Concentrated Solar Thermal Power

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In spite of several successful alternative energy production installations in recent years, it is difficult to point to more than one or two examples of a modern industrial nation obtaining the bulk of its energy from sources other than oil, coal and natural gas. Thus a meaningful energy transition from conventional to renewable sources of energy is yet to be realized. It is also reasonable to assume that a full replacement of the energy currently derived from fossil fuels with energy from alternative sources is probably impossible over the short term. For example, the prospects for large scale production of cost effective renewable electricity remains to be generated utilizing either the wind energy or certain forms of solar energy. These renewable energies face important limitations due to intermittency, remoteness of good resource regions and scale potential. One of the promising approaches to overcome most of the limitations is to implement many recent advances in solar thermal electricity technology. In this section, various advanced solar thermal technologies are reviewed with an emphasis on new technologies and new approaches for rapid market implementation.

The first topic is the conventional parabolic trough collector, which is the most established technology and is under continuing development with the main focus being on the installed cost reductions with modern materials, along with heat storage. This is followed by the recently developed linear Fresnel reflector technologies. In two-axis tracking technologies, the advances in dish-Stirling systems are presented. More recently, the solar thermal electricity applications in two axis tracking using tower technology is gaining ground, especially with multi-tower solar array technology. A novel solar chimney technology is also discussed for large-scale power generation. Non-tracking concentrating solar technologies, when used in a cogeneration system, offer low cost electricity, albeit at lower efficiencies - an approach that seems to be most suitable in rural communities.

1. Introduction

Solar thermally generated electricity is a low cost solar energy source that utilizes complex collectors to gather solar radiation in order to produce temperatures high enough to drive steam turbines to produce electric power. For example, a turbine fed from parabolic trough collectors might require steam at 750 K and reject heat into the atmosphere at 300 K, thus having an ideal thermal (Carnot) efficiency of about 60%. Realistic overall conversion (system) efficiency of about 35% is feasible with intelligent management of waste heat. The solar radiation can be collected by different concentrating solar power (CSP) technologies to provide high temperature heat. The solar heat is then used to operate a conventional power cycle, such as Rankine (steam engine), Brayton (gas turbine engine) or Stirling (Stirling engine)[1]. While generating power during the daytime, additional solar heat can be collected and stored, generally in a phase-change medium such as molten salt[2]. The stored heat can then be used during the nighttime for power generation. A simple schematic, shown in Figure 1, describes the main elements of such a system.

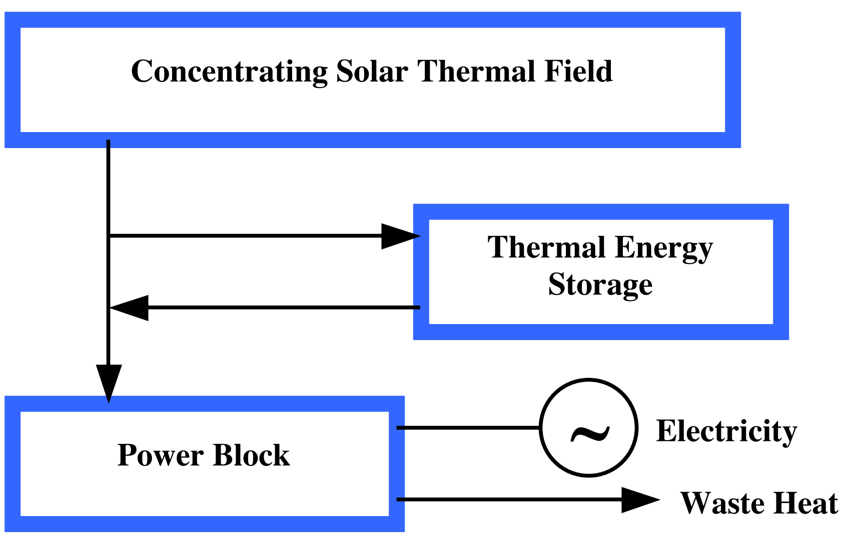

Figure 1. Main components of a Concentrating Solar Power (CSP) system.

The markets and applications for CSP dictate the category of the system and its components. Typically, the general categories considered by size are small (<100 kW), medium (<10 MW) and large (> 10 MW). The CSP systems can be made of combinations of different collectors, power cycles and, if required, thermal storage technologies. The CSP system processes heat like any conventional power plant and, as

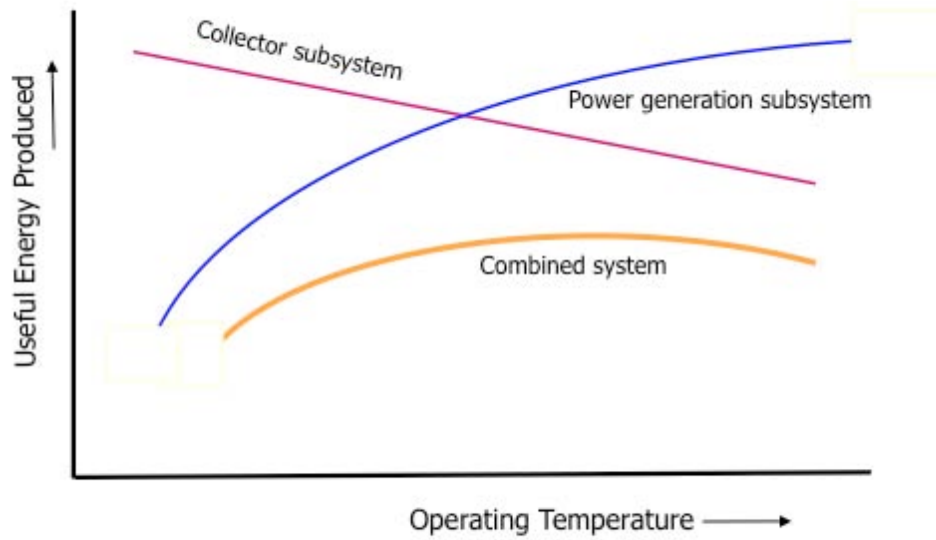

Figure 2. CSP system efficiency variation with operating temperature.

such, the plant efficiency depends primarily upon the operating temperature. Therefore, the useful energy produced will depend on the solar field collection and the power cycle efficiencies, as illustrated in Figure 2. The efficiency of a solar collector field is defined as the quotient of usable thermal energy versus received solar energy. The power generation subsystem efficiency is the ratio of net power out to the heat input.

The different CSP technologies that will be explored in the following sections are: parabolic trough, central tower receiver, dish-Stirling, linear Fresnel and solar chimney. CSP technologies require sufficiently large (> 5.2 kWh/m^2/day) direct normal irradiance (DNI), as opposed to PV technologies that can use diffuse, or scattered, irradiance as well[3]. The history of the Solar Electricity Generating Systems (SEGS) in the southwest desert of California[4], where DNI is quite favorable for CSP, shows impressive cost reductions as shown in Figure 3. These parabolic trough plants have been operating successfully for over three decades, thus providing valuable data. As indicated in the figure, the advanced concepts, with large-scale implementation and improved plant operation and maintenance, provide a great opportunity for further reductions in the levelized electricity cost (LEC), a topic that will be discussed later. Life cycle assessment of emissions and land surface impacts of the CSP systems suggest that they are best suited for greenhouse gas and other pollutant reductions. CSP systems are also best suited, because of the effortless capture of the waste heat, for multi generation applications, such as the simultaneous production of electricity and water purification.

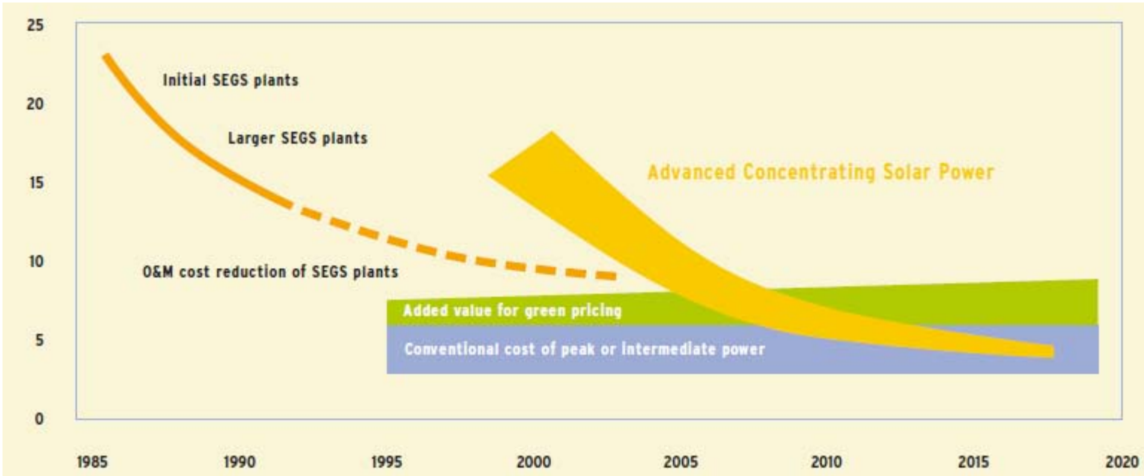

Figure 3. Levelized electricity cost (cents/kWh) projections of CSP (Source: Solar Paces).

Because of rapid developments occurring both in technology and electricity market strategies, CSP has the greatest potential of any single renewable energy area. It also has significant potential for further development and achieving low cost because of its guaranteed fuel supply (the sun).

In this chapter, a succinct review of the current technologies is given together with an assessment of their market potential. While describing some of the recent approaches in some detail, the activity around the world will also be included.

