CONTRIBUTION OF CONCENTRATED SOLAR THERMAL POWER FOR A COMPETITIVE SUSTAINABLE ENERGY SUPPLY

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Abstract This paper discusses the opportunities for solar thermal power generation in industrial nations and emerging countries. A short overview describes the most important solar thermal concentration technologies.
Today's levelised electricity costs of concentrated solar thermal power are in the order of 15 Euro cents per kWh, depending on the size and location of the power plant. In all regions with an annual global irradiation above 1100 kWh/m² the costs of solar thermal electricity are lower than the costs of photovoltaic systems. Nevertheless, the worldwide installed capacity of concentrated solar thermal power is still rather low. A strong market introduction plan with high growth rates will reduce costs by nearly 50 % within the next 10 years. In 20 years, market competitiveness to conventional fossil power plants can be achieved even if external costs are not considered.
Available sites in the Sahara desert can theoretically cover the whole electricity demand of the world. For the long term, clean electricity from North Africa can generate a significant share of the Central European demand. Therefore, new high-voltage electricity transmission lines are needed and should be planned already today.

Keywords solar thermal power, concentrating solar energy, solar electricity

INTRODUCTION

Many people associate solar power directly with photovoltaics and not with solar thermal power generation. Nevertheless, large commercial concentrating solar thermal power plants have been generating electricity at reasonable costs for more than 15 years and some new solar thermal power plants are soon to be erected.

This paper gives a short overview about the most important concentrating solar thermal power plant technologies. The amount of annual solar irradiation decides whether a region is or is not suited for their installation. Regions in South Europe with annual global horizontal irradiation values above 1800 kWh/m² and North Africa with up to 2500 kWh/m² offer nearly perfect conditions. This paper also describes operating ranges for concentrating solar thermal power plants and estimates levelised electricity costs compared to PV systems. A cost projection for the next 10 years demonstrates the high cost reduction potential.

Finally, potentials for the installation of concentrating solar thermal power plants and opportunities for import of solar thermal electricity in Central Europe are discussed.

CONCENTRATING SOLAR THERMAL POWER

Solar Thermal Trough Power Plants

The "trough" collectors that make up the solar field of a parabolic trough power plant are large cylindrical parabolic mirrors that concentrate the sunlight on a line of focus (Figure 1). Several of these collectors are installed in rows about a hundred meters long and the total solar field is composed of many such parallel rows.

Figure 1. Parabolic trough collectors at PSA (Almería/Spain)

All the collectors track the path of the sun on their longitudinal axes. The mirrors concentrate the sunlight more than 80 times on a metal absorber pipe in the line of focus. This pipe is embedded in an evacuated glass tube to reduce heat loss. A selective coating on the absorber tube surface lowers emission losses. Either water or a special thermal oil, runs through the absorber tube. The concentrated sunlight heats it up to nearly 400 °C, to evaporate water and to drive a turbine and an electrical generator with that steam. After passing through the turbine, the steam condenses back into water that is returned to the cycle (Figure 2).

A fossil burner can drive the water-steam cycle during periods of bad weather or at night. In contrast to photovoltaic systems, solar thermal power plants can guarantee capacity. This option increases its attractiveness and the quality of capacity planning on the grid. Thermal storage can complement or replace the fossil burner so that the power plant can be run with neutral carbon dioxide emissions. In this case, heat from the storage drives the cycle when there is no direct sunlight. Biomass or hydrogen could also be used in the parallel burner to run the power plant without carbon dioxide emissions.

