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Diplomarbeit

Concentrating Solar Power - State of the Art, Cost Analysis and Pre-Feasibility Study for the Implementation in China

Wen Zhang

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angefertigt von
Wen Zhang
Pfahlbühlstr. 71
71384 Weinstadt
Matr. Nr. 2116552

Betreuer:	Prof. Dr.-Ing. A. Voß Dr. sc. agr. L. Eltrop, IER
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Institut für Energiewirtschaft und Rationelle Energieanwendung, Stuttgart
Prof. Dr.-Ing. A. Voß
Abteilung Systemanalyse und Erneuerbare Energien (SEE)
Dr. sc. agr. L. Eltrop

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Acronyms and Abbreviations

Term	Definition or Clarification
CSP	Concentrating solar power
$M	Millions of U.S. dollars
BOP	Balance of Plant
Crf	Capital recovery factor
CRP	Cost-reduction-potential
DNI	Direct normal irradiation
EJ	Exa joules
GWe	Gigawatts (electrical)
HCE	Heat collection element
HTF	Heat transfer fluid
ISCCS	Integrated solar combined-cycle system
kWe	Kilowatts (electrical)
kWhe	Kilowatt-hours (electrical)
LEC	Levelized energy cost
LFR	Linear Fresnel reflector
MWe	Megawatts (electrical)
MWhe	Megawatt-hours (electrical)
MWht	Megawatt-hours (thermal)
MWt	Megawatts (thermal)
NREL	National Renewable Energy Laboratories
O&M	Operation and maintenance
PV	Photovoltaic
PW	Petawatts
R&D	Research and development
S&L	Sargent & Lundy LLC
SCA	Solar collector assembly
SEGS	Solar energy generation station
STG	steam turbine and generator

1 Executive Summary

Once in the past century, mainly the western industrialized countries were responsible for a steady increase of global energy demand. Nowadays primarily the emerging and developing countries provide a sharply growth of global energy consumption, despite efficiency gains in energy use, due to their growing populations and infrastructures. And they will also increase the global energy demand in the future. In the reference scenario of the International Energy Agency (IEA), for example, the global energy demand will be increased for a further 55% by 2030 compared to 2005. /IEA 2008/ Since the current energy supply is based for the predominant part on the fossil fuels and their reserves are finite, there are today already significant price increases caused by the changes of in supply and demand.

In addition to the limited fossil resources, their intensive use has also negative effects on human and nature. Among those, the carbon dioxide emissions from fossil fuels combustion are particularly serious. To limit the global warming and the resulting consequences to a manageable and acceptable level (2C target), according to climate experts, the emission of harmful greenhouse gases must be reduced of at least 50% by the middle of the century.

Since the combustion of fossil fuels in conventional power plants accounts for a large share of anthropogenic greenhouse gas emissions, a significant emission reduction must be taken place in this field. Clean energy generation offers enormous potential to reduce CO_2 emissions and the possibility of sustainable energy supply. Within the renewable energy sources, solar energy has besides the wind and hydropower the especially great potential.

Concentrating solar power (CSP) technology uses direct solar radiation to generate power. The CSP plants concentrate sunlight to raise the temperature of a transfer fluid in the receiver and run turbines to generate electricity. Through the implementation of thermal storage or fossil fuels fired backup, CSP plants can generate electricity according to the demand and thus replace the conventional power plants. While CSP are useful only in locations where the annual direct solar radiation over 1800 kWh/m^2, there is also the possibility of the electricity transmission. The solar-generated electricity can be transmitted from these locations to the load centers with high-voltage transmission lines, so that CSP-produced electricity could be available in the future in almost all countries. To date, the four major approaches to CSP technology are the parabolic trough, linear Fresnel reflector, solar tower and dish-Stirling systems.

Since the first commercial CSP plant has been operated in California, USA, there is now already over 660MW CSP plants in operation worldwide. The CSP industry will keep a rapid growth in the near future, approximately 1.2GW plants are under construction as of April 2009 and another 13.9GW plants with varied CSP technologies are announced globally by 2014. The most plants of those have been or will be constructed in the USA and Spain. The other Countries, which have or will have CSP plants, are Algeria, China, Germany, Israel, Morocco, UAE, etc. /REW 2009/

Compared with conventional technologies the cost of electricity generation through CSP is still much higher. However, through technology development, the mass production of key components and scale-up factors, it will have a significant cost reduction. It can be assumed that CSP plants are already able to compete directly with fossil fuel power plants in the next 10-15 years.

With the rapid economic growth in China, the energy consumption has increased sharply in the past 20 years. And in the future, the energy demand of China will be even larger. In the Westchina and Nordchina, there are abundant solar radition resouces for the large-scale implementation of CSP technology. It is estimated that solar power in almost 2% of desert area (ca. 23,960 km^2) in China was able to satisfy all of the Chinese electricity consumption in 2008 (3,450 billion kWh /NBSC 2009/). After the promulgation of the renewable energy law (REL) in China in 2006, a long term target has been set up that 1000MW energy generation capacity for CSP plants will be reached by 2020. Due to all these reasons, the CSP deployment for electricity generation in China will achieve a rapid and sustained growth

This study provides a summary assessment of four major concentrating solar power (CSP) technologies and a review of major projects built mainly in USA and Spain. The cost of these CSP projects is compared and analyzed. Based on these information, a preliminary feasibility study of a CSP project in China is prepared to indicate the enormous market potential of CSP technology.

2 CSP Technology State of the Art

2.1 Solar Resources for CSP

Within the sun, thermonuclear reactions occur violently and continuously, which is a source of energy generation in the sun. With the mass-energy conversion through E=mc2 a tremendous amount of energy is radiated from the sun into space. Approximately 3.8*1020 MW of radiation per second is released and one out of 22 billionths of it reaches the upper atmosphere of the earth. Approximately 30% of this is reflected back into space while the rest is absorbed by clouds, oceans and land masses. About half of the insolated solar energy of approximately 89 petawatts (PW) reaches the earth's surface. /NASA 2009/

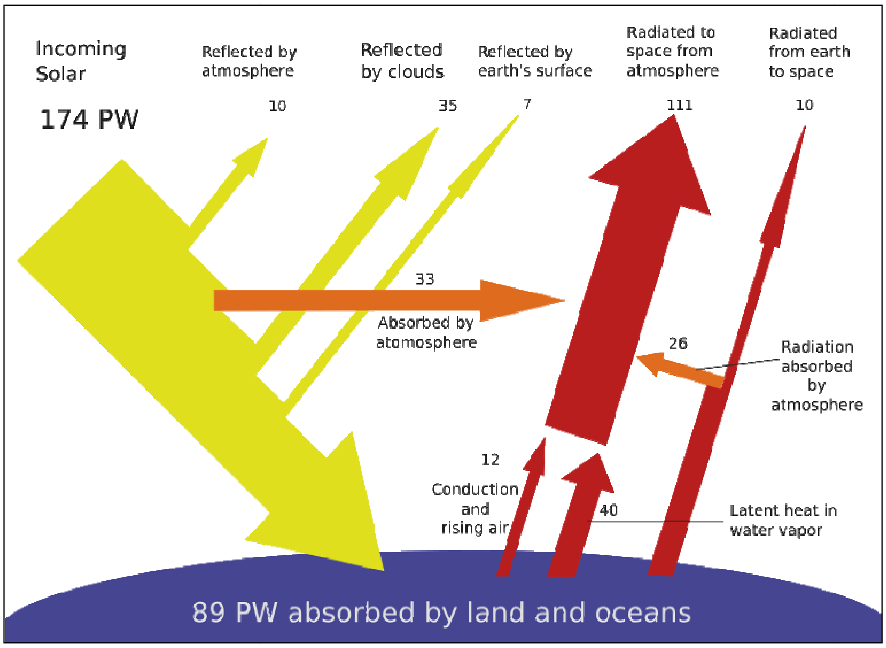

Figure 2-1: Earth's solar energy budget /Mierlo 2007/

According to International Energy Outlook 2009 from the EIA, in 2006, the total worldwide energy consumption was approximately 500 exa joules (EJ)
(= 5* 1020 J) while the annual solar energy available from the sun is approximately 3,850,000 EJ. Thus the sun provides the same energy in one hour as the world population uses in one year. However solar energy provides less than 1% of the world's total commercial energy because of its higher energy generation costs compared to conventional fuels.

Solar energy can be used in different ways. Solar heat can be used directly in the form of thermal energy in the residential sector and in industrial processes for water heating, space heating, space cooling and process heat generation. Solar energy can also produce power using photovoltaic (PV), CSP and various experimental technologies. PV has mainly been used in the small and medium-sized applications with the PV cells while the CSP plants are used in much larger-scale generation.

To become feasible and cost-effective, CSP systems require a high level of direct normal irradiation (DNI[1]) at the sites. This is an important factor in the economics of a solar plant and can be measured by satellite. **Figure 2-2** below provides one such attempt to map suitable regions worldwide for the implementation of CSP technology.

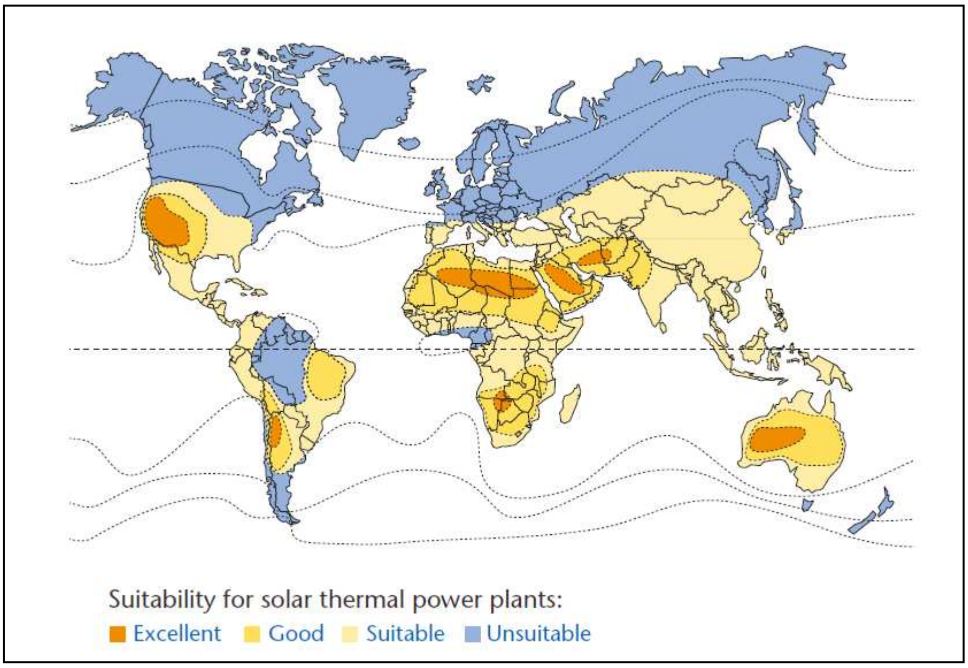

Figure 2-2: Globally solar resources distribution /SS 2006/

Suitable sites should offer at least 2,000 kilowatt hours (kWh) of electricity per m² of sunlight annually, while the best sites will offer greater than 2,500kWh/m² annually. Suitable locations are where the climate and vegetation do not offer high levels of atmospheric humidity such as, steppes, bush, savannahs, semi-deserts and true deserts. And they are ideally located within ±40° of latitude. Among the most promising areas of the world for CSP are therefore the South-Western United States, Central and South America, Africa, the Middle East, the Mediterranean countries of Europe, Iran, Pakistan and the desert regions of India, and the former Soviet Union, China and Australia.

Using CSP technology, one square kilometer of land in the obove-mentioned regions is enough to generate as much as 100 to 200 Gigawatt-hours (GWh) of solar electricity per year. This is equivalent to the annual energy-production of a 50MW conventional coal or gas-fired power plant.

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[1] DNI is the direct normal radiation on a surface which is always perpendicular to the direction of the direct radiation from the sun.

2.2 CSP Technology

CSP system produces electricity by converting solar energy into high temperature heat with reflectors and receivers. The heat is then used to produce electricity through a conventional turbine-generator system. Currently, there are four major CSP technologies, the parabolic trough systems, linear Fresnel reflector systems, solar tower systems and dish systems. The further research is being undertaken examining various CSP technologies for larger generation capabilities and higher thermodynamic efficiencies.

Parabolic trough systems

A parabolic trough system consists of trough-shaped mirror reflectors to concentrate the solar radiation on to receiver tubes containing thermal transfer fluid which is then heated to produce steam. This is the most developed, economically viable and widely accepted of the CSP technologies. Currently, most of the CSP projects that are under construction employ this technology.

Linear Fresnel reflector systems

A linear Fresnel reflector system uses an array of flat or slightly curved reflectors which reflect solar rays and concentrate them onto an elevated inverted linear absorber tube for heating the fluids and converting the solar energy into electricity. Spain is implementing a pilot project using this technology which is still in the nascent stage. Currently, Fresnel systems are less efficient but also less costly than other CSP technologies.

Solar tower systems (Central receiver systems)

A solar tower system employs an array of large individually tracked plain mirrors (heliostats) to concentrate solar radiation on to a central receiver on top of a tower to produce steam for electricity generation. Currently, CSP plants in Spain such as PS10 and PS20 are implementing central receiver system technology.

Dish-Stirling systems

Dish-Stirling systems in contrast with the other approaches are comparatively smaller units consisting of a dish-shaped concentrator that reflects solar radiation onto a receiver mounted at a focal point that heats thermal fluid for power generation. This technology has the advantage of functioning as a stand-alone system and can provide decentralized power. Currently, small CSP projects are planned in USA, Europe and Australia using this technology.

Regarding their technical features, the conversion path of all the concentrating solar power technologies rely on four basic elements: the concentrator, receiver, transport-storage system, and power conversion system (See figure below). The Fossil- fired backup system is an alternative component of CSP plants.

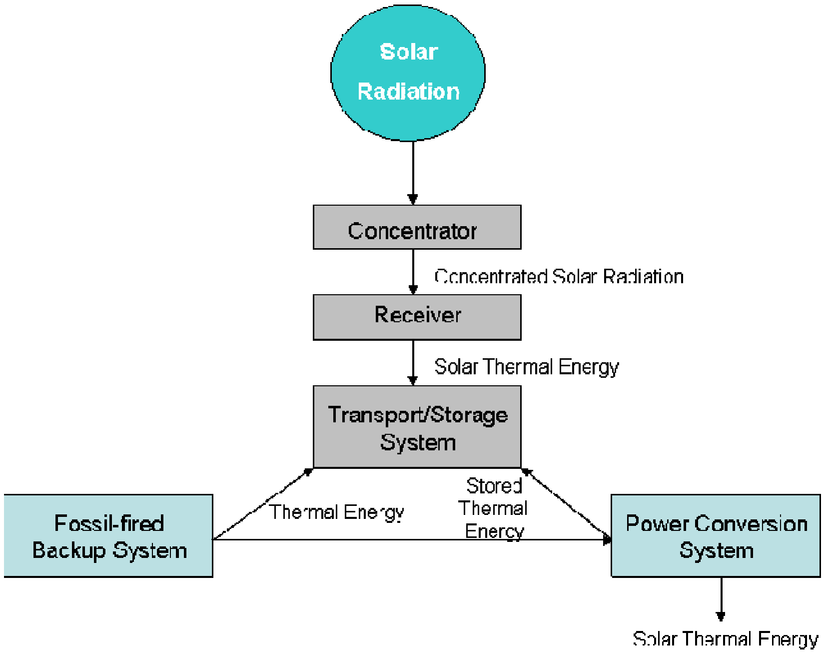


Figure 2-3: Energy conversion path in CSP plant

The concentrator captures and concentrates the solar radiation, which is then delivered to the receiver. The receiver absorbs the concentrated sunlight and transfers its heat to a working fluid. The transport-storage system passes the fluid from the receiver to the power-conversion system; in some solar-thermal plants a portion of the thermal energy is stored for later use. Several solar thermal power conversion systems have been successfully demonstrated including the Rankine, Brayton, combined or Stirling cycles. Four emerging solar thermal power generation concepts - the parabolic trough; the solar power tower; the parabolic dish and the linear Fresnel reflector system - will be described in the Section Current Technology Status below.

2.2.1 Parabolic Trough Systems

In the parabolic trough systems, a solar collector concentrates the sunlight with the curved mirrors and reflects it onto a heat absorber receiver which is located in the focal line of the collector. The receiver consists of a special tube through which heat transfer fluid is warmed up to about 400°C. Then the heat transfer fluid is used to boil water in a conventional steam generator to produce electricity.

As shown in the picture below, the reflector, absorber tube (receiver) and the solar field piping (heat transfer fluid circuit) are the main components of a parabolic trough plant. These are discussed in the following section.

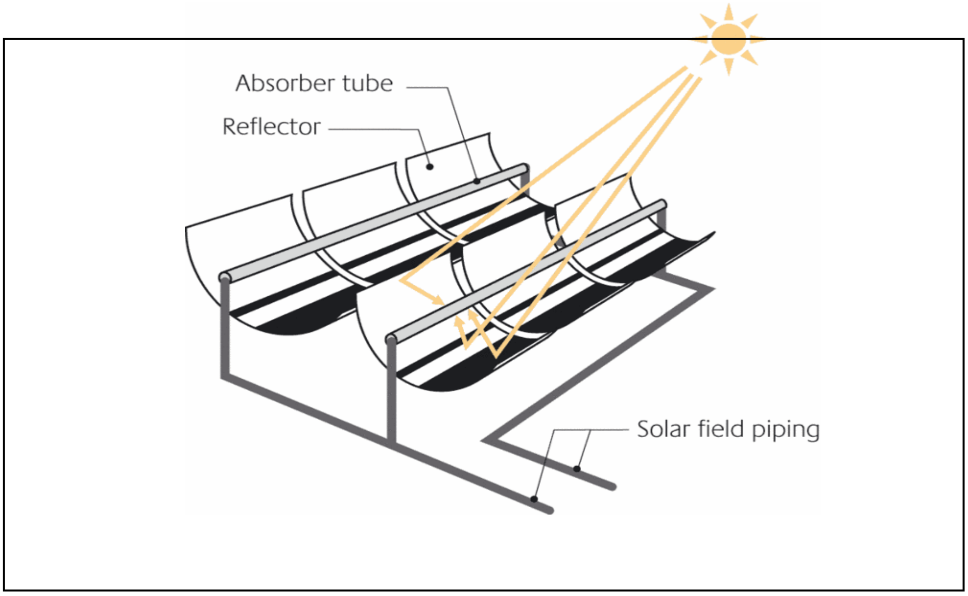


Figure 2-4: Component parts of solar field for parabolic trough power plant /Renewables 2009/

2.2.1.1 Parabolic Reflector

The parabolic reflector consists of one surface with a reflecting layer, for exemple metal foil or thin glass mirrors, or with several curved mirror segments. In commercial projects, the second variant is more usually applied. Reflectors are mounted on a steel framework and track the sun using a single axis system following the longitudinal axis.

Figure 2-5: Reflector of parabolic trough power plant /SullivanS 2009/

To achieve high reflectivity over the mean value of 94% the mirrors typically utilize back-silvered white low iron glass with the weatherproof attributes. Through regular cleaning, this high reflectivity of the mirror segments can be maintained. /Kaltschmitt et al. 2007/

In the projects SEGS in the USA and Andasol I in Spain mirrors from the company FLAGSOL have been used. The reflectors are made up of a number of sub modules each with a typical length of 12m. The type 100 has an overall length of 100m and 8 sub modules. The larger parabolic trough reflector Skal-ET150 has a length of 150m and an aperture width of 5.77 m and consists of 12 sub modules. /Flagsol 2008/

The reflectors are tracked with the sun along their long axis by drives. The driving system of SKAL-ET reflector consists of two hydraulic cylinders that are installed on the drive pylon.

2.2.1.2 Heat Absorber

The horizontal absorber tubes are installed in the focal line of the parabolic trough reflectors.

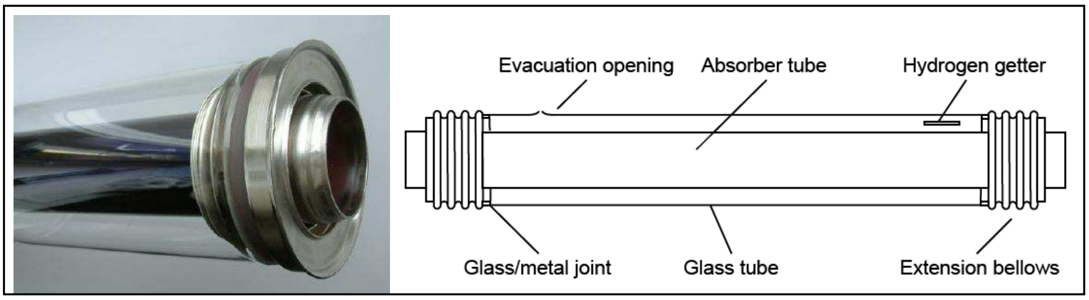


Figure 2-6: Receiver of a parabolic trough plant /SS 2006/

As shown above, in order to minimize the heat losses, steel absorber tubes with selective absorbing materials are enclosed in an evacuated glass tube. This vacuum design serves also to protect the selective coating. Nowadays, the solar absorption of such selective coatings is above 95%, and at a temperature of 400°C emissivity is below 14 %. At the surface of the glass tubes, there is a layer of anti reflective coating to collect more solar radiation. /SS 2006/

2.2.1.3 Heat Transfer Fluid (HTF)

Currently the heat transfer medium used in the absorber is synthetic thermal oil. Because of its limited thermal stability, the working temperature is limited to a maximum of approximately 400°C. This temperature requires that the oil is kept at a pressure of 12 to 16bar. Because of that, absorber tubes as well as heat exchangers must have a pressure-resistant design, and this leads to relatively high cost.

Molten salt is proposed as an alternative for the heat transfer medium. The advantages of molten salt in comparison with thermal oil are characterized by:

- lower specific costs
- higher heat capacity
- potentially higher working temperature

However, with the higher melting temperature and higher viscosity it requires more heating and pumping power,

Furthermore，research into the direct steam generation design has lead to greater cost savings and potential for greater efficiency. As the only working medium, steam has the advantage of a higher working temperature while there are no requirements for a secondary heat transfer fluid loop and heat exchangers.

2.2.2 Linear Fresnel Reflector System

A linear Fresnel reflector (LFR) power plant collects sunlight with individual long, narrow mirror segments and several of the mirror segments share one linear receiver above them. On top of the receiver, there is another long mirror to focus the light to the receiver.

The LFR system uses one axis tracking. This is similar to the trough design but different compared to the solar tower and with dual-axis. The structure of LFR system is simpler than the trough and dish-Stirling design, because the narrow flat mirrors are used instead of parabolic formed mirrors and these mirrors do not support the receiver and the receiver is stationary. As a result the cost can be reduced and the collector could have a longer lifetime. Each mirror will be adjusted by the small motors and they could also reflect sunlight to different receivers at different times of day. This design provides the possibility of more mirrors installed on the available land area.

The Figure below shows a typical linear Fresnel reflector system.

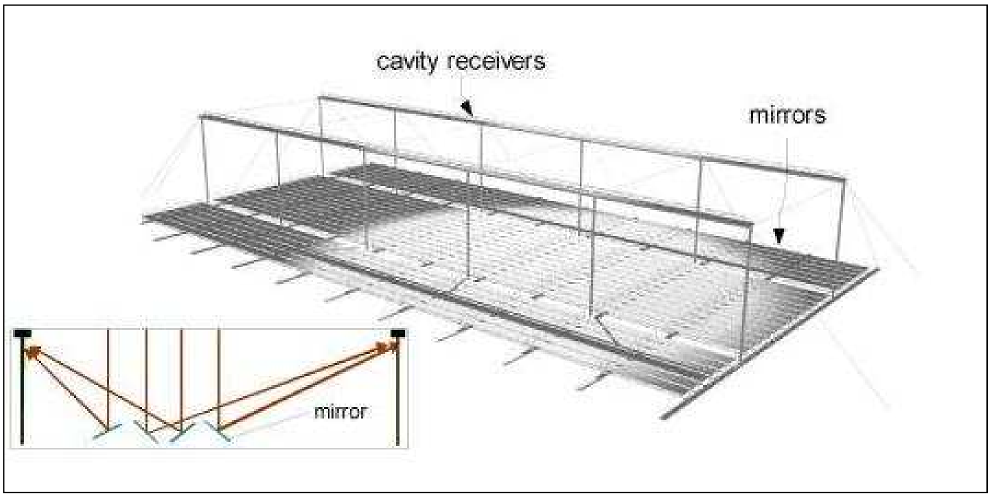


Figure 2-7: Component parts of the solar filed for linear Fresnel reflector power plant /Pye 2009/

2.2.2.1 Fresnel Reflector

The Fresnel reflector uses low-iron glass. The individual mirror segments are mounted on the steel frame at the same height and they can be roted through 360° driving by a solar tracking system. During the strong wind or hailstrom the mirrors can turn upside down to avoid damage to equipment. The lower width of the Fresnel reflectors will be also reduced their wind loads. The following figure shows the reflector structure of LFR system.

Figure 2-8: Fresnel reflectors of a LFR power plant /Greenpacks 2008/

Due to their simpler structure, Fresnel reflectors have a lower concentrations and a lower optical efficiency than parabolic trough reflectors, though individually micro-adjustment of each reflectors can compensate for such disadvantages. However, the sophisticated tracking system and the required large number of drives lead to high costs.

2.2.2.2 Absorber

Figure 2-9: Absorbers of a LFR power plant /Pye 2008/

For the linear Fresnel system absorber, tube groups are used due to their wider focal line. The cross sections of the absorbers are shown above. Pipes are mounted inside the trapezoidal cavity and the bottom of the cavity is covered with a transparent cover, which is intended to reduce convective losses by trapping a layer of hot air next to the hot steam pipes. This cover is commonly made with low-iron glass because the angled glass reduces reflective losses of solar radiation and low-iron glass has improved optical properties compared to standard grade window glass. This is the so-called secondary concentrator. The following figure illustrates the mechanisms of secondary reflection.