2. Solar radiation

The potential for CSP implementation in any given geographic location is largely determined by the solar radiation characteristics[3]. The total specific radiant power per unit area, or radiant flux, that reaches a receiver surface is called irradiance and it is measured in W/m^2. When integrating the irradiance over a certain time period, it becomes solar irradiation and is measured in Wh/m^2. When this irradiation is considered over the course of a given day it is referred to as solar insolation, which has units of $kWh/m^2/day$ (= $3.6MJ/m^2/day$). However, by assigning a number of useful solar hours in a given day then the units simplify to W/m^2. As such, the terms irradiance and insolation are typically used interchangeably. Solar radiation consists primarily of direct beam and diffuse, or scattered, components. The term “global” solar radiation simply refers to the sum of these two components. The daily variation of the different components depends upon meteorological and environmental factors (e.g. cloud cover, air pollution and

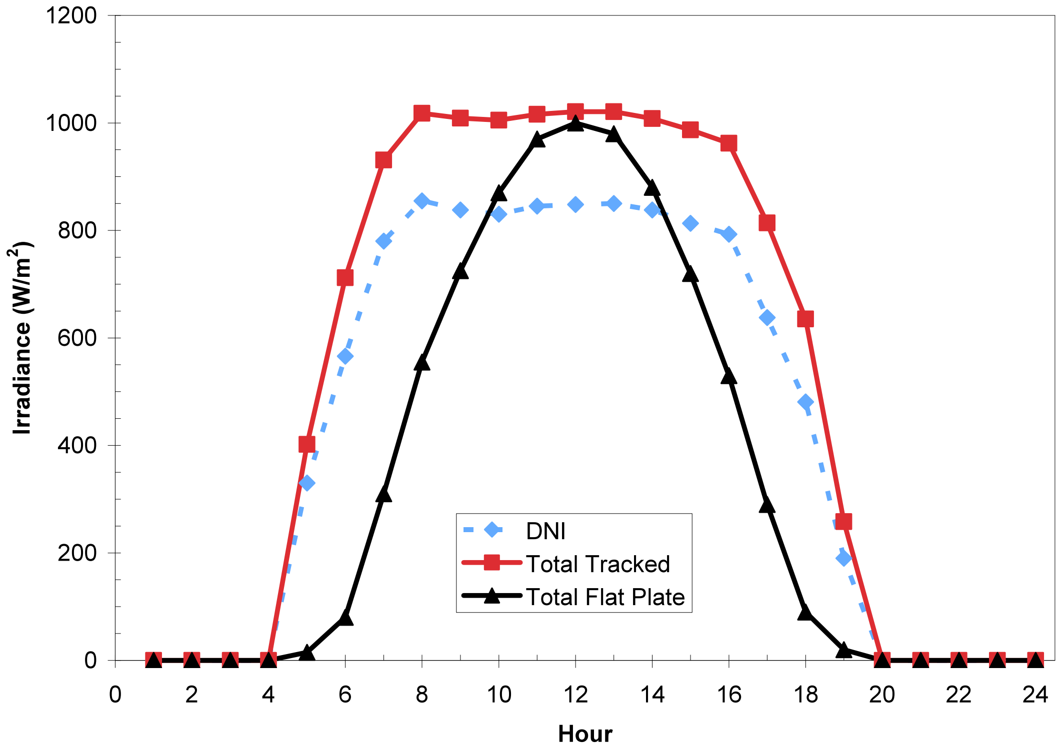

Figure 4. Solar irradiance variation within a day measured on a flat plate positioned horizontal and tracking the sun and direct normal irradiance (DNI). (source: Edith Molenbroek, ECOFYS, 2008).

humidity) and the relative earth-sun geometry. The direct normal irradiance (DNI) is synonymous with the direct beam radiation and it is measured by tracking the sun throughout the sky. Figure 4 shows an example of the global solar radiation that is measured on a stationary two flat plate and a plate that is tracking the sun. The measured DNI is also included and its lower value can be attributed to the fact that it does not account for the diffuse radiation component[5].

In CSP applications, the DNI is important in determining the available solar energy. It is also for this reason that the collectors are designed to track the sun throughout the day. Figure 5 shows the daily solar insolation on an optimally tilted surface during the worst month of the year around the world[6,7]. Regions represented by light and dark red colors are most suitable for CSP implementation. The annual DNI value will also greatly influence the levelized electricity cost (LEC), which will be discussed later. Typical values of DNI at different latitudes and selected locations around the world are given in Figure 6 and Table 1. Based on the information presented here it can be seen that desert and equatorial regions appear to provide the best resources for CSP implementation.

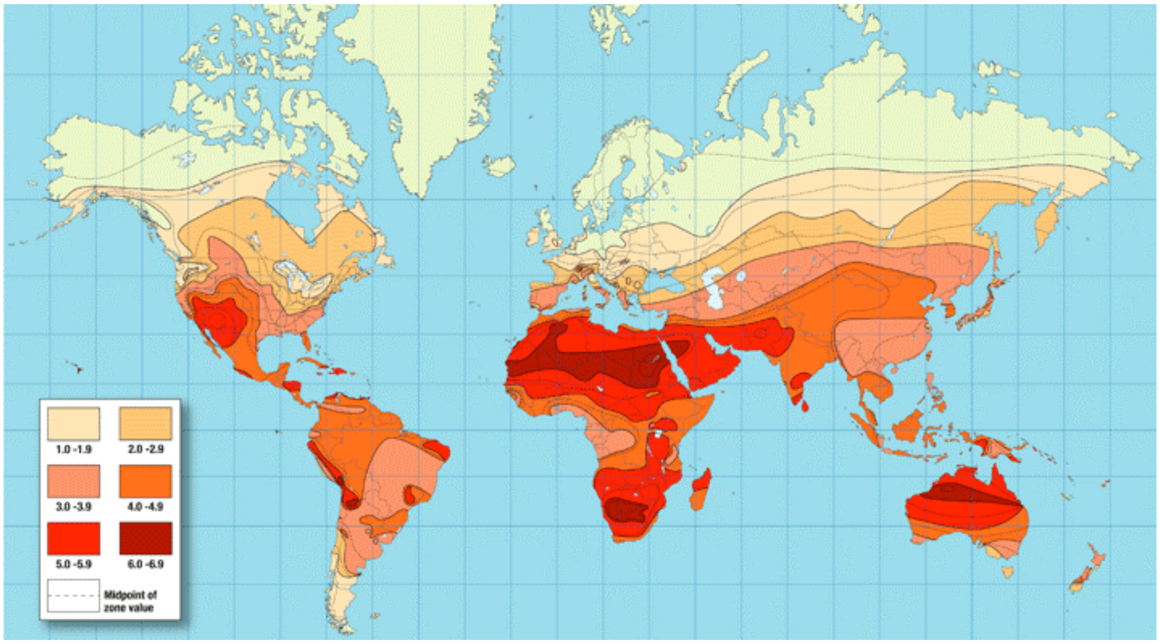

Figure 5. The solar insolation (kWh/m^2/day) on an optimally tilted surface during the worst month of the year. (source: http://www.meteostest.ch)

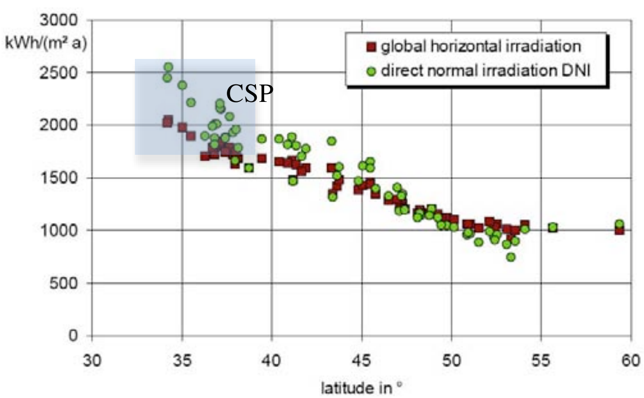

Figure 6. Annual global irradiation in Europe and USA. (Source: Volker Quascning, DLR & Manuel Blanco Muriel, CIEMAT, Spain)

Table 1. Annual DNI at selected locations

Location	Site Latitude	Annual DNI (kWh/m2)
United States		
Barstow, California	35°N	2,725
Las Vegas, Nevada	36°N	2,573
Tucson, Arizona	32°N	2,562
Alamosa, Colorado	37°N	2,491
Albuquerque, New Mexico	35°N	2,443
El Paso, Texas	32°N	2,443
International		
Northern Mexico	26-30°N	2,835
Wadi Rum, Jordan	30°N	2,500
Ouarzazate, Morocco	31°N	2,364
Crete, Greece	35°N	2,293
Jodhpur, India	26°N	2,200

3. CSP technologies

3.1. Parabolic trough technology

This technology is comprised of relatively long and narrow parabolic reflectors with a single axis tracker to keep the sun's image in focus on a linear absorber or receiver. This technology uses reflectors curved around the rotation axis (which is

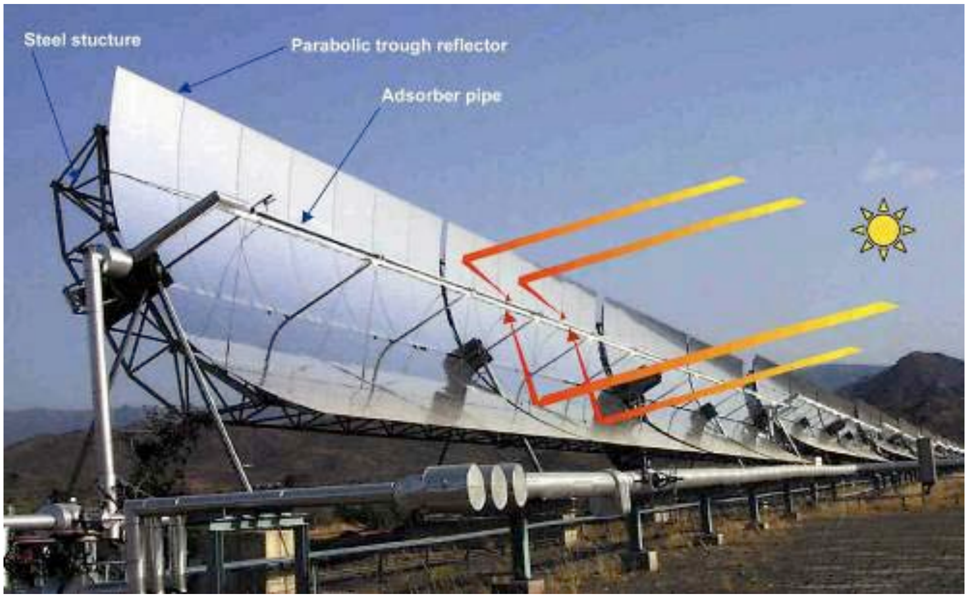

Figure 7. A typical parabolic trough system. (Source: http://www.abengoasolar.com)

typically oriented east-west) using a linear parabolic shape, which has the property of collecting nearly parallel rays from the direct solar beam in a line image. A long pipe receiver can be placed at the focus for heating of heat transfer fluid (Figure 7). The receiver is normally a tube, which contains a heat transfer fluid or water for direct steam generation.