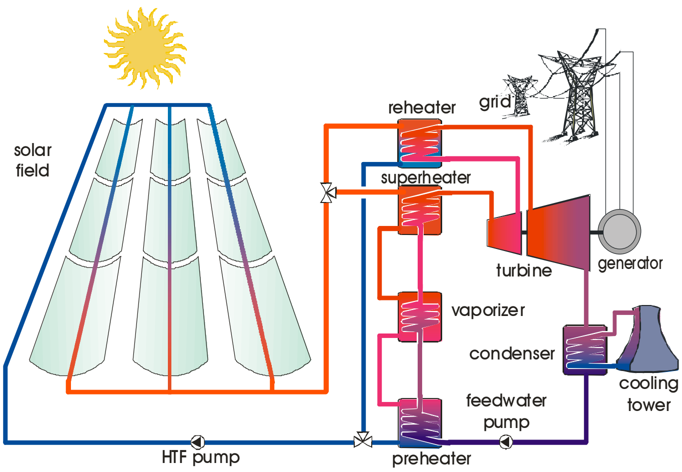

Figure 2. Principle of the parabolic trough power plant

The first commercial parabolic trough power plant was built in the Mojave Desert in California in the year 1984. By 1991, nine trough power plants with a total capacity of 354 MW_e, which feed about 800 million kWh per year into the grid, had been erected on more than 7 km^2 (Figure 3). Eight of them can also be driven with fossil fuel to produce electricity during bad weather or at night. The annual share of the thermal energy produced from gas is limited by statute to 25 percent. The total investment in all of the systems was more than 1.2 billion USD. A large number of the plant components were produced in Europe. The levelised cost of solar electricity was reduced from 0.27 USD per kWh in the first power plant to about 0.12 to 0.14 USD per kWh in the last installed system.

Figure 3. Bird's eye view on the Californian trough power plants (photo: KJC)

Although solar thermal electricity is much more economical than photovoltaic electricity, no more commercial power plants have been erected since 1991. However, an increasing number of project developments make the new construction of parabolic trough systems very probable. The World Bank has made 200 million USD in financial assistance available for new combined-cycle gas and solar thermal power plants in developing countries. In Spain, a law to increase the compensation for electricity produced from solar thermal energy with a premium of 12 Euro cents/kWh above the market price of about 4 Euro cents/kWh was published in 2002.

Solar Thermal Tower Power Plants

The solar field of a central receiver system, or power tower, is made up of several hundred or even a thousand mirrors, called heliostats, placed around a receiver at the top of a central tower. (Figure 4). A computer controls each of these two-axis tracking heliostats with a tracking error of less than a fraction of a degree to ensure that the reflected sunlight focuses directly on the tower receiver, where an absorber is heated up to temperatures of about 1000 °C by the concentrated sunlight. Air or molten salt transports the heat and a gas or steam turbine drives an electrical generator that transforms the heat into electricity.

Figure 4. Solar tower power plant at PSA (Almería/Spain)

Dish/Stirling Systems

A two-axis tracked parabolic concentrator concentrates the sunlight to a receiver of Dish/Stirling systems. The concentrator diameter is in the range of 10 m. Concentration ratios of more than 2000 can be reached. The concentrated sunlight heats up the receiver and drives a Stirling engine. Finally, a coupled electrical generator converts the motion energy to electricity.

Figure 5. Dish/Stirling System at PSA (Almería/Spain)

Operational Areas

The areas where photovoltaic systems and solar thermal power plants can operate overlap only in a narrow range (Figure 6). Due to their modularity, photovoltaic operation covers a wide range from less than one Watt to several megawatts and photovoltaic systems are able to operate as stand-alone systems as well as grid-connected systems. Solar thermal power plants can work in both areas as well. Dish/Stirling systems are small units in the kilowatt range. The above-mentioned parabolic trough and solar tower power plants operate only in the megawatt range.

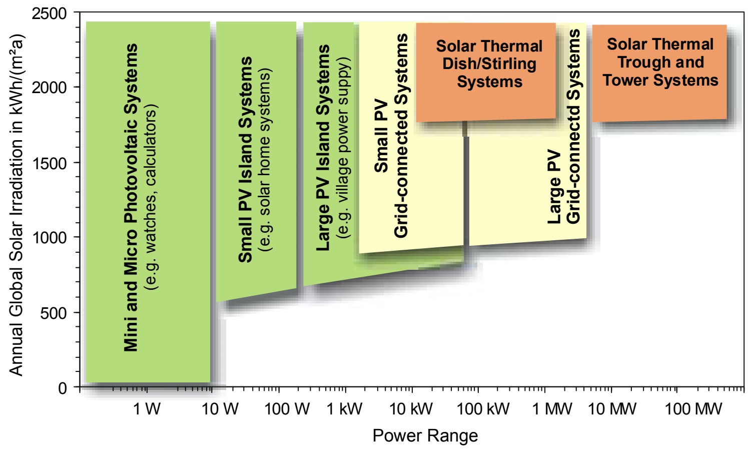

Figure 6. Operational areas for solar thermal power plants and photovoltaic systems depending on the installed capacity and the annual global solar irradiation

Global solar irradiance consists of direct and diffuse irradiance. When skies are overcast, only diffuse irradiance is available. While solar thermal power plants can only use direct irradiance for power generation, photovoltaic systems can convert the diffuse irradiance as well. That means, they can produce some electricity even with cloud-covered skies. For the installation of concentrating solar thermal power systems high annual direct irradiation values are needed. A suitable site should offer at least a direct normal irradiation of 1800 kWh/(m^2 a). Perfect sites have up to 3000 kWh/(m^2 a). Figure 7 shows that the Earth's Sun Belt offer good conditions for installation of concentrating solar thermal power plants.