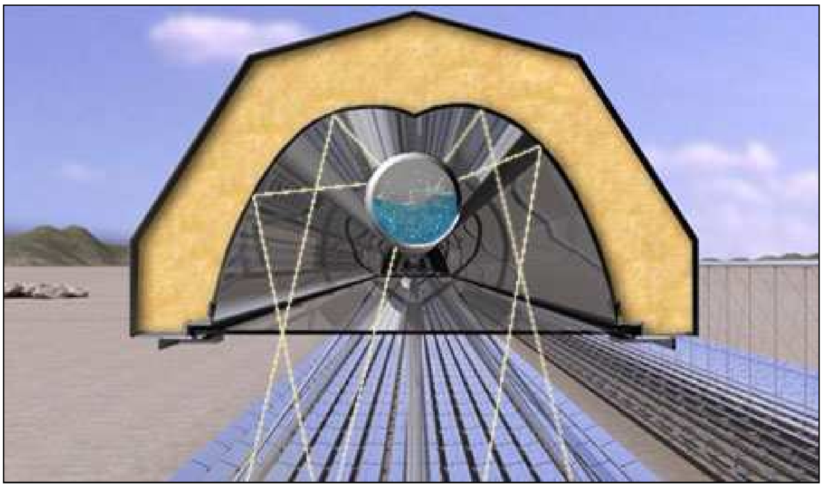


Figure 2-10: Receiver used in linear Fresnel reflector system NOVA-1 /Meyer 2009/

2.2.3 Solar Tower Systems

At a solar tower plant the solar radiation is collected by mirrors called heliostats with a dual axis tracking system, and are controlled so that they gather the incident solar light and reflect it on top of a tower, where the solar energy is absorbed by a receiver. The receiver absorbs the concentrated solar energy and then passes it to the heat transfer fluid which flows through the receiver. According to different types of heat transfer such as fluid, water/ steam, molten salt, liquid sodium and air, the temperature of the receiver can reach from 500°C to over 1000°C. The Figure below shows the basic layout of a solar power tower plant.

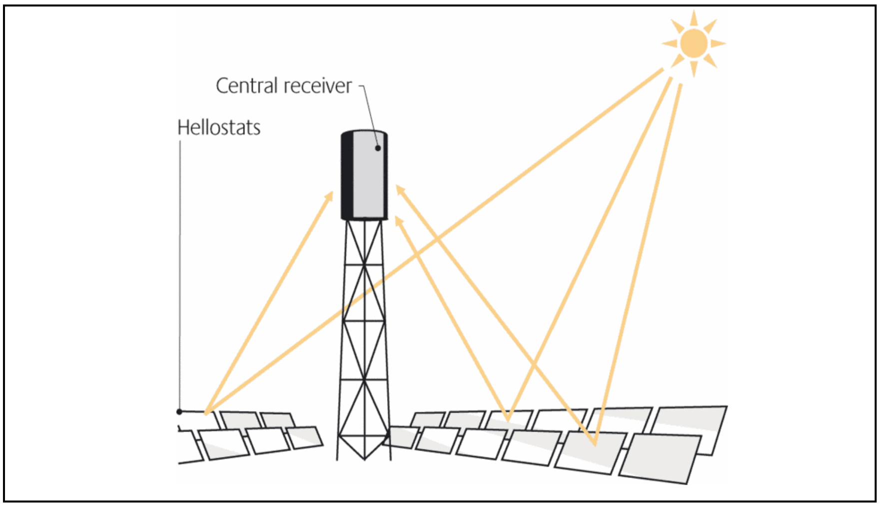


Figure 2-11: Basic layout scheme of a solar power tower plant /Sullivan 2009/

2.2.3.1 Heliostat

The heliostats field consists of a large number of individual heliostats (from several hundreds to thousands). Heliostats are mirrors that are managed by a dual axis optical solar tracking system. The analog solar tracking circuit controls two mechanical actuators that move a mirror plane on two axes. The mirror plane will reflect the sunlight to a stationary target during the day and then return to a preset morning position after sunset. The tracking electronics are capable of tracking the sun with sub degree accuracy.

Figure 2-12: Dual axis optical solar tracking /Heliotrack 2009/

A heliostat consists of:

- a sunlight reflector,
- a tracking unit with the drive motor,
- the foundation
- the electronic control system

The heliostats represent a heavy weight of the total cost of solar tower power plant. Therefore, great effort is expended on the development of heliostats with good optical quality, high reliability, with a long life and low area-specific costs. Due to economic considerations, large heliostats with areas from 100 to 200 m² are applied in the current projects. Two main types of the heliostats are available these being the faceted glass/metal heliostats and membrane heliostats and are described below. /Kaltschmitt et al. 2007/

Faceted glass/metal heliostats

Faceted glass/metal heliostats typically consist of several quadrate reflecting facets each with sizes between 2 and 4m². These reflecting facets are mounted on a steel framework. Each heliostat has an individual drive to track the sun and concentrate the solar energy onto the receiver, so that each of them has a different orientation. This leads to a high focusing accuracy but also high costs. Currently wide faceted glass/metal heliostats are more usually utilized in commercial solar tower plants. The glass/metal heliostat illustrated in the figure below is an example of this.

Figure 2-13: Faceted glass/metal heliostats /Thomas 2000/

This concentrator width of the heliostat amounts to 12.08m and concentrator height of the heliostat amounts to 10.06m. The size of the individual facets is 3 by 1.1m each. The total weight without foundation is 6.5t. /Thomas 2000/

Membrane heliostats

In order to decrease the weight of the heliostat and thus reduce the material and drive costs, stretched membrane heliostats have been developed. Taut Plastic foils or metal membranes are mounted on a circular frame to generate tension in the membrane. And thin glass mirrors are covered out of the membrane to keep a long lifetime of heliostats. This smooth surface can provide a high efficiency of solar reflection. The membrane can be deformed through changing the pressure inside the heliostat and than the focus length can be adjusted.

Figure 2-14: Membrane heliostats /Thomas 2000/

The figure above shows an example of a metal membrane heliostat. This heliostat is installed on a steel framework with six wheels for vertical rotation. The heliostat has a diameter of 14m and a concentrator area of 150m². Its weight excluding the foundation is approximately 7.5t. The drive mechanisms of this heliostat decline the cost of power plant. /Thomas 2000/

2.2.3.2 Tower and Receiver

The only receiver of central solar tower power plant is located on the top of the tower. As support of the receiver the tower is commonly with a height of 80 to 100m and made of concrete or steel lattices. A higher tower is preferable for bigger and denser heliostats field but it should to avoid the shades or objects that block the sun. At the same time, the technical factors, e.g. tracking precision and the economic factors, e.g. tower costs should also be considered to determine the height of the tower.

The Receiver of solar tower power plant transforms the solar energy collected by heliostats into the thermal energy of working fluid. This working fluid could be commonly water/steam and molten salts. In further research air is applied for use in high temperature power towers. Water/steam receivers are the most used receiver in solar tower power plants, e.g. in the early power plant 10MW Solar One in the USA and in the world largest solar tower PS20 in Spain. Meanwhile the molten salt receiver and open volumetric air receiver are applied in some demonstrate plants.

In the following section, the open volumetric air receiver， the molten salt receiver and the water/steam receiver are described.

Open volumetric air receiver

At the site of the open volumetric air receiver ambient air is drawn through an absorber, which has been heated by concentrated solar radiation at 600 to 800°C. As absorber material, steel wire or porous ceramics are applied. Due to the porous absorber structure the receiver is characterized principally by low thermal losses, because the external surface area of the absorber is much smaller than the porous heat transfer area (volumetric effect). Other advantages of the volumetric receiver consist of:

- good manageability of heat transfer medium air,
- relatively simple structure,
- sufficiently high outlet temperature,
- the low thermal inertia and
- short start-up time.

A clear disadvantage when compared to other receivers is the low specific heat capacity of heat transfer medium air, which leads to a high flow rate on the one hand and the other no energy-efficient direct storage of hot air.

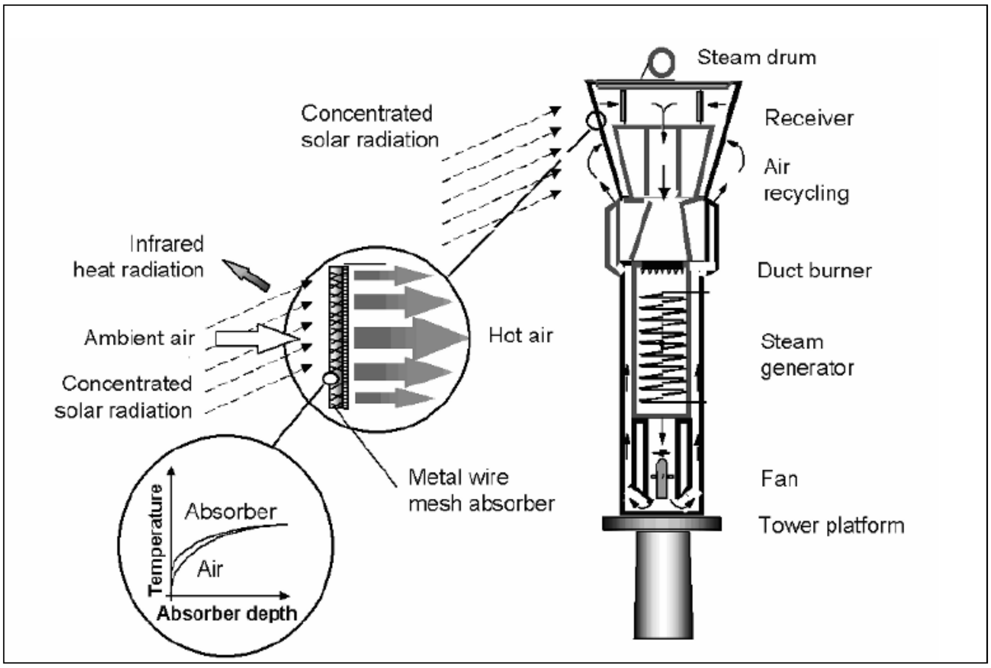


Figure 2-15: The functional principle of the Phoebus receiver /Kaltschmitt et al. 2007/

The figure above shows the functional principle of a typical open volumetric air receiver Phoebus receiver. The Phoebus receiver with metallic wire absorber was developed by FDE, Phoebus consortium and constructed and tested in the context of the TSA project. /FDE 1994/ /Haeger 1994/ This receiver has the shape of a hexagonal frustum of pyramid with downward-decreasing diameter so that the outer surfaces of the absorber incline towards the heliostat field.

Compared to other heat transfer mediums air has many advantages. Air is easily available, non-toxic, non-corrosive and thus easy to handle. Furthermore, air is not subject to restrictions of temperature in principle and keeps the single phase at the required temperature range. The major disadvantage of air is very low specific heat capacity. This requires first large volume flow and seconds a separate storage medium.

Molten salt receiver

The closed tube receiver system is currently the favorite molten salt receiver system. In the closed tube receivers the molten salt is pumped through the black colored receiver tubes and heated there. The alternative, open tube receiver concept is the salt film receiver. These are directly thin films of salt, or stainless steel plates covered by the salt film and they are heated by the concentrated solar radiation. This simplified structure is expected to inexpensive receiver. The figure below shows the closed tube receivers using molten salt as a heat transfer medium.

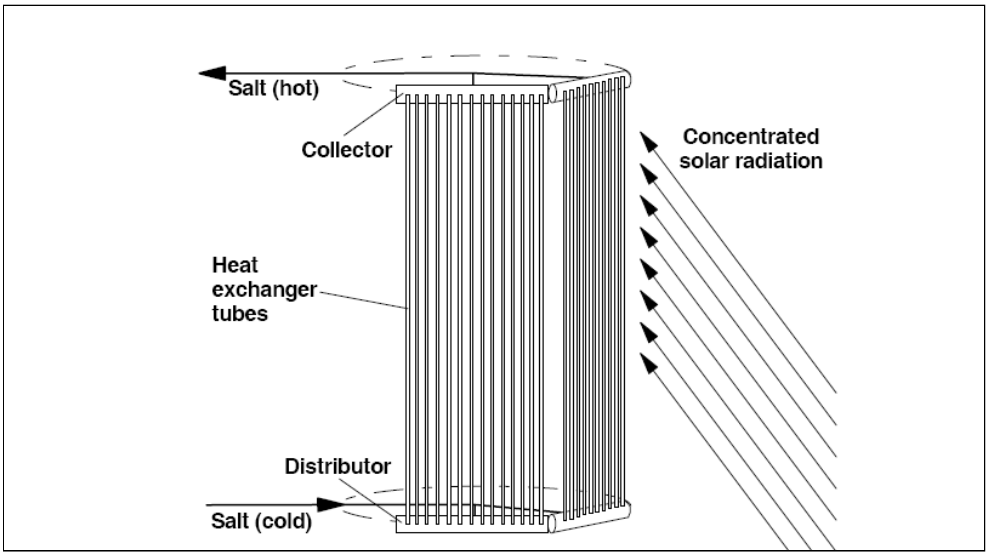


Figure 2-16: Closed Vertical tube receivers with molten salt /Kaltschmitt et al. 2007/

Molten salt consists of sodium or potassium nitrate (NaNO3, KNO3). In contrast to air, the molten salt has a much higher heat capacity and can be directly used as heat storage medium. As a result, the design cost of heat storage structure will be greatly reduced. Another advantage of the molten salt is that the heat transfer medium exists always in the liquid phase and thus no two-phase flows occur. Since the salt isn't allowed to crystallize, represents the permanent liquid phase also a disadvantage that, all plant parts filled with salt (tanks, pipes, and valves) must be heated at night during operation breaks (melting point 120 to 140°C). It increases the operating cost of the power plant. Another drawback to the molten salts is their high corrosivity.

The development of molten salt receivers was driven primarily by American research institutions as well as companies (Boeing, Bechtel pursued, etc) and its operation was successfully tested in the 10MW demonstrate plant Solar Two in 1996, California. Currently the 15MW solar tower power plant Solar Tres, which is based on the Solar Two concept, is under construction in Spain

Water/steam receiver

The structure of the water/steam receiver is essentially consistent with the previously described molten salt tube receiver. Instead of the molten salt water is evaporated in the receiver tube and possibly overheated so that the steam turbine system is directly supplied with the saturated steam.

On a number of demonstration projects of solar power tower using water/steam receiver in the 1980s showed that direct steam generation in the receiver had numerous problems. Most of them were provided by the two-phase flows (water/steam) and the related difficulties in heat transfer and material fatigue. In recent years the Spanish company Abengoa has developed the technical mature saturated steam receiver and it is applied in the solar tower PS10. A storage tank of saturated steam was integrated into the system in order to ensure the continuous operation during the time with insufficient or without solar radiation.

2.2.4 Dish-Stirling Systems

In a solar dish-Stirling system, the reflective surface which is dish-shaped collects and reflects the solar radiation onto a receiver, which absorbs the solar energy and transfers it to a Stirling engine. Then the mechanical power from the engine operates a generator to produce electricity. The main components of a solar dish plant are the parabolic reflector, receiver, and a Stirling motor as a thermal engine with attached generator. As with the solar power tower system the dish concentrator tracks the sun with a dual axes tracking system. The figure below illustrates the basic layout schema of a dish-Stirling plant.

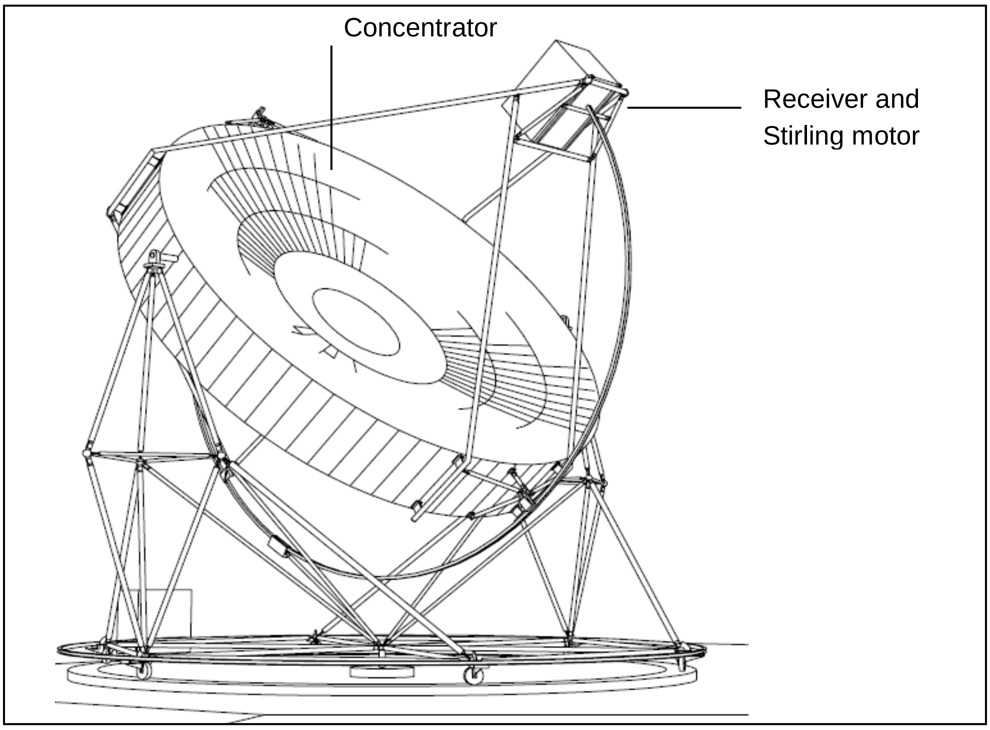


Figure 2-17: Basic scheme of a dish-Stirling plant /Bergermann et al. 1996/

2.2.4.1 Parabolic Reflector (dish)

The parabolic reflector (dish) concentrates sunlight onto a focal point. The size of this spot is dependent on the concentrator precision, condition of the surface and focal distance. For the operation of the Stirling engine high temperatures are required. Therefore a large point-focus concentrator with an axial symmetrical shape is implemented in this system. Currently dish reflectors achieve concentration ratios of between 1,500 and 4,000 and their common maximum diameters are 25m. /Liao; Long 2008/ There are two main types of dish concentrator, the facetted paraboloids and full-surface paraboloids.

2.2.4.2 Receiver

The receiver transfers the solar energy into technically useful heat. Therefore, the highest temperature of the dish-Stirling system is at the receiver. For the direct-heating systems the common operational temperature currently varies between 600 and 800°C and the pressure between 40 and 200bar. The tube receiver and the heat pipe receiver are the two main receiver types of the dish-Stirling system.

2.3 Solar Power Conversion Systems

Apart from the solar power collection systems, another major component of the concentrating solar power plant is the power conversion systems that convert the heat into electricity. Nowadays, different technologies are mainly used in the CSP plants such as the:

- Rankine Cycle system
- Integrated Solar Combined Cycle System (ISCCS) and other hybrid systems
- Stirling motor

The Rankine Cycle is a mature solar only technology that provides a high solar contribution. Meanwhile the ISCCS with a gas-fired hybrid facility offers a low cost alternative for the solar powered electricity generation. The Stirling motor is only implemented in the solar dish-Stirling system.

2.3.1 Rankine Cycle Systems

In a Rankine-cycle plant a steam-based power plant with solar energy which is implemented as the source of heat. The system is a typical Rankine cycle. The hot collector heat transfer fluid transfers its heat in the heat exchanger to the water/steam. The steam drives the turbine to produce electricity. The spent steam is condensed into water in the condenser. The water is then reheated in the heat exchanger and the cycle repeats.

Due to the seasonal and daily change in solar radiation, a Rankine-cycle without thermal storage system can only operate at full load with 25% capacity factor for about 2400 hours annually. In the majority of cases, it is meaningful to integrate a fossil-fuel heater to ensure the system can operate at full load for longer time. Back-up fuels such as coal, oil, naphtha and natural gas may be used.

Rankine-cycle systems whether powered by solar energy or fossil fuel offer relatively low efficiencies. The conversion efficiency of heat to electricity amounts to approximately 40%. If the conversion from solar energy or fossil fuel to heat is considered, the plant efficiency drops to approximately 35%. /EEL&MRCL 1999/ The following figure illustrates a typical Rankine Cycle System.

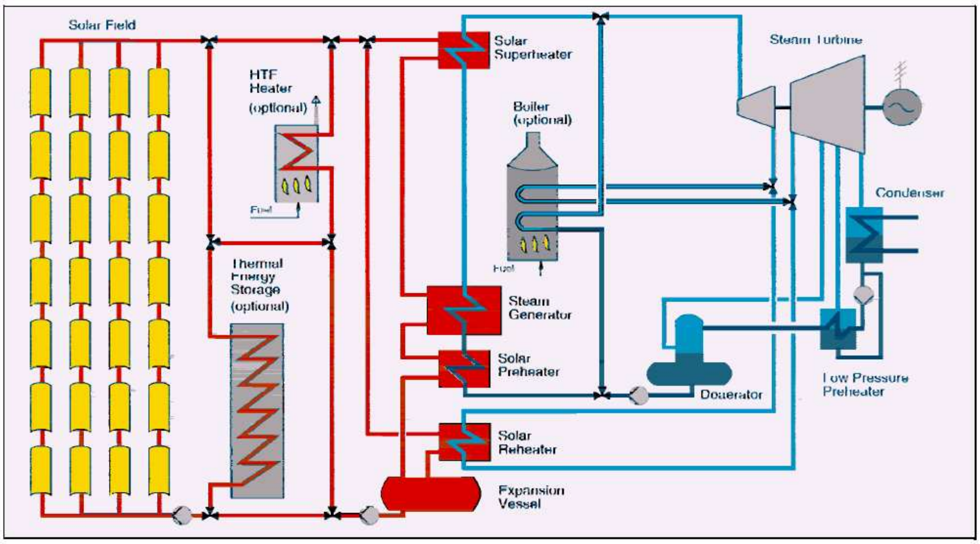


Figure 2-18: Rankine Cycle system /EEL&MRCL 1999/

2.3.2 Integrated Solar Combined Cycle System (ISCCS)

An Integrated Solar Combined Cycle System (ISCCS) differs from the Rankine-cycle system in that the solar components are an add-on to a conventional power plant, sometimes referred to as a solar boost. Solar heat can either produce additional steam in the Heat Recovery Steam Generator (option A) or can generate low-pressure steam that is fed directly into the steam turbine (option B). In both cases, the capacity of the steam turbine is greater than in a conventional combined cycle and can handle the additional steam generated by solar energy.

When the system at the peak output, the solar system has approximately 20 to 30% of combined cycle output, for example, the additional solar systems can increase the output of a 100MW combined cycle plant to 130MW. Annually, the contribution from the solar system falls to approximately 10%. The solar system cannot generate electricity on its own; it must operate as a power boost when the gas turbine is operated. Additionally, the entire system should be designed efficiently so that the operation of the combined cycle does not get worse without solar energy. /EEL&MRCL 1999/

The two main advantages of ISCCS compared to other power plants are firstly, a solar system integrated with a combined cycle can increase its power output when required; secondly, ISCCS can increase its peak capacity with a lower capital cost compared with other power plants.

At high outdoor temperature, the output of conventional combined cycle is reduced, because the lower air density means the less mass flow through the gas turbine. Generally, the solar system has its peak output in the early afternoon when the outdoor temperature is at its highest. The figure below illustrates an ISCCS.

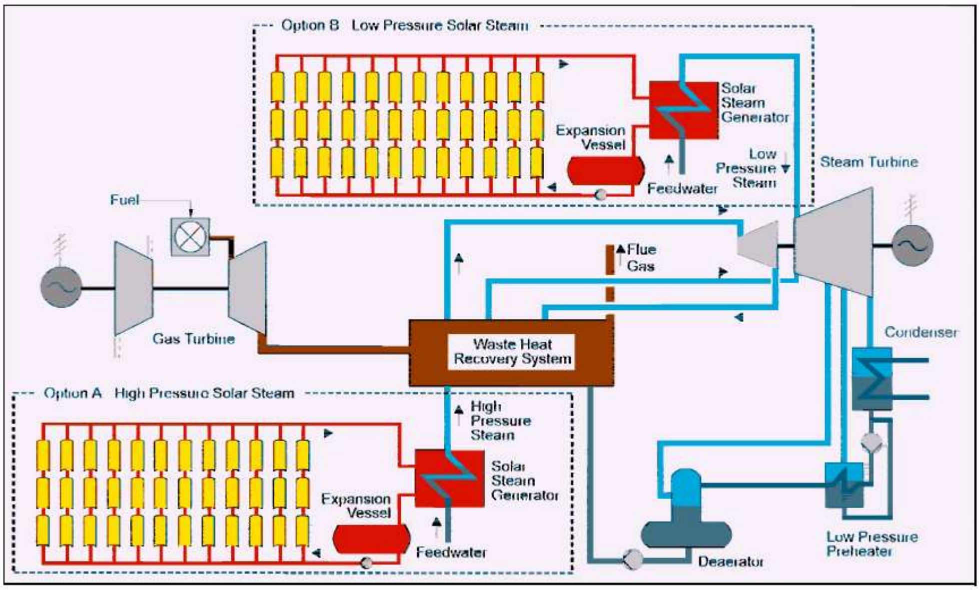


Figure 2-19: Integrated Solar Combined Cycle System (ISCCS) /EEL&MRCL 1999/

2.3.3 Hybrid Solar/Rankine-Cycle Generation Systems

The integration of solar into a conventional Rankine-cycle power plant can also be implemented in a similar manner to Option B of the ISCCS. The oversized turbine in the Rankine cycle plant is able to handle the solar generated steam. Likewise, high-pressure steam produced by the solar system may be injected into the main steam generator to boost its output. This is similar to Option A of the ISCCS. Because of the widely use of coal as the fuel source, these hybrid options can decrease the emissions from the plants.

2.3.4 Stirling Motor

Thermal energy from the concentrated solar radiation can be transformed into electrical energy with a Stirling motor that has interconnected generator. Compared to the Otto or Diesel engine, that run on internal combustion, the Stirling engine is supplied only by external heat, e.g. solar power and external combustion, etc. As a result the Stirling engine is the best choice for energy convertion from solar heat to mechanical energy. Due to the flexibility of the heat source, a Stirling engine can also be operated with hybrid operation. This means that with an additionally installed burner, the required heat can also be generated using fossil fuels (Bio-gas etc.). Thus the system is also available during cloudy periods and even during night-time.