The two major components of the collector subsystem are: the parabolic trough reflector, including its support structure, and the receiver, also referred to as the heat collector element. Important factors for the most efficient parabolic trough reflector include the stability and accuracy of the parabolic profile, optical error tolerance, method of fabrication, material availability and strength constraints. The geometry, length of the trough, the aperture and rim angle will dictate the amount of heat collection. Since there are a large number of collector modules in a typical plant, the cost optimization requires minimizing: the material weight (steel or aluminum), the operations needed to manufacture the structure and the assembly of the elements that compose the collector[8]. A typical modern structure using aluminum space frame technology to support the reflector is shown in Figure 8. These are considerably lighter per unit of aperture area compared to standard steel structures.

All utility-scale parabolic trough installations to date have utilized silvered glass mirrors as reflectors (Figure 7). These reflectors are limited in size and are typically

Figure 8. Left: Parabolic trough space frame structure (Source: NREL); Right: Lightweight trough with reflective thin film mirror (Farr &Gee, 2009).

driven by manufacturing limitations, strength, handling, shipping, and installation issues. These parabolic trough modules will have between 20 and 40 mirrors mounted to a single space frame module. The mirrors are typically 4 – 5 mm thick and are mounted to the structural frame with bolted connections. Alternatively, a UV-stabilized mirror film (i.e. ReflecTech™) laminated onto an aluminum substrate (Figure 8b) provides a reflectance of about 94%[9]. The weight of the modern reflective surface is about 3.5 kg/m^2 versus 10 kg/m^2 (2.1 lbf/ft^2) for glass mirrors and allows for a lower initial cost.

The receiver must achieve high efficiency with high solar absorptance, low thermal losses, and minimum shading. The receiver typically consists of a pipe with a solar selective coating encased in a glass tube throughout which there is a vacuum. The most commonly used thermal receiver is the SCHOTT PTR™ 70[10], shown in Figure 9, which has a highly selective absorber coating on a stainless steel tube that has an outside diameter of 70 mm. The tube is enclosed in a glass cylinder with vacuum insulation to

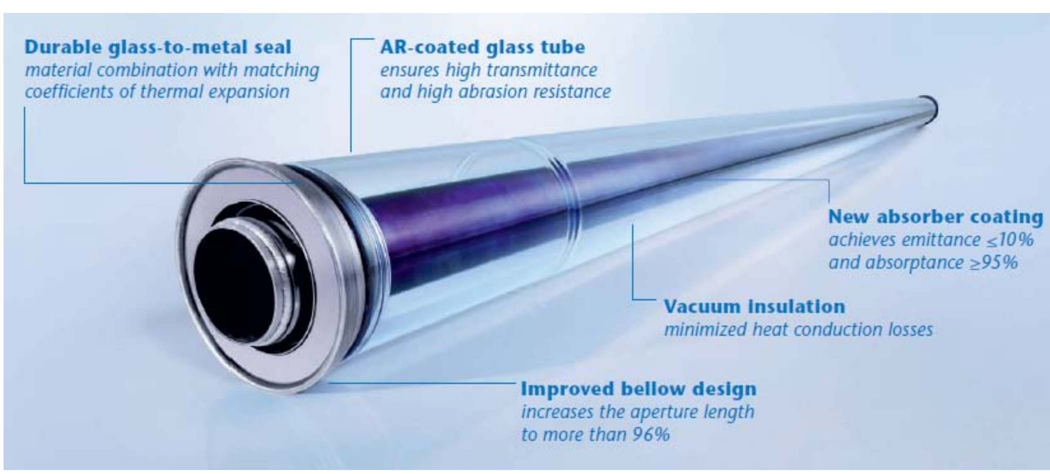

Figure 9. Schott PTR™ 70 receiver (source: http://www.schottsolar.com)

minimize the long wave IR radiation and convection losses. The receiver tube supports are designed to minimize any receiver deflection and sunlight blockage. This particular configuration is in widespread use but it has a number of drawbacks, which include the fact that it is difficult to maintain the vacuum seals, especially after welding, and, as has been observed, the heat transfer fluid and solar selective coating off-gas hydrogen into the vacuum tube, thus negating the convection reducing effects of the tube.

The typical thermal conversion efficiency (net heat collected/incident solar radiation over the trough aperture area) for a parabolic trough is shown in Figure 10 for the PT-1 concentrator[11]. The efficiency is largely affected by the collector thermal and optical losses. Since the radiation losses are proportional to the fourth power of the temperature, the efficiency decreases rapidly with increasing working fluid temperature. The nominal operating temperature of many plants (e.g. SEGS) is about 400 ºC (~350 ºC above ambient) operating at a thermal conversion efficiency of about 50% at best. The trend over the last 25 years has been to make larger collectors with higher concentration ratios in order to improve the collector thermal efficiency. However, due to increased material manufacturing and installation costs of the large aperture (> 6 m) troughs, the LEC still remains high for widespread implementation.

The concentrating parabolic trough systems typically produce power based on the Rankine cycle, which is the most fundamental and widely used steam-power cycle. The

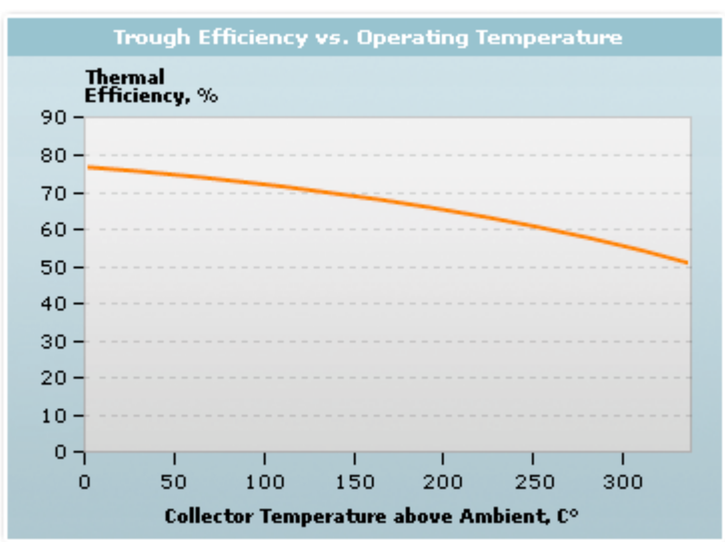

Figure 10. The variation of the thermal efficiency of a parabolic collector with operating temperature. (Dudley & Evans, 1995)

cycle starts with superheated steam generated by the heat collected from the parabolic trough field. The superheated vapor expands to lower pressure in a steam turbine that drives a generator to convert the work into electricity. The turbine exhaust steam is then condensed and recycled as the feed water for the superheated steam generation to begin the cycle again. The simple steam cycle thermodynamic efficiency can be as high as 35%. Considering that the generator sets are better than 90% efficient in converting the shaft power into electricity, it is expected that the cycle can produce electricity at an efficiency in excess of 30%. As such, the total combined plant efficiency (solar to electricity) is best estimated to be about 15%. The SEGS system experience shows that the annual solar to electric efficiency varies from 10.7 – 14. 6%, with the higher number corresponding to the case where thermal storage is included in the plant. Although the plant efficiency appears low when compared to conventional fossil fuel based plants, the operation and maintenance (O&M) costs are negligible due to the absence of any fuel costs, thus making the LEC largely depend on the capital costs. It is useful to think in terms of the cost/efficiency ratio to determine the viability of the CSP plant. Although much of the recent effort is on increasing the efficiency of the plant, it is more useful to find ways to reduce capital costs, thereby reducing the LEC. Hence, the following is a discussion assessing the components costs for a parabolic trough plant.

Figure 11 gives a breakdown of the investment costs associated with a typical parabolic trough plant utilizing the Rankine steam cycle[12]. As the pie chart indicates, the majority of the initial investment cost is associated with the solar field. Much progress has been made recently with the introduction of lightweight space frame structure designs and the development of efficient highly reflective film[13], such as ReflecTech™ and 3M's

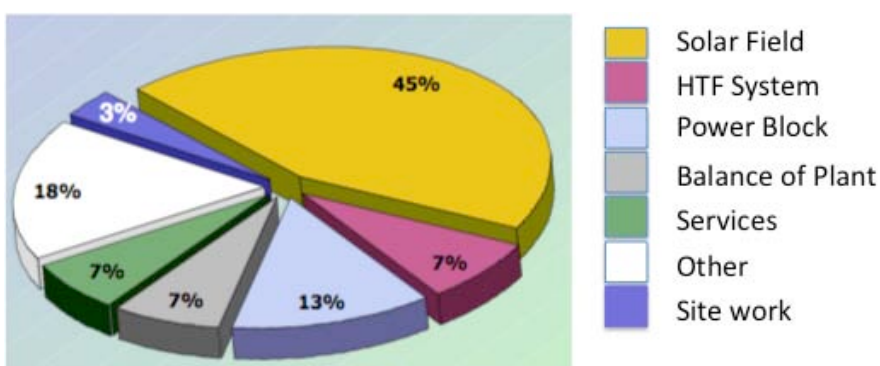

Figure 11. Typical cost breakdown of a parabolic trough SEGS plant.

new solar mirror film[14]. The heat transfer fluid (HTF) system moves the heat from the solar field to the power block and it requires an HTF with the following properties: high temperature operation with high thermal stability, good heat transfer properties, low energy transportation losses, low vapor pressure, low freeze point, low hazard properties, good material compatibility, low hydrogen permeability of the steel pipe and economical product and maintenance costs. As a result, synthetic organic HTFs are most suitable for the parabolic trough plants. For example, SYLTHERM™ 800, a high temperature HTF by Dow Chemical Company, can be used in liquid form up to 400º C and meets many of the requirements delineated above[15]. The last of the major components is the power block, which consists of a conventional steam turbine based system, the costs of which are well established and a number of new players from China and India have made the prices quite competitive. Any significant reduction in the cost of any of these three major components will result in a lower LEC for CSP systems.