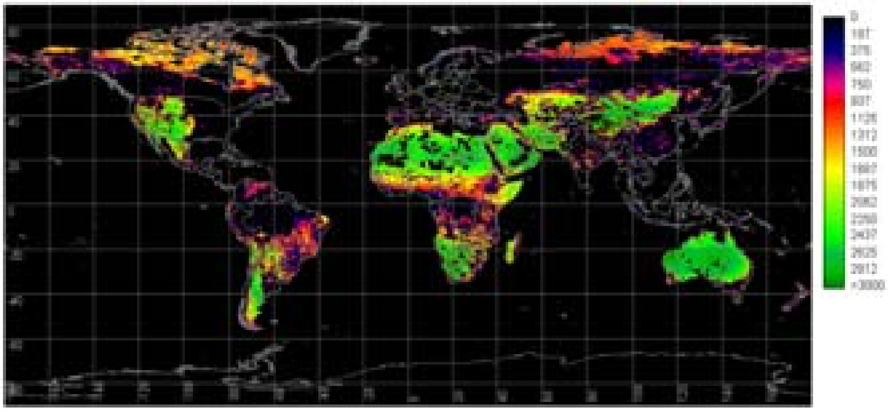

Figure 7. Annual sum of direct normal irradiation in kWh/(m² a) at usable sites (not usable sites are black, irradiation data: Gregor Czisch, graphic: Stefan Kronshage)

COSTS ESTIMATION

Simulations for 61 sites in Europe and North Africa were made for the following costs estimations. The annual output of concentrating solar thermal power plants in comparison to tracked and fixed installed PV systems and the resulting levelised electricity costs are simulation results. The software environment greenius /1/ (www.greenius.net) was used for these simulations.

Irradiation Comparison

The simulated sites cover a global annual irradiation range from 923 kWh/(m² a) in Dublin (Ireland) to 2 438 kWh/(m² a) in Luxor (Egypt). The greenius simulation environment calculated the direct irradiation on a one-axis-tracking, north-south-oriented concentrating collector (trough collector) and the global irradiation on a fixed, 30° south-tilted plane and the global irradiance on a two-axis-tracking system (Figure 8).

The direct irradiation on the one-axis-tracking system is lower than the global irradiation on a fixed system and the irradiation on 2-axis-tracked systems for irradiation values below 2 000 kWh/(m² a). This shows clearly, that the use of tracked and concentrated solar systems is difficult in Middle and North Europe regions. The absolute difference of the annual irradiations of the different tracking variants is nearly the same over the full irradiation range. Hence, the advantage of two-axis-tracking system compared to one-axis-tracking systems decreases with increasing annual irradiation sums. On the other hand, tracking systems will have a much higher output than non-tracking systems at regions with high irradiation values.

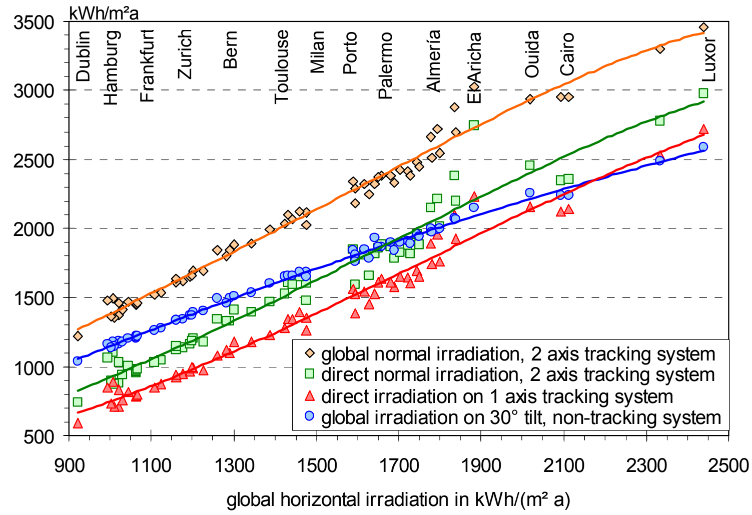

Figure 8. Direct normal irradiation, direct irradiation on a 1-axis tracked collector, global irradiation on a 30° tilted plane and global irradiation on a 2-axis tracked plane as function of the global horizontal irradiation

System Efficiencies and Output

Today's efficiencies of good systems have been chosen for the simulation. The annual system efficiency of the monocrystalline silicon PV system of about 11 % was almost constant with the site irradiation, decreasing a little at higher irradiation values due to the negative influence of correlated higher ambient temperature. This result is not astonishing because PV module efficiency is almost constant over large irradiance ranges and decreases with higher temperatures.