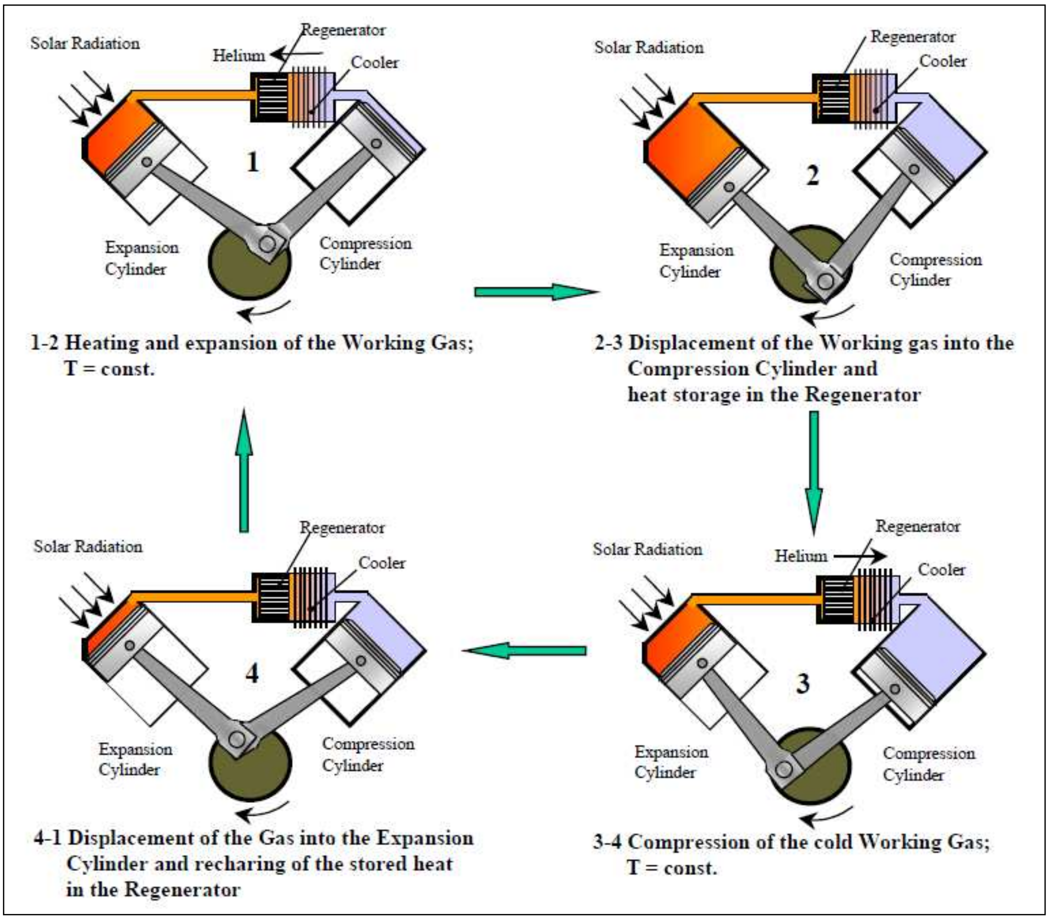


Figure 2-20: Function process of the Stirling motor /Bergermann 2001/

A simple Stirling engine is made up of a sealed system with two cylinders; these are the expansion and the compression cylinder, respectively. And the pistons of these are attached with a crankshaft. The working gas of this Stirling engine is helium. In function process 1-2 shown in figure above, the working gas is heated by the solar radiation and because of the increasing temperature expand in the expansion cylinder. This pushes the piston down and creates power. In process 2-3, the hot working gas in the expansion cylinder is pushed by the power into the compression cylinder. Between the two cylinders the hot working gas goes through a regenerator. Most of the energy is stored in the generator and then the hot gas is cooled by a gas cooler. In process 3-4, the piston will return because of the inertia of the crankshaft and at a low temperature the working gas is then compressed. In the last process, the gas is moved back into the expansion cylinder through reabsorbing of the heat in the regenerator.

The engines of the dish/Stirling power plants use helium or hydrogen at a working gas temperatures between 600 and 800°C. And the working gas mean pressure controlls the power output of the motor. /Doerte et al. 2002/

2.4 Thermal Storage Devices

Compared to other renewable energy technology, the CSP possess an advantage in that the collected energy is easy to store in the form of heat. The thermal storage can increase the availability and capacity factor of the power plant and thus improve the system flexibility. To store heat energy in CSP system, a choice can be made from several different systems: solid salt, two-tank molten salt, thermocline, solid materials (concrete), pressurized saturated water, etc. Currently the most proven thermal storage technology is two-tank molten salt system.

The two-tank molten salt system implemented in the parabolic trough power plant Andsol 1 includes the following components: an oil-to-salt heat exchanger; a cold storage tank operating at 290°C; a hot storage tank operating at 385°C, and two circulation pumps. The storage medium used in this system is a mixture of 60% sodium nitrate (NaNO3) and 40% potassium nitrate (KNO3), which has been proved as a favorable combination. On sunny days, the heat energy is transported by synthetic oil from the solar field to the oil-to-salt heat exchanger and then this heats the salt in the cold tank to 384°C, which will then be stored in the hot tank. In the evening or on the cloudy days, the salt mixture is pumped to the exchanger and heats the oil to provide thermal energy for electricity generation.

The mass storage system with heat storage medium such as concrete and ceramic has also been implemented in the demonstrate projects e.g. the LS-3 (HTF) test loop. In this project the storage system consists of four 5m³, 10-15-ton, two concrete and two ceramic storage modules. Each module presents a 175kWh storage capacity. The advantages of this storage system include the lower cost of the storage medium and simple structure. However, it has also obvious drawback: the great heat loss during charging and discharging of the storage material.

2.5 Technology Comparison of CSP

In this section the technical information of the four major CSP systems is summarized and compared to analyze their advantages and disadvantages. The technical data shown in the following table is based on a DLR report.

Table 2-1: Technology comparison of CSP

	Capacity (MWe)	Concen-tration ratio	Solar efficiency max.	Annual solar efficiency	Area requirement $M^2/(MWh)$
Parabolic Trough	10 - 200	25 - 100	20% (e)	9-11% (e)	4-6
Fresnel	10 - 200	70 - 80	21% (d)	10-15% (d) 17-18% (e)	6-8
Solar Tower	10 - 150	300 - 1000	20% (e) 35% (e)	16-18% (d) 15-25% (e)	8-12
Dish Stirling	0.01 - 0.4	1000 -3000	29% (d)	16-18% (d) 18-23% (e)	30-40

(e) expected (d) demonstrated

As is indicated in the **Table 2-1**, tower and dish Stirling are regarded as the most efficient technologies of CSP, which are expected to have a 50% better efficiency than the trough and the Fresnel plants. However, trough and Fresnel plants require less area than the two other technologies, especially for the Dish Stirling with the same capacity. /Pitz-Paal et al. 2004/

Furthermore, with relatively high efficiency and lower investment costs, the parabolic trough technology has already been proven to be commercially viable, even more with the hybrid concept or thermal storage facility.

Compared with the most mature trough technology, Fresnel possesses a simpler design, with lower requirements for the mirror and receiver material as well as better wind-resistance ability. All of these factors can reduce the cost of the Fresnel power plant and makes it possible to realize widespread implementation. However the fact that there is no commercial operating experience of Fresnel technology is a disadvantage and this could lead to a lower solar to electricity efficiency, increased costs for investment and thus loss of price advantage.

The advantage of solar tower technology is the high operating temperature, which make the energy conversion from thermal to electricity as well as energy storage more efficient. In addition, the geographical requirement for the flat ground area for the power plant is lower. The solar field tower technology has no large-block facilities. Each heliostat can have its own banking angle to concentrate the solar radiations to the tower; nevertheless, their own dual-axis tracking equipment will increase the costs and result in the system control being more difficult.

Due to the high concentration ratio, the dish Stirling system can reach very high temperatures and thereby achieve high efficiency. And the stand-alone design makes it flexible to use in many different external conditions. However, the disadvantages of the dish system are also significant. The Decentralized design of the energy conversion from solar to electricity through the dish equipment is not as efficient as a centralized approach. Moreover, the Stirling engine makes the moving structure cumbersome while the frame and the tracking system must strong enough. The huge moving parts require frequent maintenance.

3 Global CSP Projects – A Review

Since the first large CSP plant was built in 1912 in Meadi, 25km south of Cairo, CSP technology has a history of around 97 years. The first commercial CSP facility began to operate 1984, which was also the first plant of the 354 megawatts SEGS power plant group. From 1980 until the end of 2008, the total capacity of the cumulative installed concentrating solar power worldwide comes to around 603 megawatts. By 2012 this figure will reach 6,400 megawatts, about 10 times the current capacity. Among this over 90 percent of the planed new capacity will be in the United States and Spain, with a combined total of over 5,600 megawatts expected to come online by 2012. /EPI 2009/

The figure below shows the development of concentrating solar power in the period 1985 to 2014.

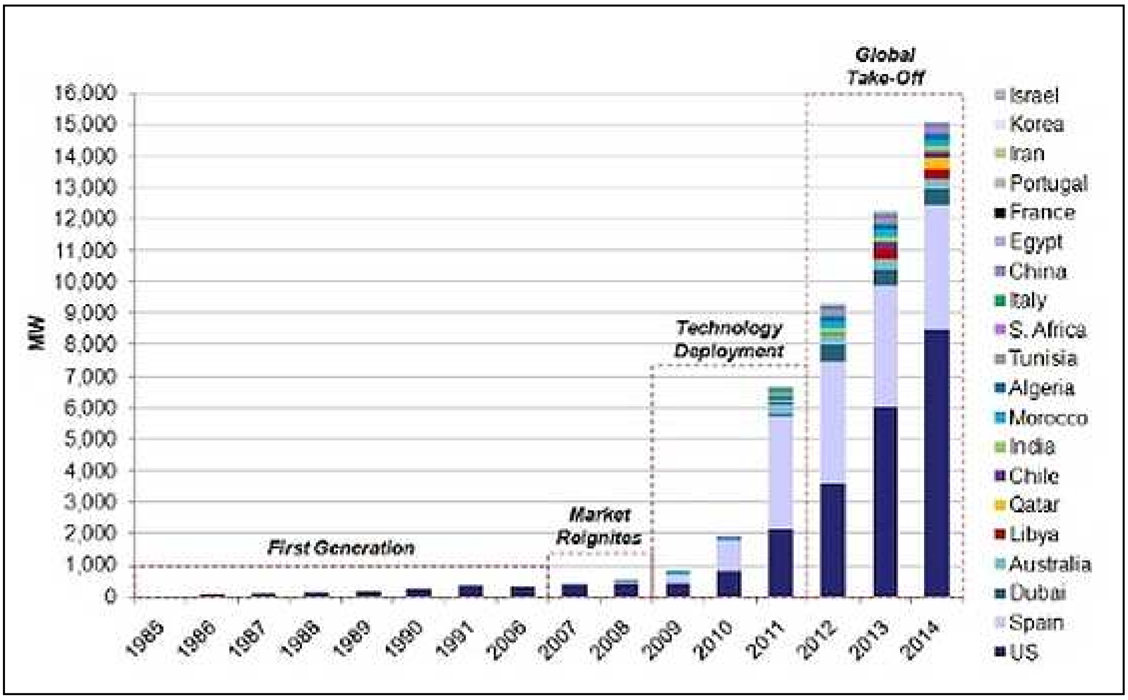


Figure 3-1: World cumulative installed CSP capacity 1985 – 2014 /REW 2009/

Owing to previous developments in the US with around 350MW operating CSP plants since 1980, the parabolic trough system is regarded as the most mature large scale technology. The first commercial CSP plant in Europe, 50MW Andasol 1 project with 7.5 hours of storage, utilized also the parabolic trough technology. This project has been in operation in Granada in Spain since 2008. Two additional plants of 50MW each, Andasol 2 and 3, are scheduled to be built on the same site. The second main CSP technology is solar tower system. Since March 2007, an 11MW saturated steam solar tower project, named PS10, has been operating in Andalusia in Spain. This was the first commercial scale solar tower project in Europe. Solar Tres is another project under development in Spain based on a molten salt central receiver system. In November 2008, the Spanish engineering company group SENER announced the start of its construction. /PS 2008/ Dish/Stirling technology with proposing modular systems of relatively small size (between 5 to 50 kW) is still in the development phase. This technology will be implemented primarily for a decentralized power supply. The 5MW Kimberlina Solar Thermal Energy Plant will be built in Bakersfield, California. This project uses Ausra's linear Fresnel reflector technology. Another linear Fresnel solar power plant named Liddell Power Station is currently operating in the Hunter Valley, New South Wales, Australia.

The average annual load factor of a solar only CSP plant without thermal storage is approximately 1800 to 2500 full-load hours. In additional, CSP technologies can operate with thermal storage and hybridized or combined cycle systems in order to increase and secure the power dispatch. For example, the 15 hours of molten salt storage in the Solar Tres project increase the capacity factor by 64% without fossil fuel hybrid operation. A number of Integrated Solar Combined Cycle (ISCC) projects that use solar and natural gas as energy source are currently under development, for example, in Algeria, Egypt, India, Italy and Morocco. /CEC 2007/ The following figure illustrates the countries, which have already built or have announced large-scale CSP plants. /EPI 2009/

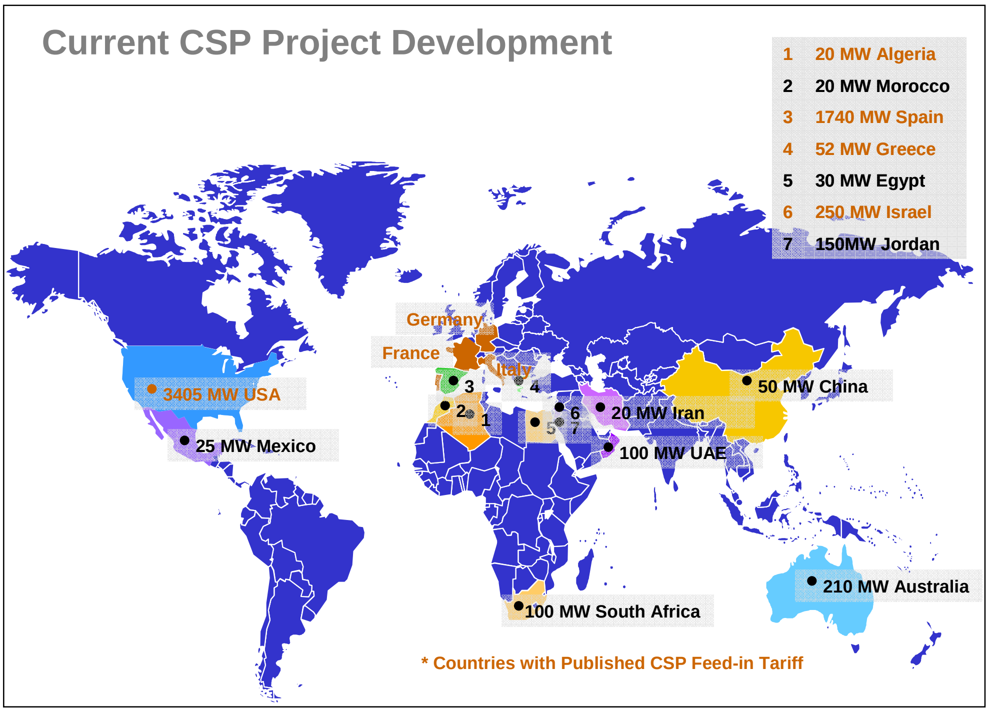


Figure 3-2: Current large-scale CSP projects global

In the following sections the projects of major CSP technologies will be described in detail.

3.1 Parabolic Trough Projects

Parabolic trough plants are considered to be the most economical and the most mature CSP technology available today. The cumulative installed capacity of parabolic trough power plant accounts for over 97 percent worldwide /SullivanM 2009/. This chapter will provide a review of all operated commercial projects using trough technology. In particular, the 50MW Andasol 1 plant in Spain will be described in detail.

3.1.1 Commercial Activities

The table below lists the current commercial parabolic trough plants operated globally.

Table 3-1 : Commercial parabolic trough plants worldwide (status Juli 2009)

Name	Location	Capacity	Technology	Developer
Operational				
SEGS	California, USA	354 MW	Trough	FPL Energy
Nevada Solar One	Nevada, USA	64 MW	Trough	Acciona Solar Power
Andasol 1	Spain	50 MW	Trough + storage	Solar Millenium
Under Construction				
Andasol 2, 3	Spain	each 50 MW	Trough	Solar Millenium
Announced				
Mojave Solar Park	California, USA	553 MW	Trough	Solel
Beacon Solar Project	California, USA	250 MW	Trough	FPL Energy
Shams 1	Abu Dhabi	100 MW	Trough	ADFEC
Solana Station	Arizona, USA	280 MW	Trough + storage	Abengoa Solar
Barstow	California, USA	59 MW	Trough + storage	Solar MW Energy
Yazd	Iran	67 MW	Trough ISCCS*	*Unknown*
Victorville 2	California, USA	50 MW	Trough + storage	City of Victorville
Kuraymat Plant	Egypt	40 MW	Trough ISCCS	Iberdrola
Ben Mathar Plant	Morocco	30 MW	Trough ISCCS	Abengoa
Hassi R'mel	Algeria	25 MW	Trough ISCCS	Abener

SEGS Power Plants

Since 1984 SEGS parabolic trough power plants with a total capacity of 354MW have been connected to the Southern California grid. The facilities have a total collector area of over 2 km² and cover altogether more than 6.5km² with a long term availability of over 99%. The annual electricity output of the SEGS power plants group can reach up to 800 million kWh. The data of the 9 SEGS power plants are shown in **Table 3-2**. /NREL 2009/

Table 3-2 : Key data of SEGS power plants

Plant Name	Location	Year of Operation	Net Output (MW_e)	Solar Field Outlet (°C)	Solar Field Area (m^2)	Solar Turbine Effic. (%)	Power Cycle	Dispatchability Provided By
SEGS I	Daggett, CA	1985	13.8	307	82,960	31.5	40 bar, steam	3-hrs TES
SEGS II		1986	30	316	190,338	29.4	40 bar, steam	Gas boiler
SEGS III	Kramer Junction, CA	1987	30	349	230,300	30.6	40 bar, steam	Gas boiler
SEGS VI		1989	30	390	188,000	37.5	100 bar, reheat	Gas boiler
SEGS V		1988	30	349	250,500	30.6	40 bar, steam	Gas boiler
SEGS VI		1989	30	390	188,000	37.5	100 bar, reheat	Gas boiler
SEGS VII		1989	30	390	194,280	37.5	100 bar, reheat	Gas boiler
SEGS VIII	Harper Lake, CA	1990	80	390	464,340	37.6	100 bar, reheat	HTF heater
SEGS IX		1991	80	390	483,960	37.6	100 bar, reheat	HTF heater

Until recently SEGS were still the largest solar energy generation facilities in the world. There are several special incentives for SEGS power plants to promote the utilization and widespread use of the new CSP technology:

- Federal and state investment tax credits
- Solar property tax exclusion
- Accelerated depreciation

The SEGS power plants were built by Luz Industries and commissioned between 1984 and 1991. After a lapse of over 15 years since the Southern California systems were commercially deployed, there are now a number of parabolic trough pre-commercial and fully-commercial deployments underway.

Nevada Solar One

The Nevada Solar One project is a 64MW parabolic trough system developed and owned by a subsidiary of global Acciona Energía group: Acciona Solar Power. On February 11, 2006 it began its 16 months' construction and began operating in mid July, 2007. With an investment of over 250 million US Dollars, it supplies up to 134 million KWh of electricity per year.

/REW 2007/ **Table 3-3** provides the technical data of the Nevada Solar One power plant. /NREL 2009/

Table 3-3: Major data of Nevada Solar One power plant

Plant Name	Location	Year of Operation	Net Output (MW_e)	Solar Field Out-let (°C)	Solar Field Area (m^2)	Solar Turbine Effic. (%)	Power Cycle	Dispatch-ability Provided By
Nevada Solar One	Boulder City, NV	2007	64	390	357,200	37.6	100 bar, reheat	None

Mojave Solar Park

In July, 2007 Solel Solar Systems announced the development of a 553MW parabolic trough power plant system situated in the Mojave Desert in California that will be completed and fully operational in 2011. Solel has signed a long-term power purchase agreement with the California utility PG&E that will bring renewable energy to 18% of the company's total power supply in the coming years, and will bring compliance closer to the California requirement of 20% by 2010. The complete power plant will cover up to 24 km^2 of land in the Mojave Desert and use 1.2 million mirrors and 317 miles of vacuum tubing to capture the desert sun’s heat. /YNN 2007/

Beacon Solar Project

In March 2008 Beacon Solar, a subsidiary of Florida Power & Light Energy, filed an application for certification with the California Energy Commission with the intention of constructing, owning and operating a 250MW solar power plant in the Mojave Desert which is called the Beacon Solar Energy Project. The Beacon Solar Project will use the parabolic trough solar thermal technology which has an approximate 5km^2 mirror area and 8.1km^2 plant site. This project costing approximately 1 billion Dollars is scheduled to begin construction in late 2009 with commercial operation commencing approximately two years later. /FS 2008/

Andasol Projects

Spain is leading the way in Europe with new deployments of CSP technologies due to its favorable feed-in tariff for solar power. Andasol-1 is a 50MW parabolic trough system being developed by the Spanish ACS Cobra Company who is the majority shareholder, and the German Solar Millennium Group being the minority shareholder. The Andasol project is the first application of parabolic trough power plant using the molten salt thermal storage technology.

Shams 1

The Abu Dhabi Future Energy Company (ADFEC) of the United Arab Emirates has announced that it will invest US$400-500 million to build a parabolic trough CSP plant with a capacity of 100MW that is expected to be operational by the end of 2010. The plant called Shams 1 will be constructed in the town of Madinat Zayad in the western of Abu Dhabi, and is reported to be the first of many CSP plants to be set up in the UAE to feed electric power to the national grid. ADFEC has been authorized to develop and execute the Masdar Initiative of future energy in Abu Dhabi in order to promote the commercialization of renewable energy technologies.

3.1.2 Andasol 1-3: Parabolic Trough Plant with Thermal Storage

The Andasol power plants were constructed in the southern Spanish province of Granada. Andasol 1 was the first parabolic trough power plant in Europe and is currently the largest in Europe, when considering its collector area of over 0.51 square kilometers. Three power plants that each with 50MW capacity will be constructed in a similar way are planned for this site. After the entire project is completed, Andasol is eble to supply up to 600,000 people with environmentally-friendly solar electricity and achieve a emission reduction of CO2 by 450,000 tons annually.The following table shows the general technical data of the Andasol power plant.

Table 3-4: Technical data of Andasol project /SM 2008/

Data about the Andasol-power plants (Data per power plant)	
Location	
Project names	Andasol 1, Andasol 2, Andasol 3
Location	10 km east of Guadix in the municipal area of Aldeire and La Calahorra in the Marquesado del Zenete region, Granada Province
Terrain	approx. 195 hectares (1300m x 1500M), North-South Axis
High-voltage line access	Connection to the 400kV line near Huéneja (about 7 km away)
Solar Field	
Parabolic trough technology used	Skal-ET
Size of the solar field	510,120 m^2
Number of parabolic mirrors	209,664 mirrors
Number of receivers (absorption pipes)	22,464 pipes each measuring 4 m
Number of solar sensors	624 sensors
Annual direct standard radiation (DNI)	2,136 kWh/m^2a
Solar field efficiency	approx. 70% peak efficiency, approx. 50% annual average
Heat storage capacity	28,500 t salt for 7.5 peak load hours
Power plant capacity	
Turbine capacity	49.9 MW
Annual operating hours	ca. 3.500 h
Forecast gross electricity volume	about 180 GWh
Efficiency of entire plant	approx. 28% peak efficiency, approx. 15% annual average
Estimated lifespan	at least 40 years

3.1.2.1 Site Selection

Location

The site for Andasol projects are selected near the Spanish city of Aldeire in the province of Granada on the Guadix plateau. The location of the power plants has an average elevation of over 1,090 meters above mean sea level. The land of the whole area has been leveled and all plants and stones those provide shade has been removed. The power plants are sited directly on the A92 highway and remote from the residential district. The figure below shows the site of Andasol project.

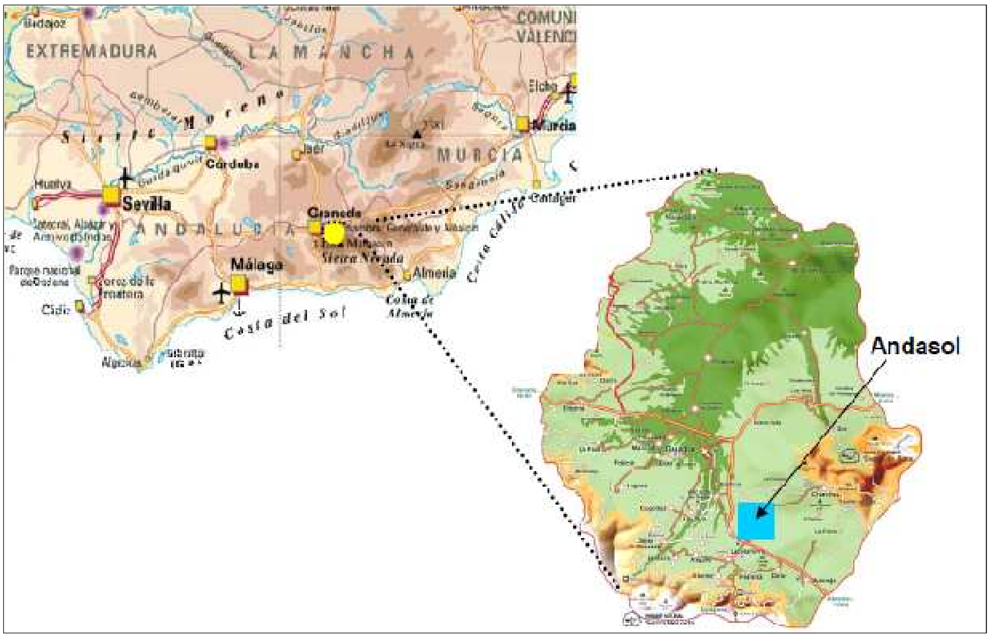


Figure 3-3: Location of the Andasol project /Andasol 2008/

Solar Resource

The evaluation of the solar resource for the site of Andasol projects is due to the measurements on site and the satellite data of the long-term information of the site. A Rotating Shadow band Pyranometer (RSP) Sensor was implemented for the on site measuring, which is a professional instrument used to measure the global solar radiation and the direct solar radiation. The sensors are monitored regularly by the German Aerospace Center (DLR) to insure their accuracy. The local measurement provides also the data of ambient temperature, humidity, wind direction as well as the wind speed at meteorological stations, which started operation in March 2000.

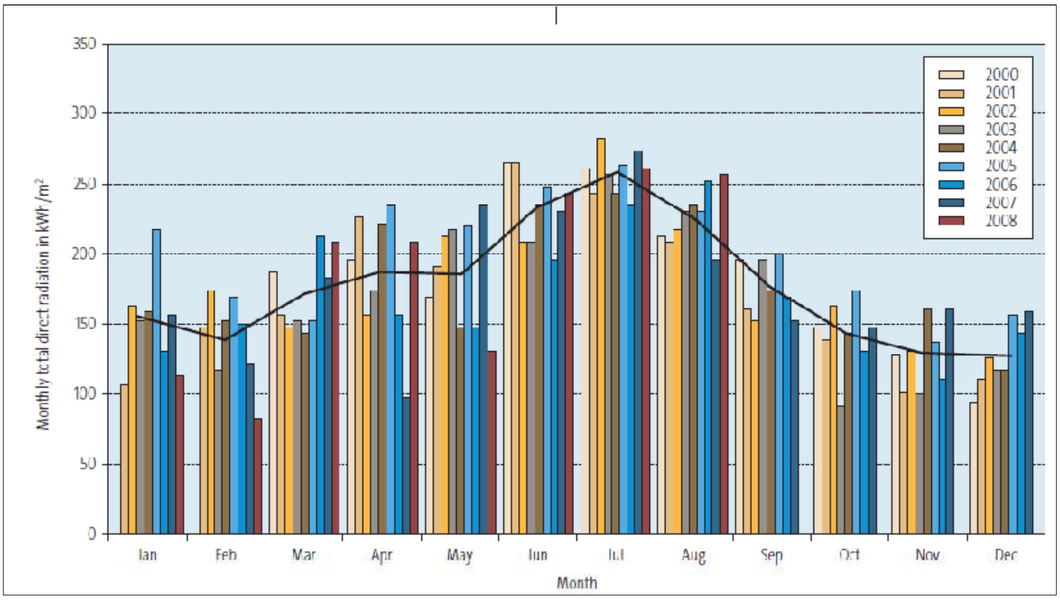


Figure 3-4: Monthly total direct radiation at the site of Andasol project /SM 2008/

The graph above illustrates the solar radiation values at the site of Andasol project. Besides the on site measuring, satellite data contributes to provide a long-term value of the solar radiation for the project site. Based on the data measured on site and from the satellite the direct solar radiation at the site of Andasol power plants, an average value of 2,144 kWh/ (m^2•a) was estimated.

