies that are widely studied. This paper not only gives a brief introduction about the fast developing solar technologies industry, but also may help us avoid long term switching cost in the future and make the solar systems performance more efficient, economical and stable.

1. Introduction to Solar Energy

1.1 Why Solar Energy is One of the Key Solutions to World Energy Demand

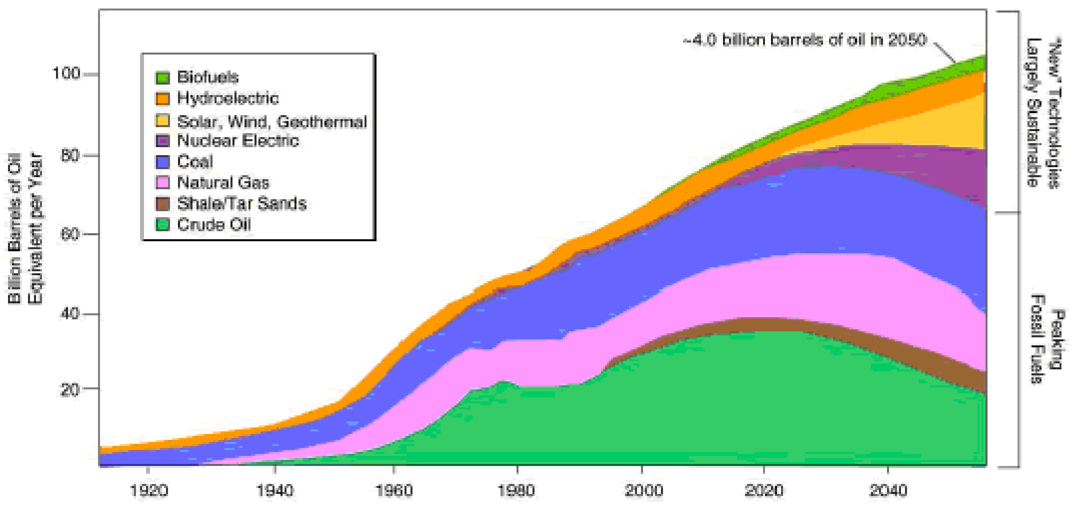
The sun is the most plentiful energy source for the earth. All wind, fossil fuel, hydro and biomass energy have their origins in sunlight. Solar energy falls on the surface of the earth at a rate of 120 petawatts, (1 petawatt = 10^{15} watt). This means all the solar energy received from the sun in one days can satisfied the whole world's demand for more than 20 years.

We are able to calculate the potential for each renewable energy source based on today's technology. (Figure 1) Future advances in technology will lead to higher potential for each energy source. However, the worldwide demand for energy is expected to keep increasing at 5 percent each year.[1] Solar energy is the only choice that can satisfy such a huge and steadily increasing demand.



[1] Enerdata Global Energy Intelligence, *World Energy Use in 2010: Over 5% Growth*, May, 2011

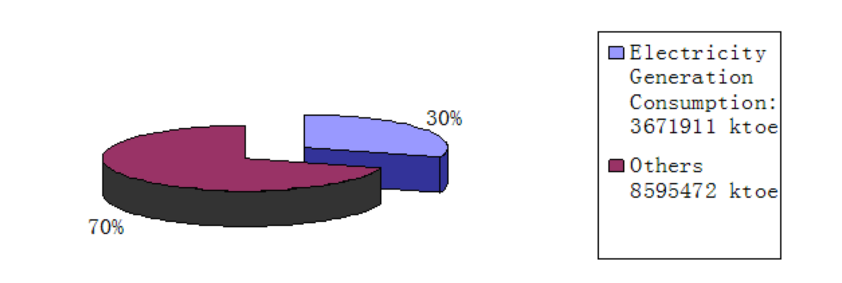
Figure 2: Word Energy Demand and Forecast



Sources: Lynn Orr, *Changing the World's Energy Systems*, Stanford University Global Climate & Energy Project (after John Edwards, American Association of Petroleum Geologists); SRI Consulting.

There are several applications for solar energy, for instance: electricity generation, photochemical, solar propulsion, solar desalination, and room temperate control. The collection of solar energy and its transfer to electricity energy will have wide application and deep impact on our society, so it has attracted the attention of the researchers.

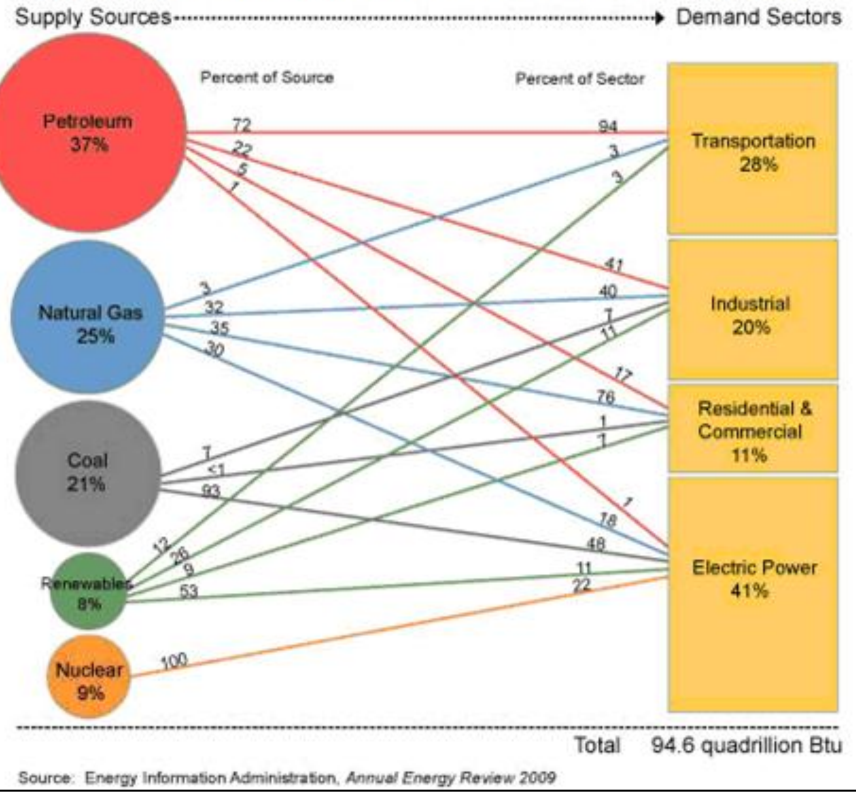
Figure 3: Electricity Energy Consumption Percentage of Total Energy Production in 2008



Source: Energy Balance for World, International Energy Agency

According to 2010 *Energy Balance for World Report* provided by International Energy Agency (IEA), about 30 percent of the total energy produced is consumed by electricity generation sectors with an efficiency rate of 42.6 percent.

Figure 4: Energy Supply Sources and Demand Sectors in USA



In developed country like the United States, electricity generation consumption occupies even larger shares (Figure 4 – 41 percent).

Electricity is high grade energy. This means it can be easily transferred into other forms like mechanical energy or heat. If we are able to generate economic and plentiful electricity energy, together with the easy transportation electricity energy transmission, the electric power will increase it shares in demand sectors dramatically.

1.2 Environmental Aspects

Solar energy is clean and renewable. It doesn’t emit carbon dioxide during operation. The major material of photovoltaic panel which is the most commonly used today is silicon. Silicon is abundant and environmentally safe.

Figure 5: A Nest on Solar Field

Figure 5 is shows at a 1 MW photovoltaic station in Merced, CA. We can see birds have located their nest on the tracking system of the station. Since the arid or semi arid area usually is more suitable for building solar power stations, the occupation of large areas of land by large utility stations will not be a serious problem.

However, the application of solar energy technologies can be dangerous under several conditions. Multi-junction photovoltic cells (III–V), which can achieve relatively higher energy converting efficiency than commonly used silicon cells, are usually made with poisonous materials like gallium arsenide (GaAs) or cadmium telluride (CdTe), can cause harm to the environment if leaked. More study about the safety and materials recycling for these cells must be conducted if we want to adopt these techniques into our solar industry. For concentrated solar power techniques, coolant and lubricant can be a problem if leaked.

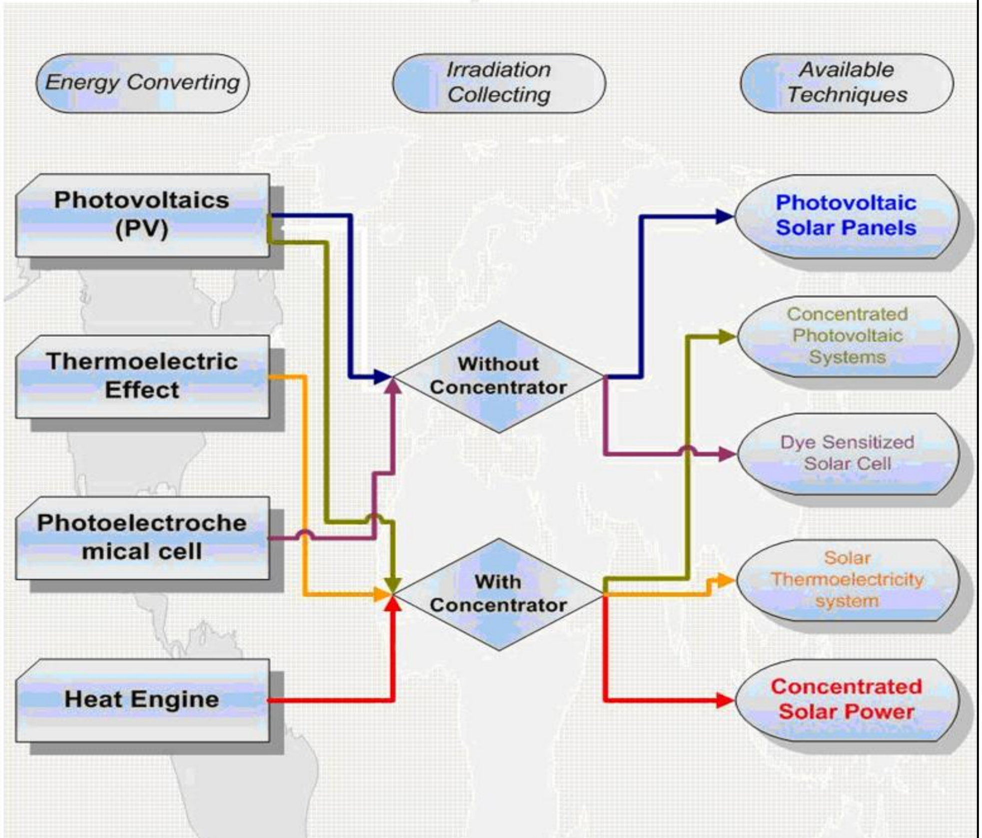
If these drawbacks are avoided, we are able to conclude that solar energy is clean and safe.

2. Solar Technologies

2.1 Overview

There are several kinds of solar techniques that are currently available. However, each of them is based on quite different concepts and science and each has its unique advantages. Analysis and comparison between different technologies will help us to adopt the most efficient and beneficial technology given a specific set of conditions.

Figure 6: Overview of Solar Technologies



Photovoltaic Solar Panels	Most commonly used techniques in today's market
Concentrated Photovoltaic Systems	The highest efficiency ever achieved in lab
Dye Sensitized Solar Cell	Biomimics techniques based on cheap organic materials
Solar thermoelectricity system	Based on the application of thermoelectricity materials
Concentrated Solar Power	Commonly used based on the application of mature heat engine

Generally speaking, non-concentrated photovoltaic solar panels (PV) and concentrated solar power (CSP) are the two most mature technologies. They have been commercialized and expected to experience rapid growth in the future, thus our emphasis will be on these two technologies.

Solar thermoelectricity systems (STA), dye sensitized solar cell (DSPV) and concentrated photovoltaic systems to our reader emerging technologies and under intensive study. Eventually, they may claim a significant share of the solar energy market if they achieve the necessary technical breakthroughs to make them sufficiently competitive to be commercialized.

Some reports characterize them into the other two domains –CPV, DSPV into PV domains and STS into CSP domains, however, each uses unique mechanisms, structures and materials. Their mechanisms will be discussed, and their advantages and drawbacks will be listed. Then, photovoltaic solar panels and concentrated solar power will be discussed in detail, including their technologies, subcategory, structures, deployment and trend of improvement in future.

2.2 Solar Thermoelectricity

Solar thermoelectricity uses parabolic disc technology to capture thermal energy basted on the thermoelectric effect. Electricity is produced through a concentrator thermoelectric generator (CTEG)　A thermoelectric device is divided into two (2) parts　IT produces energy by converting differences in temperatures in the two parts into volts using a semi-conductor.

Conversely, when a voltage is applied to the device, it creates a temperature difference. At the atomic scale, an applied temperature gradient causes charged carriers in the material to move from the hot side to the cold side. This effect was discovered since 182 and has been developed in recent years. Now we are able to see that it works in astronautic devices and automotive engine systems.

Figure 7: A Sample Solar Thermoelectricity Device

Chen, Jincan,Thermodynamic analysis of a solar-driven thermoelectric generator, Journal of Applied Physics

For each kind of thermoelectric material, there is a Seebeck coefficient (S). This a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material.[2] The thermo-power has units of volts per kelvin (V/K). Then, with the value of both electrical and thermal conductivity, we are able to calculate the figure of merit, which is used to quantify the performance of a device, methodology or system:[3]

$$Z = \frac{\sigma S^2}{\kappa},$$

Where σ is the electrical conductivity, κ is the thermal conductivity, and S is the Seebeck coefficient. The final working efficiency of thermoelectric materials is depended on the figure of merit:[4]

$$\eta = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$

Where $\mathbf{T_H}$ refers to the temperature on the hot side while the $\mathbf{T_C}$ refers to the temperature on the cold side.