The most recent 64 MW (nominal) installation in Nevada (Nevada Solar One), shown in Figure 12, uses 5.77 m aperture parabolic troughs with PTR-70 receivers, resulting in a geometric concentration ratio of 26. The total solar field is 357,200 m^2 and the plant site area is 1.62 km^2. Field inlet and outlet temperatures are 300 ºC and 390 ºC, respectively. The solar steam turbine inlet temperature is about 371º C at 86.1 bar. The plant uses a supplementary gas heater to provide 2% of the total heat requirement. The plant produces about 134 x 10^6 kWh of electricity annually, which yields a plant capacity factor of about 0.24. Coal power plants have a capacity factor on the order of 0.74 and as such they can produce the equivalent electricity output from a 21 MW plant. The solar to

Figure 12. Left: Parabolic trough field; Right: Power block at Nevada Solar One Power Plant. (Source: www.acciona-na.com)

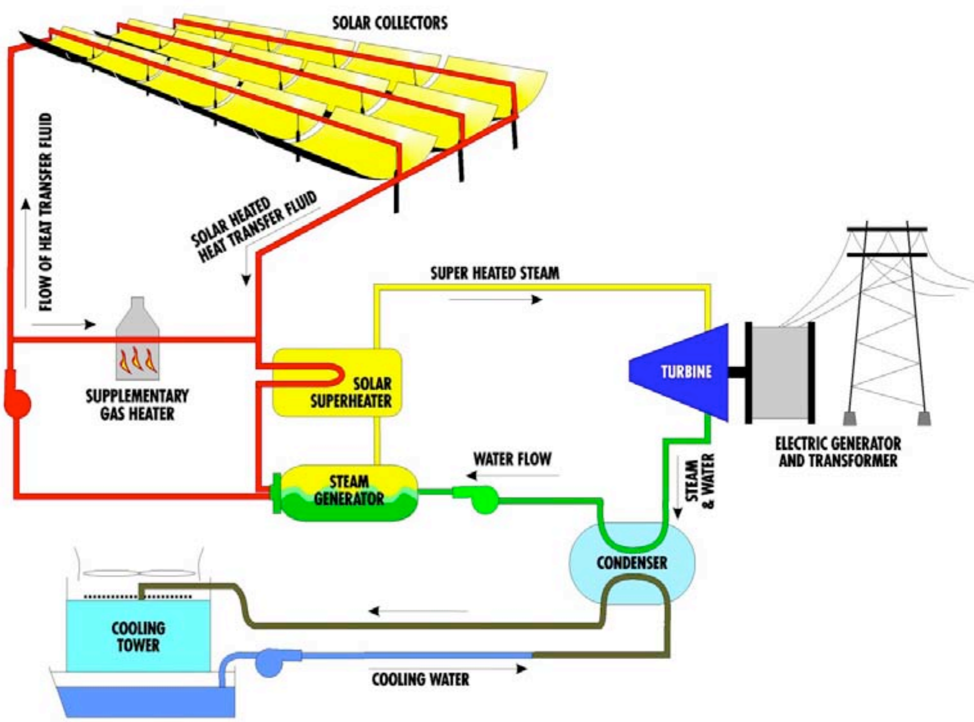

Figure 13. Nevada Solar One plant schematic. (Source: www.acciona-na.com)

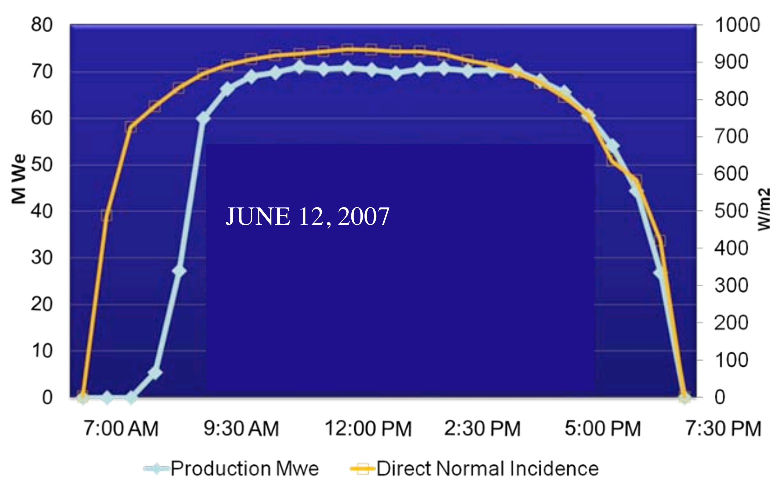

Figure 14. Nevada Solar One electricity output and DNI for a typical summer day. (source: www.acciona-na.com)

electricity efficiency of the plant (Figure 13 shows the plant schematic) is estimated, based on the annual DNI of 2573 kWh/m^2, to be 14.6%. The CO_2 emissions reduction (as compared to a equivalent coal plant) is estimated to be about 100,000 MT/year. A typical electricity production in a day is depicted in Figure 14, where the hourly DNI variation is also displayed. The total installed cost of the project was \$266 million resulting in a nominal price of about \$4.15/W. With medium temperature (250 - 300º C) parabolic troughs and advanced receiver designs, it is anticipated that the installed costs may reach as low as $2.50/W, thus making the parabolic trough systems competitive with many other renewable energy solutions.

The ability to provide near-firm power through the use of thermal energy storage is gaining prominence. This characteristic differentiates CSP from PV technology, as the utilities can tailor the use of CSP electricity as needed. The thermal storage can also provide more uniform output over the day and increase annual electricity generation, thereby increasing the plant capacity factor. For example, while solar energy availability peaks at noon, demand peaks in the late afternoon when the energy from the sun is already going down. Figure 15 shows a parabolic trough plant schematic with molten salt thermal storage incorporated[16]. A high-temperature thermal energy storage option has been developed for parabolic troughs that uses molten nitrate salt as the storage medium in a two-tank system; it has an oil-to-salt heat exchanger to transfer thermal energy from the solar field to the storage system[17]. A more desirable option under development is an advanced heat transfer fluid (HTF) that is thermally stable at high temperatures, has a high thermal capacity, a low vapor pressure, and remains a liquid at ambient temperatures. The effect of storage to follow the utility system demand is clearly depicted in Figure 16. When compared to the data shown in Figure 14, where the electricity supply follows closely with the sun's energy, the storage extends the availability of

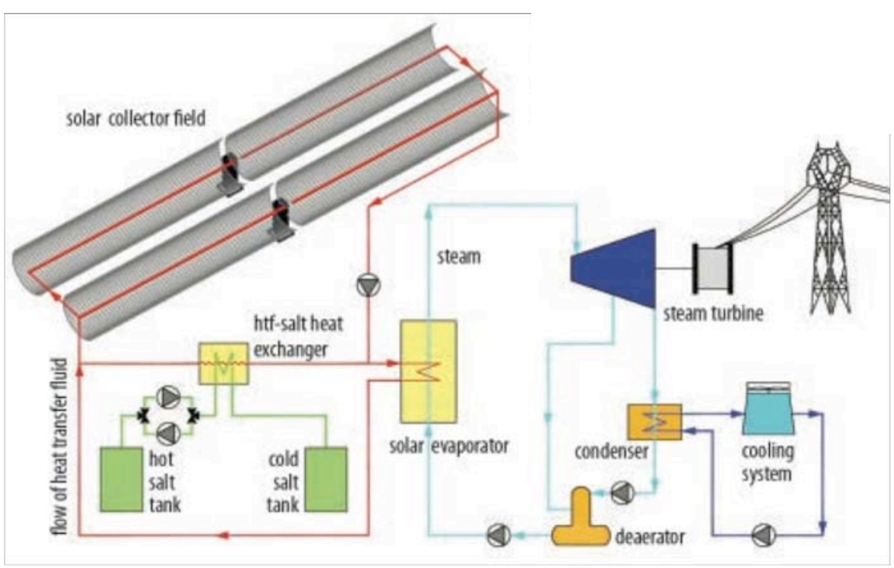

Figure 15. A schematic of a parabolic trough plant with added thermal storage. (Kearney & Morse, 2010)

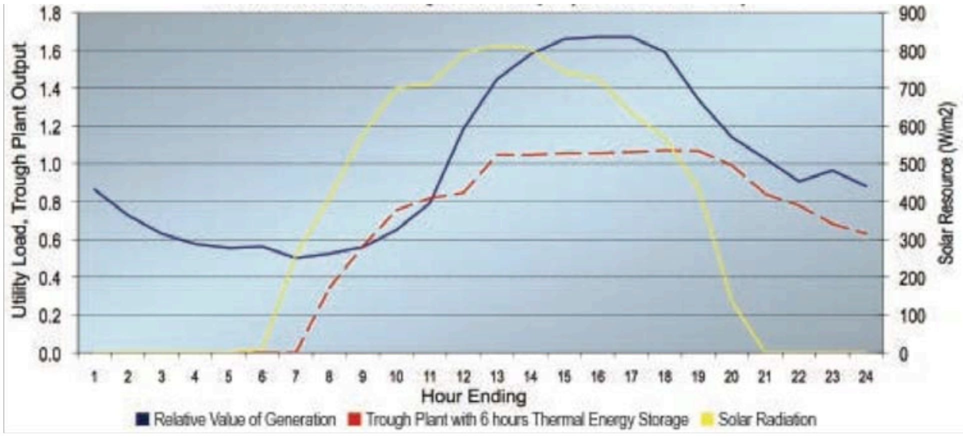

Figure 16. The effect of storage on utility load during a typical day. (Kearney & Morse, 2010)

electricity through evening hours.