Water Availability

Spain is possessed of an above average water availability. The selected site of the power plants is surrounded by the Sierra Nevada mountain range and owns extensive underground water resources. The water consumption of Andasol power plants is estimated to be approximately 870,000 m3 per year, among them water used for cooling in the cooling towers account for the largest part. And the water requirements can be met through the use of ground water extracted from wells at the power plant's site.

3.1.2.2 Power Plant Components

Each of the three Andasol power plants has an area of 195 hectares, which approaches to $2km^2$ and is in a north-south orientation. The 312 parabolic trough collector rows in the solar field of each power plant are possessed to an area of around $0.51km^2$. The absorber tubes used as the receiver in each power plants account for approximately 90 kilometers. /SM 2008/

The figure below shows a whole view of power plant Andasol 1 with solar field, power cycles, storage tanks and other supporting infrastructure.

Figure 3-5: Parabolic through power plant Andaosl 1 /SM 2008/

Collectors

The 150m collector used in the Andasol parabolic trough power plants consist of mirrors, absorber tubes and the steel support structures. The supporting structure is attached to the ground with a steel pylon. The sun- tracking mirrors reflect the solar radiation onto the absorber tubes. This solar tracking system adjust the collector through the use of the hydraulic drives along a north-south single axis. The precision of the tracking system can achieve 0.1mm and is controlled by computers in the control room. Those computers gather the information from each collector individually and direct the orientation of collectors automatically. The collectors were designed to tolerate extreme weather conditions. For instance, the wind load that the solar field can withstand attains to 13.6 m/s (about 49 km/h).

The 4mm thick, white parabolic glass is implemented in the mirrors of the collector and outside this back-silvered glass there is a protective layer. According to the Flabeg Group, the mirror supplier of Andalsol power plants 1 and 2, the used RP-3 mirrors have two typical sizes of 2.79 and 2.55m2 and have a reflectivity of about 93%. Each power plant utilizes a total of nearly 201,000 mirrors in their solar field. For Andasol 3, Rioglass Solar S.A. will supply the parabolic mirrors. /SM 2008/

Receivers

Absorber tubes were specially designed for the application in parabolic trough power plants as receiver. The receivers used in the Andasol power plants are provided by Solel Solar Systems Ltd. of Israel and Schott Solar AG, Germany. Solel has years of experience in the manufacture of absorber tubes and has already provided the absorber tubes for the parabolic trough power plants established in the late 1980s, in California. Schott has developed in recent years new material for absorber tubes of parabolic trough power plants, which allows the absorber tube to tolerate much greater temperature differences, increases the solar absorption and reduces the reflection from the metal pipe.

The Schott absorber tubes are made of 4m long stainless-steel pipes with multi-coating. At the operating temperature of around 400oC it can achieve an absorption ratio of 95% and maintains a thermal radiation of 14%. Approximately 22,500 absorber tubes are implemented in each of the Andasol power plants.

Power Cycles

Similar to the conventional fossil fuel fired power plants, the power cycles of parabolic trough power plants are composed of turbines, generators and other auxiliary facilities. An advantage of the 50MW turbine for Andasol power plant is characterized by its specifically design, which ensures the daily smooth start-up and shut down of the turbine. For Andasol 1 and 2 Siemens produced the turbines and for Andasol 3 MAN Turbo will be the turbine supplier.

Storage System

To allow the power plants providing scheduled power, the Andasol power plants utilize the thermal storage system that the plants can work even in bad weather or at night with approximately 28,500 tons of molten salt for maximum 7.5 hours. The molten salt thermal storage system operates at atmospheric pressure and is made of two tanks each power plant. The storage tank has a height of 14m and a diameter of 36m. During the function process, the temperature of molten salt mixture in the cold tank amounts to about 290oC of and is raised to 390oC in the hot tank. Figure below shows the two-tank molten salt thermal storage system used by Andasol 1.

Figure 3-6: Two-tank molten salt thermal storage system /SM 2008/

3.1.2.3 Operation

In the Andasol power plants, the collectors in the solar field follow the sun course in the day and they are controlled by the high-precision solar tracking system. The sun light is reflected on the receiver and heat the HTF (synthetic oil) flowing through the absorber tubes. The thermal energy within this HTF can directly drive the turbine and generator or it can be stored in the thermal storage system. The following figure illustrates a basic operation shame of Andasol plant.

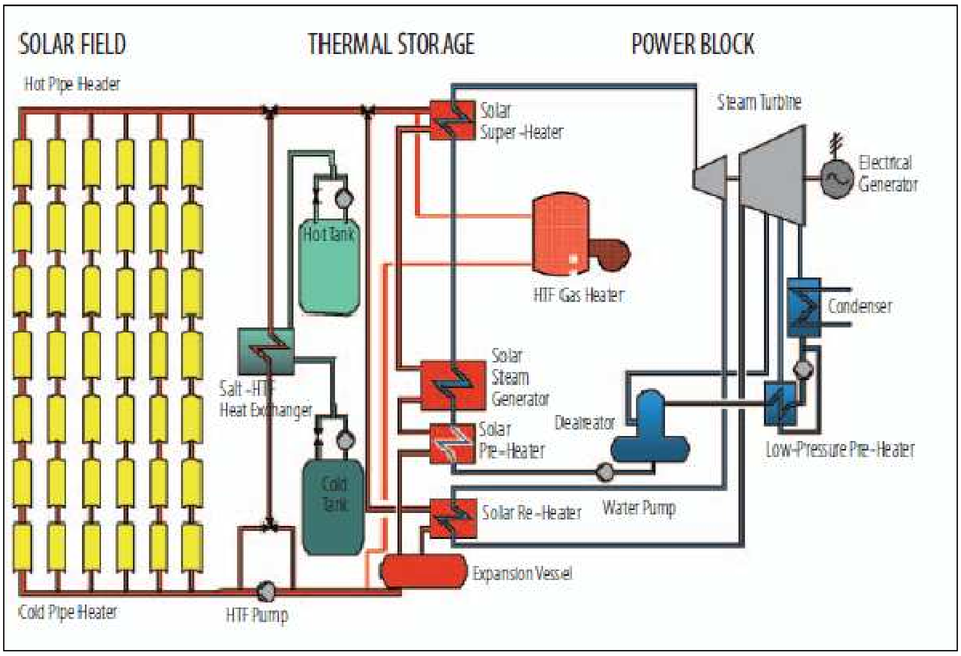


Figure 3-7: Basic operation shame of Andasol 1 /New 2009/

At midday during maximum sunlight, electricity is generated and simultaneously the storage system is charged. The heat within the HTF is sent to the molten-salt fluid as the thermal storage medium. During the process that the molten salt is pumped from a cold tank to a hot tank, thermal energy will be collected until the hot tank is completely filled.

When the intensity of the solar radiation is not strong enough, heat is only used to produce electricity but no longer transferred to the storage system. When there is no sunshine or in the evening, the solar field stops working and the thermal storage system begins to discharge to run the power cycle continuously, so that the Andasol power plants can dispatch the power demand at any time. To maintain the liquid state of the HTF in the receiver and storage salt in the tanks, gas fired heaters are auxiliary installed.

3.2 Solar Power Tower Projects

To date, most solar power tower plants were built and are operating as demonstration plants except for the 11MW solar tower plant PS10 in Spain. In this chapter, the major projects of demonstration plants as well as the commercial PS10 are discussed.

3.2.1 Projects Overview

In the past, several solar tower power plants have been realized within R&D projects sponsored by public money and industry. In the following sections descriptions of some of these research plants are presented.

Solar One

Solar One is a 10MW solar tower power plant that was operated in the period from 1982 to 1988 in the Californian Mojave Desert. It successfully proved the possibility of the large scale power generation contributed by solar tower plants. At the receiver, Water was implemented as heat transfer medium. The major difficulty revealed by the Solar One was the continuous operation during cloudy days. Beyond that, the efficiency of electricity generation depends to a high degree on the water/steam tube receiver technology, which can be optimized through the molten salt volumetric receivers.

Solar Two

With the aim of solving the problems shown by the Solar One plant, the Solar Two plant employed molten salt (40% of KNO3 and 60% of NaNO3) as the HTF and heat storage medium. As a result of the implementation of thermal storage system, it is more independent from the availability of solar radiation. The functional scheme of the Solar Two tower power plant is: The cold salt is pumped into the receiver, which is mounted on the top of the tower and is heated by the concentrated solar energy. Then, it is moved to the hot tank, from where the hot salt is transferred to a steam generator to produce electricity. Following this, the cooled salt returns to the cold tank. Solar Two has an electricity capacity of 10MW and can operate for up to three hours without solar radiation due to the thermal storage system.

Phoebus/TSA/Solair

Phoebus/TSA/Solair is a solar tower power plant employed the open volumetric air receiver technology. This plant was operated from 1993 to 1997 with a thermal capacity of 3MW.

At the power plant, the hot air generated by the receiver is transferred to the steam generator and provides the superheated steam that can drive the turbine/generator unit and produce electricity. In order to generate power at times without sunlight, an additional natural-gas-fired turbine is implemented. The Phoebus solar tower plant is characterized by its low thermal inertia of the system that can ensure the fast start-up of the power plant. In the further approach this concept will simplify the plant structure and optimize the heat transfer of fluid air.

PS10

Due to the positive experiences using the Phoebus/TSA/Solair System, a 10MW solar tower power plant PS10 began to design and constructe in the Southwest of Spain in 2004 and has been operational since 2007. Different from Phoebus system PS10 employs a tube saturated steam receiver which consists of four tube panels with the size of 5.36 x 12.0m and heats steam at 40bar to 250oC. The receiver is situated on a tower of approximately 110m high. The heliostat field of PS10 consists of 624 faceted glass/metal heliostats with the type of Sanlúcar 120. Each heliostat has a mirror surface of 121m². The thermal storage system of PS10 solar tower power plant allows the plant 30min operation at 70% of its load without solar radiation. /FTPR 2005/

Solar Tres

The 15 MW Solar Tres solar tower power plant is designed and constructed based on the operational experience of the plant Solar Two (using salt as heat transfer and heat storage medium). As a result of that this power plant was named Solar Tres, the Spanish of Solar Three. A molten salt tube receiver is equipped in the Solar Tres plant using salt as HTF and heat storage medium. The designed thermal capacity of the receiver is 120MW. The heliostat field of Solar Tres consists of 2,494 faceted glass/metal heliostats with simplified design. Each heliostat uses highly reflecting mirrors with a surface size of 96m². In additional, the thermal storage system of the power plant can maintain a normal operation for 16hours on cloudy days and at night. /Kaltschmitt et al. 2007/

3.2.2 PS 10: An 11MW Solar Tower Power Plant in Southern Spain

The PS10 solar tower power plant has an electricity capacity of 11MW and is located at Sanlúcar la Mayor, southern Spain. This power plant is the first commercial concentrating solar thermal power plant using solar tower technology of the world. In Europe, it is also one of the largest solar power plants.

The PS10 power plant started its construction in June 2004. The heliostats using mobile mirrors controlled by dual-axis solar tracking system concentrate the sunlight onto the top of a tower with the height of 115m. The receiver mounted on top of the tower creates saturated steam and transfers it to a conventional steam turbine-generator unit that produces the electricity. PS10 solar tower plant can produce electricity of around 23GWh annually and deliver it to the grid.

3.2.2.1 Location

The PS10 plant is constructed in the town of Sanlúcar la Mayor, which is located 25km west of the Spanish city of Seville. PS10 is the first plant of a plants set to be constructed in the same area developed by the company Abengoa Solar. All the plants belong to a large solar project called Plataforma Solar de Sanlúcar la Mayor, PSSM. The figure below shows the planned location of PSSM.

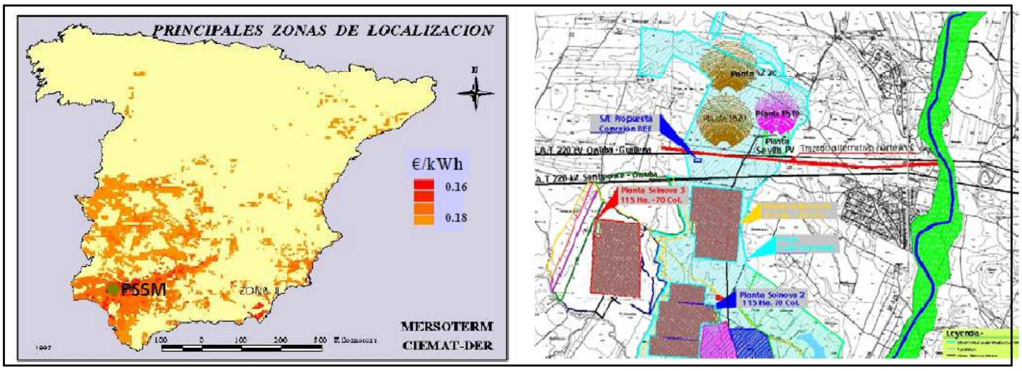


Figure 3-8: Location of solar tower plant PS10 /FTPR 2005/

The location of PSSM is selected in one of areas that has low cost of solar electricity generation in Spain due to the high solar radiation as well as the availability of suitable land.

3.2.2.2 Power Plant Components

The technical data presented in this section is mainly in accordance with the final technical report of PS10. /FTPR 2005/

Heliostats Field

PS10 heliostat field is composed of 624 heliostats for a total reflective surface of 75.216m². It is arranged in 35 circular rows around the tower. Each heliostat, of the Sanlúcar 120 type, is a mobile 121m² curved reflective surface mirror that concentrates the solar radiation onto a receiver placed on top of a 100m tower. For this purpose, every heliostat is spherically curved so that its focal point is at a distance equal to the slant range to the receiver. The figure below shows the frontal view for a Sanlúcar 120 heliostat. /PSA 2004/

The Sanlúcar 120 heliostat consists of 28 curved mirrors with high reflectivity. With the aims of minimizing the losses caused by cosine effect, shadowing, blocking, etc, the heliostat field is designed with the use of computational procedures and simulation tools. This is the reason why the losses due to, for example, shadows and blocks are lower than 4.5% every year.

The angle of heliostats is adjusted with the dual-axis solar tracking system that inclusive the mechanical drives on each heliostat and the local control system. This control system has two major tasks. First, it gathers information of sun position, for example the azimuth and elevation angle of the sun, with high accuracy. Second, the current information of heliostat position is detected and compared with the required position. Based on the calculation result of the control system, the heliostats are tilted to an appropriate angle by the mechanical drives, thus the sun light is efficiently reflected onto receiver.

Tower

The tower design has been undertaken with the aim of obtaining a great visual effect for the big tower of 115m high. For this reason, the tower has a thin body of 8m and for supporting the 14m receiver, it is 18m wide. In the middle part, about half height of the tower has been hollowed out so as to obtain a lighter body. An observation platform has been planned to construct at a height of 30m in order to have a good sight of its heliostat field in the north of the tower and the 1.2MW Sevilla photo voltaic power plant in the south. The tower has been constructed in the period of August to November 2005. The figure below shows the designed view and final view of the PS10 tower.

Figure 3-9: Tower of PS10 /FTPR 2005/

Receiver

The tube saturated steam receiver of PS10 plant is mounted on the top of the tower with a cavity concept that can reduce the radiation and convection losses. The receiver is exposed by 4 vertical panels with each one 5.40m wide and 12.00m high, which has a total heat exchange area of approximately 260m2. The 4 panels are arrayed in a semi-cylinder with the radius of 7.00m. At the full load operation of the PS10 receiver, the solar radiation can be received with the peak power of 650kW/m² and at the same time, over 100.000kg/h saturated steam can be produced at 40bar, 250ºC.

For the purpose of ensuring the operation at possible high temperature, special steel alloys have been implemented in the receiver. With the aims of providing the energetic calculation, performance information as well as the temperature alarm, calorimeters and thermocouples are employed for the flow and temperature measurements of the receiver.

Power Block

The turbine of PS10 plant works at 250ºC, 40bar and with saturated steam as operating medium. After the turbine-generator unit, steam is cooled by a water-cooled condenser at low pressure. Out of the condenser steam is preheated with the turbine extractions. Afterwards, the steam from the first preheater is moved to a deaerator and is heated with steam from a different turbine extraction. Then, the third and final preheater with steam from the receiver preheated the steam once more. As a result, the water temperature is raised to about 245ºC and is sent to the receiver again.

Thermal Storage Tank

For briefly cloudy periods during the day, the PS10 plant is operated with a 20MWh saturated steam thermal storage system. At 50% turbine load, the thermal storage system can provide the plant operation for 50 minutes. This thermal storage system consists of 4 tanks and is loaded during the full load operation in abundant solar radiation sequentially. When there is no sufficient sunlight, energy from the thermal storage system will cover it at a pressure from the designed minimum pressure to 40bar and the turbine will be driven at 50% workload. The figure below illustrates the thermal storage system of PS 10 plant.

Figure 3-10: Thermal storage tanks of PS 10 /FTPR 2005/

3.2.2.3 Operation

The figure below illustrates the system design of the PS10 power plant. /EC 2007/

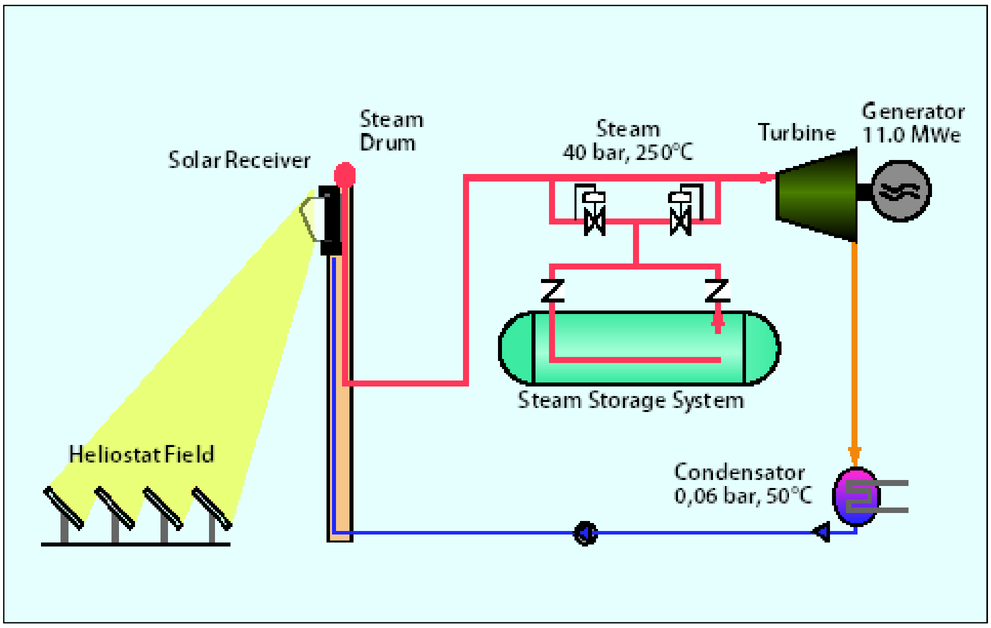


Figure 3-11: Basic system design of solar tower plant PS 10 /FTPR 2005/

With the clean heliostats and wind speed lower than approximately 36km/ h, PS10 can be operated smoothly. During full load operation, the receiver on the top of the tower can accept and transferred the concentrated solar radiation with a thermal capacity of about 55MW. During cloudy periods, the thermal storage system of the plant provides the energy to the turbine and run it at 50% workload. In additional, natural gas-fired backup plant can also supply 12% to 15% of its capacity. The 11MW PS10 solar tower power plant has an annual capacity of 24.3GWh and achieves a total solar to electricity efficiency of around 17%. /AS 2009/

4 Cost Status of CSP

For the widespread use of CSP as a large scale electricity generation technology, costs will play an important role. In the current CSP projects, the cost of electricity generation through CSP is much higher compared with the cost of electricity generation through conventional technologies. However, with large scale implementation and technological advancements, the cost of electricity generation from CSP is expected to decrease continuously.

According to a study of renewable energy made by the IEA, the current CSP technology systems are implemented in the cost range of 0.19$/kWh to 0.25$/kWh. In the conventional power market, CSP competes with mid-load power in the range of 0.037$/kWh to 0.05$/kWh. As different scenarios have predicted, the costs of CSP can be reduced to competitive levels in the next 10 to 15 years. Competitiveness is affected not only by the cost of the technology itself, but also by potential price increases of fossil energy and by the internalization of associated social costs, such as carbon emissions. Therefore, it is assumed that in the medium to long term, competitiveness will be achieved at a level of 0.05$/kWh to 0.075$/kWh for dispatchable mid-load power. /IEA 2006/

According to another report prepared by Electric Power Research Institute, when the global cumulative capacity of CSP implementation reaches 4GW, the cost of electricity generation from new plants in 2015 could be as low as 0.08$/kWh (nominal 2015 dollars) or nearly 0.05$/kWh (real 2005 dollars). /EPRI 2006/

To analyze and compare the cost of different CSP technologies an explanation of the methodology for levelized energy cost calculation and an overview of CSP cost will be given in this chapter.

4.1 Methodology for Calculation of Levelized Energy Cost

4.1.1 Definition of Levelized Energy Cost

Levelized Energy Cost (LEC) is defined as the total cost of a system over its lifetime divided by the expected energy output over its useful lifetime. LEC includes all costs through the lifetime of a plant including the initial investment, operations and maintenance, cost of fuel, and cost of capital. It is a measurement of the cost of producing energy from a technology and is an important parameter to gauge the commercial viability of any electricity generation technology. The LEC is the minimum price at which energy must be sold for an energy project to break even.

4.1.2 Methodology

The methodology employed in the calculation of the LEC is based on a simplified IEA method /IEA 1991/. The goal of this thesis is the comparison of different CSP technologies, therefore any project specific data (e.g. tax influences, or financing conditions) are neglected. The approach is kept simple, but will be appropriate to perform the relative comparisons necessary to quantify the impact of different innovations. For each reference system, for example Fichtner database, S&L study, a detailed performance and cost model has been designed using Microsoft Excel and it is presented in **Appendix B** and **Appendix C**. Due to the simplified calculation method, there are slight differences between the results of the LEC in this thesis and in the referenced studies, although the same technical data are used.

This simplified IEA method is a procedure of classical, dynamic investment calculation. The present value of an investment is distributed throughout the service life, so that the payment sequence from deposits and disbursements is converted into the so-called annuity. Thus rather than the total goal value being determined, instead it is the goal value per period. The annuity is calculated by the multiplication of the total investment cost Cinvest and the capital recovery factor crf. The total investment cost consists of the cost of site works, solar collectors, receivers, power block, HTF system and other components. The breakdown of total investment cost will be described in the following sections.

As previously described the LEC is the sum of the annual operation and maintenance costs and the product of the capital cost multiplied by the fixed charge rate. The total annual costs are the sum of the annuity and annual operation and maintenance costs. And the LEC is determined by the quotient of the total annual costs and the annual net electricity output.

$$LEC = \frac{crf * C_{invest} + C_{O\&M}}{E_{net}}$$

crf : capital recovery factor
C_{invest} : total investment cost of the plant
$C_{O\&M}$: annual operating and maintenance costs
E_{net} : annual net electricity output

A capital recovery factor is the ratio of a constant annuity to the present value of the total investment cost of the plant.

$$crf = \frac{k_d\left(1+k_d\right)^n}{\left(1+k_d\right)^n - 1}$$

k_d : real debt interest rate = 8%
n : life time = 25 years

The life time is defined as the useful life of the major technology components which are usually within a range of 20 to 30 years. In this research a 25-year life time and an 8% interest rate are assumed.

4.2 Overview of CSP Costs

4.2.1 Parabolic Trough

4.2.1.1 Investment Cost

The total investment cost of a parabolic trough power plant includes several major cost components. In related studies prepared by different companies or research institutes the major cost components are classified into different categories. This research focuses on 6 major cost components:

- Support Structure
- Receivers
- Mirrors
- Solar Balance of Plant
- Power Block/ Balance of Plant
- Thermal Storage

The remainder of this section discusses the cost for these 6 major components based on five projections from Fichtner and Sargent & Lundy study (S&L study). /S&L 2003/
/S&L 2009/ The technical data for these five projections are shown in **Table 4-1**.

Table 4-1: Technical data for S&L and Fichtner projections

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Collector area	km²	0.188	0.496	0.767	1.11	0.58
Electrical capacity	MWe	30	50	100	100	100
Capacity factor	%	22%	47%	33%	51%	25%
Annual electricity output	GWh/yr	58	206	290	451	223

As shown in **Table 4-1**, SEGS VI is an operational trough power plant with gas fired back up situated in the USA. The other four projections are all estimated or planned deployments.

Support Structure

The structure consists of the metal support system of the collectors which consist of the pylons and reflector support elements. Thus, the steel price exerts a great influence on the cost of this part. Wind loads during maximum wind speeds dictate the required strength of these units. Recent wind tunnel testing has provided improved data for use in optimizing the structural design, and reducing the weight necessary for long-term reliability.

The costs of support structure according to the Fichtner database, S&L study are shown in **Table 4-2**.

Table 4-2 : Cost of support structure for parabolic trough power plant

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Sopport Structure	$/m²	67	67	171	172	160

As a result of the significant rise in the price of steel from the year 2003 to 2008, the cost of a support structure for the parabolic trough power plant has increased approximately 2.5 fold during this period.

Receivers

The receivers are a major contributor to trough solar field performance. As a result of the utilization of different receivers from varied manufacturers and various models, there is a discrepancy in the costs between projects.

The **Table 4-3** shows the costs of receivers used in different projects.

Table 4-3 : Cost of receivers for parabolic trough power plant

Trough	**Unit**	**Sargent & Lundy**				**Fichtner**
		2003		**2008**		**2008**
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Receivers	$/m²	43	43	53	53	60

There are only two suppliers of receivers for the parabolic trough power plant: Solel and Schott. The scale of production of receivers has enlarged although not very much in the last five years. Furthermore, a lack of competition and high demand will maintain the high price of the receivers in the short term. As shown in **Table 4-3**, the price of receivers was raised to 60 $/m², one-half of the price in 2003.