Figure 8 illustrates the working mechanism of a solar thermoelectricity system. The concentrator collects the sun light and focuses the irradiation on a small area that can increase the temperature of the receiver to very high temperature depends on the concentration ratio. Then, the heat flow from the hot side to the cold side through the thermoelectric material and generates voltage between the two ends at the efficiency **η**.

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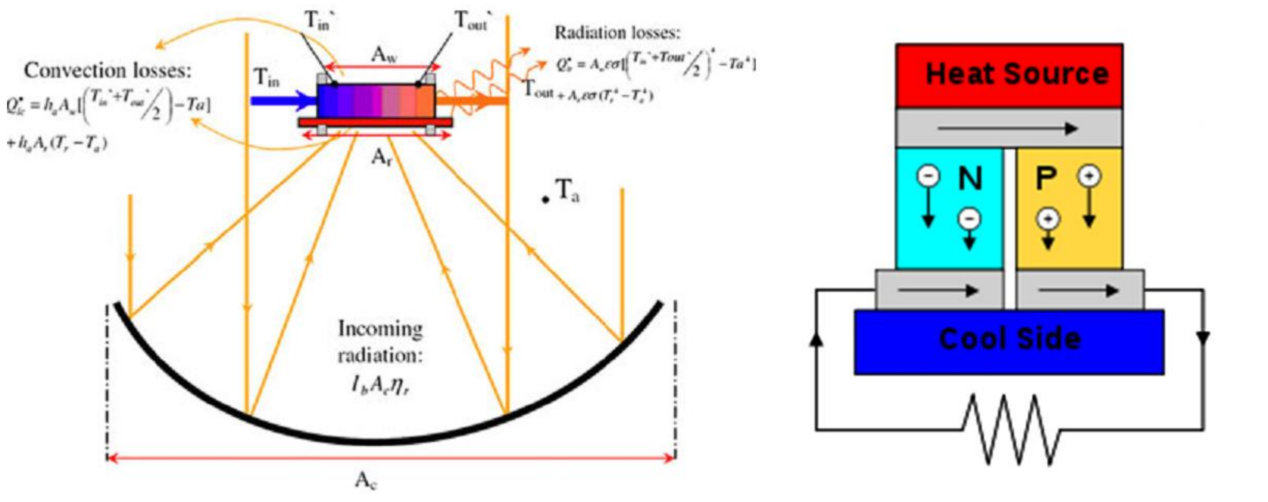
2 Blundell, Katherine and Blundell, Stephen, *Concepts in Thermal Physics*, 2009

3 Chen, Jincan,"Thermodynamic Analysis of a Solar-driven Thermoelectric Generator," *Journal of Applied Physics*, Volume 79, Issue 5, March 1, 1996, pp.2717-2721

4 Fan, Hongnan, Singh, Randeep, and Akbarzadeh,Aliakbarm **"**Electric Power Generation From Thermoelectric Cells Using a Solar Dish Concentrator, *Journal of Electronic Materials* , 2011

Figure 8: Working Mechanism of a Solar Thermoelectricity System



Source: Chen, Jincan,Thermodynamic analysis of a solar-driven thermoelectric generator, Journal of Applied Physics

According Hongnan Fan, Randeep Singh, and Aliakbar Akbarzadeh, laboratory tests of a single thermoelectric generator under controlled experimental conditions were conducted and revealed a maximum power of 4.9 watts (W) for a temperature difference of 110 degrees Kelvin (K), corresponding to 2.9 percent conversion efficiency. Moreover, several tests were conducted to obtain the actual capacity of the parabolic dish, and a maximum temperature at the electric power generation from thermoelectric cells using a solar dish concentrator receiver of 143 degrees Celsius with overall efficiency of 11.4 percent was achieved.

Advantages

- A simple system that can be deployed on roof tops.
- Able to work in harsh environments.
- Quiet in operation.
- Capable of virtually endless shelf life.
- The thermoelectric part has simple structure without any moving parts.
- Extremely reliable.
- Driven by low grade heat energy.

Drawbacks

- The efficiency of the thermoelectric materials is still very low, the recently achieved figure of merit is only 1.3~2.0.
- Like most of the other solar technologies with concentration requirements, this system

is unable to collect diffuse irradiation and must rely on direct radiation only.

- In order to have sufficient output, high temperatures are needed to make it work efficiently (~200^{o} C based on Carnot or thermal efficiency), which lead to higher concentration ratio of the collector (10~100 suns) and more precise tracking systems. Higher concentration collector will increase capital cost and maintenance cost.
- Thermoelectric material like Bismuth telluride is toxic and expensive.
- Cooling systems are required to decrease the temperature of the cold side in order to increase to total efficiency.

Solar thermoelectricity is a new idea in the laboratory and still not matures enough to meet the market requirement. However it has many special advantages and will probably occupy a niche market in the future. Due to it special nature and the use of low grade thermo energy, the thermoelectricity generator should be combined other solar technology systems. Such a hybrid system will able to achieve overall higher final efficiency.

2.3 Dye Sensitized Solar Cell (DSSC)

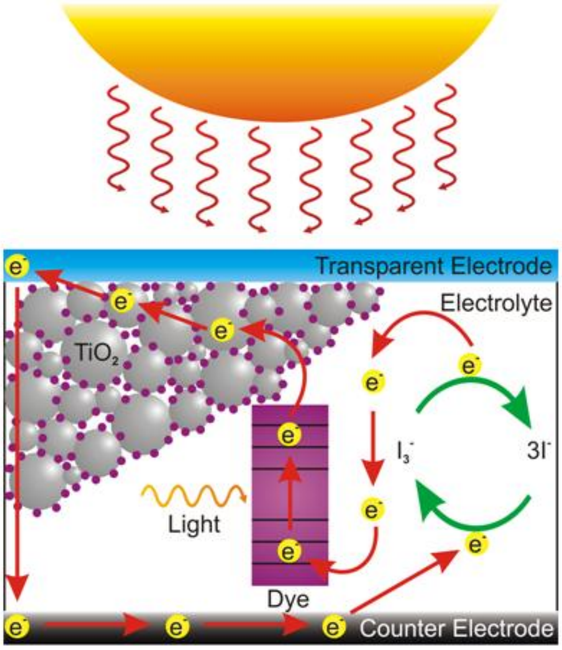
A dye-sensitized solar cell (DSSC, DSC or DYSC) is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photoelectrochemical system. This cell, also known as the Grätzel cell, was invented by Michael Grätzel and Brian O'Regan at the École Polytechnique Fédérale de Lausanne in 1991.[5]

Figure 9: Samples of Dye Sensitized Solar Cells

Source: en.wikipedia.org/wiki/Dye-sensitized solar cell#Operation

[5] Fan-Tai Kong, Song-Yuan Dai, and Kong-JiaWang, *Review of Recent Progress in Dye-Sensitized Solar Cells*, 2007.

Figure 10: The Mechanism of DSSC



Source: Wikipedia/Dye sensitized solar cell

The mechanism of DSSC is illustrated in figure 10. Michael Grätzel, of the *Institute of Photonics and Interfaces, provides a basic description of the DSSC process.*[6] Sunlight enters the cell through the transparent cover, striking the dye on the surface of the TiO_2. This creates an excited state of the dye, from which an electron is injected into the conduction band of the TiO_2. From there, it moves by diffusion (as a result of an electron concentration gradient) to the clear anode on top.

The dye molecule loses an electron and will decompose if another electron is not provided. The dye strips one from iodide in electrolyte below the TiO_2, oxidizing it into triiodide. This reaction occurs quickly compared to the time required for the injected electron to recombine with the oxidized dye molecule. Preventing this recombination reaction is essential as it would effectively short-circuit the solar cell. The triiodide then recovers the missing electron by mechanically diffusing to the bottom of the cell, where the counter electrode re-introduces the electrons after flowing through the external circuit.

The injection process used in the DSSC does not create a hole in the TiO_2, only an extra electron. Although it is possible for the electron to recombine back into the dye, the rate at which this occurs is slow compared to the rate at which the dye regains an electron from the surrounding electrolyte. Recombination directly from the TiO_2 to species in the electrolyte is also possible although, for optimized devices this reaction is rather slow. On the contrary, electron transfer from the platinum coated electrode to species in the electrolyte is necessarily very fast.

[6] Grätzel, Michael "Photoelectrochemical Cells," *Nature,* November 1, 2001

DSSCs are extremely efficient. Due to their "depth" in the nanostructure there is a very high chance that a photon will be absorbed, and the dyes are very effective at converting them to electrons. Most of the small losses that occur in the system are due to conduction losses in the TiO_2 and the clear electrode, or optical losses in the front electrode. The overall efficiency for green light is about 90 percent, with the "lost" 10 percent, largely accounted for by the optical losses in the top electrode. Overall peak power production efficiency for current DSSCs is about 10.9 percent tested in January, 2011.[7]

Advantages

- DSSCs use low-cost materials; are simple to manufacture, and are technically attractive.
- DSSCs can be replacements for existing technologies in "low density" applications like rooftop solar collectors, where mechanical reliability and light weight of the glass-less collector are important factors.
- The process of injecting an electron directly into the TiO_2 is qualitatively different to that occurring in a traditional cell, where the electron is "promoted" within the original crystal. In theory, given low rates of production, the high-energy electron in the silicon could re-combine with its own hole and generate less volume of current.[8]
- As a result of these favorable "differential kinetics" (the reaction rate), DSSCs work even in low-light conditions, allowing them to work under cloudy skies and non-direct sunlight when traditional designs would suffer a "cutout" at some lower limit of illumination, when charge carrier mobility is low and recombination becomes a major issue. The cutoff is so low that this technology is being considered for indoor use, collecting energy for small devices from the lights in the house.
- Common semiconductor systems suffer noticeable decreases in efficiency as the cells heat up internally. DSSCs are normally built with only a thin layer of conductive plastic on the front layer, allowing them to radiate away heat much easier, and therefore operate at lower internal temperatures.

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[7] Green, M.A., Emery, K. Hishikawa, Y., Warta, W., Dunlop, E.D."Solar Cell Efficiency Tables (Version 38)," *Progress in Photovoltics*, 2011.

[8] Sustainable Action Day, *Desentizied Solar Cell*, 2010.

Drawbacks

- Current efficiency is still relatively low compare with traditional semiconductor solar cells.
- Dyes will degrade when exposed to ultraviolet radiation that limits the lifetime and stability of the cells adding a barrier layer will increase the cost and may lower the efficiency.
- Generally, DSSC technology uses liquid electrolyte that has temperature stability problems. At low temperatures, the electrolyte can freeze, stopping power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem.
- The electrolyte solution contains volatile organic solvents and must be carefully sealed. This, along with the fact that the solvents permeate plastics, precludes large-scale outdoor application and integration into flexible structures.
- Although the dye is highly efficient at converting absorbed photons into free electrons in the TiO_2, only photons absorbed by the dye will produce electric current. The rate of photon absorption depends on the absorption spectrum of the sensitized TiO_2 layer and upon the solar flux spectrum. The overlap between these two spectra determines the maximum possible photocurrent. Typically, dye molecules have poorer absorption in the red part of the spectrum compared to silicon, which means that fewer of the photons in sunlight can be used for electrical current generation. These factors limit the current generated by a DSSC; for example, a traditional silicon-based solar cell offers about 35 mili-ampere per square centimeter ($mA/cm^{2)}$, whereas current DSSCs offer about 20 mA/cm^2.[9]

Both researchers and business are very interested in the DSSC technology. Companies like Dyesol are well established in this area of the industry. However, there are problems that prevent the mass production and wide use of DSSC technology. DSSCs are still in the early stages of the development cycle. Efficiency gains are possible and more widespread studies are underway. These include the use of quantum dots (small particles of semi-conductor

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[9] Ibid.

materials) for conversion of higher-energy (higher frequency) light into multiple electrons and changing the doping of the TiO_2 to better match it with the electrolyte being used. Replacing the liquid electrolyte with a solid is an ongoing area of research. Recent experiments using solidified melted salts have shown some promise, but currently suffer from higher degradation during continued operation, and are not flexible.

Overall, DSSC technology may not be attractive for large-scale deployments where higher-efficiency cells are more viable, although more expensive. But, even small increases in the DSSC conversion efficiency may make them suitable for some of these roles.

The dye sensitized solar cell is a brilliant idea because it applies different mechanisms and has many advantages compare with traditional semiconductor solar cell. Though it is far from mature, DSSCs technology will be an important renewable energy source in future if some technology breakthroughs are made. It may be possible to use mixed dye to overcome the band absorption limits of each dye to improve the overall efficiency.

2.4 Concentrated Photovoltaic (CPV)

Concentrated photovoltaic technology uses optics, such as lenses to concentrate a large amount of sunlight onto a small area of solar photovoltaic materials to generate electricity.

Figure 11:A Sample of Concentrated Photovoltaic Systems

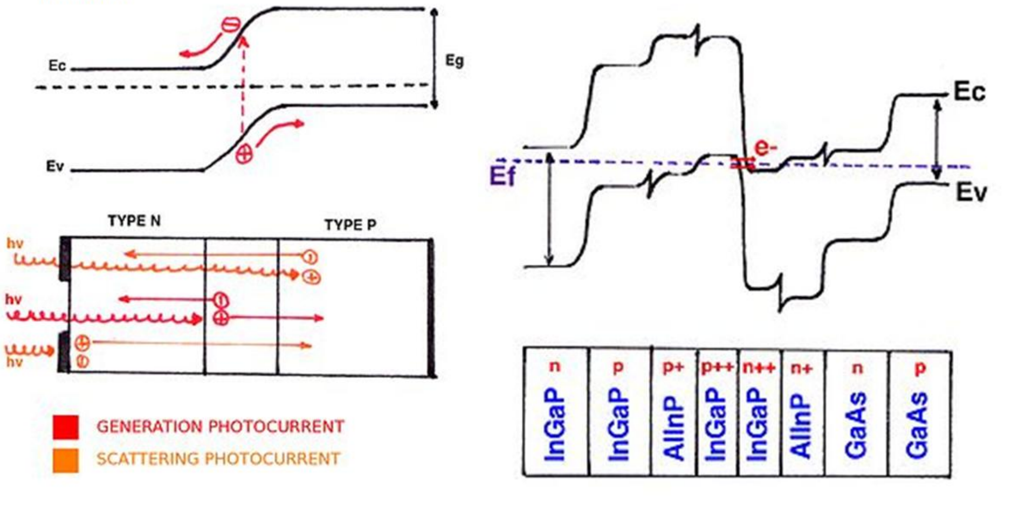
Source: blog.vertography.com/2008/08/04/concentrating-photovoltaic-technology

CPV systems are categorized according to the amount of solar concentration, measured in *suns* (the square of the magnification).