The performance of SEGS plants, the successful development of Nevada Solar One and the progress made by industry innovations have greatly increased interest in utility scale CSP projects in the USA and Europe. Abengoa Solar's proposed 250 MW Solana parabolic trough plant provides an example of the potential of this technology[18].

3.2. Linear Fresnel reflector technology

Fresnel lenses are used as solar concentrators where the reflector is composed of many long row segments of flat mirrors, which concentrate beam radiation onto a fixed receiver, located at few meters height, running parallel to the mirrors axis of rotation (Figure 17). Linear Fresnel follows the principles of parabolic trough technology, but replaces the curved mirrors with long parallel lines of flat, or slightly curved, mirrors.

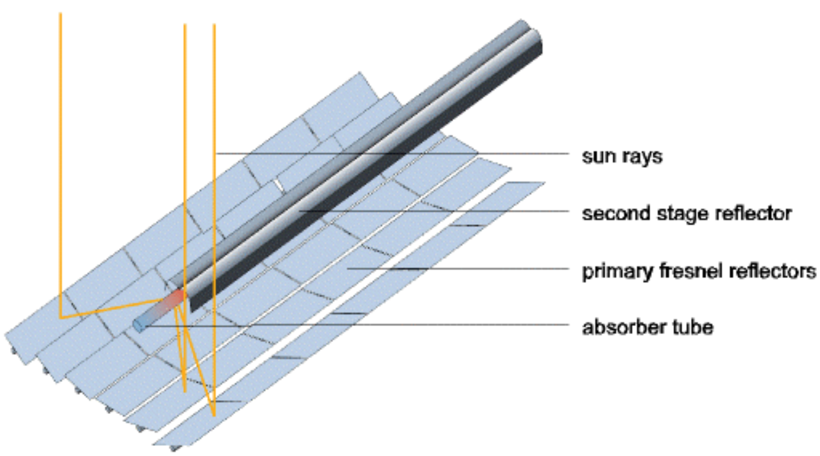

Figure 17. The principle of a typical Fresnel collector. (Haberle, et al., 2002)

Figure 18. 2500 m^2 reflected area Fresnel concentrator prototype in Belgium. (Haberle, et al., 2002)

Unlike, parabolic troughs where the aperture is limited to few meters, a large aperture can be achieved by the linear Fresnel reflector at low cost. Although, the original idea is quite old[19,20], only recently has this concept been brought to fruition by two teams in Australia and Belgium. The concentration ratios used in this system are quite similar to those achieved using parabolic troughs (10-80). Hence, the operating temperatures are also in the same range of the parabolic trough systems: 250 – 400^o C. A picture of the Solarmundo prototype system[21] erected in Liege, Belgium, is shown in Figure 18. The collector area is 2500 m^2 (25 m wide and 100 m long) and the absorber tube has an outer diameter of 18cm. The prototype used a black (non selective) absorber. However, in order to achieve satisfactory thermal performance, a highly selective absorber coating that is stable at high operation temperatures, must be applied. A pilot plant, a 1 MW (peak) thermal, system similar to the prototype was built at PSA in Almeria, Spain. Water flows through this absorber pipe, which is heated to temperatures of up to 450 ^{o}C. This produces steam (as in a conventional power plant), which is converted into electrical energy through the use of a steam turbine.

A 5 MW_e Compact Linear Fresnel Reflector (CLFR) power plant was built by Ausra in California as a demonstration plant[22] (Figure 19). The solar-field aperture area

Figure 19. The Ausra 5 MW Kimberlina solar thermal demonstration plant. (source: http://www.ausra.com)

was 26,000 m^2, with three lines, each 385 m length with a mirror width of 2 m. The plant produces 354ºC superheated steam at 70 bar. The CLFR utilizes multiple absorbers, which is an alternate solution to the Linear Fresnel Reflector (LFR) where only one linear absorber on a single linear tower is used. This prohibits any option of the direction of orientation of a given reflector. Therefore, if the linear absorbers are close enough, individual reflectors will have the option of directing reflected solar radiation to at least two absorbers. This additional factor gives potential for more densely packed arrays, since patterns of alternative reflector inclination can be set up such that closely packed reflectors can be positioned without shading and blocking.

The main advantages of linear Fresnel are its lower investment and operational costs. Firstly, the flat mirrors are cheaper and easier to produce than parabolic curved reflectors and so are readily available from manufacturers worldwide. The structure also has a low profile, with mirrors just one or two meters above ground. This means the plant can operate in strong winds and it can use a lightweight, simple collector structure. Although the technology offers a simpler and more cost effective solution, it has not been tested long enough to determine its viability as an alternative to parabolic trough technologies.

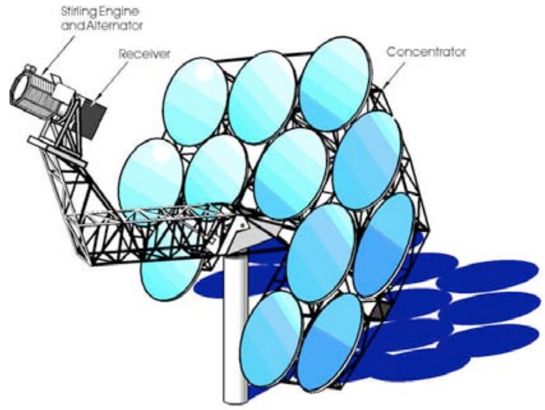

Figure 20: Left: Euro Dish (source: http://www.sbp.de); Right: SAIC-Sandia dish. (source: http://www.energylan.sandia.gov/)

3.3. Dish-Stirling technology

Dish-Stirling systems are relatively small units that track the sun and focus solar energy onto a cavity receiver at the focal point of the reflector, where it is absorbed and transferred to a heat engine/generator. The ideal concentrator shape is a paraboloid of revolution (Figure 20, left). Some concentrators approximate this shape with multiple spherically-shaped mirrors supported with a truss structure (figure 20, right). An engine based on the Stirling cycle is most commonly used in this application due to its use of an external heat supply that is indifferent to how the heat is generated[23]. Hence, it is an ideal candidate to convert solar heat into mechanical energy. The high efficiency conversion process involves a closed cycle engine using an internal working fluid (usually hydrogen or helium) that is recycled through the engine. The working fluid is heated and pressurized by the solar receiver, which in turn powers the Stirling engine. Stirling engines have decades of recorded operating history. For over 20 years, the Stirling Energy System[24] dish-Stirling system has held the world's efficiency record for converting solar energy into electricity with a record of 31.25% efficiency. Their size typically ranges from 1 to 25 kW with a dish that is 5 – 15 m in diameter. Because of their size, they are particularly well suited for decentralized applications, such as remote stand-alone power systems.

One of the most advanced dual axis tracking parabolic dish-Stirling systems is manufactured by Stirling Energy Systems (SES) and it produces 25 kW_e peak power (at

Figure 21. Left: SES Sun Catcher™ (source: http://www.stirlingenergy.com/); Right: Power Dish™ by Infinia (Source: http://www.infiniacorp.com).

1000W/m^2 DNI)[24]. This unique design uses a radial solar concentrator dish structure that supports an array of curved glass mirror facets as shown in Figure 21. The dish has a diameter of about 11.6 m (glass surface area ≈ 90 m^2), which results in a concentration ratio of about 7500. The heat input from the sun is focused onto solar receiver tubes (at a focal length of 7.45 m) that contain hydrogen gas. The solar receiver is an external heat exchanger that absorbs the incoming solar thermal energy. This heats and pressurizes the gas in the heat exchanger tubing, which in turn powers the Stirling engine at a typical operating temperature of about 800 ºC. A generator that is connected to the engine then provides the electrical output. Waste heat from the engine is transferred to the ambient air via a radiator system similar to those used in automobiles. The gas is cooled by a radiator system and is continually recycled within the engine during the power cycle. The solar energy to electricity peak conversion efficiency is reported as 31.25%. A much smaller 3 kW_e advanced parabolic dish-Stirling system is manufactured by Infinia (Figure 21). The single free piston Stirling engine uses helium in a hermetically sealed system, thereby avoiding maintenance issues generally associated with moving parts. The solar to electric peak efficiency is reported to be around 24%.

Dish-Stirling systems are quite flexible in terms of size and scale of deployment. Owing to their modular design, they are capable of both small-scale distributed power output and large, utility-scale projects. Although dish-Stirling systems have been tested and proven for over two decades with no appreciable loss in the key performance criteria,

 

Figure 22. Left: 1.5 MW Maricopa Solar installation (source: http://www.srpnet.com/maricopasolar); Right: 1 MW solar installation in Villarrobledo, Spain (source: http://www.infiniacorp.com).

there were no utility-scale plants in operation until very recently. Within the past year, 60 SES SunCatcher™ systems were installed as part of the Maricopa Solar demonstration plant in Arizona (Figure 22). The plant is currently operational and it is capable of producing 1.5 MW_e. Two other plants in California, totaling over 1.4 GW are slated to begin construction soon using thousands of the SES systems. A similar 1 MW system is under construction in Villarobledo, Spain using the Infinia 3 kW units[25]. The successful installation and operation of these dish-Stirling systems in a scale beyond a handful of units will demonstrate their technical viability for the large-scale utility scale plants. Unlike steam cycles, this technology uses no water in the power conversion process; a key benefit compared to other CSP plants.