Mirrors

Currently there are only three suppliers of mirrors for parabolic trough solar power plants worldwide: Flabeg GmbH & Co. (Flabeg), RioGlass, and Saint Gobain. With many activities related to CSP projects in Spain, there is high demand for the supply of mirrors, and so the cost of mirrors will remain high in the short term. The data from the Fichtner and S&L study are shown in the following Table.

Table 4-4 : Cost of mirrors for parabolic trough power plant

Trough	**Unit**	**Sargent & Lundy**		**Fichtner**
		2003	**2008**	**2008**

Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Mirrors	$/m²	43	40	63	63	60

From 2003 to 2005 there was little improvement in mass production and competition between manufacturers. Due to the continuous high demand the cost of mirrors for a parabolic trough power plant did not drop but instead increased from 40$/m² to 63$/m². With more projects starting in the near future, new additional mirror manufacturing facilities and glass manufacturers are expected to enter the market.

Solar Balance of a Plant

The solar balance of a plant (Solar BOP) consists of the remaining systems, components and structures that comprise of a complete solar field system that are not included amongst the steel support structure, receivers and mirrors. For instance:

- Solar tracking system
- Heat Transfer Fluid (HTF) system
- Interconnection piping
- Electronics and others

The costs of a solar balance of a plant are shown in the following table.

Table 4-5 : Cost of solar balance of a plant for parabolic trough power plant

Trough	**Unit**	**Sargent & Lundy**				**Fichtner**
		2003		**2008**		**2008**
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Solar BOP	$/m²	234	250	141	141	150

The cost of parts has sharply decreased in the last five years thanks to the Research & Development (R&D) of the solar tracking system, the HTF system (new medium of HTF, higher temperature of HTF) and other components. Based on continuous R&D the cost of the solar balance of a plant for a parabolic trough power plant is expected to steadily decrease over time.

Power Block/ Balance of Plant

The power block is the combination of the steam turbine and generator, the steam turbine and generator auxiliaries, and feedwater and condensate systems. The balance of plant (BOP) costs include the cost for the general balance of the plant equipment, the condenser and cooling tower system, the water treatment system, fire protection, piping, compressed air systems, closed cooling water system, plant control system, electrical equipment, and cranes and hoists. The costs of the power block and balance of plant are shown in **Table 4-6**.

Table 4-6: Cost of power block and balance of plant for parabolic trough power plant

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Power Block /BOP	$/kWe	527	306	1183	1183	2500

In the last five years and in the near future some advanced but cost intensive technologies have been used or are planned to be used in CSP projects. For instance, instead of a water cooling system, air cooling facilities are employed in water-deficient areas such as deserts. Moreover, because of the price increase of conventional energy generating and the balance of plant equipment the capital costs have shown a massive growth. As a result of the current state of the power block mentioned above, its cost figure from Fichtner has increased significantly compared to 2003 prices.

Thermal Storage

The capacity and type of thermal storage have significant impact on the total investment required for the CSP power plant and are key consideration in cost reduction. Based on information from the S&L study the detailed costs of the currently used two-tank thermal storage system are illustrated in **Table 4-7**. /S&L 2009/

Table 4-7: Break up of two-tank thermal storage cost

Components	$/kWeh	$/kWth	6 hours storage	
			$/kWe	$/kWt
Tanks	16.30	5.70	97.80	34.20
Pumps	19.18	6.71	115.08	40.26
Heat Exchanger	17.07	5.98	102.42	35.88
Instrumentation	1.25	0.44	7.50	2.64
Piping	6.15	2.15	36.90	12.90
Structural Steel	2.17	0.76	13.02	4.56
Insulation	11.71	4.1	70.26	24.60
Electrical	6.49	2.27	38.94	13.62
Concrete	3.2	1.12	19.20	6.72
Storage Media	43.95	15.38	23.70	92.28
Total	127.47	44.61	764.82	267.66

For 6 hours the two-tank indirect thermal storage total cost is 764.82 $/kWe (267.66 $/kWt). An overview of the thermal storage costs from the S&L reports is shown in the following Table.

Table 4-8: Cost of thermal storage for parabolic trough power plant

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Thermal Storage	$/kWe	-	958	-	765	-

Until now thermal storage systems have not been widely used in CSP projects due to its higher costs and solar collector area. To reduce the thermal storage system capital costs the HTF and storage material will be optimized for maximum steam cycle efficiency and storage compatibility. As an example the HTF temperature is expected to increase from the current 400C° to 500C° to improve the power cycle efficiency and reduce the further the costs of thermal storage.

Total Investment Cost

To summarize the information in this section the total investment costs based on S&L and Fichtner project are illustrated in **Table 4-9**.

Table 4-9: Comparison of total investment cost for parabolic trough power plant

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Total investment cost	M $	92	254	447	671	559
	$/kWe	3052	5073	4471	6708	5594

From this table the total investment costs for a parabolic trough power plant are currently between 4500 – 6700 $/kW. The costs for the additional hybrid and storage facilities are still relatively high but will decrease into the future.

4.2.1.2 Operating & Maintenance Cost

The operating and maintenance (O&M) costs are those costs associated with operating the CSP power plant and include the costs for the:

- Solar field
- Power block and balance of plant
- Water and process
- Staffing
- Capital equipment and other miscellaneous equipment
- Spare parts

This section provides a simplified introduction for each of the O&M costs and an O&M costs overview of different projects.

Solar Field

The solar field maintenance cost is mainly based on the replacement rate of mirrors, receivers, HTF pump seals and other solar field component.

Power Block and Balance of Plant

The O&M costs for the power block and the balance of plant cover the costs for the steam turbine overhaul, generator rewind, maintenance of the boiler feedwater pumps and cooling tower and other maintenance activities.

Water and Process

Water and process costs are based on the amount used for the weekly washing of the collectors, cooling water and power plant operating.

Staffing

The staffing costs are based on cost of the following 4 staff groups: Administrative, operating, solar field maintenance and power plant maintenance.

Capital Equipment and Miscellaneous

The capital equipment is the equipment for operating and maintaining the solar field and power plant facilities, for example the HTF evacuation rig, mirror wash rig, tractor etc.

Miscellaneous costs include the cost of vehicle fuel, safety & training, travel, the offices, and first aid equipment etc.

Spare Parts

Spare parts costs are based on 10% maintenance cost for the solar field and the power block/BOP.

The annual O&M cost depends on the size of the solar field and the electricity generation per year. For the early years it is relatively low at about 2% of total investment cost. The data are shown in **Table 4-10**.

Table 4-10: Cost of thermal storage for parabolic trough power plant

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Annual O&M	$/kWe	63	115	67	78	120

4.2.1.3 Levelized Energy Cost

Based on the methodology described in **Section 4-12** the Levelized energy costs (LEC) are calculated and shown in **Table 4-11**.

Table 4-11: Levelized energy costs for parabolic trough power plant

Trough	Unit	Sargent & Lundy				Fichtner
		2003		2008		2008
Power Plant		SEGS VI	Trough 50	Trough 100	Trough 100	Trough 100
		Hybrid	Storage	No Storage	Storage	Hybrid
Annual net electricity output	GWh	58	206	290	451	223
LEC	$/kWhe	0.181	0.143	0.168	0.157	0.293

crf : 9.37%

From the table shown above it is evident that the parabolic trough power plant with a hybrid operation and thermal storage system is more cost effective than the simple solar-only power plant.

4.2.1.4 LEC for project Andasol 1

In Section 3.1.1.1 a technical review of the first commercial CSP project in Europe the Andasol 1 was described. As an example in this section an economic review of Andasol 1 will be described.

Investment Cost

Based on the Fichtner database the major cost components for Andasol 1 are classified differently compared to the previous section. The five major cost components of the investment costs are the solar field, power block, civil & structure, thermal storage system, the HTF system incl. solar heat exchangers and other costs.

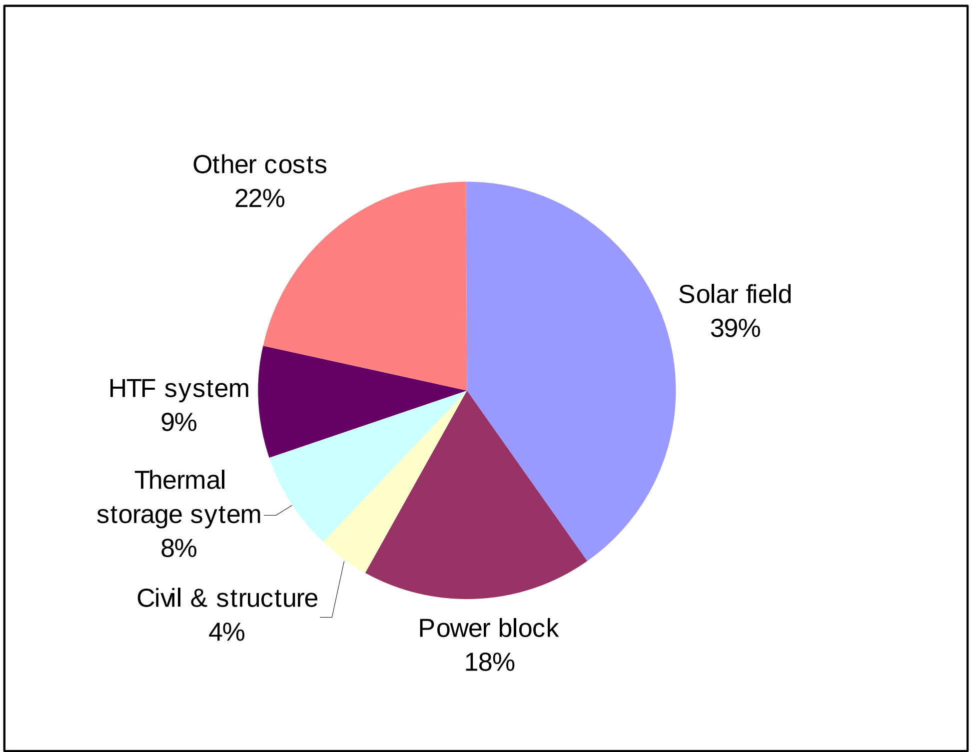


Figure 4-1: Major cost components for parabolic trough power plant Andasol 1

Figure 4-1 illustrates the six major cost components for the investment costs of Andasol 1. Among them the largest contributor to costs is the solar field with 39%, followed in descending order by other costs (22%), power block (18%), HTF system (9%), thermal storage system (8%) and civil & structure (4%).

O&M Cost

The O&M cost in this project is based on the cost of fuel consumption, water for cleaning, the condenser and power block and other operating and maintenance costs.

Table 4-12 provides a summary of the investment cost, O&M cost and the end result; the levelized energy cost.

Table 4-12: LEC for parabolic trough power plant Andasol 1

Andasol 1		
Technical Data		
Reflector Area	km²	0.51
Storage	h	9
Electricity Capacity	MWe	50
Annual Electricity Generation, net	GWh	179
Investment costs		
Solar field	M $	172

Power block	M $	76
Civil and structure	M $	18
Thermal storage system	M $	33
HTF system incl. solar heat exchanger	M $	37
Other costs	M $	92
Total	M $	428
Specific	**M $** **$/kWe**	8551
O&M Cost		
Total	**M $**	12.8
Specific	**$/kWe**	0.072
Electricity Generation Cost		
LEC	**$/kWh**	0.296

crf : 9.37%

The LEC for Andasol 1 is approximately 0.296 $/kWh. As the project began to operate last year this result is more reliable.

4.2.1.5 Cost Reduction Prospects

With a comparison of energy costs generated by conventional fuels the LEC of parabolic trough power plant is still quite high. Due to advanced technology, mass production, construction efficiency improvements and scaling up of current capacities the costs are expected to decrease. The components and cost of repairs will also become more cost effective thanks to technological advancements and competitive intensity among spares suppliers.

Technological Advancements

The technological advancements are expected to be realized by enhancing the efficiency of the solar field components, optimizing the thermal storage technology and improving the compatibility of the conventional power block for the CSP plant operation.

- To improve the efficiency of the solar field the reflectivity of mirror and the absorber absorption of receiver will be increased
- Advanced structural design with lower weight and costs.
- Through application of advanced HTF (for example HitecXL) this will raise the HTF outlet temperature and the storage efficiency.
- The turbines for the CSP power plant are designed to adapt to the night-time shutdown of the plant through the handling of the rapid start and stop times. Otherwise the reheat solution improves efficiency and reduces problems with erosion/corrosion and moisture in the LP turbine. The surplus heat can also be put into thermal storage to extend the production time for the plant.

The figure below illustrates the cost reduction curve from the year 2007 to 2025 based on an ESTELA report. The energy sale price of the parabolic trough power plant is expected to reduce from the current 26 US cents to about 15 cent in 2025 with a forecasted 3% reduction rate per year. /ESRELA 2008/

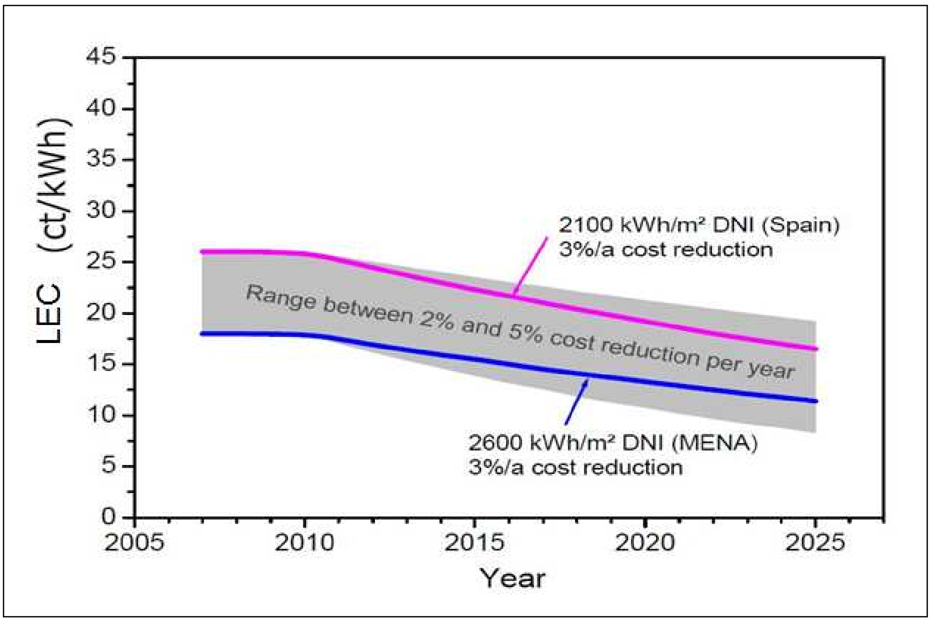


Figure 4-2: Cost reduction of parabolic trough power plant until 2025 /ESRELA 2008/

4.2.2 Solar Power Tower

4.2.2.1 Investment Cost

In this research the total investment costs of a solar tower power plant has been classified into seven major cost components:

- Site development & Infrastructure
- Heliostat field
- Receiver
- Tower & Piping
- Power Block/Balance of Plant(BOP)
- Thermal Storage
- Indirect costs

This section will discuss the investment costs for these seven major components mainly based on Fichtner database and the S&L study in 2003 and 2009. Among these the figures from the S&L study are estimated for a solar tower project in Spain, Solar Tres.

Site Development & Infrastructure

Site development is the first step in the construction of a CSP power plant. It is the site preparation for the heliostat field and also for the area of the tower, power block & BOP, thermal storage system and buildings. The activity typically involves site selection & planning as well as land-disturbing tasks such as clearing, excavating and grading.

These costs also include the land cost and construction costs for buildings (power house, storage depot and administration building) and roads inside the power plant and those connecting to the main roads. The required land area for the heliostat field is calculated according to the dissertation of Mr. Weinrebe from the University of Stuttgart using the following formula:

*Required land area of heliostat field = collector area * 1.3 + 0.18 km²*

The costs of site development & infrastructure according to Fichtner database, Sargent & Lundy Study are shown in **Table 4-13**.

Table 4-13 : Cost of Site development and Infrastructure for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Site development /Infrastructure	$/m²	11.6	-	25.3

In the Sargent & Lundy study of 2009 there are no data for site development & infrastructure. The topographic conditions and the price of the land and construction materials are the main influential factors that impact on the cost of site development & infrastructure.

Heliostat Field

The investment cost for the heliostat is composed of the costs for heliostats (including drive and foundation), the wiring, process control and assembly. The solar field for the project Solar Tres plans to utilize 2493 glass-metal heliostats. Each heliostat is 96m², which means the entire heliostat field has a collector area of 0.24km². The **Table 4-14** shows the investment costs of the heliostat field.

Table 4-14 : Cost of heliostat field for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Heliostat field	$/m²	160	230.6	191.2

In the S&L study 2003 a heliostat price of 160$/m² was given. Compared with a price of 230.6$/m² given in the S&L study 2009 the estimated price may rise higher. In accordance with the Fichtner database, for a relatively large scaled project the heliostat field has a price of 191.2$/m².

Through technical advancements, for example thinner glass with better reflectivity, improved aiming techniques and updated control system mass produced heliostats have great potential to reduce costs.

Receiver

The heliostat field receiver system is another cost intensive component of a solar tower power plant. For this cost a figure from ECOSTAR study was used from the Fichtner project: 151.5$/kWht with a receiver capacity of 155MWht. The other two figures from the S&L study were given with the units of $/m² rec. area.

Table 4-15 shows the investment costs of the receiver system for a solar tower power plant.

Table 4-15 : Cost of receiver system for solar tower power plant

Tower	Sargent & Lundy		Fichtner
	2003	2008	2008
Power Plant	Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
	Storage	Storage	Solar-only

Receiver	280 m²	280 m²	155 MWth
	57143 $/m²	121680 $/m²	151.5 $/kWth

The S&L study 2009 provides a price that is over twice as high for a receiver than the price given in Solar Tres, which is considered a more reasonable price. Through the reduction of heat losses at the receiver, an increase of the receiver absorbance and the scaling up, the cost of the receiver system is expected to drop in the future.

Tower & Piping

To support an even larger heliostat field and to collect more solar energy the tower in the solar tower power system is designed to be higher than before:

- Solar Two (10MWe), 90m
- PS 10 11 (MWe), 115m
- Solar Tres (13.65MWe), 130m

The investment cost of tower is related to its height and the figure given by Fichtner is calculated using the following formula:

$$C_{Tower} = 552000 * e^{\left(\frac{Height[m]}{100}\right)}$$

The tower height in this projection is 150m. The costs of the tower and piping are shown in the following table:

Table 4-16 : Cost of Tower & Piping for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Tower & Piping	$/m²	11.6	21.99	18.9

The investment cost of the tower is influenced by the price of the construction materials, and therefore cost will be different every year. The piping efficiency will increase due to larger piping and shorter lengths per kWe in the large scaled project, ultimately resulting in lower costs.

Power Block & Balance of Plant

The power block and balance of the plant costs include: the steam turbine and generator, steam turbine and generator auxiliaries, steam generator, feedwater and condensate systems, condenser and cooling tower system, water treatment system, fire protection, piping, compressed air systems, closed cooling water system, instrumentation, electrical equipment, etc. The costs of the power block and the balance of the plant are shown in **Table 4-17**.

Table 4-17: Cost of power block and balance of plant for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Power Block & Balance of Plant	$/kWe	1397.7	4719.6	1556.6

The cost reduction for the power block and the balance of the plant can be realized due to the efficiency increase of the turbine, for example the reheat turbine with higher operation temperatures, and through scaling up.

Thermal Storage

The Solar Tres solar tower power plant will make use of a large thermal storage system with 16 hours, 593MWth thermal storage capacity. The Fichtner project discussed in this research has no thermal storage design.

Following table illustrates the investment costs of the thermal storage system.

Table 4-18: Cost of thermal storage for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008

Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Thermal storage	$/kWt	49	24.9	-

The main components for the current two-tank thermal storage system are the hot storage tank, cold storage tank and piping. The advanced thermal storage concept, for instance the direct thermocline molten-slat storage system can reduce the thermal storage cost significantly.

Total Investment Cost

A summary of the information in this section including the total investment costs based on the S&L and Fichtner project are illustrated in **Table 4-19**.

Table 4-19: Comparison of total investment cost for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Total investment cost	M $	119	219	214
	$/kWe	8753	16905	4534

According to this table the total investment cost for solar tower plant is currently from 4500 to 16900$/kW. These costs are much higher than for the parabolic trough power plant of 3000 to 6700$/kW, which was shown in **Section 4.2.1.1**.

4.2.2.2 Operating & Maintenance Costs

Operating and maintenance (O&M) costs are those costs associated with operating the CSP power plant. This includes the costs for the:

- Solar field
- Power block and balance of the plant
- Water and process

- Staffing
- Capital equipment and miscellaneous
- Spare parts

These O&M cost components have been described in Section 4.2.1.2 and will not be repeated here.

The annual O&M cost depends on the size of the solar field and the electricity generated per year. The data are shown in **Table 4-20**.

Table 4-20: Cost of thermal storage for parabolic trough power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
O&M	$/kWh	0.03	0.01	0.05

The power plant with thermal storage can obtain a high capacity factor and a large annual electricity generation capacity, thus the annual O&M cost will be decreased.

4.2.2.3 Levelized Energy Cost

Based on the methodology described in **Section 4.12** the Levelized energy costs (LEC) are calculated and shown in **Table 4-21**.

Table 4-21 : Levelized energy costs for solar tower power plant

Tower	Unit	Sargent & Lundy		Fichtner
		2003	2008	2008
Power Plant		Solar Tres 13.65 MW	Solar Tres 13.65 MW	Tower 47.25 MW
		Storage	Storage	Solar-only
Annual net electricity out-	GWh	93	93	116

put				
LEC	$/kWhe	0.15	0.22	0.22

crf : 9.37%

From the figure shown above it is evident that, the current levelized energy cost for the solar tower system is around 22 US cent/ kWh. The S&L study prepared in 2003 anticipated a higher scaling factor and a rapid cost reduction for the solar tower system. Therefore the price estimated in that study is much lower than the current price.

4.2.2.4 LEC for Project PS 10

In **Section 3.1.2.2** a technical review of the first commercial solar power tower project in Europe PS10 was given. As an example, an economical review of PS10 will be described in this section.

Investment Cost

According to /TEB 2007/ the investment cost for the solar tower power plant PS10 amounted to € 35 million (US$ 47 million), with a contribution of €5 million (US$6.7 million) from the EU's Fifth Framework Program for research, awarded for the project's innovative approach.

O&M Cost

The O&M cost in this project is calculated based on the average O&M cost rate of Fichtner database and the S&L study at 2.5%/yr of total investment cost. **Table 4-22** provides a summary of the investment cost, O&M cost and the end result; the levelized energy cost.

Table 4-22: LEC for solar tower power plant PS10

PS10		
Technical Data		
Reflector Area Electricity Capacity Annual Electricity Generation, net	km² MWe GWh	0.075 11 24
Investment costs		
Total Specific	M $ $/kWe	47 4273
O&M Cost		
Total Specific	M $ $/kWe	1.175 0.05
Electricity Generation Cost		
LEC	$/kWh	0.23

crf : 9.37%

The LEC for PS10 is approximately 0.23$/kWh. This is even lower than the LEC of for the parabolic trough power plant Andasol 1.

4.2.2.5 Cost Reduction Prospect

Due to advanced technology, mass production, construction efficiency improvements and scaling up of the current capacities the energy generation cost for the solar tower system is expected to gradually decrease.

The figure below illustrates the cost reduction curve from the year 2012 to 2025 based on the S&L study 2009. The levelized energy cost of the solar tower power plant is expected to reduce from 0.205$/kWh to 0.076$/kWh with a reduction rate at 63%.

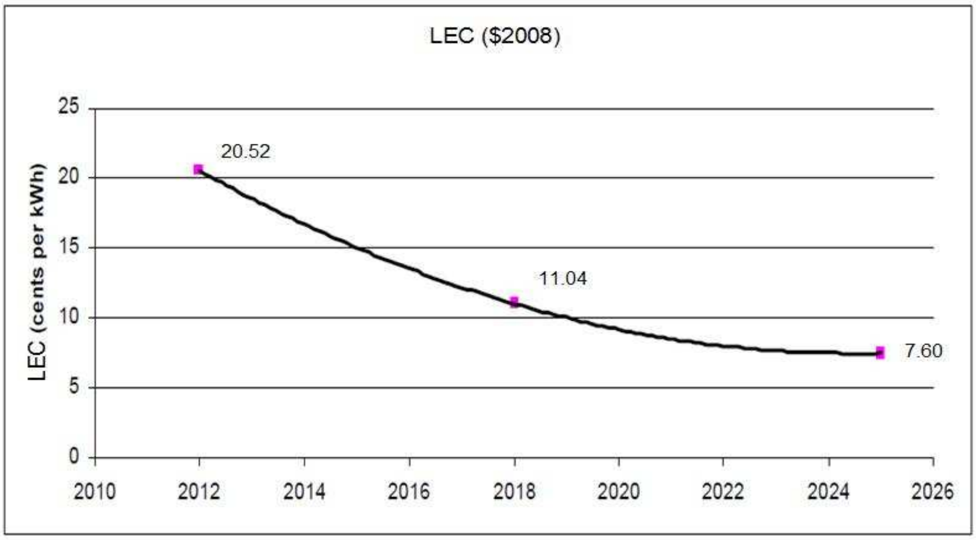


Figure 4-3: Cost reduction of solar tower power plant until 2025 /S&L 2009/

4.2.3 Cost Comparison of Different CSP Systems

In the previous sections the detailed energy generation costs of the parabolic trough power plant and the solar tower power plant have been analyzed. Based on the technical and cost-component data from the S&L study 2009, the electricity generation cost of the parabolic trough plant with storage is about 28.6% lower than solar tower plant with storage. Based on Fichtner internal data, the operational commercial plant Andasol 1 has a higher cost than the solar tower PS10. This is mainly due to the lower cost input for the solar tower in the Fichtner database than for the real data.

Due to the high potential for technology advancement and the efficiency increase of solar tower technology, it is expected that the costs will decrease more than for the parabolic trough technology. Until 2025, the forecast cost of the solar tower plant is expected to be over 30% lower than for the parabolic trough plant.

At present, the technology of the linear Fresnel and dish-Stirling are relatively immature and are still not used in commercial projects. There are only some demonstration plants with small capacity using this technology. As a result, the simple and lower- cost design for linear Fresnel has not met its intended goal. According to data from the Novatec Biosol AG for 1.4MW project Puerto Errado 1 (PE1), the LEC is approximately 0.386$/kWh, which is 30% higher than for the parabolic trough system. The project site is located near Calasparra in the region of Murcia, Southern Spain.

5 Pre-feasibility Study of a CSP Project in China

5.1 Background

In recent years with the rapidly growing energy demand, more environmental problems and limited fossil resources in China mean that new sustainable electricity generation options are required.

According to the EIA, in 2007 the total installed electricity capacity in China was 624 million kilowatts which was 20% more than in 2006. /EIAC 2009/ Meanwhile the total net electricity generation in 2007 was 3,042 billion kilowatt-hours, which has also increased by 12% compared with the previous year. /EIAG 2009/ The following figure illustrates the significant growth of electricity demand in China from 1980 to 2007 with the sharp growth in recent years.