Part	Class of CPV	Typical Concentration Ratio	Type of Converter
I	High-concentration, MJ cells	>400X	Multijunction
II	Medium-concentration, cells	~3X–100X	Silicon or other cells
III	Enhanced concentration, modules	<3X	Silicon modules

Figure 12 shows a schematic illustration of the photovoltaic effect. Photons give their energy to electrons in the depletion or quasi-neutral regions. These move from the conduction band to the valence band. Depending of the location, electrons and holes are accelerated by the drift field E_{drift}, which gives generation photocurrent, or by E_{scatt}, which gives scattering photocurrent. From the layers and structure of the tunnel junction, we can see the length of the depletion region is narrow and the band gap is high, electrons can tunnel.

Figure 12: Schematic Illustration of the Photovoltic Effect and Band Structure of the Tunnel Junction



Source: en.wikipedia.org/wiki/Multi-junction_solar_cell

Advantages

- Despite the energy lost during the concentrating process, CPV can achieve the highest efficiency among all kinds of solar technologies.
- Unlike traditional, more conventional flat panel systems, CPV systems are often much less expensive to produce, because of the reduced use of semi-conductor material compared with flat-plate silicon. This reduces risk for the investor and allows more rapid adjustment of plans based on changing markets.

Drawbacks

- Like most concentration systems, CPV is unable to collect diffuse irradiation... Some researchers suggest equipping the CPV unit with a tracking system. However CPV can collected more energy than non-concentrated PV techniques due to superior performance during morning and late afternoon time. Although the energy consumption by a tracking system is minimal, the moving parts of the tracking system make it less reliable and increases both manufacturing and maintenance costs.
- Even a small cloud may drop the production to zero. Unlike concentrated solar power, the storage system that can mitigate this problem above is expensive since it is much easier to store heat than electric energy. This kind of instability will not be preferable when connected to the grid.
- For HCPV, the price for the multi-junction cell can be 100 times more expensive than a silicon cell of the same size. This means that the concentration ratio must 100 times

higher in order to make the system more economic than silicon panels. However, such a high ratio of concentration will lead to greater requirements of tracking system and cooling systems. These will further increase the capital cost of the whole system.

The use of concentrated sunlight on very small, but highly efficient (~40 percent) solar cells has the potential to provide cost-effective, large-scale, solar-electricity generation, especially in sunny locations. More than a dozen companies are manufacturing multi-junction concentrator cells, positioning themselves to respond to the growing demand for this technology. The approach is attracting large companies, such as RF Micro Devices (RFMD) and JDSU, both of which have expressed interest in the multi-junction concentrator cell business.

At least three dozen companies are developing concentrator photovoltaic systems, and several have already deployed units generating less than 1 megawatt (MW) of energy in the field. This industry is showing signs of being poised for substantial growth in the next few years as the world enthusiastically embrace solar energy. Many companies have moved from prototype development into manufacturing with an aggregate yearly production capacity of more than 100 MW/y.

CPVs are developing and improving in every few months. Compared with the traditional photovoltaic panel techniques, CPVs are better suited to solar farm rather than rooftop use. Like other solar technologies, CPVs have both advantages and drawbacks. Theoretically, CPVs can achieve a lower cost. However, if major improvements are made in silicon purification due to mass production or technologies breakthrough like what happened to Aluminum in 1860s, the silicon panels may regain their advantage due to the silicon’s abundance and safety. The following table shows the parameters, status and goals for CPV technology.

Parameter	Status 2007	Status 2009	Future Goal (2015)
$/W installed cost	$7–$10/W	*	<$2/W
¢/kWh	>30¢/kWh	*	<7¢/kWh
System reliability	5 years	*	20 years
Commercial system efficiency	17%	25% (champion module 29%)	29%–36%
Champion device efficiency	40.7%	41.6%	48%
Commercial device efficiency	35%–37%	Typically 39%	42%
Optical efficiency	75%–85%	*	80%–90%
III-V cell cost, $/cm^2	$10–$15/cm^2	*	$3–$5/cm^2
Systems in the field	<1 MW**	~4 MW**	
Manufacturing capacity	<1 MW/y	~100 MW/y	

*These numbers are not well defined.
**Systems counted here incorporated multijunction cells.

Source: S. Kurtz, Technical Report, Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry

Concentrated photovoltaics and thermal (CPVT), also called combined heat and power solar (CHAPS), is a co-generation or micro-cogeneration technology used in concentrated photovoltaics that produces both electricity and heat in the same module. The heat may be employed in district heating, water heating and air conditioning, desalination or process heating. It is possible that concentrated photovoltaics may be combined with concentrated solar power to create a higher efficiency performing hybrid system.

2.5 Photovoltaic Solar Panels (PV)

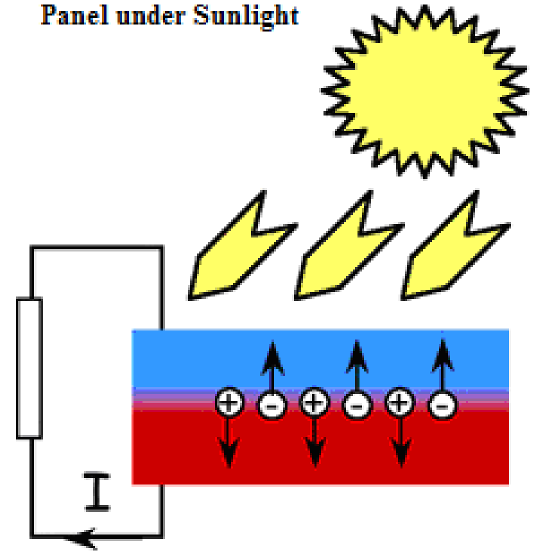
Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide. Photovoltaic solar panel is the most commonly used solar technology to generate electricity energy.[10]

[10] International Energy Agency (IEA), *Technology Roadmap-Solar Photovoltaic Energy*, 2010

Figure 13: Examples of Current Commercialized Photovoltaic Applications

The basic idea of photovoltaic effects is simple (see figure 14). Electrons will emit from matter (metals and non-metallic solids, liquids or gases) as a result of their absorption of energy from electromagnetic radiation of very short wavelength, such as visible or ultraviolet light. Electrons emitted in this manner may be referred to as "photoelectrons". First observed by Heinrich Hertz in 1887, the phenomenon is also known as the "Hertz effect".[11]

Figure 14: Schematic Illustration of a Photovoltaic Panel under Sunlight



2.5.1. Major Types of Photovoltaic Panels

Crystalline Silicon

The majority of PV modules (85 percent to 90 percent of the global annual market) are based on wafer-based crystalline-Si. The manufacturing of c-Si modules typically involves growing ingots of silicon, slicing the ingots into wafers to make solar cells, electrically interconnecting the cells, and encapsulating the strings of cells to form a module. Modules currently use silicon in one of two main forms: single- sc-Si or mc-Si. Current commercial single sc-Si modules have higher conversion efficiency about 14 to 20 percent. Their efficiency is expected to increase to 23 percent by 2020 and 25 percent in the longer term.[12]

Multi-crystalline silicon modules have a more disordered atomic structure, leading to lower efficiencies. But they are less expensive and more resistant to degradation due to irradiation. The degradation rate is about 2 percent per year for multiple crystalline technologies. Their efficiency is expected to reach 21 percent in the long term. Crystalline silicon PV modules are expected to remain a dominant PV technology until at least 2020, with a forecasted market share of about 50 percent by that time *(Energy Technology Perspectives* 2008*)*. This is due to their proven and reliable technology, long lifetimes, and

[11] Fowler, Michael, *The Photoelectric Effect*, 2011,

[12] Green Energy – Solar Energy, *Photovoltic (PV) Cell*, 2011,

abundant primary resources. The main challenge for c-Si modules is to improve the efficiency and effectiveness of resource consumption through materials reduction, improved cell concepts and manufacturing automation.[13]

Thin Films

Thin films are made by depositing extremely thin layers of photosensitive materials in the micrometre (μm) range on a low-cost backing, such as glass, stainless steel or plastic. The first generation of thin film solar cell produced was a-Si. To reach higher efficiencies, thin amorphous and microcrystalline silicon cells have been combined with thin hybrid silicon cells. With II-VI semiconductor compounds, other thin film technologies have been developed, including cadmium telluride (CdTe) and copper-indium-gallium-diselenide (CIGS).[14]

The main advantages of thin films are their relatively low consumption of raw materials; high automation and production efficiency; ease of building integration and improved appearance; good performance at high ambient temperature; and reduced sensitivity to overheating. The current drawbacks are lower efficiency and the industry's limited experience with lifetime performances. For utility production, thin film technologies will require more land than crystalline silicon technologies in order to reach the same capacity due to their lower efficiency. So, land availability and cost must be taken into consideration when thin film technology is considered.

Thin film technologies are growing rapidly. In recent years, thin film production units have increased from pilot scale to 50 MW lines, with some manufacturing units in the gigawatt (GW) range. As a result, thin films technologies are expected to increase their market share significantly by 2020.

II-VI semiconductor thin films

CdTe cells are a type of II-VI semiconductor thin film that has a relatively simple production process, allowing for lower production costs. CdTe technology has achieved the highest production level of all the thin film technologies. Also, it has an energy payback time of eight months, the shortest time among all existing PV technologies. For CIGS cells, the

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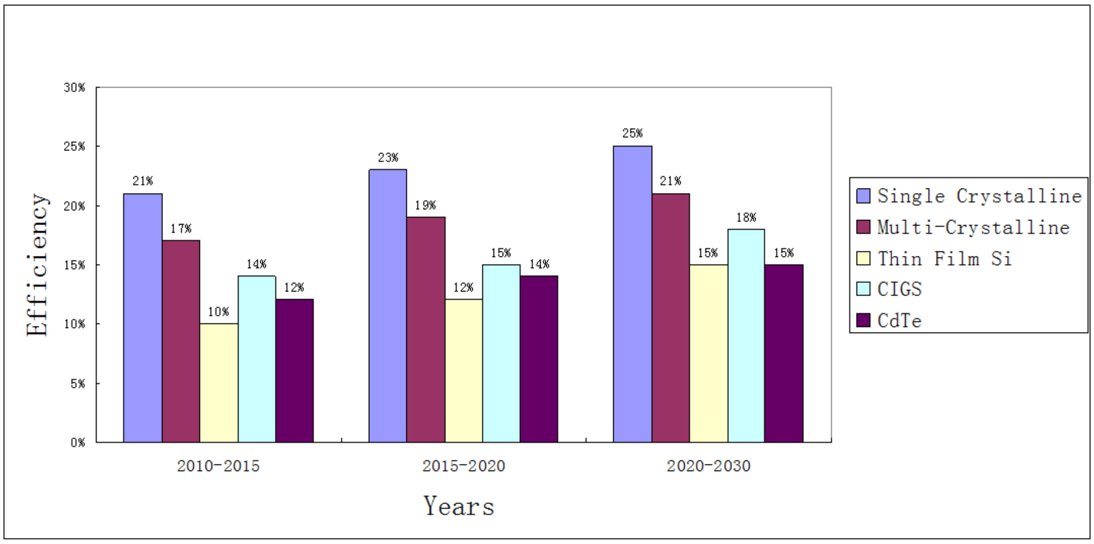
[13] International Energy Commission, *Energy technology Perspectives: Scenarios and Strategies to 2050,* 2008
[14] Op Cit

fabrication process is more demanding and results in higher costs and efficiencies compared to CdTe cells. Today, CdTe cells have achieved a dominant position in the thin film and have a market-leading cost-per watt. However, these materials are toxic and less abundant than silicon. It is difficult to predict which of the thin film technologies will reach higher market shares in the long-term. However, figure 15 forecasts potential efficiency improvements over the next 20 years.

Figure 15: The Expectation of Photovoltaics Efficiency Improvement in Future



Source: International Energy Agency (IEA), Technology Roadmap-Solar photovoltaic energy

PV systems reached a total global capacity of 40,000 MW at the end of 2010 which is about 3 percent of whole renewable energy capacity – about 16 percent of global final energy consumption comes from renewables.[15]

Figured 16 – 19 summarize world wide data on PV technology including distribution, capacity and cost.