Current installed cost for the dish-Stirling systems at demonstration scale, with few units (mostly built in semi-automated manufacturing facilities) is about $6,000 /kW. This cost is approximately distributed with 40% in the concentrator and controls, 33% in the power conversion unit, and the remaining 27% of the costs in the balance of plant and installation of the system. Mass production techniques, such as those employed at the automotive scale, will provide great cost benefits to these systems. With the economies of scale in their favor and because of higher solar to electricity efficiency (25-30%), the dish-Stirling systems will become competitive with the photovoltaic and parabolic trough systems. However, unlike the parabolic trough systems, the 20-year life cycle costs of these systems are yet to be determined.

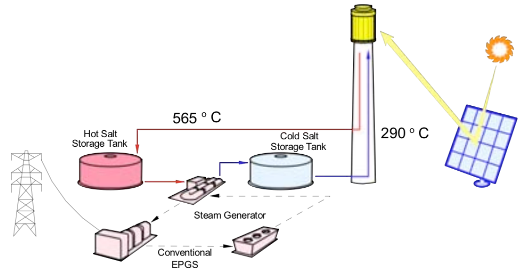

Figure 23. Left: Solar One/Two central solar tower receiver plant; Right: Schematic of the plant's major components. (source: USDOE)

3.4. Power tower technology

The solar central receiver power tower is a concept that has been under study both in the USA and Spain over the last three decades. This technique utilizes a central power tower that is surrounded by a large array of two-axis tracking mirrors—termed heliostats—that reflect direct solar radiation onto a fixed receiver located on the top of the tower. The typical concentration ratio for this approach is in excess of 400. Within the receiver, a fluid transfers the absorbed solar heat to the power block where it is used to generate steam for a Rankine cycle steam engine-generator. Until recently, the largest demonstration plant employing this technology was the 11.7 MW_e "Solar One" plant in Barstow, California (Figure 23) that was constructed and operated in the 1980's. Solar One operated at a nominal temperature of 510 ºC and it had a peak solar to electric efficiency of about 8.7%. In the 1990's Solar One was converted to "Solar Two" through the addition of additional heliostats and a two-tank molten salt storage system to improve the capacity factor of the system[26].

Two important components of the power tower technology are the heliostats and the receiver. Heliostats are the most important cost element of the power tower plant and they typically contribute to about 50% of the total plant cost. Consequently, much attention has been paid to reduce the cost of heliostats to improve the economic viability of the plant. The most commonly used design is the two-axis sun tracking pedestal-mounted system as shown in Figure 24. A heliostat consists of a large mirror with the motorized mechanisms to actuate it, such that it reflects sunlight onto a given target throughout the day. A heliostat array is a collection of heliostats that focus sunlight

Figure 24. Typical advanced heliostat field. (source: Plataforma Solar de Almeria - PSA, Spain)

continuously on a central receiver. A 148 m^2 ATS glass/metal heliostat has successfully operated for over 20 years at the National Solar Thermal Test Facility in Albuquerque, USA without much degradation of the beam quality. It has also survived high winds in excess of 40 m/s. Depending upon the production rates, the installed price of the ATS heliostat was estimated to be between \$126 - \$164 per square meter[27] With increasing installations, the estimated installation price will be around \$90/m^2. The Sandia study also suggests that large heliostats are more cost efficient than small ones on a cost per square meter basis[27].

A relatively new facility that began operation in 2006 is the PS10 solar power tower in Spain[28]. The main goal of the PS10 project was to design, construct and operate a power tower on a commercial basis and produce electricity in a grid-connected mode. This 11 MW_e facility generates about 23,000 MWh of grid-connected electricity annually at an estimated solar to electricity efficiency of about 15%. However, it should be noted that the plant also uses natural gas for 12-15% of its electricity production. The solar radiation is concentrated through the use of 624 reflective heliostats, each of which has a 121 m^2 curved reflective surface, arranged in 35 circular rows, as shown in Figure 25. As a result, the total reflective surface is 75,216 m^2. The heliostats concentrate the solar radiation to a cavity receiver that is located at the top of a 115 m high tower. The cavity receiver is basically a forced circulation radiant boiler designed to use the thermal energy supplied by the concentrated solar radiation flux to produce more than 100,000 kg/h of saturated steam at 40 bar and 250 ºC. The saturated steam is then sent to the turbine where it expands to produce mechanical work and electricity. For cloudy transient

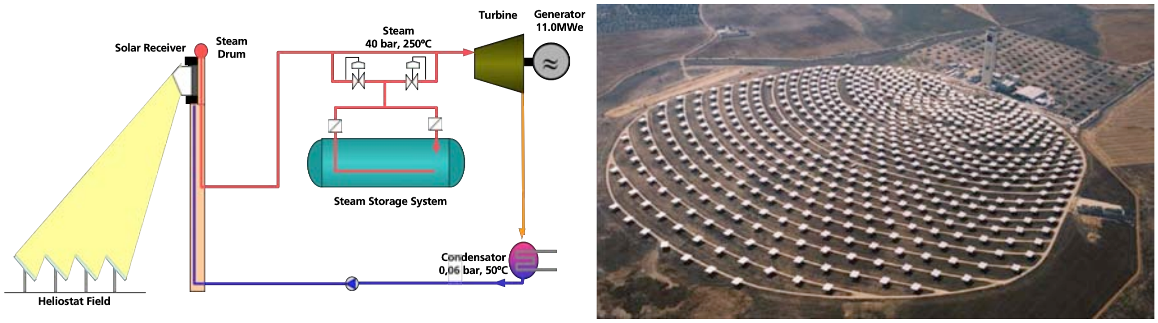

Figure 25. PS10 11 MW Central Receiver Tower project in southern Spain. Left: Plant schematic; Right: The PS10 plant aerial picture. (source: Abengoa Solar)

periods, the plant has a saturated water thermal storage system with a thermal capacity of 20 MWh, which is equivalent to an effective operational capacity of 50 minutes at 50% turbine workload. This is a relatively short storage time, partially because the tower uses water rather than molten salt for heat storage. The water is held in thermally clad tanks and reaches temperatures of 250 – 255 °C (instead of around 600 °C for systems using salt).

The investment cost of the PS10 plant was about 35 million Euros, thus resulting in an installed cost of about 3000 Euros per $kW_{e.}$. Of this cost, the heliostat cost was reported to be about 140 Euros/m^2. From this experience, it appears that about 30% of the total installed cost of a solar power tower goes toward the heliostat expense.

A second-generation plant, referred to as PS20 has twice the PS10 output (20MW), with 1,255 two-axis sun-tracking heliostats. The receiver is located on top of a 165m tower and it utilizes the same technology as that of PS10 for electricity generation. The new plant features include control and operational systems enhancements, an improved thermal energy storage system and a higher efficiency receiver.

A utility scale 400 MW solar tower power project, referred to as the "Ivanpah Solar Power Complex", is being built in California by a consortium led by Bright Source Energy and it is expected to be operational in 2012[29]. The heliostats in this project will consist of smaller flat mirrors, termed the LPT 550, each having a reflecting area of 14.4 m^2. 50,000 of these LPT 550 heliostats will be required for every 100 MW of installed capacity. The receiver is a traditional high-efficiency boiler positioned on top of the tower. The boiler tubes in the receiver are coated with a solar selective material that maximizes energy absorbance and there are sections within the receiver for steam

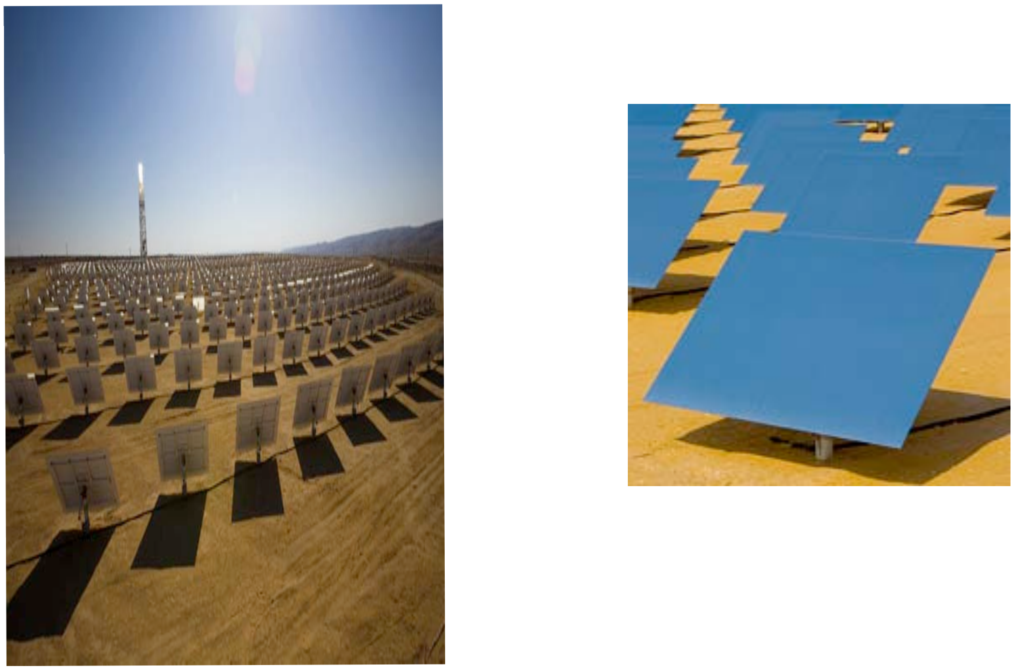

Figure 26. The LPT 550 Central receiver tower demonstration plant in Israel's Negev desert. Left: heliostat field with central tower, Right: 7.22 m^2 heliostat. (source: Brightsource Energy)

generation, superheating and reheating. This results in the generation of superheated steam at 550^o C and 160 bars (unlike the saturated steam that is produced in the PS10 and PS20). The power block consists of a conventional Siemens steam turbine generator with a reheat cycle, and auxiliary functions of heat rejection, water treatment, water disposal and grid interconnection capabilities. The technology demonstration plant, as shown in Figure 26, has 1641 heliostats (reflecting area ~ 12,000 m^2) with each measuring 2.25m x 3.21m (7.22 m^2). The tower height was 75 m (60m tower plus 15 m receiver) and the thermal energy collected by the receiver was between 4.5 to 6 $MW_{th.}$. Because of the higher operating temperature, the solar to electrical efficiency of these plants is expected to be about 20%. Although there is not yet any experience with utility scale plant installations, it appears that the installation cost of these plants may be in the range of $3000/$kW_e$.