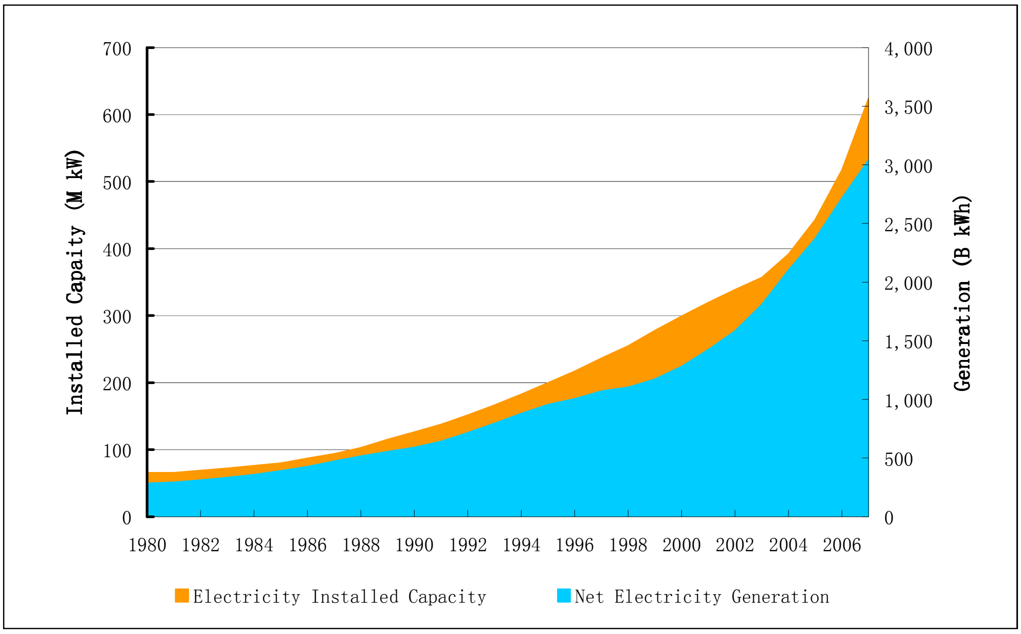


Figure 5-1: Increase of electricity generation and installed capacity in China between 1980 and 2007

As a major electricity producer China has also consumed a large amount of energy. Based on the figures for 2006, coal, oil and natural gas have accounted for 69.7%, 20.3% and 3% of the energy consumed respectively and the remaining 6% and 0.8% have come from hydro and nuclear power. /Li; Wang 2007/ This is illustrated in **Figure 5-2**.

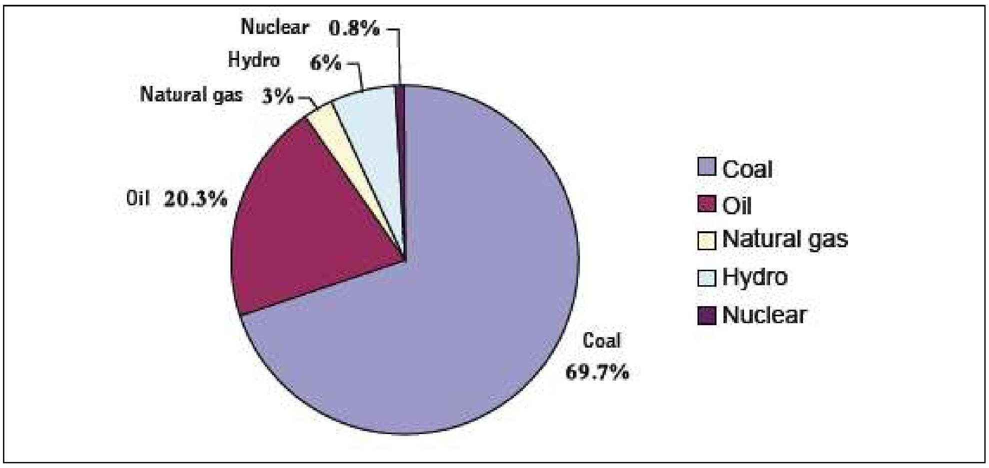


Figure 5-2: Primary energy consumption in China 2006

The most important primary energy resources in China are coal and oil but these reserves are of a very finite amount. In **Figure 5-3** a forecast of the major energy reserves in china compared to the rest of the world is shown.

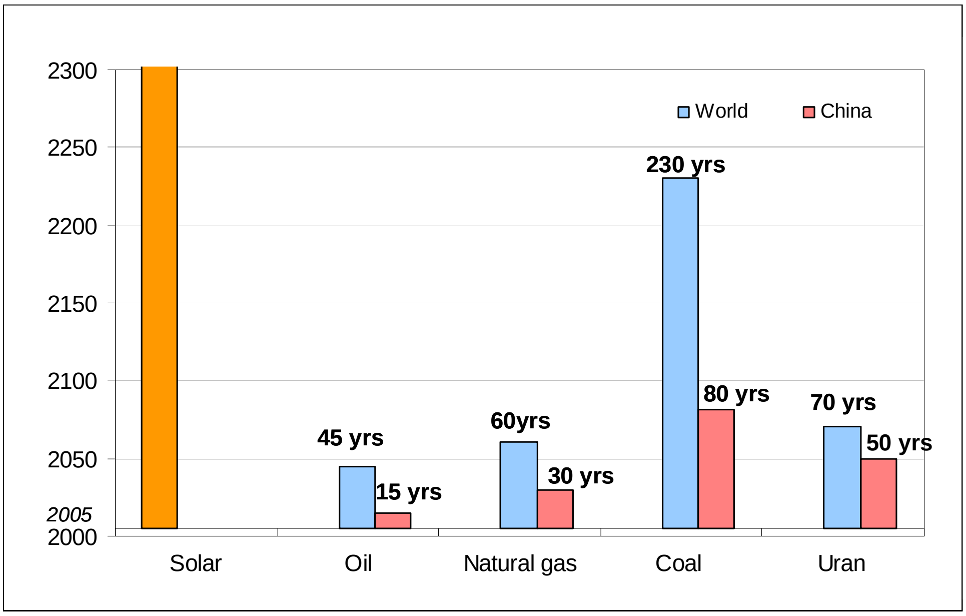


Figure 5-3: Forecast of major energy reserves in china and in the world

From the figure above it is evident that the reserves of the three major conventional fossil fuels, oil, natural gas, and coal will be exhausted in the very near future and even the uran ore used for nuclear energy will run out in China in less than 50 years. To optimize the current electrical power structure and decrease dependency on energy imports, the increasing use of renewable energies, such as wind, solar, biomass energy becomes a priority.

In order to improve the development of renewable energy technologies and create markets for renewable energy, the first renewable energy law (REL) in China was been approved in February 2005 and begun to take effect in 2006. Aiming to implement this REL a target of 10% renewable energy of the total primary energy consumption by 2010 and 15% by 2020 has been established.

As a renewable and clean energy source, solar power has great development potential in China. A long term target of 1000MW energy generation capacity for concentrating solar power plants will be reached by 2020. Presently, there is still no large scale commercial CSP plant operated in China. The only operational demonstration plant is a 75kW solar tower plant in Nanjing, Jingsu Province which was built in 2005. This year (2009) China will build a new experimental solar tower plant with a 1.5MW capacity near Beijing and this will start to operate next year. /Zara 2009/

In this chapter a prefeasibility study for a 100MW parabolic trough power plant and a further 1000MW CSP project will be described.

5.2 Site Selection

To select a suitable site for CSP plants many factors such as technical, environmental and economical perspectives must be considered. The main siting factors are listed in **Table 5-1** and will be examined in this section. /Cohen et al. 2005/

Table 5-1: Main siting factors of concentrating solar power plant

Siting Factor	Requirement
Solar resource	Direct incidence radiation > 1,800kWh/ (m^2•a) for economical operation
Land requirement Area Site topography Land cover	 20,000 - 40,000m^2 per megawatt of electricity generation Flat, slope < 3% (slope < 1% most economical) Limited agriculture value
Infrastructure	Proximity to transmission-line corridor, natural gas pipeline and rail transportation
Water availability	Adequate supply, otherwise dry cooling

5.2.1 Solar Resource

The solar resource is the most important siting factor for a cost effective CSP power plant, and it is related directly to the energy generation price. According to **Table 5-1**, a CSP power plant is only economical for locations with more than 1,800kWh/ (m^2•a) direct radiation (equivalent to approximately 5kWh/(m²•day). China belongs to the so-called sun-belt countries with parts of western and northern China complying with this requirement, see **Figure 5-4**. Compared with countries at the same latitude, the solar resource in China is similar to those in the US and better than in Europe and Japan.

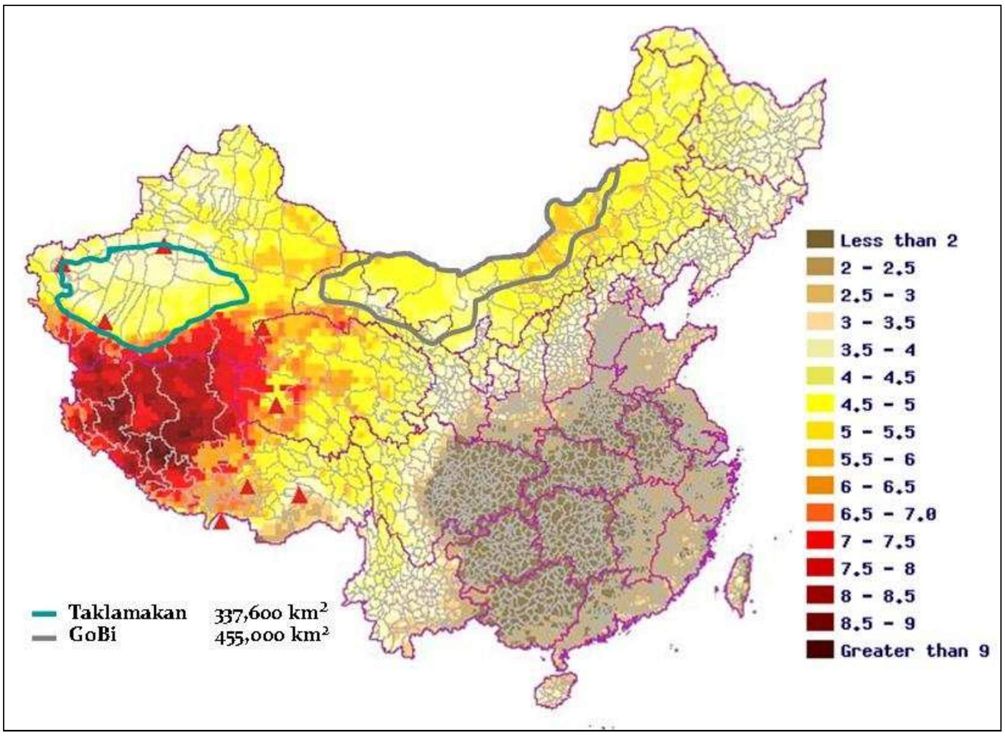


Figure 5-4: Solar resource of China (DNI data with unit: kWh/ (m²•day)) /GENI 2008/

The green and grey lines circled areas in Figure 5-3 are the two biggest deserts in China: the Taklamakan in northwest China with 337,600km² area and the Gobi desert with 455,000 km². Both of them have an average DNI of 5.0kWh/(m²•day). That is to say, the solar power in ca. 23,960 km² of the desert area would be able to satisfy all Chinese electricity consumption requirements in 2008 (3,450 billion kWh /NBSC 2009/. Besides, Tibet and parts of Qinghai and Gansu province also have extremely high DNI and long sunlight durations. The solar resource data from China are described in **Table 5-2**. /EEUSE 2008/

Table 5-2: Distribution of solar energy resource in China

Annual sunshine duration (h)	Annual solar radiation kWh/ (m^2d)	Area	Equivalent foreign areas
3200 - 3400	5.0 - 6.5	North Ningxia/ North Gansu/ Southeast Xinjiang/ West Qinghai/ West Tibet	India, North Pakistan
3000 - 3200	4.5 - 5.0	North Hebei/ North Shanxi/ South Ningxia and Inner Mongolia/ Middle Gansu/ East Qinghai/ Southeast Tibet and South Xinjiang	Jakarta, Indonesia area
2200 - 3000	4.0 - 4.5	Shandong/ Henan/Southeast Hebei/South Shanxi/ North Xinjiang/ Jilin/ Liaoning/ Yunnan/ North Shaanxi/ Southeast Gansu/ Guangdong and South Fujian/ Jiangsu and North Anhui/Beijing	Washington DC area in USA
1400 - 2200	3.5 - 4.0	Hubei/ Hunan/ Jiangxi/ Zhejiang/ Guangxi/ North Guangdong/ South Shaanxi/ Jiangsu and South Anhui/ Heilongjiang	Milan region in Italy
1000 - 1400	2.5 - 3.0	Sichuan and Guizhou	Paris and Moscow

5.2.2 Land Requirement

Compared with a conventional power plant a CSP project requires more area because of the large collector area and area for storage. As shown in Table 5-1 about 20,000 – 40,000m^2 of land is required by a typical CSP plant per MW of electricity generation. This also depends if heat storage facilities are used. A CSP plant without thermal storage system requires approximately 20,200 (5 acres) of land per MW of installed capacity, which will increase to ca. 32,000 m^2 per MW for a CSP plant with 6 hour thermal storage.

In addition to area requirements, a CSP project also has strict demands on the land slope. A land slope of less than 1% is the most cost effective and most efficient. However a land slope of between 1% and 3% would still be acceptable, but would cause costs to increase.

Land cover is also an important characteristic for siting of a CSP project. Land used for agriculture, commerce and residence should not be considered as a CSP location. And this criterion is more important for China, which is the most populous country on earth. China is the third largest country in total area behind Russia and Canada. However, its arable land area accounts for only 10% of the total and China's average per capita amount of arable land is only 40% of the world's average. Therefore, the location for the CSP project must be chosen in wasteland or semi-wasteland. China has wasteland of an area of 1.79 million km² (18.6% of China's total land area), among which, 13.3% is desert, 4.8% is uncovered rock and 0.5% is glacier and permanent snow. /MLR 2009/ Most of this wasteland is located in the western and northern part for example in Tibet, Inner Mongolia and Qinghai, which also has the best solar resources in China. These areas would be suitable locations for large scale CSP projects.

5.2.3 Infrastructure

The large scale implementation of CSP technology requires a sufficient grid infrastructure. For CSP plants built in distant places from the load center dedicated high-voltage (HV) transmission lines would be required.

According to the development plan of the national wide grid interconnection in China made by Electric Power Research Institute of China, the nation's total installed capacity of long distant HVDC transmission will reach 500GW in the year 2010. The first 10-15 years of the 21st century will be a key period to form a nationwide interconnected grid. By the year 2010-2020, a nationwide interconnected grid will be basically established, which will cover all major regional and provincial power grids with a total installed capacity of about 750GW by the year 2020. /NI 2007/ The following figures show the planned nationwide grid interconnection for china in the year of 2010 and 2015-2020. Additionally, all existing and expected HVDC transmission projects until 2020 in China will be listed in **Appendix D**.

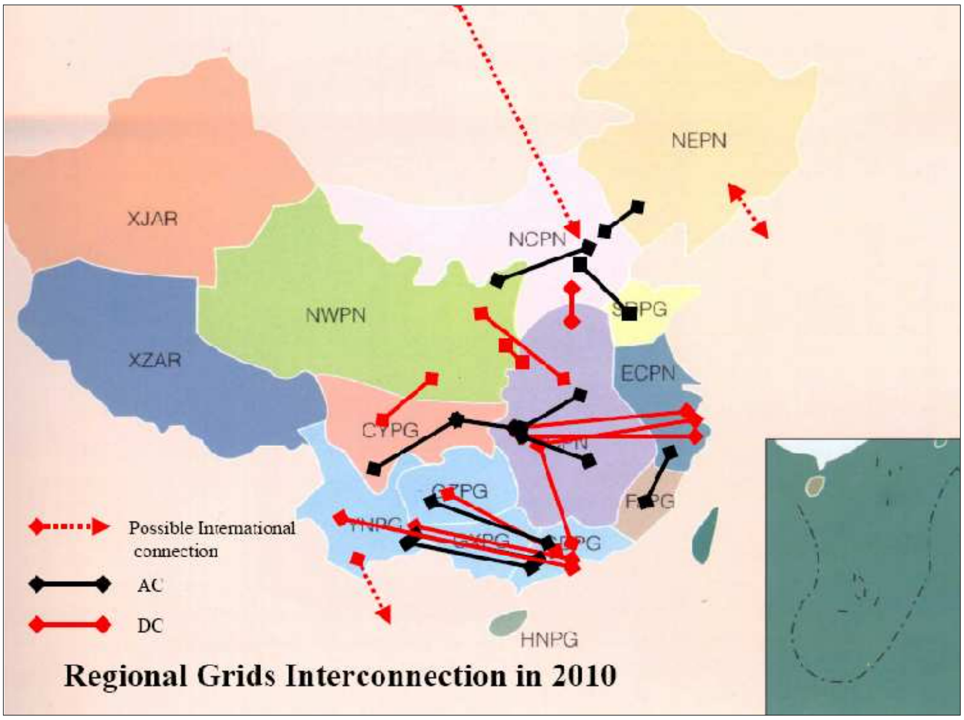


Figure 5-5: HVDC/AC transmission net in 2010 /NI 2007/

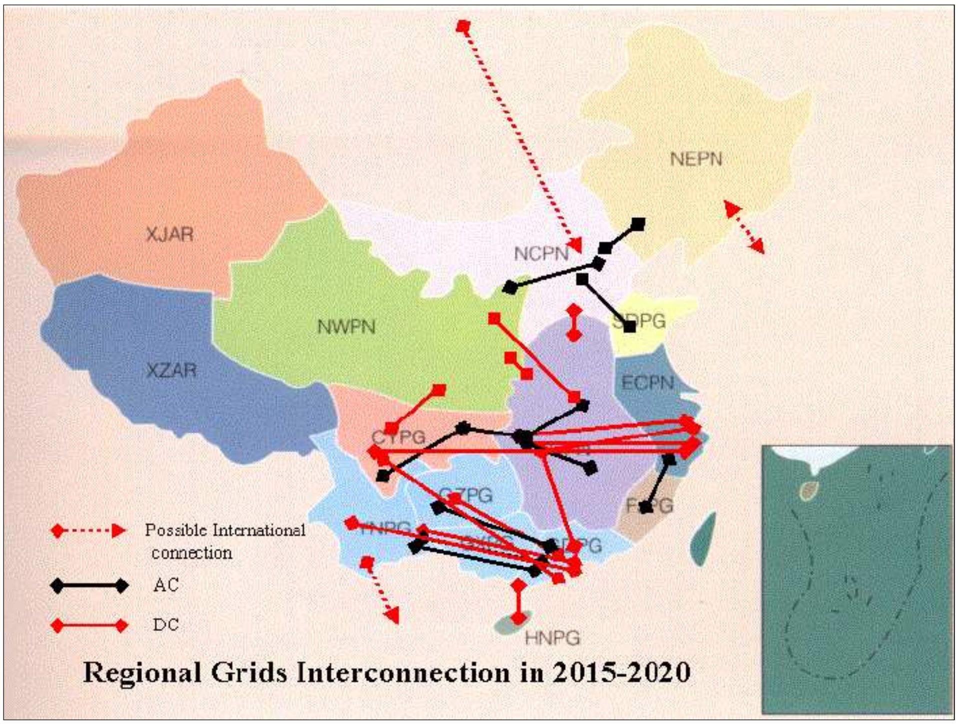


Figure 5-6: HVDC/AC transmission net in 2015-2020 /NI 2007/

It is worth noting that in this development program there are no HVDC transmission lines built inside West China or between West and Mid China, which have the best solar resources in China. When large scale CSP projects are built in these high solar radiation regions, new dedicated HVDC transmission lines should also be planned and built.

5.2.4 Water Availability

Another critical siting issue is the availability of water. For CSP plants water is required continually for steam generation, mirror washing and mostly cooling. If water cannot be supplied in sufficient quantities, for example in desert regions, a dry cooling system can also be used. However, in this case the electricity cost for the plant will be raised by some 10%. According to research by the University of Arizona, for a 280MW capacity CSP power plant this would be expected to consume approximately 2.3 – 2.6 million m^3 of water per year. /Avery et al. 2007/

Water resources in China are distributed unevenly, in northern China the provinces face severe water shortage but in the south the water resource are relatively affluent. Rivers and lakes are the major fresh water resources in China while in western China over 59,000 km^2 is covered by glaciers which are another important water resource. Figure 5-5 illustrates the current distribution of water resources in China.

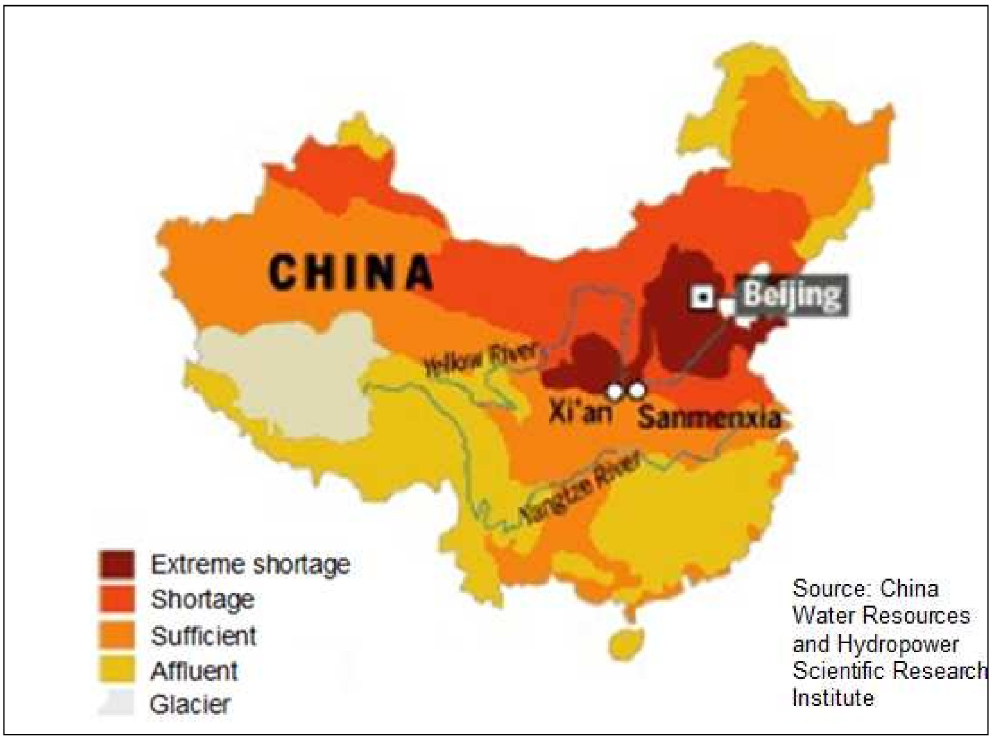


Figure 5-7: Water resource distribution of China /See 2008/

5.2.5 Location

Based on the siting factors discussed in the previous sections three suitable locations for the CSP plants are considered (See **Figure 5-8**).

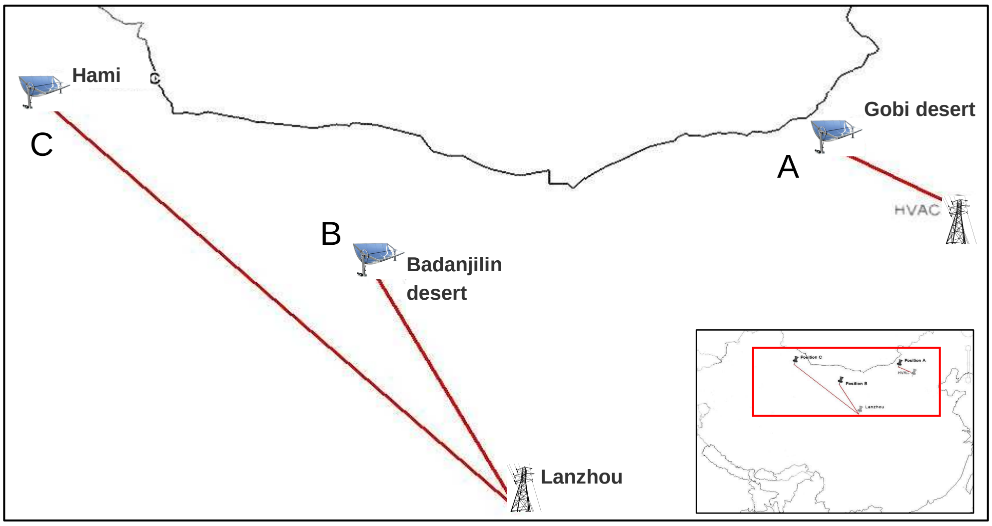


Figure 5-8: Selected locations of distribution channels

- Point A in Inner Mongolia: This is located at 42°N and 111° E between Baotou and Erlian-haote city, in Gobi desert, 200km away from the HVAC trunk lines and 400km away from the load center of the North China power grid and 38km away from the Aibugai River. According to the solar radiation map shown in Figure 5-4 this point has an average direct solar radiation of between 5 and 6kWh/(m²•day).

- Point B in Inner Mongolia: This is located at 40°N and 101° E in Badanjilin desert 100 km to the north of Zhangyi city of Gansu province, 150 km to the east of Jiuquan city of Gansu Province. In this area the solar resource has an average of 5 to 5.5kWh/(m²•day).

- Point C of Xinjiang province: This is located at 42°N and 93°E near to Hami city and is the nearest to a grid facility, the distance is about 25km. The solar factor in this area is around 5.5 kWh/(m²•day).