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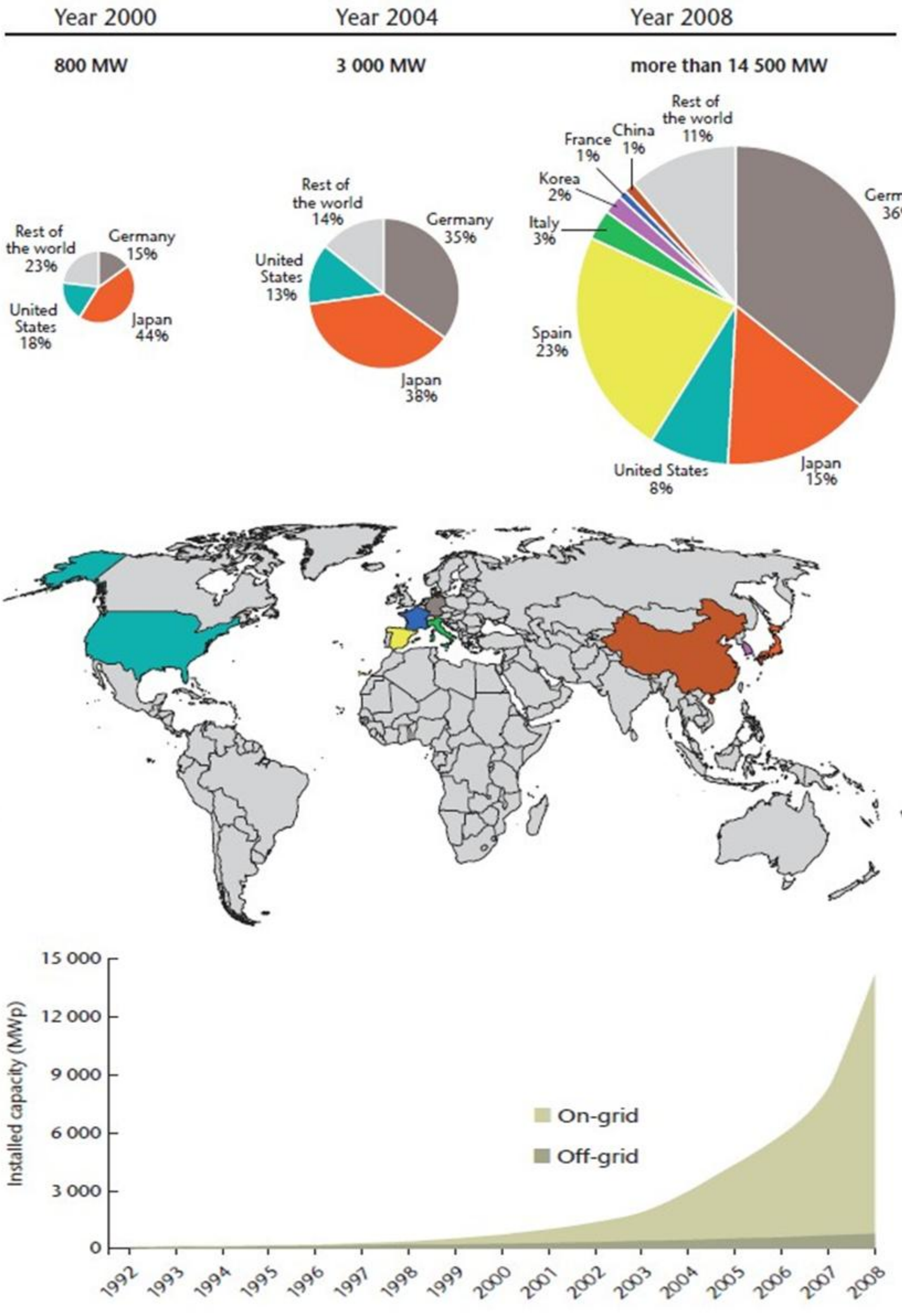
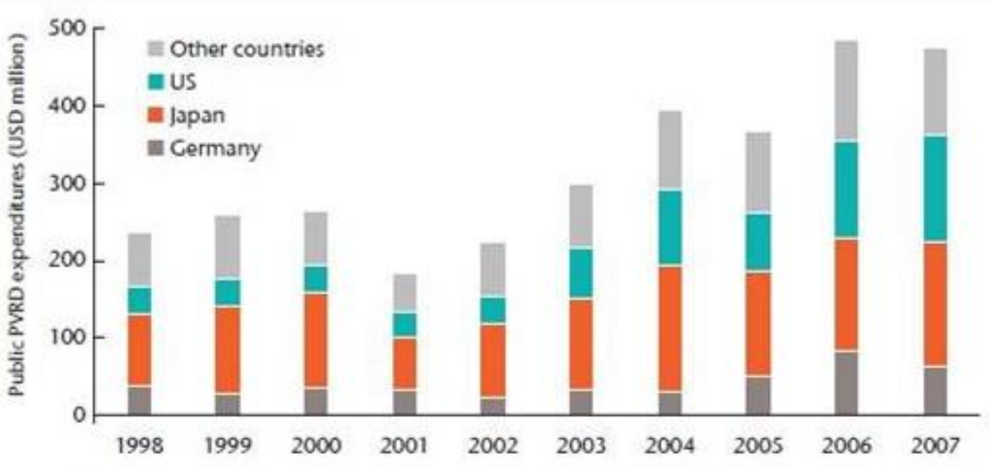
[15] Wang, Ucilia, "The Rise of Concentrating Solar Thermal Power", *Renewable Energy World*, July 6, 2011,

Figure 16: The Growth of Photovoltaic Capacity in Recent Years



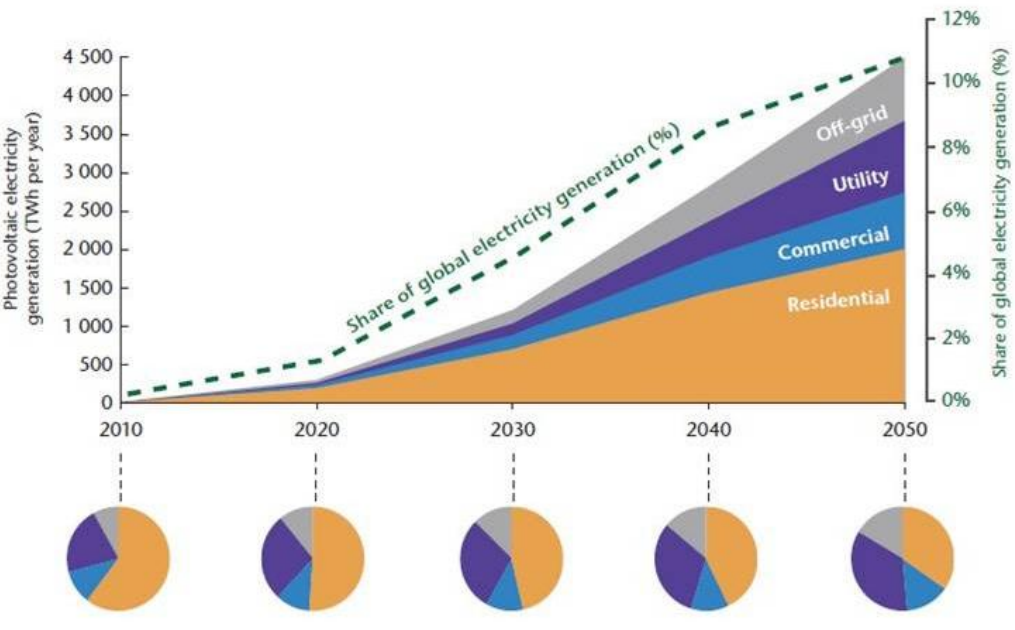
Source: International Energy Agency (IEA), Technology Roadmap-Solar photovoltaic energy

Figure 17: Spending in Photovoltaic around the world



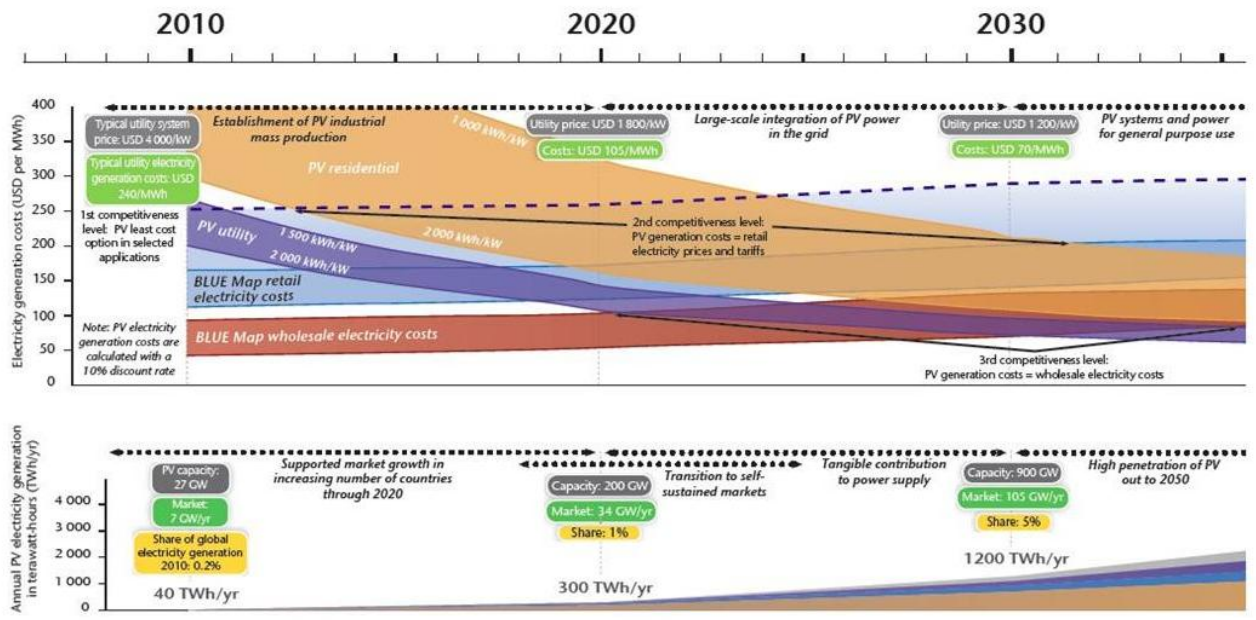
Source: International Energy Agency (IEA), Technology Roadmap-Solar photovoltaic energy

Figure 18: Expectation of Photovoltaic Capacity Growth in the World till 2050



Source: International Energy Agency (IEA), Technology Roadmap-Solar photovoltaic energy

Figure 19: PV Market Competitiveness Levels and Related Deployment Levels



Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); O&M costs 1%.

Source: International Energy Agency (IEA), Technology Roadmap-Solar photovoltaic energy

Despite the optimistic prediction of photovoltaic industry, this technology has disadvantages that will need more effort to solve: Solar electricity is still more expensive than most other forms of small-scale alternative energy production. Without governments mandating feed-in tariffs for green solar energy, solar PV is in less affordable to homeowners than solar hot water or solar space heating. Solar electricity is not produced at night and is greatly reduced in cloudy conditions. Therefore, a storage or complementary power system is required. Solar electricity production depends on the limited power density of the location's insolation.

Average daily output of a flat plate collector at latitude tilt in the contiguous United States is 3 – 7 kilowatt·h/m²/day and the performance will be less n high-latitude areas like Europe. Solar cells produce direct current (DC) which must be converted to alternating current (AC) using a grid tie inverter in existing distribution grids that use AC. This incurs an energy loss of 4 – 12 percent. However, high voltage DC grid transportation has less energy waste than AC grid; so, there is a trade-off consideration in deciding to construct high voltage DC grids and apply the inverter at the consumers' end.

Applying tracking systems to PV is also possible. The cost of a PV tracking system is usually greater than the cost of fixed PV system and its performance is greater than the performance of the fixed PV system – approximately 20 percent more energy produced on a yearly basis. In terms of land occupation, fixed PV field requires about half of the area necessary for a tracker PV system and, as highlighted above, the selection of PV modules may play an important role in determining the area required by the plant. Therefore, it can be concluded that for a large utility scale PV plant, the fixed PV field arrangement should be preferable when land impact is considered.[16]

Photovoltaic technologies are the most commonly used solar energy collecting technologies today and will continue to see rapid and steady growth. Each of these photovoltaic technologies have its own advantage and drawbacks and it is not certain which one will dominate the market in the following decades; however it is certain is that the photovoltaic technologies will help countries develop a clean and renewable future.

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[16] Quaschning, Volker**,** Technical and Economical System Comparison of Photovoltaic and Concentrating Solar Thermal Power Systems Depending on Annual Global Irradiation. *Solar Energy*, 2006

2.6 Concentrated Solar Power (CSP)

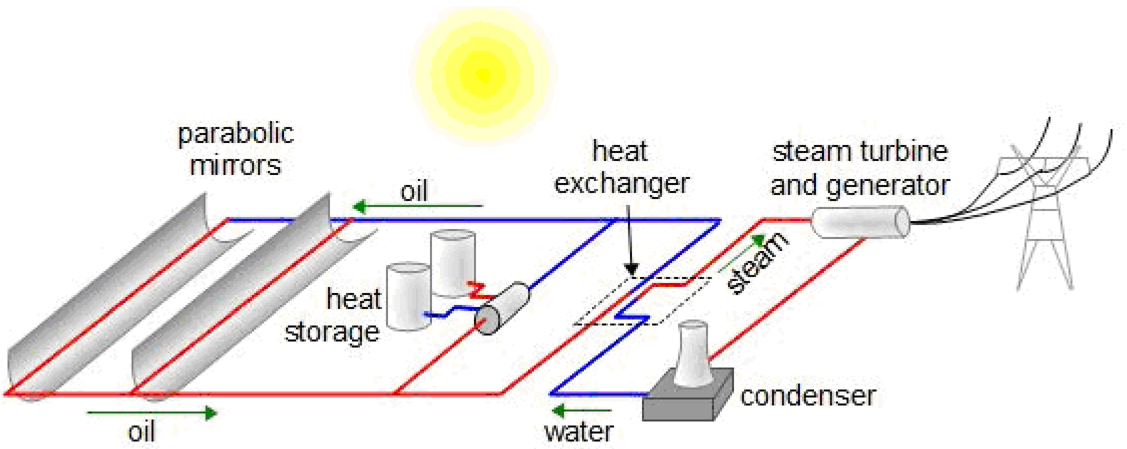
Concentrated solar power systems use mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electrical power is produced when the concentrated light is converted to heat which drives a heat engine (usually a steam turbine) connected to an electrical power generator.[17]

Figure 20: Examples of Concentrated Solar Powers: Parabolic Trough System and Solar Tower System

2.6.1. How Concentrated Solar Power System Works

Unlike the photovoltaic solar cells, converting energy from sunlight to electricity by CSP systems is based on the application of heat engine rather than photovoltaic effect which is directly transfer photon energy into electricity energy.