In an attempt to bring down the installed cost of the solar power plant technology, eSolar, a California company introduced a modular/distributed tower design with a 1-m^2 reflected area heliostat[30]. These much smaller heliostats, with fully automated two-axis sun tacking system, are easy to assemble and install in large numbers. Each central tower unit is capable of producing 2.5 MW_e through the use of 12,000 mirrors that reflect the

Figure 27. 5 MW twin central receiver tower facility with 1 m^2 heliostats in California. (source: eSolar)

radiation onto a 47 m high tower. The thermal receiver in the tower has external evaporator panels for producing superheated steam at 440 ºC and 60 bar. Figure 27 shows a technology demonstration plant with two-tower system that nominally produces 5 MW_e of electricity. Since the performance details of the plant are not disclosed in any public domain, it is difficult to assess the solar to electric efficiency and the installed plant cost. In principle, the smaller heliostats are easy to manufacture, install and maintain. However, the solar energy collection may involve significant losses due to spillage reaching the thermal receiver. Hence, it is important to study the pilot plant performance characteristics before a utility scale plant design is considered.

3.5. Solar chimney power plant technology

A solar chimney power plant has a high chimney (tower) that is surrounded by a large collector roof made of either glass or resistive plastic supported on a framework (Figure 28)[31]. Towards its center, the roof curves upwards to join the chimney, thus creating a funnel. Solar radiation (direct and diffuse) strikes the collector and transmits part of its energy that heats up the ground and the air underneath the collector roof. At the ground surface, part of the transmitted energy is absorbed and the rest is reflected back to the roof, where it is subsequently reflected to the ground. The multiple reflections result in a higher fraction of energy absorbed by the ground. The warm ground surface heats the adjacent air through natural convection. The buoyant air follows the upward incline of the roof until it reaches the chimney thereby drawing in more air at the collector perimeter.

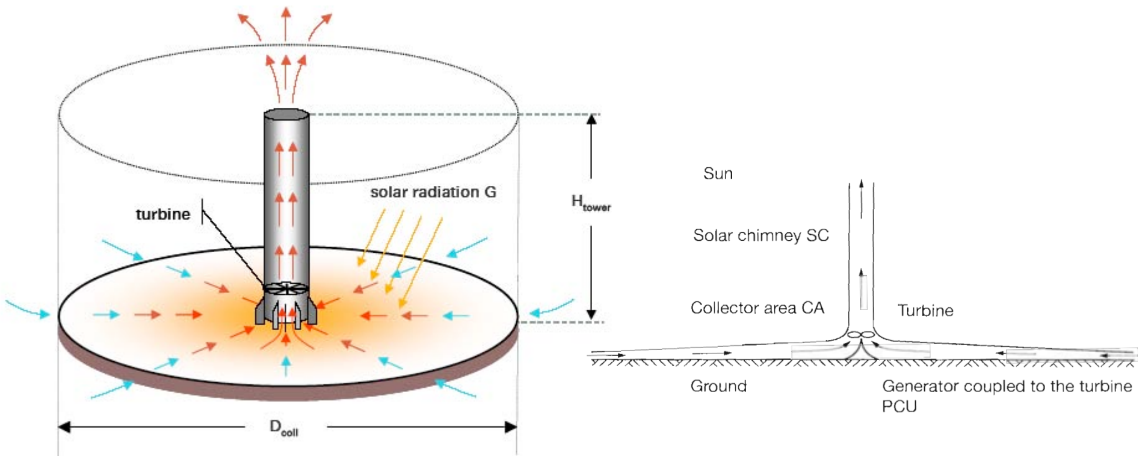

Figure 28. Left: An artist rendering of a 5 MW solar chimney plant (Source:http://www.sbp.de) ; Right: a schematic indicating the main components of the plant (von. Backstrom et al, 2008).

The natural and forced convection set up between the ground and the collector flows at high speed through the chimney and drives wind generators at its bottom. As the air flows from the collector perimeter towards the chimney, its temperature increases, while the velocity remains constant due to the increasing collector height at the center as shown in the schematic (Figure 28). The pressure difference between the outside cold air and the hot air inside the chimney causes the air to flow trough the turbine. The ground under the collector roof behaves as a storage medium, and can even heat up the air for a significant time after sunset. The efficiency of the solar chimney power plant is below 2% and depends mainly on the height of the tower. As a result, these power plants can only be constructed on land that is very cheap or free. Such areas are usually situated in desert regions. However, this approach is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes.

A 200 m high solar chimney demonstration plant based was constructed in Manzanares, Spain[32]. The peak power output of this demonstration plant was 50 kW and it operated for over 8 years without any significant degradation in performance. However, as with other CSP plants, the minimum economical size of the solar chimney power plant is in the several MW range. Although no pilot plant has been built to demonstrate the viability of this technology in the MW range, computer simulations suggest its promise as a low cost solar thermal technology. Figure 29 shows the results from a simulation of a large-scale solar chimney power plant with a 5000 m collector diameter (~ 20 km^2 area),

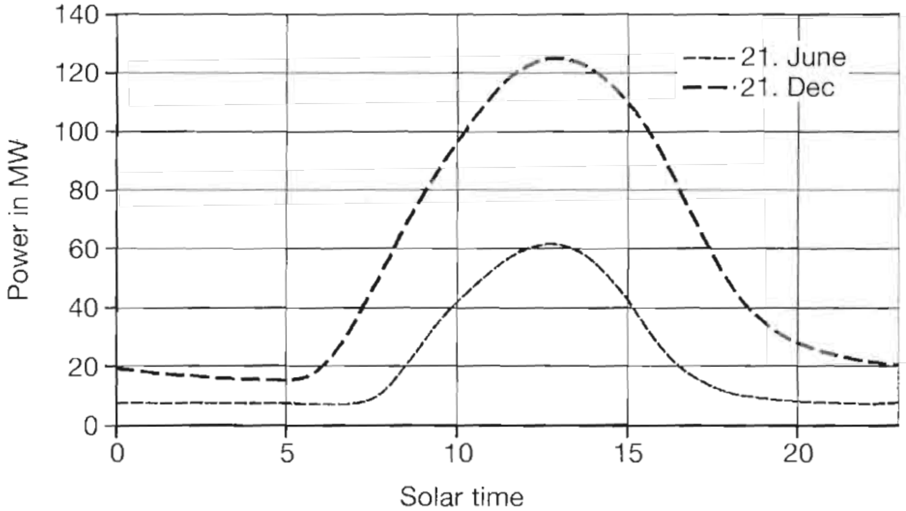

Figure 29. Simulated results of electrical power output of solar chimney power plant during summer and winter (von Backstrom et al., 2008).

and a chimney height of 1000 m and inside diameter 210 m[31]. With the vast expanse of unpopulated land in Australia, it may be possible to economically erect a solar chimney plant of this size.

3.5. Nonimaging concentrator technology

All of the concentrating technologies discussed thus far require some type of active solar tracking in order to account for the change in the elevation of the sun on any given day and throughout the year. Nonimaging concentrators, such as the compound parabolic concentrator (CPC), allow for the use of a non-tracking stationary concentrator that can account for the daily and annual excursion in solar elevation[33]. Figure 30

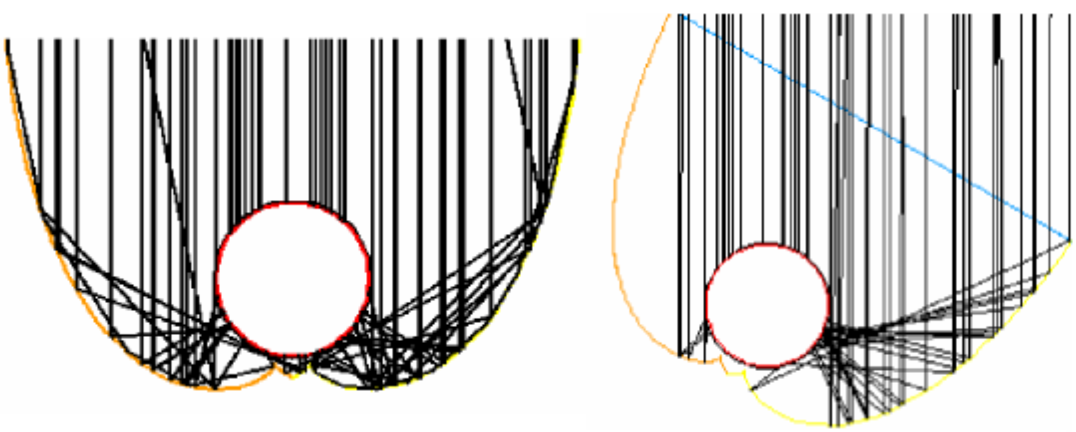

Figure 30. Ray tracing diagrams for the Winston Series CPC. Left – incoming light rays directly overhead; Right – incoming light rays at the acceptance angle of the design. (source: www.soalrgenix.com)

illustrates how the light rays in a commercial CPC collector are concentrated when the source is directly overhead (left), such as solar noon on the equinox, and when it is at the acceptance angle of the CPC design (right), such as would be observed during the solstice.