The more accurate solar resources for the three selected locations are acquired from the RETScreen International Clean Energy Project Analysis Software. This data is summarised in Figure 5-9 and Figure 5-10 with the details presented in **Appendix E**. /RETS 2009/

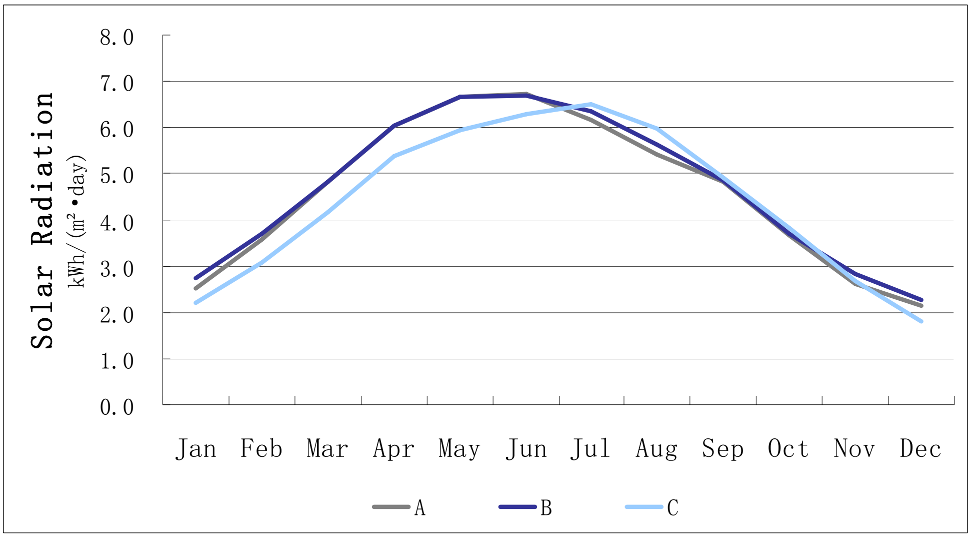


Figure 5-9: Monthly solar radiation in selected locations

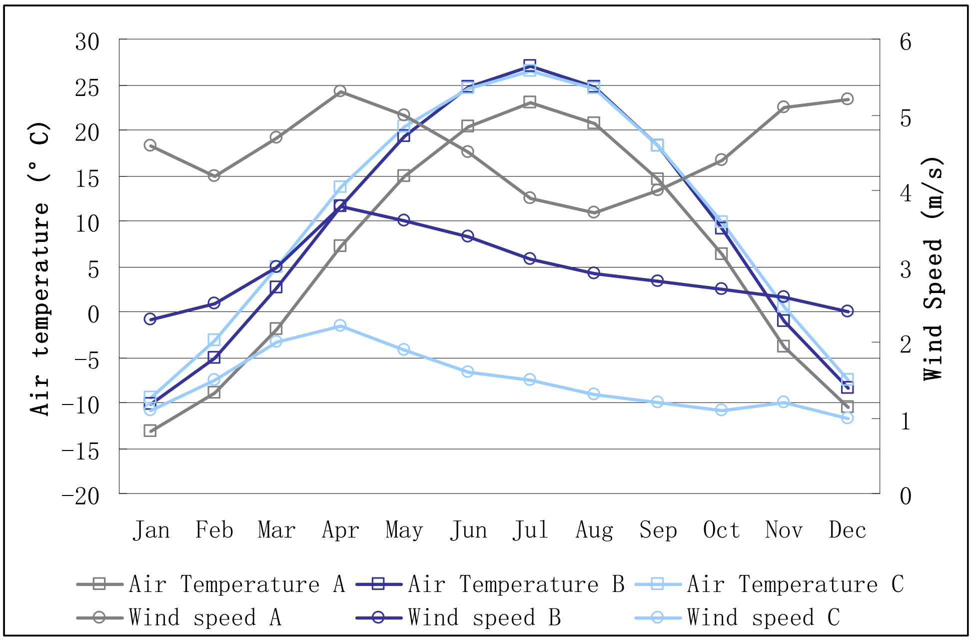


Figure 5-10: Air temperature and wind speed of selected locations

In any of these proposed locations it is geologically feasible to build a CSP facility. However, by considering a comparison of the wind speed at the three locations, B and C would be more appropriate for the CSP plant. Location B and C both possess similar air temperatures, but B has the advantage in that it is sited near the load center. As a result, it is suggested that point B is the most suitable place for the large scale CSP facilities.

5.3 System Design

Through consideration of the technology maturity, investment and O&M costs and the local conditions, in the first phase a 41MW parabolic trough solar power plant with 6 hours thermal storage will be built at the selected locations. Following this, more plants will be set up in the same region and the total design-capacity of this project will be 1000MW. The following table shows the technical data of the 41MW parabolic trough solar power plant.

Table 5-3: Technical data of the planned parabolic trough solar power plant

Technical data	
Electrical capacity	41 MW
Collector area	580,000 m²
Total power plant area	ca. 2 km²
Thermal storage	6 hours
Annual operating hours	ca. 4000 hours
Forecast electricity generation	about 165 GW per year

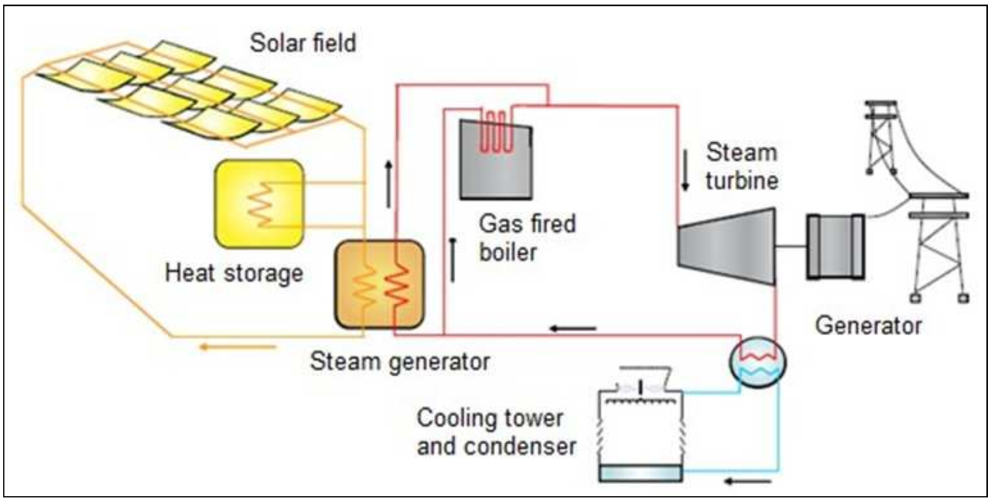


Figure 5-11: Process diagram of the planned parabolic trough solar power plant

As shown in **Figure 5-11** the solar energy collected by the parabolic reflectors and receiver will be transferred by synthetic oil. The heat energy will be transmitted to the heat exchangers and will then be converted to superheated steam. The steam drives a conventional turbine and then electricity will be produced by the connected generator.

During the daytime with intensive solar radiation, the thermal energy will be stored by molten salt in large tanks. In the evening and on cloudy days, the stored heat can be returned to the steam generator and thus driving the turbine and generating electric power.

Due to the water shortage in the selected location dry cooling facilities will be used in the CSP power plant.

For the first CSP plant a 6 hour molten salt thermal storage system is utilized and in the following plants that are built a hybrid operation could also be an alternative. To realize the 24h energy supply all year round a gas or biogas fired turbine will run additionally when sufficient solar energy is not available. The thermal storage system and hybrid operation give the CSP power plant the ability to produce not just peak load, but also a base load of electricity.

5.4 Cost Status of CSP Project in China

If the solar thermal power plant is erected in China there are several components or services that can be obtained directly from the Chinese market and these will lead to great cost-reduction-potential (CRP) for the CSP project in China. On the other hand there are parts which need to be imported from countries with technology leadership this being due to patent regulations or a lack of technology in China.

In the following sections the estimated values of the cost-reduction-potential for the investment cost and O&M costs are considered.

5.4.1 Investment Cost

In general the cost-reduction-potential (CRP) of the CSP project in China lies in the lower costs of steam turbine and the generator set, the steel construction works and civil works. The method to determinate the CRP is that the prices of comparable products or services in China are set into a relation to the typical price in Europe/North America. The next table shows the product or service and the resulting cost reduction factors.

Table 5-4: Comparison of costs of relevant products / services and CRP

Product / service	Price Europe / N. America	Price China	CRP
100 MW STG set	200 $/kW [1)]	68 $/kW [2)]	~ 1/3
Steel construction works	–	–	~ 0.3 [3)]
Civil works	–	–	~ 0.4 [4)]

Source: [1)] /FISE 2008/ [2)] /CPC 2009/ [3)] /BCIS 2007/ [4)] /Baulinks 2006/

Based on various sources listed under Table 5-5 the price of a 100MW steam turbine and generator set (STG set) in China is approximately one third of the price in Europe/North America. The cost reduction potential of steel construction works and civil works between China and Europe/North America can reach 30% and 40% respectively.

After the application of these CRP, the specific investment costs for the parabolic trough power plant could decrease by 39%. The detailed data is shown in the following table and figure

Table 5-5: Comparison of major cost components for parabolic trough plant in China and in Europe/North America

Components	Price Europe / N. America	Price China	CRP
Solar BOP ($/m²)	150	150	
Steel support structure ($/m²)	160	48	~ 0.3
Receiver ($/m²)	60	60	
Mirrors ($/m²)	60	60	
Power block ($/kWe)	2900	957	~ 1/3
Thermal storage ($/kWe)	765	765	
Site development ($/m²)	30	12	~ 0.4
Specific investment cost ($/kWe)	11140	6810	39%

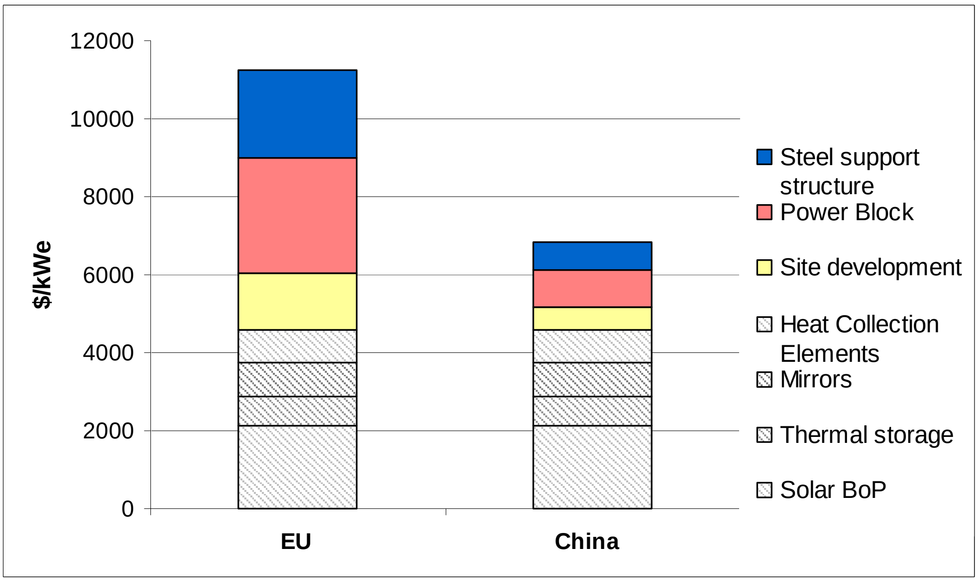


Figure 5-12: Comparison of cost reduction potential for investment cost

The cost reduction factor of 0.4 for the civil works must be treated carefully, as the selected location for the CSP power plant is usually remote and desolate. Therefore the savings due to lower wages etc. in China may be compensated for by the requirement to build new roads or a complete new infrastructure in the desert.

The distribution of the investment costs of parabolic trough project as an example (41MWe), are illustrated in **Figure 5-13**.

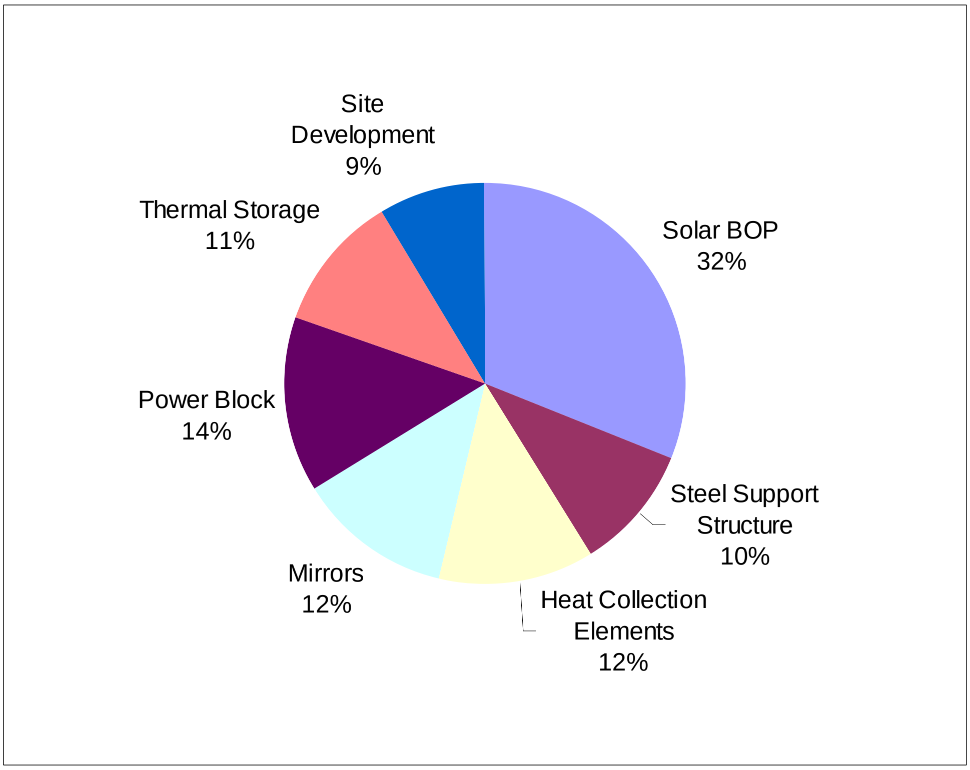


Figure 5-13: Distribution of investment cost for parabolic trough project in China

It can be seen that there is CRP in about 35 percent of the total investment cost.

5.4.2 O & M Cost

In the operation and maintenance sector it is also possible to reduce costs compared with a plant operated in Europe and North America. For a common scenario in Europe and North America O&M costs are usually about 2% of the total investment cost per year. In consideration of all cost reduction factors described below, this proportion could be reduced to 1.25%/yr.

Figure 5-14 shows the typical costs for O&M of a 100MW parabolic trough power plant with storage in North America. /S&L 2009/

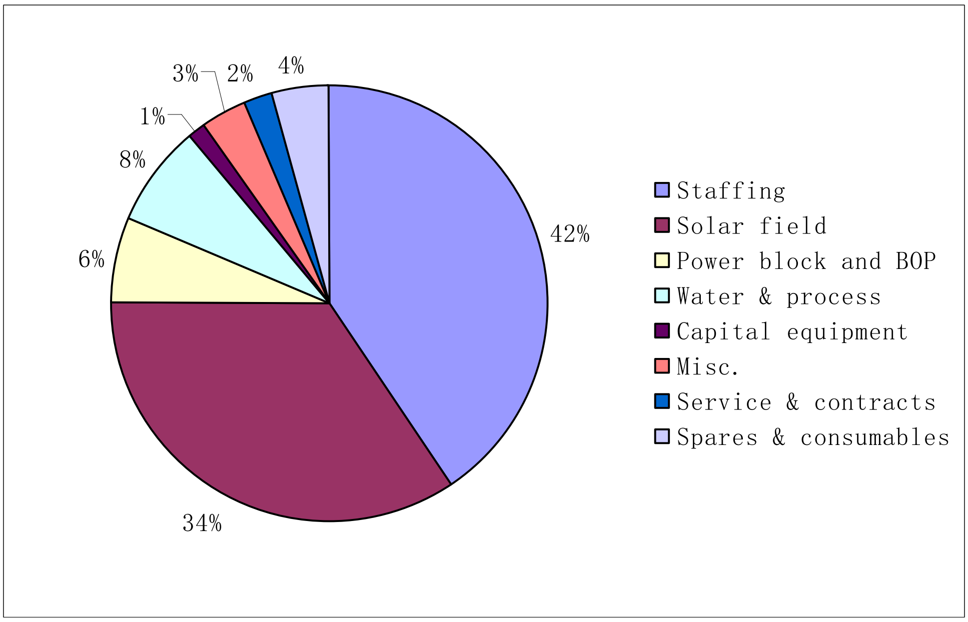


Figure 5-14: Costs distribution of O&M

Based on **Figure 5-14**, it is evident that the largest component of the O&M costs is the staffing costs. The following table shows a comparison of the staffing costs for China and Germany.

Table 5-6: Comparison of staffing costs between China and Germany

Staff	Germany $/h	China $/h	CRP %
Industrial workers	24.5	1.6	94%
Seller	15.5	2.5	84%
Chief secretary	23.3	4.1	82%
Engineer	35.8	6.3	72%
Head of department	47.3	9.8	79%
Product manager	41.6	19.1	54%

For the operation and maintenance costs only the staffing cost reduction will be considered. For the calculation of the O&M costs a 72% CRP for an engineer will be used. Due to relatively low productivity in China, a CRP of 0.3 for staffing costs has been chosen.

Based on the O&M costs from the Sargent & Lundy Study in 2009 and the proportion of staffing costs, a rough 2.5 $M/a cost reduction is estimated. **Figure 5-15** illustrates the cost distribution for O&M in China, it can be seen that the cost for the solar field is the largest component.

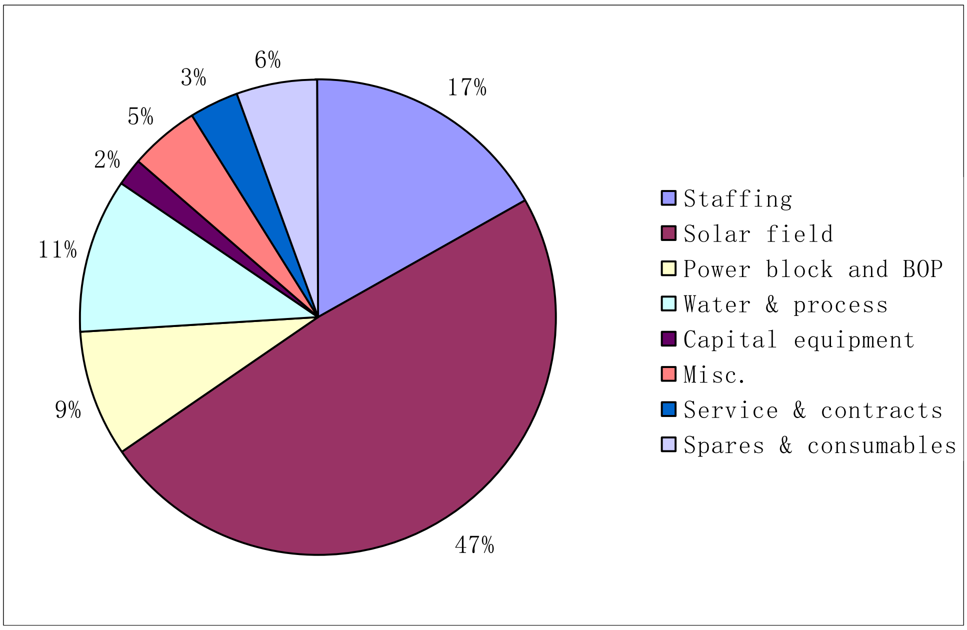


Figure 5-15: Cost distribution O&M in China

5.4.3 Levelized Energy Cost

As summarised from the figures shown in the previous sections and based on methodology described in **Section 4.1.2**, the levelized energy cost of parabolic trough project in China is calculated. (See **Table 5-7**)

Table 5-7: Comparison of LEC of parabolic trough plant in Europe/North America with in China

Trough	Unit	Fichtner	China
		2008	2009
Power Plant		Trough 41	Trough 41
		Storage	Storage
Annual net electricity output	GWh	196	194
LEC	$/kWhe	0.369	0.208
Cost Reduction	%	44%	

With the utilization of the lower cost of local products and staffing, the electricity cost of a 41MW parabolic trough power plant in China is 44 percent lower than that in Europe/North America.

Due to technology advances, mass production, and more competition the cost for the CSP system will steadily decrease. According to a report of the CSP industry made by Deutsche Bank the electricity costs can be reduced by 15%-65% until 2020. /DBR 2009/ (See Figure 5-16)

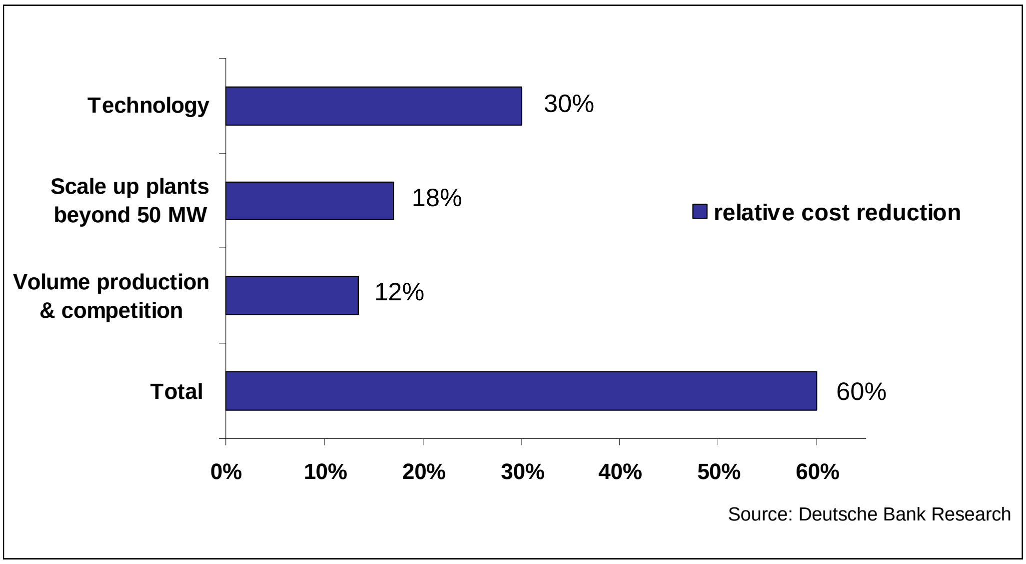


Figure 5-16: Electricity cost reduction for parabolic trough plant until 2020

Based on this expected CRP the costs for further parabolic trough plants in China are estimated based on the three scenarios described below and are illustrated in **Figure 5-17**.

- **Case I:** 100MW Solar trough power plant, with Chinese market CRP, project in recent years
- **Case II:** 1000MW Solar trough, with Chinese market CRP and economics of scale CRP, project in recent years
- **Case III:** 1000MW Solar trough, with Chinese market CRP, economics of scale CRP and learning factors, project in 2020

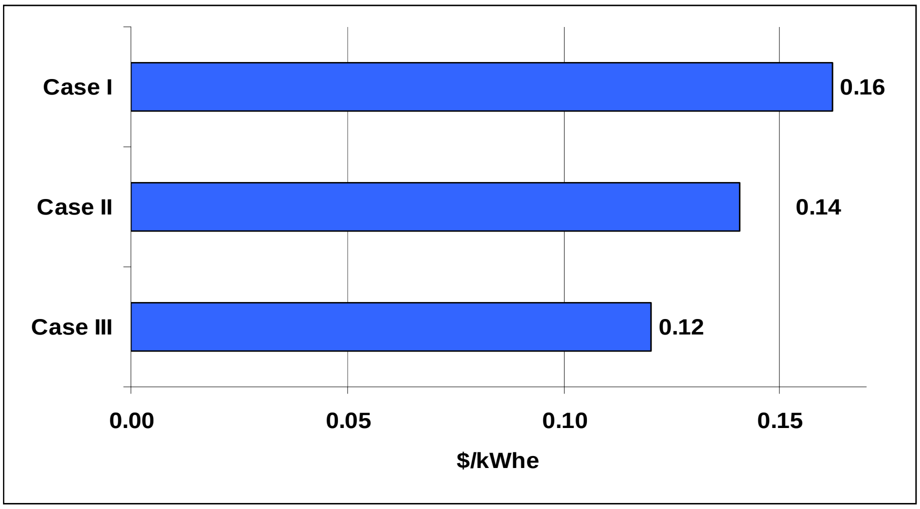


Figure 5-17: Electricity cost for three scenarios in China

In 2020 the electricity cost of 1000 MW parabolic trough project in China is expected to be reduced at 0.12 $/kWhe, which takes only 75% of the cost for current 100 MW plant.

All of the costs shown above are electricity costs at the power plant. However, most generated electricity must be transported and used in the load centers, for example, from Xinjiang or Gansu provinces to South China or East China and from Inner Mongolia to Beijing. These transmission distances are normally a distance of 200km to 2000km. To obtain the electricity costs at the load center the electricity losses of 0.5GWh/(km•a) (Fichtner data), the investment cost for 1000kV HVAC transmission line of approximately 3,980$/km /TDW 2007/ and the investment cost for 500kV HVDC transmission lines of approximately 383,000$/km /TDW 2005/ must be considered. The result is illustrated in the following figure and detailed figures are presented in **Appendix F**.

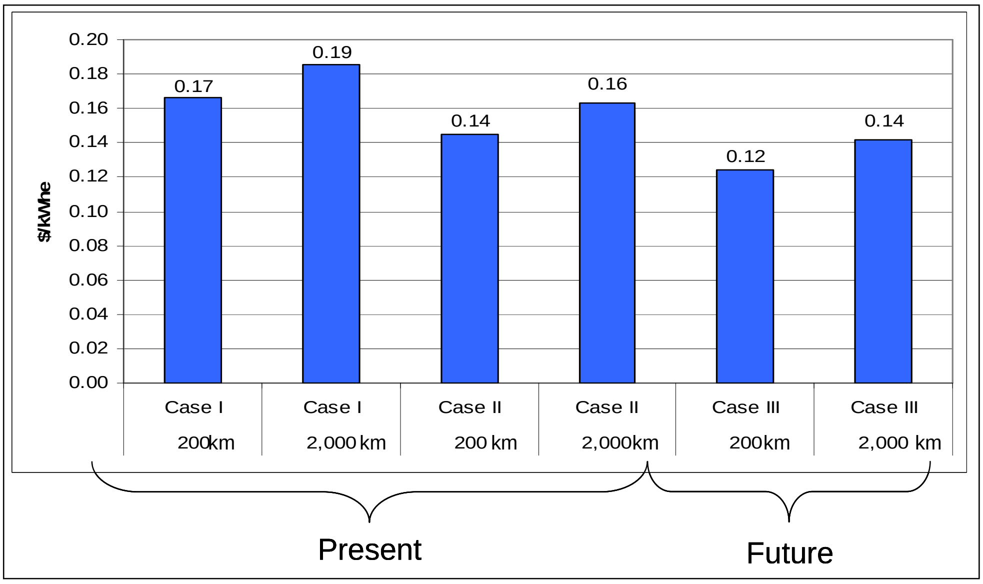


Figure 5-18: Electricity cost at the load center

For short distance transmission (200km) AC is preferred and DC is used for a long distance transmission of 2000km.