Figure 21:A Typical Parabolic CSP System

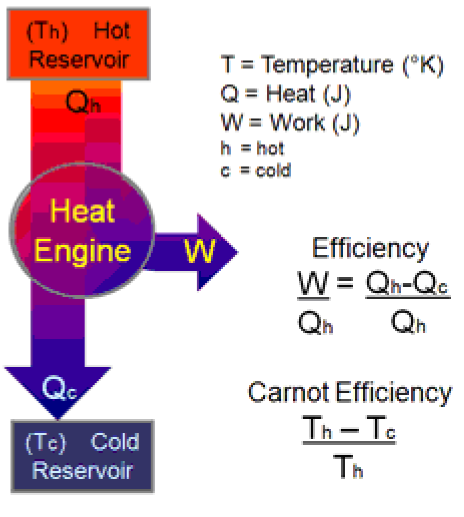


[17] *TransWorld News* "Concentrating Solar Power Systems: Market Shares, Strategies, and Forecasts, Worldwide, 2011 to 2017," September, 2011,.

Figure 21 illustrates how a commonly used parabolic CSP system works. The collectors concentrate the sunlight, collect it as heat energy and store it. Then, the heat energy is used generate steam that runs heat engines to produce electricity, which is transferred to the grid.

Heat engines have been around since antiquity; but, were only made into useful devices during the industrial revolution. They continue to be developed today and are very mature technologies. Most of the electricity generated today is by heat engines driven by burning of fossil fuels or hydropower. Their efficiency is limited by the laws of thermodynamics. The theoretical maximum efficiency that can be achieved is determined by Carnot's cycle, which declares that the efficiency of a heat engine is determined by the difference between the lowest and highest temperatures reached in one cycle as shown below.[18]

Figure 22: The Heat Engine



$$\eta_{\max} = 1 - \frac{T_c dS_c}{-T_h dS_h} = 1 - \frac{T_c}{T_h}$$

Where T_c is the temperature at the cold side and T_h is the temperature at the hot side.

The efficiency of various heat engines proposed or used today ranges from 3 percent (97 percent waste heat) for the Ocean Thermal Energy Conversion (OTEC) power proposal through 25 percent for most automotive engines, to 45 percent for a supercritical coal plant, and 60 percent for a steam-cooled combined cycle gas turbine.[19]

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[18] Start Your Engines *The Carnot Cycle*, 2011

[19] Lee S. Langston, "Efficiency by the Numbers," *Mechanical Engineering Magazine*, 2004

2.6.1. Concentration Techniques

Concentrating collectors exhibit certain advantages as compared to the conventional flat-plate type. The main ones are:

- The working fluid can achieve higher temperatures in a concentrator system when compared to a flat-plate system of the same solar energy collecting surface. This means that a higher thermodynamic efficiency can be achieved base on Carnot Efficiency discussed above.[20]
- The thermal efficiency is greater because of the small heat loss area relative to the receiver area.[21]
- Reflecting surfaces require less material and are structurally simpler than flat panel collectors (FPC). For a concentrating collector, the cost per unit area of the solar collecting surface is therefore less than that of a FPC.
- Owing to the relatively small area of receiver per unit of collected solar energy, selective surface treatment and vacuum insolation techniques are used to reduce heat losses and improve the collector efficiency are economically viable.

Their disadvantages are:

- Concentrator systems collect little diffuse radiation depending on the concentration ratio.
- Some form of tracking system is required so as to enable the collector to follow the sun.
- Solar reflecting surfaces may loose their reflectance with time and may require periodic cleaning and refurbishing.

In relatively cloudless areas, the concentrating collector may capture more radiation per unit of aperture area than a FPC. It will be more preferable to adopt concentrating collectors in arid or semi arid area.

2.6.2. Tracking Systems

Tracking systems are required for collectors to follow the sun in order to concentrate the direct solar radiation onto the small receiver area. High concentration ratio collectors cannot work without a tracking system. Various forms of tracking mechanisms, varying from simple to complex, have been proposed. They can be divided into two broad categories –mechanical

[20] Op Cit

[21] Kalogirous, Soteris, *Solar Energy Engineering: Processes and Systems*, 2009

and electrical/electronic systems. The electronic systems generally exhibit improved reliability and tracking accuracy. These can be further subdivided into the following:

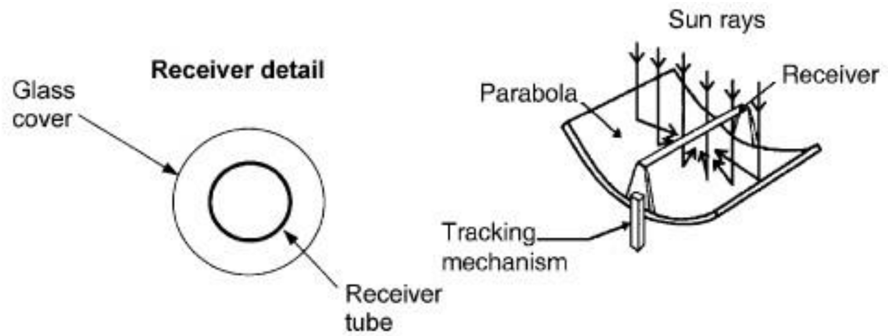
- Mechanisms employing motors controlled electronically through sensors that detect the magnitude of the solar illumination.
- Mechanisms using computer controlled motors with feedback control provided from sensors measuring the solar flux on the receiver.

There are four categories of concentration collectors, each of which is discussed below:

- Parabolic trough collectors (PTC)
- Linear Fresnel collectors (LFR)
- Solar towers (Heliostat field collectors)
- Parabolic dish reflectors (PDR)

Parabolic trough collectors (PTC) are made by bending a sheet of reflective material into a parabolic shape, A metal black tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver. It is sufficient to use a single axis tracking of the sun thus producing long collector modules. The collector can be orientated in an east–west direction, tracking the sun from north to south.[22]

Figure 23: Parabolic Trough



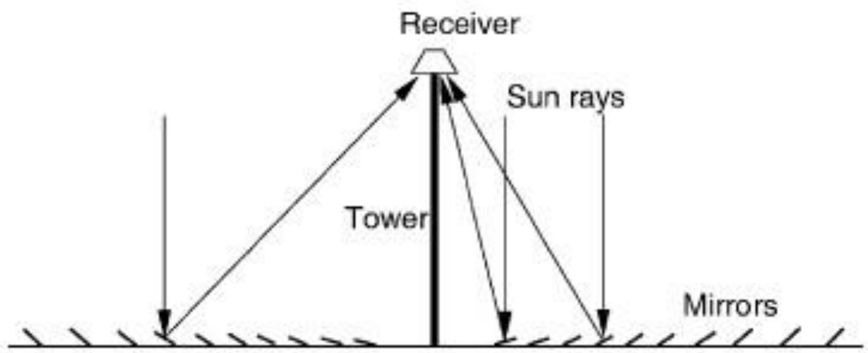
Over the period of one year, a horizontal north–south trough field usually collects slightly more energy than a horizontal east–west collector. However, the north–south field collects a lot of energy in summer and much less in winter. The east–west field collects more energy in the winter than a north–south field and less in summer, providing a more constant annual output. Therefore, the choice of orientation depends on the application and whether more

[22] Alternative Energy Tutorials, *Parabolic Trough Reflector*, 2011

energy is needed during summer or during winter. PTCs can effectively produce heat at temperatures between 50 and 400 °C and they are the most mature solar technology to generate heat at temperatures up to 400 °C for solar thermal electricity generation or process heat applications.[23] However, use of oil-based heat transfer media restricts operating temperatures today to 400°C, resulting in only moderate steam qualities. [24]

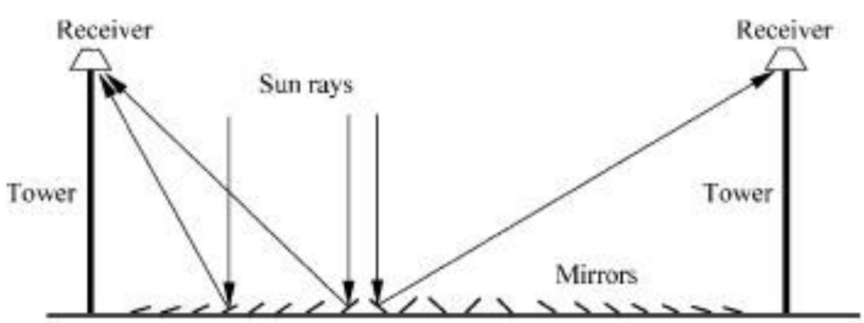
Linear Fresnel Reflector (LFR) technology relies on an array of linear mirror strips that concentrate light on to a fixed receiver mounted on a linear tower. The LFR field can be imagined as a broken-up parabolic trough reflector. The main advantage of this type of system is that it uses flat or elastically curved reflectors which are cheaper compared to parabolic glass reflectors. Additionally, these are mounted close to the ground, thus minimizing structural requirements.

Figure 25: Advanced Design of Linear Fresnel



In order to avoid the shading and blocking between adjacent reflectors, advanced design is adopted as shown in the following chart:

Figure 25: Advanced Design of Linear Fresnel

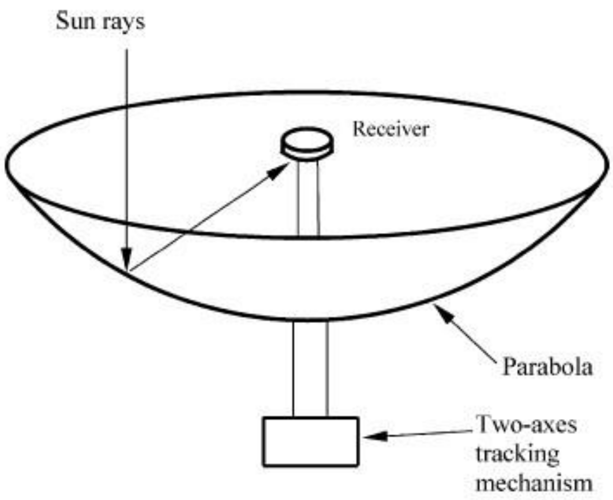


[23] Kalogirous, Soteris, *"Solar Thermal Collectors and Applications," Progress in Energy and Combustion Science*, 2004, 231 –295

However, LFRs are less efficient than troughs in converting solar energy to electricity and it is more difficult to incorporate storage capacity into their design.

A **Parabolic Dish Reflector** is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must track fully the sun to reflect the beam into the thermal receiver.

Figure 26: Parabolic dish reflector (PDR)



The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then either be converted into electricity using an engine-generator coupled directly to the receiver, or it can be transported through pipes to a central power-conversion system. Parabolic dish systems can achieve temperatures in excess of 1500^{o} C.[24]

Parabolic dishes have several important advantages:

- Because they are always pointing at the sun, they are the most efficient collector systems.
- Typically, they have a concentration ratio in the range of 600–2000 and are highly efficient at thermal-energy absorption and power conversion systems.
- They have modular collector and receiver units that can either function independently or as part of a larger system of dishes.

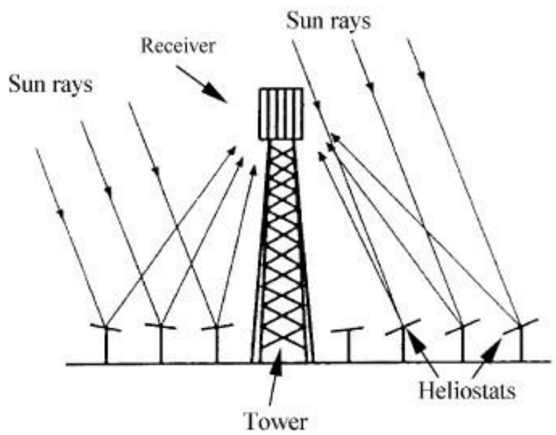
Parabolic-dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat-transfer fluid to the power-conversion systems. The need to circulate heat transfer fluid throughout the collector

[24] Ibid

field raises design issues, such as piping layout, pumping requirements, and thermal losses. The Stirling engine is the most common type of heat engine used in dish-engine systems. For this system, certain level of reliability and mass production still need to be achieved.

Solar Tower (Heliostat field collector) can be used for extremely high inputs of radiant energy to reflect their incident direct solar radiation onto a common target as shown in Figure 17. This is called the heliostat field or central receiver collector. By using slightly concave mirror segments on the heliostats, large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure.[25]

Figure 27: Solar Tower



The concentrated heat energy absorbed by the receiver is transferred to a circulating fluid that can be stored and later used to produce power. Central receivers have several advantages:

- They collect solar energy optically and transfer it to a single receiver, minimizing thermal-energy transport requirements.
- They typically achieve concentration ratios of 300 –1500 and are highly efficient, both in collecting energy and in converting it to electricity.
- They can conveniently store thermal energy.
- They are quite large (generally more than 10 MW) and thus benefit from economies of scale.[26]

The average solar flux impinging on the receiver has values between 200 and 1000

[25] Ibid.

[26] Sorenson, B., Breez, P., *Renewable Energy Focus Handbook*,2009.

kW/m^2. This high flux allows working at relatively high temperatures of more than 1500^o C and integrates thermal energy into more efficient cycles. Central receiver systems can easily integrate in fossil fuelled plants for hybrid operation in a wide variety of options and have the potential to operate more than half the hours of each year at nominal power using thermal energy storage.

Central receiver systems have potential for mid-term cost reduction of electricity compared to parabolic trough technology since they allow many intermediate steps between the integration in a conventional Rankine cycle up to the higher energy cycles using gas turbines at temperatures above 1000^o C. This subsequently leads to higher efficiencies and larger throughputs. The Rankine cycle is a closed loop cycles that converts heat into energy; for example converting water the steam. Another alternative is to use Brayton cycle turbines, which require higher temperatures than the ones needed for in Rankine cycle. Projected annual performance values, investment and operating costs still need to be proven in commercial operation.