The stationary benefit of the CPC comes at the expense of a concentration ratio of 2 for the design. This is an order of magnitude lower than what can be achieved through the use of a parabolic trough but it is twice that of a typical flat-plate collector. As such, the CPC design is capable of producing sensible heat at temperatures well in excess of 120 °C, thus making it a good candidate for use with an absorption refrigeration system. It can also be paired with a low temperature power cycle, such as an organic Rankine cycle, to generate electricity. The resulting system would be fairly inefficient when compared to a dish-Stirling system but it would have a cost-to-efficiency ratio that would make it attractive for use in rural areas.

4. Concentrating solar power (thermal) systems economics

The concentrating solar power (CSP) for electricity generation technologies examined in the previous sections are the most dominant and have the greatest potential for commercialization. Current projects are targeted so that they meet specific needs at an economic benefit. Once success is achieved, the price points will come down and good economics will drive the CSP projects. The following discussion is included here to indicate that CSP is becoming more economically attractive. Component manufacturers, utilities and regulators are making decisions now that will determine the scale, structure and performance of the CSP industry. Since each country's approaches to the renewable electricity industry is different, only the observations that are more common globally are included here. When considering the economic viability of CSP, often the levelized electricity cost (LEC) is calculated and compared among different technologies. Therefore, in the following, a general method is given for determining LEC.

The LEC is dependent on many variables related to the site, technology chosen and the plant financing. The LEC is defined as[34]:

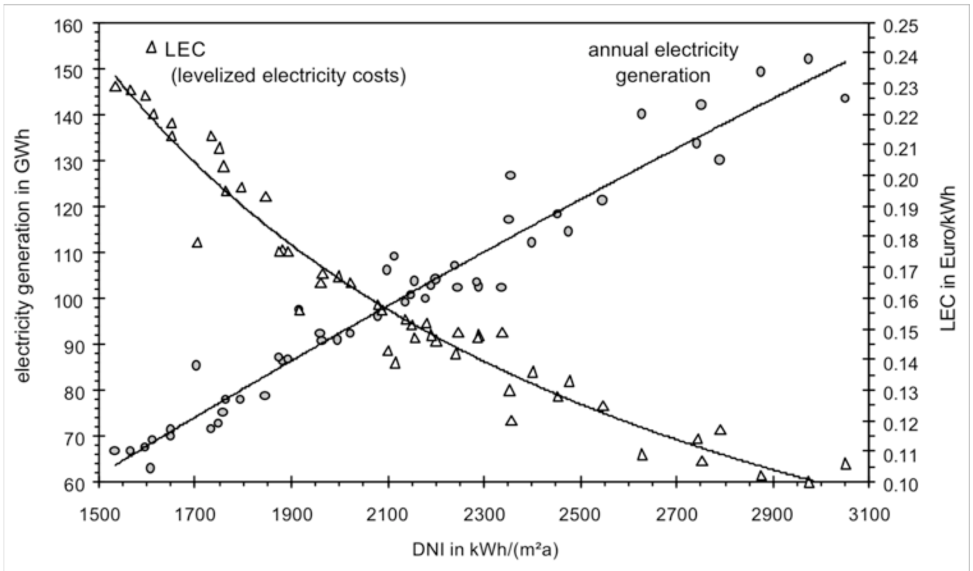

Figure 31. The variation of annual electricity generation and LEC for a 50 MW_e parabolic trough plant with a 375,000 m^2 solar field for fifty chosen sites (Quaschning, Kistner & Ortmanns, 2001).

$$LEC = \frac{CRF \times K_I + K_{OM} + K_F}{E}$$

where

$$CRF = \frac{k_d (1 + k_d)^n}{(1 + k_d)^n - 1} + k_i$$

CRF: Capital Recovery Factor; K_I: total investment of the plant; K_{OM}: annual operation and maintenance costs; K_F: annual fuel costs (any fossil fuel, such as natural gas); *E:* annual net electricity revenue; k_d: debt interest rate; *n:* depreciation period in years (~30); k_i: annual insurance rate (~1%).

The many factors that determine the LEC vary greatly due to government subsidies, tax incentives and annual net electricity production. One of the key parameters in the above formula is the determination of the annual electricity generation, which depends largely on the available DNI at the plant location. For example, Figure 31 shows the impact of the annual DNI on the annual power generation and the LEC of a 50 MW_e parabolic trough SEGS type power plant with a 375,000 m^2 solar field. The economic parameters (e.g. discount rate of 6.5%, solar field costs of 200 Euro/m^2, power block costs of 1,000 Euro/kW and O&M costs of 3.7 million Euro per annum) have been kept constant[35]. Although, some of the financial data may be outdated, the intent here is

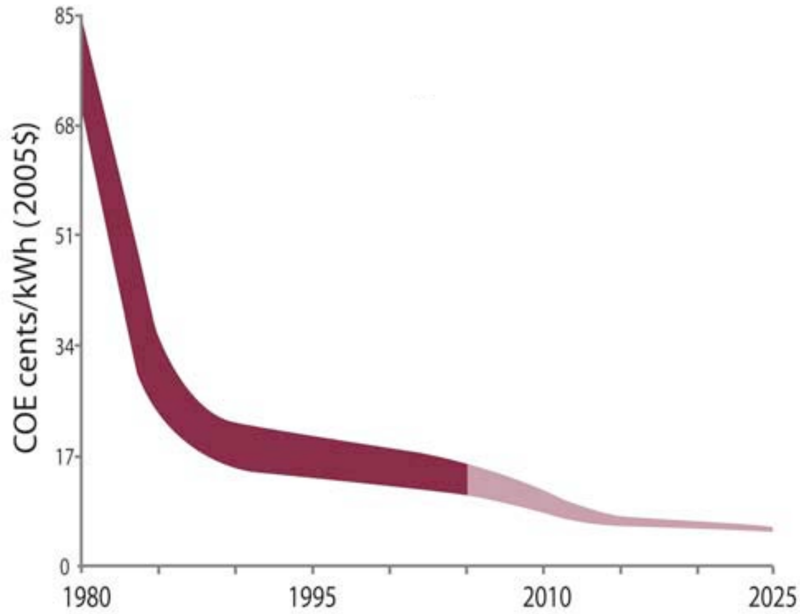

Figure 32. The variation of the LEC for concentrating solar thermal power. (source: National Renewable Energy Laboratory, USA)

simply to show that the annual electricity generation is approximately proportional to the DNI. This suggests that a careful analysis needs to be carried out for the determination of an economically optimized project site that not only depends on the solar irradiance (DNI) but on many other influencing parameters.

The present evaluation estimates (Figure 32) from a number of sources is that the LEC for CSP systems, shown here as cost of electricity (COE), will be around \$0.15 – 0.20/kWh, assuming a load demand between 9:00 am and 11:00 pm. However, the absolute cost data on many of the CSP systems considered here, and those planned for commercial deployment around the world, is largely unavailable so these numbers must be considered with some caution. Cost reductions due to technological improvements, such as the implementation of thermal storage, and large-scale deployment are estimated to be around 10-30% for parabolic trough systems, 20-35% for central receiver systems and 20-40% for dish-Stirling systems[33]. Given the rapid deployment of CSP systems, it is suggested that within the next five years, the LEC will be \$0.10 - 0.15/kWh. With the additional benefit of carbon credits, CSP technology is poised to become the dominant solar electricity generating plant development in places where there is good DNI.

5. Summary and conclusions

Concentrating solar thermal power (CSP) is a proven technology, which has significant potential for further development and achieving low cost. The history of the Solar Electricity Generating Systems (SEGS) in California demonstrates impressive cost reductions achieved up to now, with electricity costs ranging today between $0.10 and $0.15/kWh. Advanced technologies, mass production, economies of scale and improved operation will allow for a reduction in the cost of solar produced electricity to a competitive level within the next 5 to 10 years. Hybrid solar-and-fuel plants, at favorable sites, making use of special schemes of finance, can already deliver competitively priced electricity today. With over two decades of experience, parabolic trough technology is mature enough that its investment cost estimates can be made with confidence. Given the rapid growth contemplated within the immediate future (mostly in the southwest USA) and medium temperature CSP systems (250-300^o C), it is very likely that the LEC price target of $0.10/kWh may well be met within the next three years using the parabolic trough technology. When the parabolic trough technology is combined with biomass gasification in a hybrid system, the overall plant efficiency will be substantially increased, thus resulting in a relatively low LEC. This is an approach that is ideally suited for regions of moderate DNI (5.2-5.5 kWh/m^2/day) and for distributed power applications (1- 5 MW power plants). A greater opportunity lies in the thousands of niche markets that are primed for smaller scale (1-10 MW) parabolic trough projects at a lower cost.

The central receiver tower (CRT) systems are being pursued aggressively by a number of companies with approaches that mostly differ in the heliostat size. The distributed approach with multiple towers appears to gain prominence because of their lower installation costs. Both parabolic trough and central tower systems benefit from heat storage, especially when the power demand is during off-peak solar hours. The CRT systems are best suited in areas of good annual solar insolation (>2000 kWh/m^2/year) and utility scale plant sizes (>50 MW). Because of the steam cycle used in the power block, the water availability can be an issue, especially in desert regions. The problem can be overcome by the use of an air-cooling system, which will have the adverse effect of reducing the overall plant efficiency.

The recent advances made in dish-Stirling systems in improving their solar to electric efficiency in the range of 30% make them attractive for utility scale power plant implementation. Because of their small unit electricity output (< 25 kW), they are most attractive for distributed applications, especially when hermetically sealed Stirling engines are used as this may result in much lower operation and maintenance costs.

In summary, CSP is poised to become a significant player in the renewable electricity generation in countries where a significant solar energy resource is available, such as those near desert and equatorial regions.

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