5.4.4 Comparison with PV in China

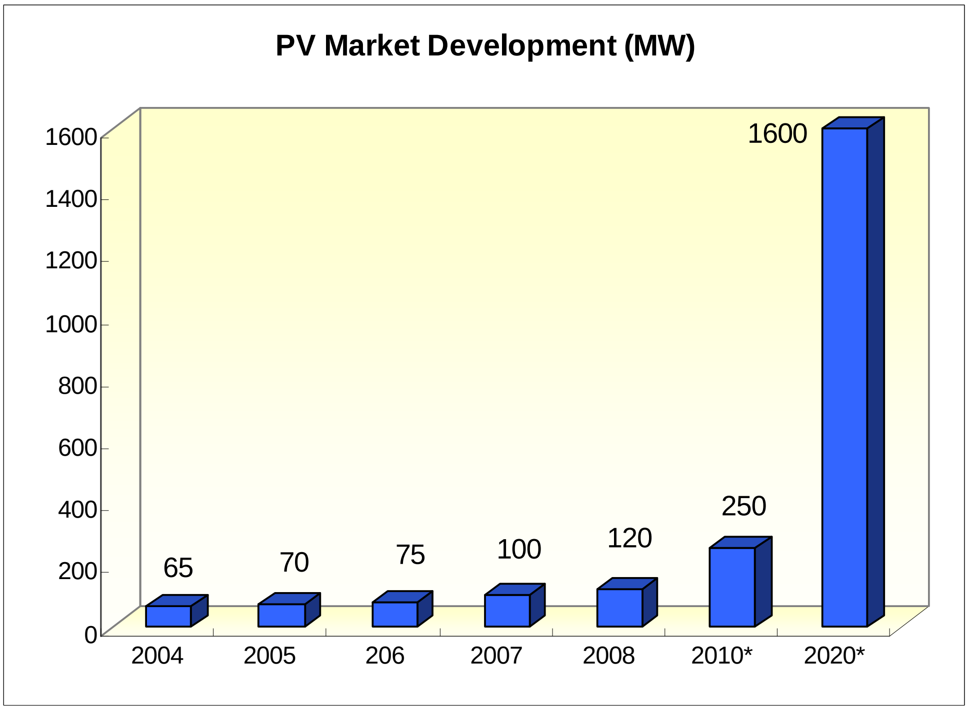
As another choice for large scale solar energy applications, photovoltaic technology (PV) has the world's fastest growth and is expected to maintain a high speed of development. According to a recent status report of global renewable energy use, since 2002 the PV production has been doubling every 2 years and increasing on average by 48% each year. At the end of 2008, the cumulative installed PV capacity reached 15GW worldwide and 90% of the capacity is grid-connected solar PV.

Due to the large demand, the manufacture of solar cells and PV arrays has expanded dramatically in recent years. By the end of 2007, there are over 50PV manufacturers in China and the annual production capacity has reached 2900MW. In the year 2007, Chinese manufacturers have produced almost 1200MW solar cells and PV modules and become one of the biggest PV producers in the world. Despite the large production capacity, the cumulative installed PV capacity by 2007 was only 100MW, less than 1% of the world cumulative installed capacity. Roughly 98% of the PV production of China has been exported.

In March 2009 the Ministry of Finance and Ministry of Housing (Urban-Rural) in China has promulgated the "Implementing the Opinion Concerning the Speeding up the Promotion of the Use of Solar Energy/PV Power in Buildings" and decided to subsidize a maximum 20 RMB/W for the building of integrated photovoltaic solar energy. /MFMHURC 2009/ This policy will promote the widespread utilization of PV technology in China. The following table and figure demonstrate the development forecast of the PV electricity generation in China. /Lu et al. 2009/

Table 5-8: Forecast of PV market in China by 2010 and 2020

Market segment	2010		2020	
	Capacity MW	Share %	Capacity MW	Share %
Rural electrification	80	32%	200	12.5%
Communication & Industry	40	16%	100	6.25%
Photovoltaic product	30	12%	100	6.25%
On-grid PV building	50	20%	1000	62.5%
On-grid PV power plant	50	20%	200	12.5%
Total	**250**	**100%**	**1600**	**100%**



* The figures for 2010 2020 are estimated

Figure 5-19: China PV market development 2004-2020

The new technology of PV to improve the efficiency and reduce the costs has also been developed very quickly. From standard crystalline silicon modules newer alternatives include casting wafers instead of sawing, thin film, concentrator modules, 'Sliver' cells etc. Due to competition, and the economics of scale and technology advancement, the capital cost of PV has decreased. The PV cost of development in California and China is shown in **Figure 5-20**. /Shah 2008/

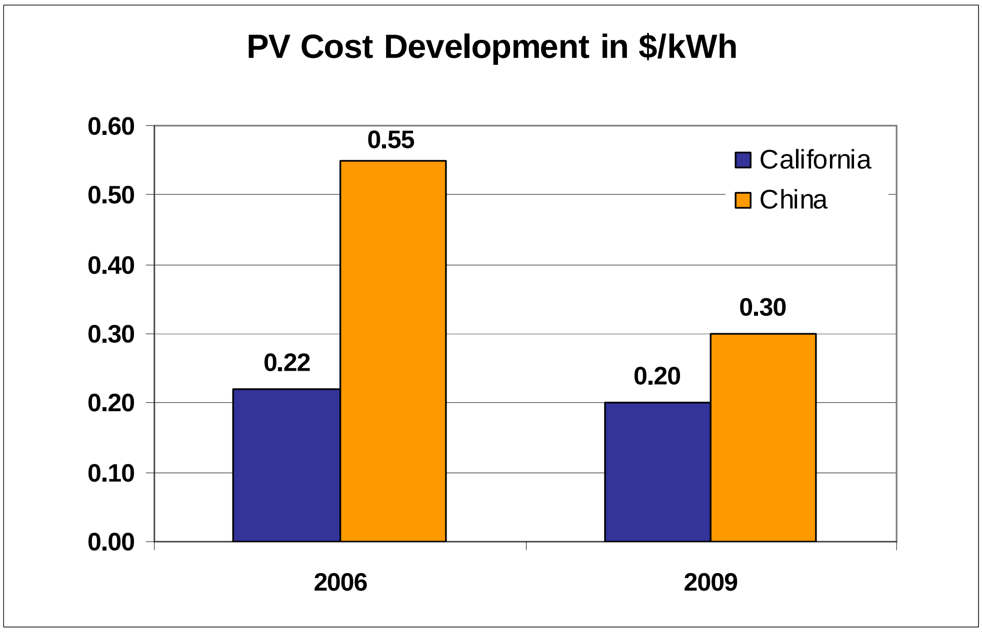


Figure 5-20: PV cost development in California and China

The sharp reduction of the PV cost from 0.55$/kWh in 2006 to 0.30$/kWh currently in China is mainly the result of competition by manufacturers and mass production.

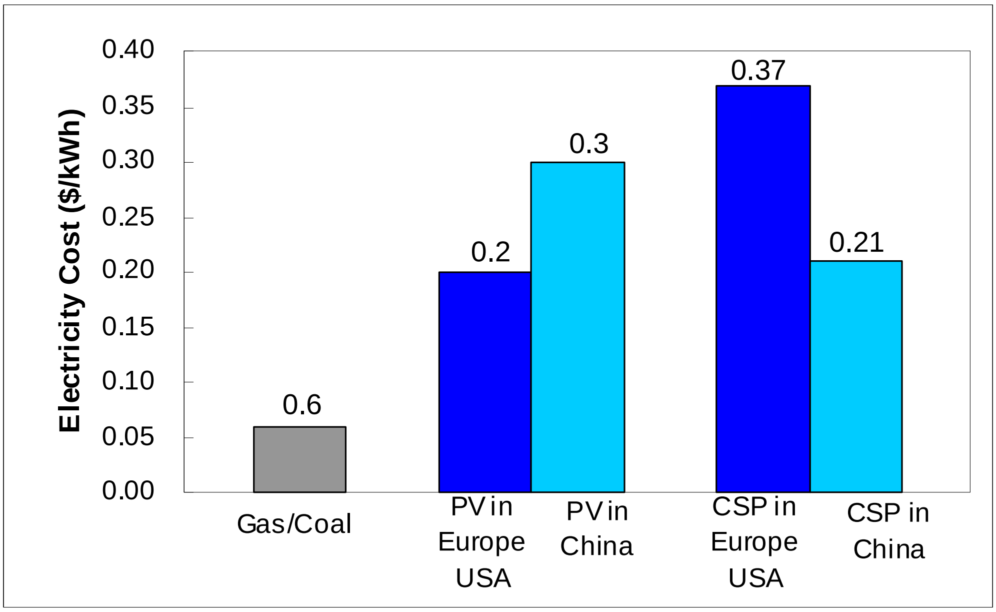


Figure 5-21: Comparison of current electricity cost

The **Figure 5-21** indicates that compared with conventional energy, for example natural gas and coal, the cost of electricity generated by PV and CSP technologies is still high. At present, CSP has the cost advantage over PV technology in China for large-scale power plants in terms of their energy storability. However, for small-sized energy generation in the residential, commercial and industrial sector or in countries with low solar radiation PV technology plays a dominant role. Due to the price increase of conventional fuels and continuously declining costs for solar energy, CSP and PV will become more competitive and become the sources of energy provision.

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Appendix A: CSP Projects Overviw

(Status: March 2009)

Technology	Region	Country / (project name)	Companies involved	Projected	EPC	Operation
Dish Stirling	Europe	Spain Aznalcóllar	Abengoa Group	0.8		
	Europe Total			0.8		
	USA	USA (California)- Solar one	Stirling Energy systems (SES)	800		
		USA (California) - Solar two	Stirling Energy systems (SES)	950		
	USA Total			1750		
Dish Stirling Total				1750.8		
Fresnel trough	ROW	Australia (Liddell)	Solar Heat & Power		15	1
	ROW Total				15	1
	USA	USA ,California	Ausra	177		
		USA ,Florida	Ausra	300		
	USA Total			477		
Fresnel trough Total				477	15	1
Parabolic trough	Europe	Greece	Theseus A.E , Solar Millenium	50		
		Italy	ENEA,Enel	40		
		Spain (Alvarado)	Acciona Group		50	
		Spain (Majadas)	Acciona Group	50		
		Spain Extremasol -1	Solar Millenium, Hidro cantabrico	50		
		Spain Andasol 1	Solar Millenium AG, ACS Cobra			50
		Spain Andasol 2	Solar Millenium AG, ACS Cobra		50	
		Spain Andasol 3	Solar Millenium AG, EDP		50	
		Spain Andasol 4	ACS Cobra	50		
		Spain (Ciudad Real) Helios 1,2	Abengoa Group	100		
		Spain (Ciudad Real) Manchasol 1&2	ACS Cobra		100	
		Spain (Cordoba)	Acciona	100		
		Spain (Ecija)	Abengoa Group	100		
		Spain (Palma del Rio/Cordoba)	Acciona Group	100		
		Spain Consol 1-2	Conergy group	100		
		Spain Murcia	Solar Millenium	100		
		Spain	Iberdrola	400		
		Spain Solnova 1-3	Abengoa Group		150	
		Spain (Badajoz) Extresol-1-3	ACS Cobra		150	
		Spain (Puertollano)	Iberdrola		50	
		Spain Andasol 5-7	ACS Cobra	150		
		Spain Termesol	SENER	50		
		Spain Solnova 4,5	Abengoa Group	100		
	Europe Total			1690	600	50
	MENA	Algeria	Abengoa/NEAL		20	
		Morocco	Abengoa/ONE	20		
			GEF Morrocco	6		
		Egypt	Solar Millenium, Orascom	30		
		Jordania	Rfp,Solar Millenium AG	70		
		Israel	Solel as promoter	70		
		United Arabic Emirates	MASDAR, RfP	100		
	MENA Total			296	20	
	ROW	Mexiko	RfP		29	
		India	Fichtner Solar	30		
		Iran (Yazd)	Fichtner Solar	65		
		China	Solar Millenium AG	1000		
	ROW Total			1095	29	
	USA	California (SEGS)	FLP, LUZ, Solel			354
		USA (Arizona)	Abengoa	280		
			Solargenix/Acciona/Schott			1
		USA (Nevada)	Solargenix/Acciona/Schott			64
		USA ,California	Solel	533		
			Bright source , SCE	1300		
		USA ,Nevada	Solar Millennium, NV Energy	250		
	USA Total			2363		419
Parabolic trough Total				5444	649	469
Solar Tower	Europe	Spain Solar tres	SENER/Rocketdyne		17	
		Spain PS10	Abengoa Group			10
		Spain PS20	Abengoa Group		20	
		Spain (Almaden)	Abengoa Group	20		
		Spain AZ20	Abengoa Group	20		
	Europe Total			40	37	10
	MENA	United Arabic Emirates	SENER, MASDAR	17		
	MENA Total			17		
	ROW	South Africa	ESKOM	100		
	ROW Total			100		
	USA	USA ,California	Bright source , PG&E	900		
	USA Total			900		
Solar Tower Total				1057	37	10
Updraft tower	ROW	Australia	SBP/EnviroMission	200		
		China	SBP/EnviroMission	200		
	ROW Total			400		
Updraft tower Total				400		
Technology TBD	MENA	Israel	RfP	250		
	MENA Total			250		
	USA	USA	Acciona Group	2000		
	USA Total			2000		
Technology TBD Total				2250		
Grand Total				**11378.8**	**701**	**480**

(Unit: MW; Source /DBR 2009/)

Appendix B. Cost Calculation for Trough

Trough		Trough No Storage	Trough storage	Trough No Storage	Trough No Storage	Trough Storage	Trough No Storage	Trough storage
Source		S&L03 SEGS VI Hybrid	S&L03 Trouph 50 TES Spain	Fichtner UAE 100 Hybrid	Fichtner UAE 75 Solar only	Data base for China project	S&L08	S&L08
TECHNICAL DESIGN DATA								
Solar field								
Collector area	km²	0.188	0.496	0.58	0.58	0.58	0.767	1.11
area total				2	2	2		
Power plant								
Thermal capacity, power plant	MWt	103.6	154.3	260.0				
Power plant efficiency	%	28.9%	32.4%	38.5%				
Electrical capacity, net	MWe	30	50	100	75	41	100	100
Storage								
Thermal capacity	GWht		1.4					
full-load hours	h		9					6
OPERATIONAL DATA								
Utilization								
Capacity factor	%	22%	47%	25%	25%	46%	33%	51%
- actual plant	h/yr	1927	4117	2230	2230	4000		
Annual electricity generation, net	GWhe/yr	58	206	223	167	166	290	451
Fuel consumption	GWh/yr			160				
Gas electricity generation, net	GWhe/yr			56				
Solar electricity generation, net	GWhe/yr			167				
Fuel price	$/kWh			6				
FINANCIAL CONSTRAINTS								
Lifetime	yr	25	25	25	25	25	25	25
Interest rate, inflation adjusted	%/yr	8%	8%	8%	8%	8%	8%	8%
Annuity	%/yr	9.37%	9.37%	9.37%	9.37%	9.37%	9.37%	9.37%
O&M	%/yr	2.1%	2.3%	2.1%	2.1%	2.1%		
CAPITAL EXPENDITURES								
Solar BoF	$/m²	250	234	150	150	150	141	141
Steel support structure	$/m²	67	67	160	160	160	172	172
Heat Collection Elements	$/m²	43	43	60	60	60	53	53
Mirrors	$/m²	43	40	60	60	60	63	63
Power Block	$/kWe	527	306	2500	2500	2900	1183	1183
Thermal storage	$/kWe	0	958	0	0	762	0	762
Site development	$/m²			30	30	30	0	0
Solar BoF	M $	47	116	87	87	87	108	157
Steel support structure	M $	13	33	93	93	93	132	191
Heat Collection Elements	M $	8	21	35	35	35	41	59
Mirrors	M $	8	20	35	35	35	48	70
Power Block	M $	16	15	250	188	120	118	118
Thermal storage	M $	0	48	0	0	32	0	76
Site development	M $			60	60	60		
Indirects								
Total capital expenditures	Mln $	92	254	559	524	461	447	671
Specific capital expenditures	$/kWe	3052	5073	5594	6992	11136	4471	6708
ELECTRICITY GENERATING COSTS								
O&M	M $/yr	2	6	12	11.2	9.9	6.7	7.8
- Avg. burdened labor rate	M $/yr							
- Staff cost	M $/yr							
- Ann. material& services cost	M $/yr							
Annuity	M $/yr	9	24	52	49	43	42	63
Insurance								
O&M	$/kWe	64	115	120	150	0.060	67	78
O&M	$/kWhe	0.033	0.028	0.054	0.067		0.023	0.017
Fuel costs	M $/yr			1.008				
Total electricity generating costs	M $/yr	11	30	64	60	53	49	71
Specific electricity generating costs	$/kWhe							
- LEC	$/kWhe	0.182	0.143	0.293	0.362	0.321	0.168	0.157
- figure in report	$/kWhe		0.1037	0.33			0.1275	0.1198

Appendix C: Cost Calculation for Tower

Tower				
Source		S&L03 Solar Tres S&L storage	S&L08 Solar Tres storage	Fichtner DT-2a no storgae
TECHNICAL DESIGN DATA				
Solar field				
Heliostat field area	km²	0.234	0.228	0.609
Heliostat area	km²			0.330
Receiver area	m²	280	280	
Receiver leistung	MWht			155
Power plant				
Thermal capacity, power plant	MWt	105.0	120.0	360.9
Efficiency	%	13.0%	13.5%	13.1%
Electrical capacity, net	MWe	13.65	13.65	47.25
Storage				
Thermal capacity	GWht	1.7	1.9	
full-load hours	h	16	16	
OPERATIONAL DATA				
Average insolation	kWh/(m²*d)	6	6	6
	MWh/(m²*yr)	2.19	2.19	2.19
Availability	%	92%	92%	92%
Utilization				
Capacity factor	%	78%	78%	28%
- actual plant	h/yr	6833	6833	2448
Annual electricity generation, net	GWhe/yr	93	93	116
FINANCIAL CONSTRAINTS				
Lifetime	yr	25	25	25
Interest rate, inflation adjusted	%/yr	8%	8%	8%
Annuity	%/yr	9.37%	9.37%	9.37%
O&M	%/yr	2.34%	0.11%	2.69%
CAPITAL EXPENDITURES				
Site development & Infrastructure	$/m²	11.6		25.3
Heliostat field	$/m²	160	230.6	191.2
Receiver	$/m² rec	57143	121680	151.5
Tower and piping	$/m²	11.6	21.99	18.9
Thermal storage	$/kWt	49	24.9	0.0
Power block/BOP	$/kWe	1397.7	4719.6	1556.6
Indirect Costs	$/kWe	2666	4382	653.8
Site development & Infrastructure	M $	2.7		15.4
Heliostat field	M $	37.4	52.6	63.1
Receiver	M $	16.0	34.1	23.5
Tower and piping	M $	2.7	5.0	7.8
Thermal storage	M $	5.1	3.0	0.0
Power block/BOP	M $	19.1	64.4	73.5
Indirect costs	M $	36.4	59.8	30.9
Total capital expenditures	Mln $	119	219	214
Specific capital expenditures	$/kWe	8753	16905	4534
ELECTRICITY GENERATING COSTS				
O&M	M $/yr	2.794	0.238	5.766
- Avg. burdened labor rate	M $/yr	0.062		
- Staff cost	M $/yr	2.046		
- Ann. material& services cost	M $/yr	0.686		
Annuity	M $/yr	11	21	20
O&M	$/kWhe	0.0300	0.0026	0.0499
Total electricity generating costs	M $/yr	14	21	26
- LEC	$/kWhe	0.1500	0.2224	0.2234
- figure in report	$/kWhe	0.1431	0.2052	

Appendix D: HVAC/DC Transmission

Projects until 2020 in China

System/Project	Year	Capacity [MW]	Voltage [kv]	Distance [km]	Location
Ge- Nan	1989	600	500	1000	Gezhouba-Nanqiao
GeSha	1990	1200	500	1046	Gezhouba-Shanghai
Tian-Guang	2001	1800	500	960	Tianshengqiao-Guangzhou
Three Gorges-Changzhou	2003	3000	500	860	Longquan-Zhengping
Zhou Shan Project	1982	50	100	42	Zhoushan
Three Gorges-Guangdong	2004	3000	500	940	Jinzhou-Huizhou
Gui-Guang	2004	3000	500	936	Guizhou-Guangdong
Three Gorges-Shanghai	Under construction 2007	3000	500	900	Three Gorges – Shanghai
Northeast-North(Goaling)	Planned 2008	1500		B-B	
Yunnan-Guangdong	Planned 2009	5000	800		Yunnan-Guangzhou
Lingbao Expansion	Planned 2009	750	168	B-B	Henan-Shaanxi
Hulunbeir(Inner Mongolia)-Shenyang	Planned 2010	3000	500	920	Hulunbeir – Shenyang
Ningxia-Tianjing	Planned 2010	3000			Ninaxia-Tianjin
NW-Sichuang	Planned 2011	3000			Baoji-Deyang
North Shaanxi-Shandong	Planned 2011	3000			Shaanxi-Shandong
Shandong-East	2011	1200		B-B	
Gezhouba-Shanghai	2011	3000			Gezhouba-Shanghai

Expansion					
Xianjiaba-Shanghai	2011	6400	800		Xinjiaba-Shanghai
Jingping-East	2012	6400	800		
North-Central	2012	1000			
Xiluodu-Hunan	2014	6400	800		Xiluodu-Hunan
Xiluodu-Hanzhou	2015	6400	800		Xiluodu-Hanzhou
Nuozhadu-Guangdong	2015	6400	800		Nuozhadu-Guangdong
Humeng-Shandong	2015	6400	800		Humeng-Shandong
Jinsha River-East China	2016	6400	800		
Humeng-Tianjing	2016	6400	800		Humeng-Tianjing
Goupitan-Guangdong	2016	3000			Goupitan-Guangdong
Humeng-Liaoning	2018	6400	800		Humeng-Liaoning
Jinsha River-Fujian	2018	6400	800		
Hami-C.China	2018	6400	800		
Jinsha River-East China	2019	6400	800		

Appendix E: Climate of Three Selected Locations

A	Daily solar radiation kWh/(m²•day)	Air Temperature °C	Relative humidity %	Atmospheric pressure kpa	Wind speed m/s	Earth temperature °C
Jan	2.53	-13.1	52.0%	88.4	4.6	-19.9
Feb	3.57	-9	42.4%	88.2	4.2	-14.9
Mar	4.83	-2	30.7%	87.9	4.7	-2.7
Apr	6.05	7.2	23.1%	87.6	5.3	9
May	6.66	15	27.6%	87.4	5	18
Jun	6.73	20.3	35.5%	87.1	4.5	23.8
Jul	6.16	22.9	45.3%	87.1	3.9	25.5
Aug	5.42	20.7	50.9%	87.4	3.7	21.8
Sep	4.81	14.6	42.4%	87.9	4	15.2
Oct	3.66	6.4	38.8%	88.2	4.4	5.7
Nov	2.61	-3.8	43.8%	88.3	5.1	-5.5
Dec	2.16	-10.5	51.3%	88.5	5.2	-15.6

B	Daily solar radiation kWh/(m²•day)	Air Temperature °C	Relative humidity %	Atmospheric pressure kpa	Wind speed m/s	Earth temperature °C
Jan	2.73	-10.1	41.6%	89.7	2.3	-15.8
Feb	3.71	-5	28.2%	89.5	2.5	-10
Mar	4.82	2.6	22.5%	89.1	3	2.2
Apr	6.03	11.5	19.1%	88.8	3.8	12.9
May	6.67	19.3	20.4%	88.5	3.6	22
Jun	6.69	24.7	24.5%	88.1	3.4	28.3
Jul	6.34	27	31.4%	88	3.1	31.1
Aug	5.62	24.7	33.7%	88.3	2.9	28.1
Sep	4.87	18.2	29.7%	88.9	2.8	20.1
Oct	3.7	9.1	30.5%	89.4	2.7	9.3
Nov	2.82	-1.1	34.5%	89.7	2.6	-2
Dec	2.27	-8.4	44.3%	89.8	2.4	-11.5

C	Daily solar radiation kWh/(m²•day)	Air Temperature °C	Relative humidity %	Atmospheric pressure kpa	Wind speed m/s	Earth temperature °C
Jan	2.22	-9.4	55.60%	88.6	1.1	-15.6
Feb	3.08	-3.1	38.60%	88.3	1.5	-10.5
Mar	4.16	5	28.00%	88	2	1.6
Apr	5.38	13.6	25.00%	87.7	2.2	13
May	5.95	20.3	31.50%	87.5	1.9	22.2
Jun	6.28	24.6	38.10%	87.2	1.6	28.2
Jul	6.52	26.5	42.40%	87	1.5	30.7
Aug	5.98	24.5	43.40%	87.3	1.3	28.1
Sep	4.91	18.3	43.70%	87.8	1.2	20.2
Oct	3.82	9.8	47.40%	88.3	1.1	9.5
Nov	2.67	0.5	48.90%	88.5	1.2	-1.5
Dec	1.81	-7.5	58.70%	88.7	1	-11.1

Appendix F: Cost Calculation of China Case Study

Transport distance Scenario	km	200 Case I	2,000 Case I	200 Case II	2,000 Case II	200 Case III	2,000 Case III
Technical data							
Line capacity	MW	5,000	5,000	5,000	5,000	5,000	5,000
Electricity input	GWh/yr	20,000	20,000	20,000	20,000	20,000	20,000
Electricity losses	GWh/yr	100	1,000	100	1,000	100	1,000
Electricity output	GWh/yr	19,900	19,000	19,900	19,000	19,900	19,000
Specific transmission losses	%/1000 km	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Total transmission losses	%	0.5%	5.0%	0.5%	5.0%	0.5%	5.0%
Utilization of line	h/yr	4000	4000	4000	4000	4000	4000
Voltage	kV	+/- 800	+/- 500	+/- 800	+/- 500	+/- 800	+/- 500
Basic economic constraints							
Electricity cost at transmission line inlet	$/MWh	162	162	141	141	120	120
Interest during construction	% of capex	5%	5%	5%	5%	5%	5%
Life time	yr	40	40	40	40	40	40
Interest rate	%/yr	8%	8%	8%	8%	8%	8%
Annuity	%/yr	8.39%	8.39%	8.39%	8.39%	8.39%	8.39%
Fixed operating costs	% of capex/yr	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Capital expenditures (excluding interest during construction)							
Transmission line	10^6 $	0.234	0.766	0.234	0.766	0.234	0.766
Terminal	10^6 $	490.000	490.000	490.000	490.000	490.000	490.000
Total capital expenditures	10^6 $	490.000	490.000	490.000	490.000	490.000	490.000
Specific capex transmission line	10^3 $/km	1.170	0.383	1.170	0.383	1.170	0.383
Transmission costs (referred to electricity output)							
Electrictity losses	10^6 $/yr	16.214	162.145	14.057	140.573	12.041	120.415
Fixed costs	10^6 $/yr	4.900	4.900	4.900	4.900	4.900	4.900
Annuity	10^6 $/yr	41.091	41.091	41.091	41.091	41.091	41.091
Total transmission costs	10^6 $/yr	62.206	208.136	60.049	186.565	58.033	166.406
Specific total transmisson costs	**$/MWh$_e$**	**3**	**11**	**3**	**10**	**3**	**9**
Total generation and transmission costs	**$/MWh$_e$**	**165**	**173**	**144**	**150**	**123**	**129**
	$/kWh$_e$	**0.165**	**0.173**	**0.144**	**0.150**	**0.123**	**0.129**
Electricity supply	TWh/yr	1520	1521				
Total costs	10^9 $/yr	251	263				

1RMB= 0.14 $