2.6.1 Storage Systems

Since we do not have sunlight 24 hours a day, a storage system is needed to extend the working hours of a solar energy plant to satisfy demand during the night time as shown in figures 28 and 29.

Figure 28: Functions of the Storage Systems

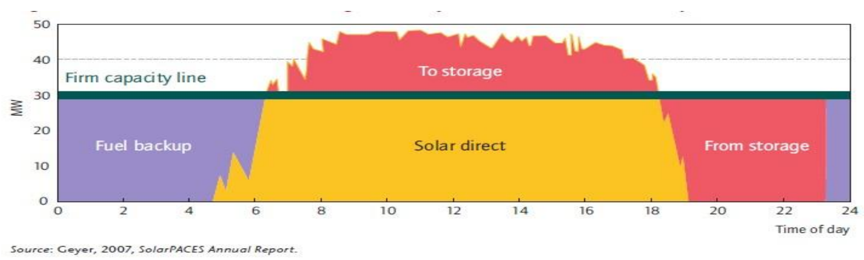
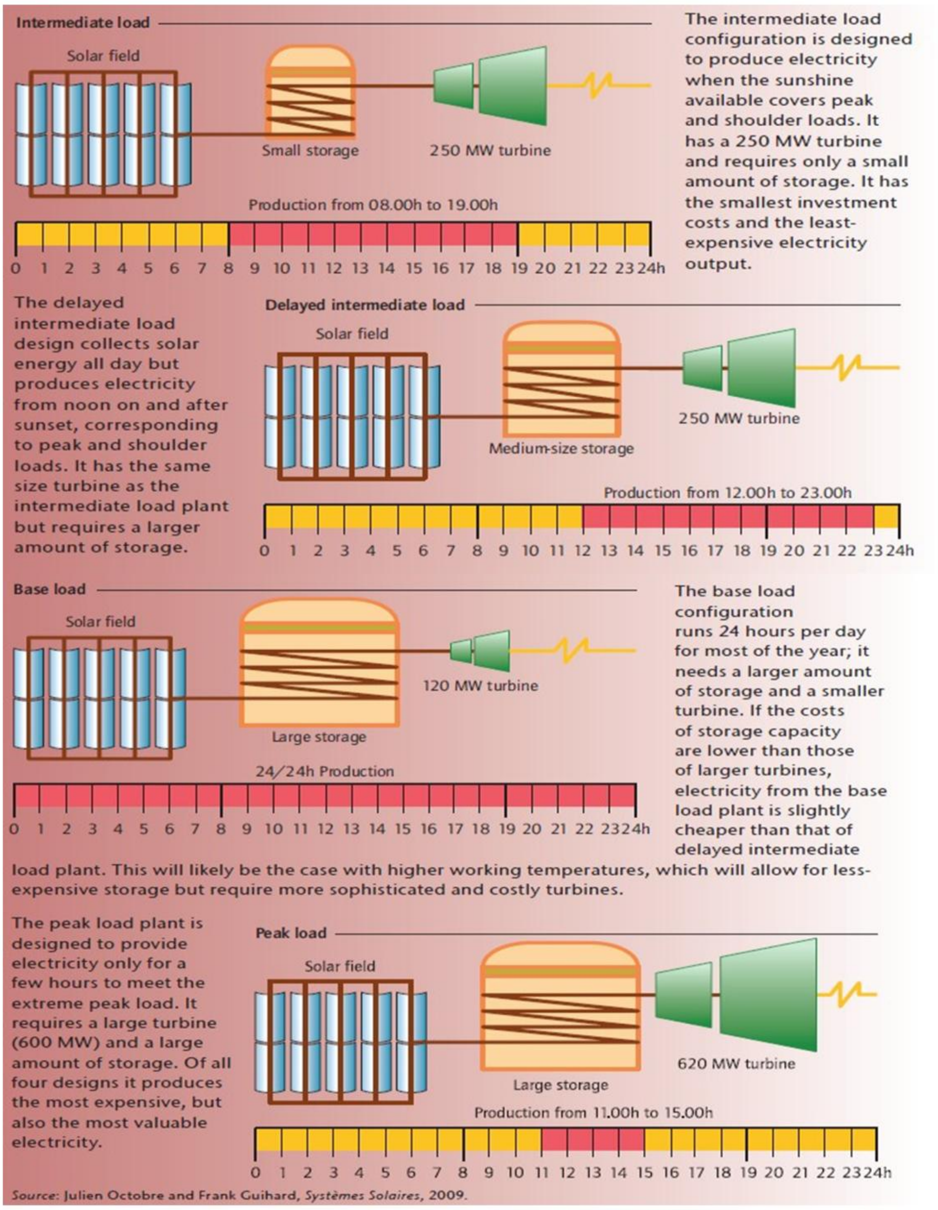


Figure 29: Four kinds of storage systems which can enhance the value of CSP Capacities.



Concentrated solar power (CSP) is being widely commercialized, with about 1.17 GW of CSP capacities in 2011, with 582 MW of them are located in Spain, and the 507 megawatts of capacity in the United States. About 17.54 GW of CSP projects are under development worldwide, and the United States leads with about 8.67 GW. Spain ranks second with 4.46 GW in development, followed by China with 2.5 GW.[27] Figures 30 – 33 project CSP electricity production and consumption by 2050.

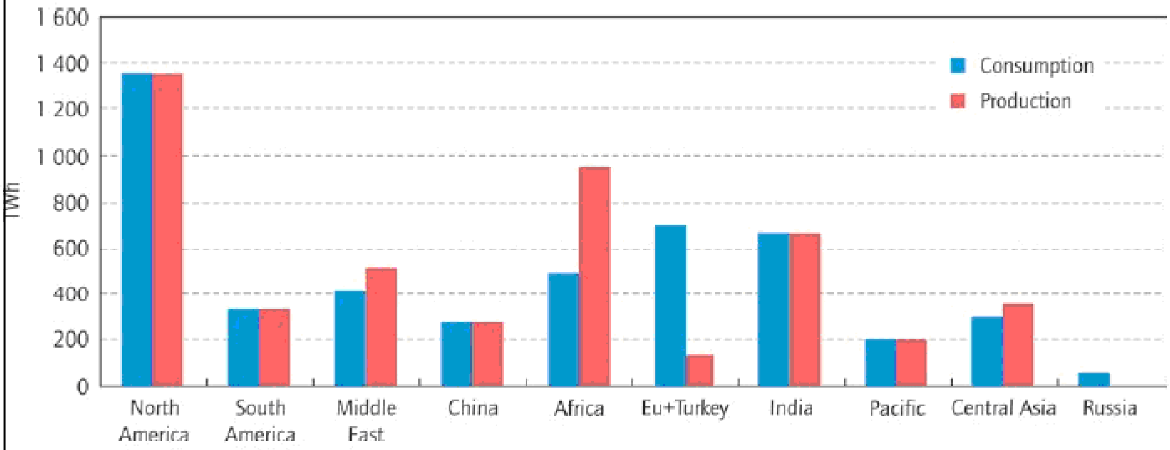
[27] Hussain Ahmad Siddiqui, "Cheaper Options of Solar Power." *Technology Times*, April 16, 2012,

Figure 30: Electricity from CSP Plants as Shares of Total Electricity Consumption

Countries	2020	2030	2040	2050
Australia, Central Asia,[4] Chile, India (Gujarat, Rajasthan), Mexico, Middle East, North Africa, Peru, South Africa, United States (Southwest)	5%	12%	30%	40%
United States (remainder)	3%	6%	15%	20%
Europe (mostly from imports), Turkey	3%	6%	10%	15%
Africa (remainder), Argentina, Brazil, India (remainder)	1%	5%	8%	15%
Indonesia (from imports)	0.5%	1.5%	3%	7%
China, Russia (from imports)	0.5%	1.5%	3%	4%

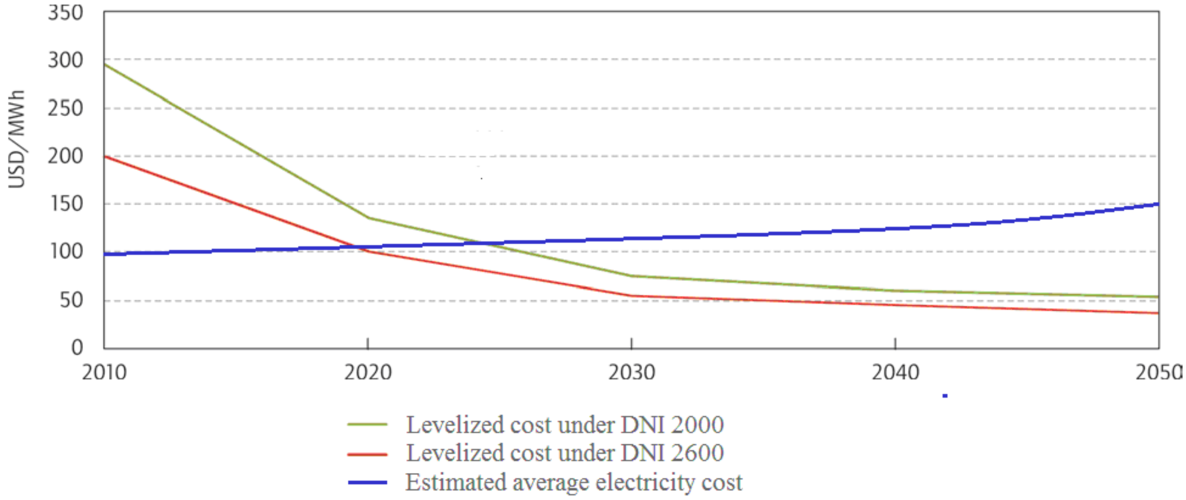
Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

Figure 31: Production and Consumption of CSP Electricity by 2050 (in TWh)



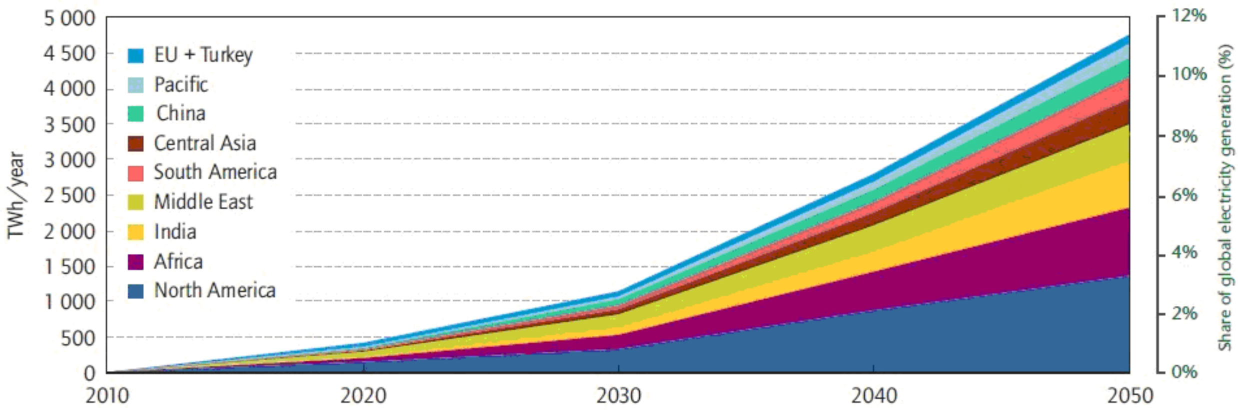
Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

Figure 32: Estimated Decrease Trend of CSP Levelized Cost Compare to the Average Electricity Price



Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

Figure 33: Growth of CSP Production by Region (TWh/y)



Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

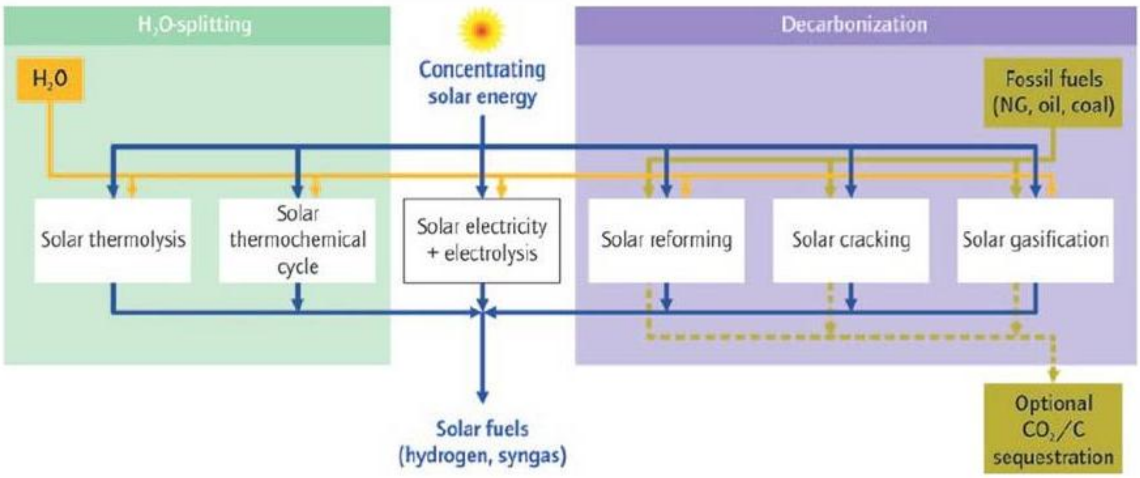
The capacity of CSP is estimated to reach 1089 GW in 2050 that accounts for about 11.3 percent of global electricity (9.6 from solar power and 1.7 percent from back up).

2.6.3 Plus Benefits

CSP generates very high temperatures that allow many important production procedures or chemical reactions occur.

Concentrating solar thermal technologies also allows the production of hydrogen (H_2), which forms the basis of fuels, or carriers, that can help store solar energy and distribute it to industry, households and transportation, substituting fossil-based fuels with low-emission solar energy. Solar towers and large dishes are capable of delivering the required amount of heat at the appropriate temperatures. Other industry applications that may integrated with CSP include solar decarbonization, solar desalination etc.

Figure 34: CSP for solar fuel production



Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

Concentrated solar power provides an alternative technology for renewable energy. It has very different mechanism from photovoltaic technologies and thus has very special features. We shall compare and discuss more of them in the next section.

3. Discussion and Comparison

3.1. Expectations for Overall Growth

Although the solar energy occupies a small fraction of the current energy mix – about 0.01 percent for whole world; developed country like the United States may have a little bit higher shares. (Shown in figure 36)

Figure 35: The Market Share of Global Solar Energy Today: About 0.01%

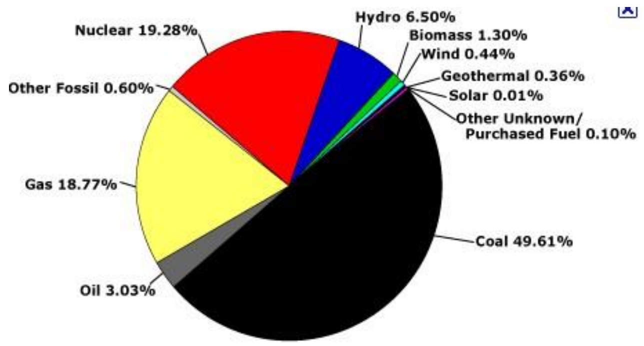
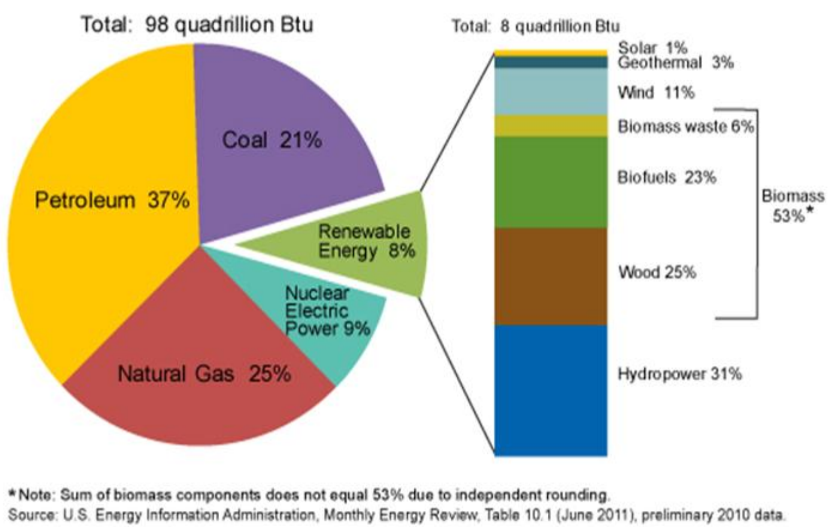
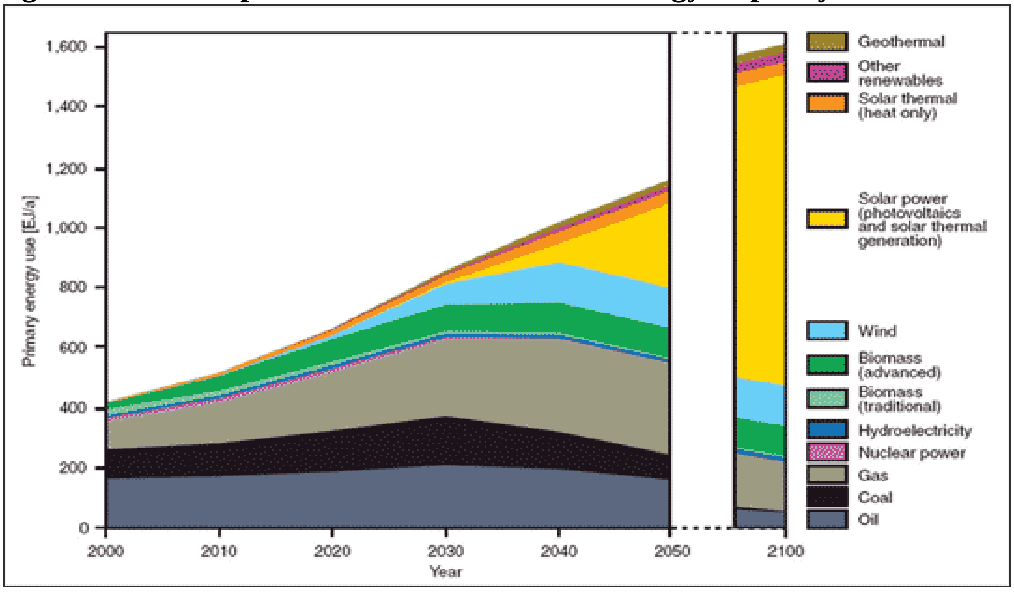


Figure 36: The Market Share of Solar Energy in USA Today



However, it is expected to have rapid and constantly growth in the future and will eventually provide for the largest share of energy in the global energy mix (in figure 37, below).

Figure 37: The Expectation Growth of Solar Energy Capacity in the Future



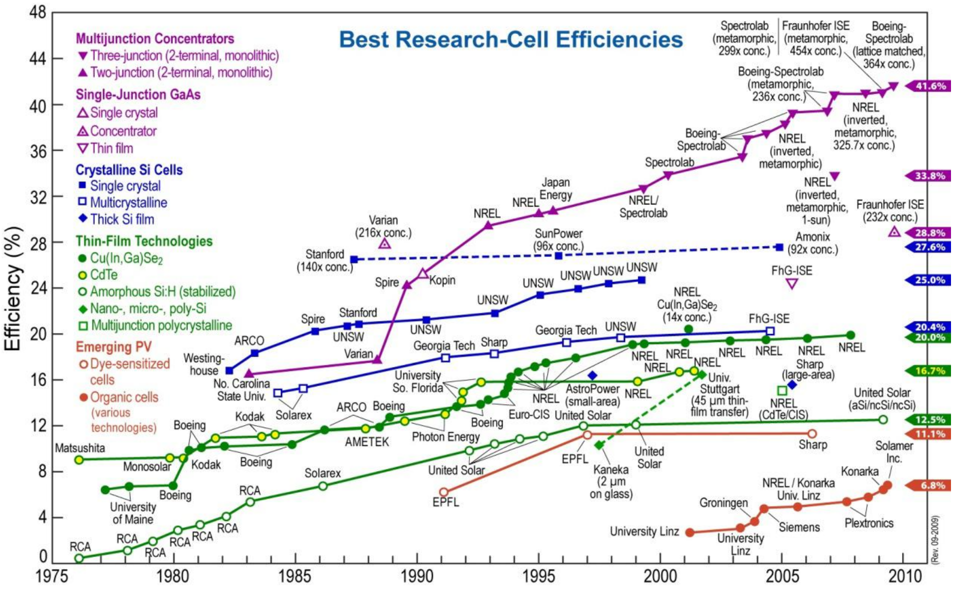
Source: German Advisory Council on Global Change

Concentrated photovoltaic systems (CPV), dye sensitized solar cells (DSSC), and solar thermoelectricity are emerging technologies and still have many technical obstacles to overcome. Some technologies like CPV are moving from pilot facilities to commercial-scale applications. Such technology is used only in smaller or prototype PV installations and, therefore, cannot yet be considered as a viable alternative to other technologies for bigger utility scale PV plant installations.[28]

However, unless there are major technical breakthroughs that mitigate existing drawbacks and lower the cost per watt output, photovoltaic solar panels and concentrated solar power will remain the two dominant forms of solar technology that can provide electricity to society and reduce carbon dioxide emissions. The shares of global electricity generation are expected to reach over 10.5 percent for photovoltaic and 9.6 percent for concentrated solar power in 2050.

[28] Quaschning, Volker, "Technical and Economical System Comparison of Photovoltaic and Concentrating Solar Thermal Power Systems Depending on Annual Global Irradiation," *Solar Energy*, 2006.

Figure 38: Efficiency Trend Recent for Research Photovoltaic Cells (PV, CPV, and DSPV are listed)



Source: S. Kurtz, Technical Report, Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry

Recent efficiency trend research on photovoltaic cells (PV, CPV, DSPV) show that they have achieved high efficiency and the remaining obstacle to enter the market involve the unstable performance and high capital cost.[29]

3.2 Photovoltaic Solar Panels and Concentrated Solar Power Systems

Photovoltaic technology is relatively mature and already has achieved a certain level market shares. However, their output is not very stable in the continuously changing weather and depends on the sun spectrum.[30]

Like photovoltaic panel systems, CSP systems have been widely commercialized and under rapid development, with 1.17GW (40GW capacity was achieved by photovoltaic sectors in 2010).[31] Analysts predict that it will reach same level of market share as photovoltaic systems in 2050. Both exceed 4000TWh/year and each will occupy more than10 percent of global electricity generation. Solar thermal have offers advantages in lower set up and energy storage system cost. Recent development of thermoelectric technology may also push the solar thermal electricity technology into a new stage.

[29] Kurtz, S., “Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry,” *Technical Report of NREL/TP-520-43208*, Revised November 2009.

[30] Research and Markets, *Crystalline Solar Photovoltaics PV Panel Systems Market Shares, Strategies, and Forecasts, Worldwide, 2011 to 2017*, August 2011,

[31] Wang, Ucilia, "The Rise of Concentrating Solar Thermal Power", *Renewable Energy World*, July 6, 2011.

Figure 39 below compares the PV and CSP energy technologies.

Figure 39 Table of Comparison between PV and CSP

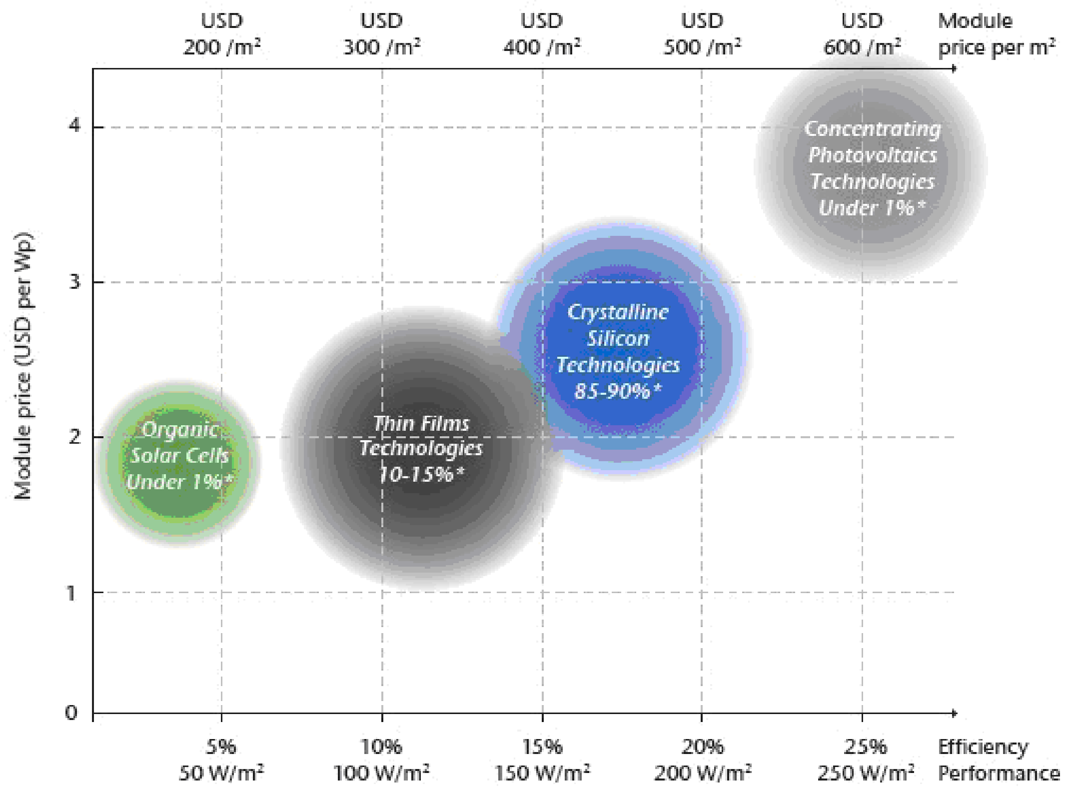
Characteristics	PV	CSP
Use	Direct and diffuse sunlight	Direct sunlight
Size	from Watt to MW	10 MW to a few hundred MW
Installation:	everywhere (roof etc.)	flat unused land
Capacity:	700 – 2000 full load hours	2000 – 7000 full load hours
Reserve capacity:	External	Internal (fossil operation)
Proofed life time:	> 20 years	> 20 years
Annual production (2004)	>25 000 GWh	> 2 500 GWh
LEC (today)	0,20 – 0,35 €/kWh	0,15 – 0,25 €/kWh

Source: Robert Pitz-Paal, Concentrating Solar Power Answers to key questions, DLR

3.2.1 Efficiency and Levelized Cost Comparison

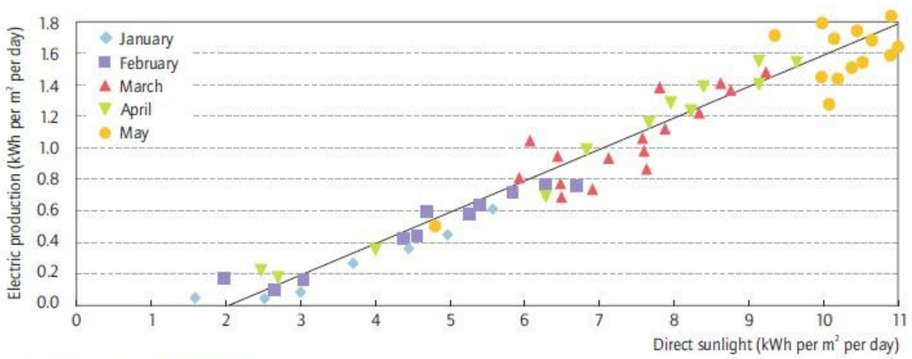
As illustrated in figures 40 and 41, CSP performance largely depends on direct sunlight. The graph is an example collected from a solar energy generating system (SEGS).

Figure 40: Performance and Price Range of different PV Technologies



Source: International Energy Agency (IEA), Technology Roadmap-Solar photovoltaic energy

Figure 41: Dependence of CSP Performance on Direct Insolation



Source: Pharabod and Philibert, 1991.[2]

Most of today's efficiency of commercialized PV panels fall in the range of 10 –15 percent and expected increased to 25percent in long terms. The efficiency of the concentrated solar power systems varies a lot due to their complexity. Heat engine technology very mature and its efficiency is determined by working temperatures; so, the efficiency of a CSP system is based on the chosen structure and the gain in efficiency may not compensate for the cost and complication of the cycle.

The efficiency for high temperature tower technology includes atmospheric air as the heat transfer fluid (tested in Germany with the Jülich solar tower project) with solid material storage. The annual system efficiency of today's solar thermal trough power plant varies between 10 – 14 percent for considered irradiation range. Solar-to-electricity efficiencies of up to about 25 percent can be delivered while solar-based Brayton cycles offer solar-to-electricity efficiency could be as high as 35 percent. CSP systems with the same size solar field (collecting area) as PV systems are expected to produce more energy each year.

The lifetime of photovoltaic technologies is expected to be 25 years and the energy payback time is approximately two (2) years. This time is expected to shrink to half a year in long terms. While the CSP systems have better performance, their lifespan of approximately 25 to 30 years with an energy payback time of just five months. In addition, CSP solar field materials can be recycled and used again for future plants.[32] The lifetime of both technologies is expected to go down in long terms.

Compared with PV systems, CSP requires higher capital investment and maintenance cost. However, initial investment costs are likely to fall steadily as plants get bigger as a function of economies of scale, competition increases, equipment mass production, technology improvements and the financial community gains confidence in CSP. In total, investment costs for CSP have the potential to be reduced by 30 percent to 40 percent in the next decade while for the solar tower investment costs could fall by 40 percent to 75 percent.

So far, the purification and refinement of silicon is still rather expensive. This raise the investment cost of PV deployment. However, if the production capability of c-silicon is hugely increased due to either mass production or technology breakthrough, the price of PV investment will drop.

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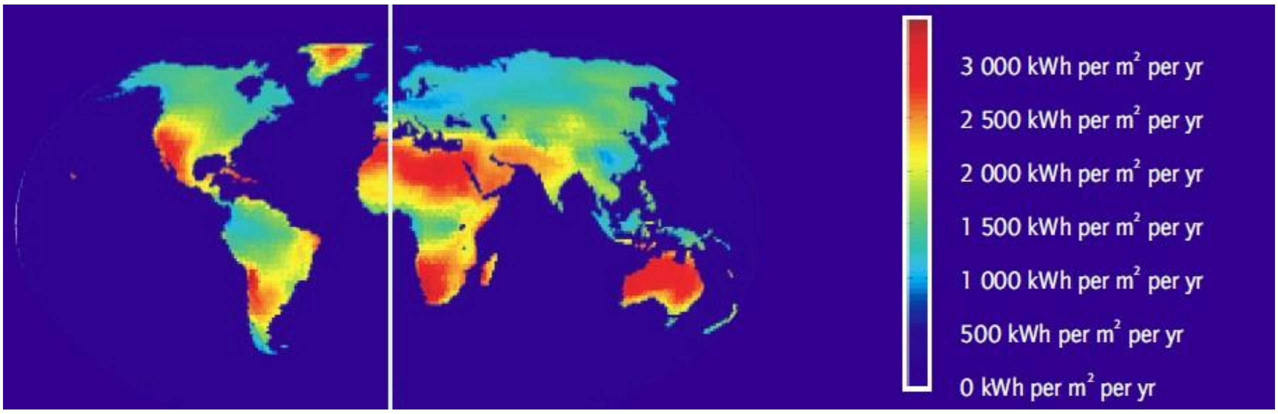
[32] Green Peace, *Concentrated Solar Thermal Power-Now!* 2005

The perspective growth of CSP industry is less likely to be impaired by a scarcity of raw materials. Large mirror areas will be required, which would only account for a few percentage points of the global production of flat glass panels. However, only molten salts for thermal storage may raise some production problems. They are used in large quantities as fertilizers for agriculture, but their use as a storage medium requires a high degree of purity.

Today, concentrated solar power plants are more economical than photovoltaic technologies at sites with annual global irradiations of more than 1300kwh/m^2 and the critical level may move to 1600 in 10 years due to the rapid technological improvement of PVs.

Figure 42: Global Insolation Map

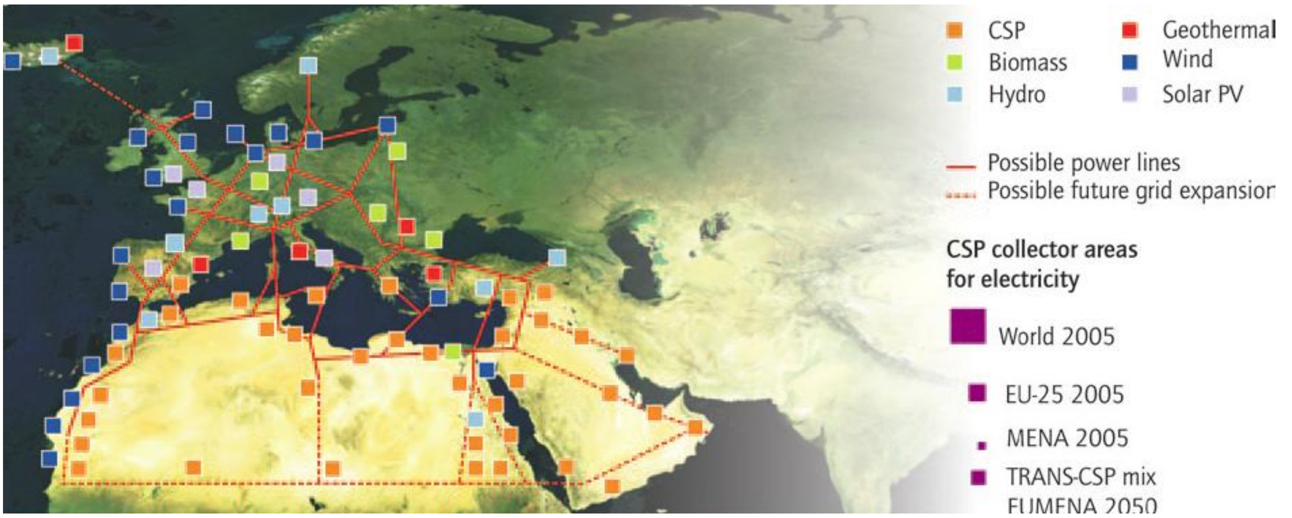


Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

Although CSP is preferable in some regions, they are abundant enough to support world demand. CSPs in southwest region of United States can satisfy the whole demand of North American. Large scale CSP energy distribution tends to be limited by the power grid capacity and location.

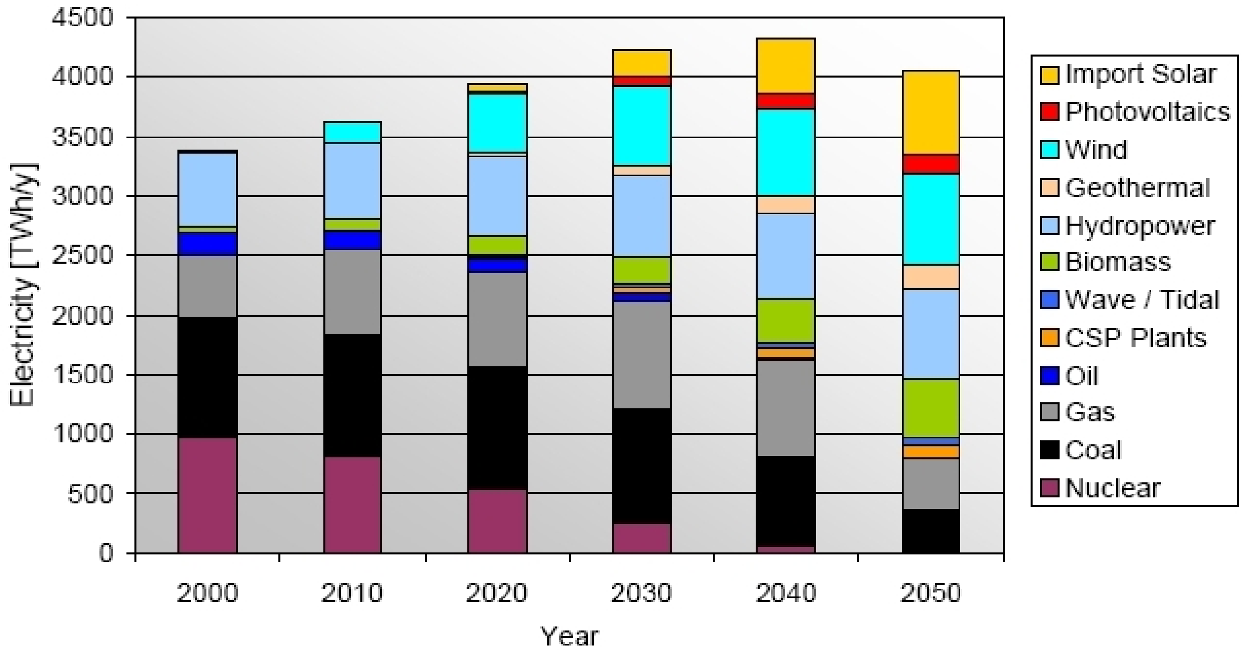
Europe has an ambitious plan to build international clean energy networks over the Mediterranean Sea. Import solar energy from North Africa is mainly from CSP which will take about more than 17 percent of its total electricity energy mix in 2050. Figures 43 and 44 illustrate European power grid capacity and demand.

Figure 43: Plan of International Energy Network Over the Mediterranean Sea



Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

Figure 44: Energy Mix Forecast of Total Electricity Consumption in European



Source: International Energy Agency (IEA), Technology Roadmap-Concentrated solar power

3.2.1. Additional Discussion

An advantage of photovoltaic panels is that they are able to collecting both direct and diffuse irradiations, so the technology can work even on cloudy days. Approximately 25 percent of the incident radiation is captured when the sun is high in the sky, depending on the amount of dust and haze in the atmosphere, There is a 1MW photovoltaic solar electricity generation station located in Merced, California whose records suggest that the panels can reach about 10 percent of peak capacity even a rainy day when the direct sunlight is almost zero.

Power grids usually prefer CSPs over PVs. Most of today's electricity energy generated is by engine that convert heat into mechanical energy first and then into electricity energy; producing alternating current (AC). Most electric devices run on AC power; however photovoltaic cells produce direct current (DC) which must be converted to alternating current using a grid tie inverter in existing distribution grids that use AC. This leads to an energy loss of 4 – 12 percent. However, a high voltage DC grid has less energy waste than an AC grid. So, there is a tradeoff consideration when deciding to construct a high voltage DC grid and apply the inverter at the consumers' end. Since CSP uses the heat engine and does not have the conversion problem, not only can it directly connect to the grid, but also CSP plants can be equipped with backup power from combustible fuels.[33]

More importantly, hen connecting the sectors to the grid, CSP is more predictable energy and able to provide network ancillary services while PVs need more control features or additional equipment. The concentration process is affected by the weather conditions. Unlike Concentrated photovoltaic (CPV) technologies; CSP has an inherent capacity to store heat energy for short periods of time for later conversion to electricity which enhances energy security. The battery used to store electricity energy generated by PV is very expensive. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sundown.

The construction process is simpler for PV than CSP systems. Utility construction of CSP systems require more land than PV systems since additional surface is required for the power

[33] Op cit

block and heat storage, both usually located in the middle of the plant area. For places where land is more costly, this factor must be considered. Furthermore, locating a utility-scale PV plant is usually easier than finding a site for a CSP plant because the PV system does not need flat land but can be installed on slopes, Unlike a CSP plant, modular utility scale PV plants, usually including several power blocks of 1MW, can be easily expanded as the demand increases. PV plants can be built in shorter time than CSP Plants, provided that materials (mainly PV panels) are available and all permits have been obtained in advance. The time required to build a 50 MWp utility-scale PV Plant is about 14 –16 months, while to build a 50 MWe CSP it would require 24 – 36 months. PV arrays are fairly easy and quick to install while CSP really look like as conventional power plant, mainly for the part relevant to the steam process part.[34]

PVs are more suitable than CSP for off-grid applications. They do not have moving parts and work quietly, which means maintenance cost will be much less. PV technology is already competitive today in selected off-grid applications.

[34] Op cit

Conclusion

We selected five of the most commonly studied and discussed solar technologies and reviewed their structure, performance, advantages and drawbacks. Concentrated photovoltaic systems, dye sensitized solar cells and solar thermoelectricity systems are emerging technologies under intensive study. In the long-term, they may occupy a significant share of the market if technical breakthroughs are achieved and the system can be competitively priced.

Emphasis has been put on photovoltaic solar panels (PV) and concentrated solar power (CSP), since they are the two most commonly deployed technologies and are expected to have rapid growth in both the short- and long-terms. We have evaluated and compared their mechanism, structure, efficiency, along with other technical details. We have also studied and compared their deployment, levelized cost and expected growth. We are still unable to predict which technologies will gain the most market share in the future; however, with the discussion in this report, we understand that each technology has its own advantages and drawbacks. Rather than saying one is better than another, what matters is which one is most suitable in a given situation.

This report is intended to provide a brief summary for those who are interested in solar energy technologies and as a reference for those who want to invest or work in this field.

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