On the contrary, the annual system efficiency of the parabolic trough system increases significantly with the annual irradiation sum. The part load efficiency of the steam turbine cycle is much lower than the nominal efficiency. The efficiency is also reduced at days with fluctuating irradiance values due to the capacitive behaviour of the thermal system. Therefore, the annual system efficiency of a today's solar thermal trough power plant varies between 10 % and 14 % for the considered irradiation range.

Up to annual global irradiation values of about 1700 kWh/(m² a) the output of the solar thermal system is the lowest because the efficiency and the usable irradiation are disproportionally low. Since the system efficiency of the solar thermal system at very high irradiation values is much higher than the efficiency of the PV system, the specific annual output of the solar thermal system becomes here nearly the same as of the two-axis-tracked PV system.

Costs Assumptions and Results

For comparability reasons all costs are related to square meters of effective system area. Assuming a nominal PV module efficiency of 13.5 % one square meter can hold PV panels with a capacity of 135 W_p. Finally, overall system costs of 5320 €/kW_p result in area related costs of 720 €/m². Operation results of existing PV systems have provided net present values of the costs for operation and maintenance of about 200 €/m². Installation and operation costs of tracked PV systems are higher than the costs of non-tracking systems. The cost assumptions for the parabolic trough power plant are valid for a system with a capacity of about 30 MW. These costs are much lower than the costs of PV systems (see table 1) but still in the same magnitude as in the 1990s, since the installation rates for solar thermal power plants are not very high today. For all systems a lifetime of 30 years and an overall discount rate of 7 % were assumed.

Table 1. Assumptions for today's systems costs

Net present value in €/m² for system	Installation	Operation	Total
Non-tracking PV system	720	200	920
2-axis-tracked PV system	900	270	1170
Parabolic trough power plant	450	180	630

Figure 9 shows the levelised electricity costs combining the specific output and the specific costs assumptions of table 1. Since today's costs of solar thermal power plants are lower than that of PV systems, levelised electricity costs are also lower above global irradiations of 1100 kWh/(m² a) although the specific output of the PV system is higher until 1700 kWh/(m² a). Nevertheless, there is a high uncertainty in the simulation results of solar thermal power plants at very low irradiations. Due to the high investment costs for multi megawatt solar thermal power plants, sites with higher annual irradiations are recommended.

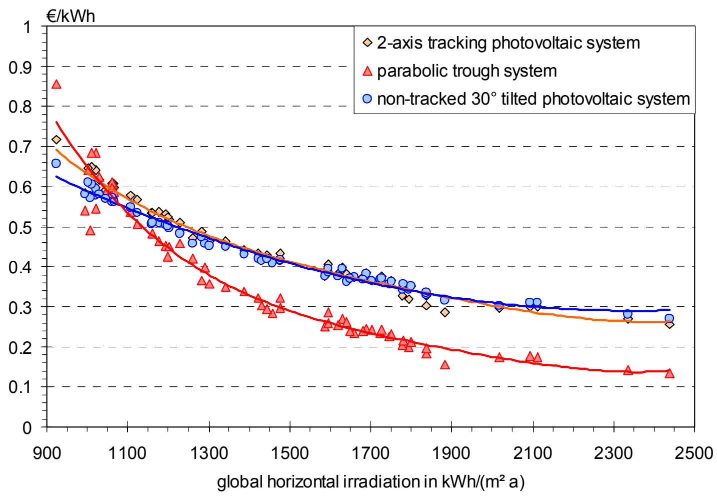

Figure 9. Today's Levelised electricity generation costs for photovoltaic systems and 1-axis tracked concentrated parabolic trough systems as function of the global horizontal irradiation

Looking at the PV learning curve, there is a cost reduction by 20 % when doubling the market volume /2/. In the past, this doubling was achieved almost every 4 years. Assuming the same growth rates for the next decade, there will be a cost reduction by 50 %.

For solar thermal parabolic trough power plants the progress ratio is about 0.88 /3/. In other words, a price reduction by 12 % can be expected when doubling the market volume. On the other hand, possible growth rates of solar thermal power are higher. These power plants start from a lower annual production rate and they have not the same production limits as PV. Combining lower price reduction and higher growth rates leads to an overall cost reduction for parabolic trough power plants of about 40 % within the next 10 years. Table 2 summarizes the assumptions for solar thermal power and PV.

Table 2. Assumptions for system costs in 10 years

Net present value in €/m² for system	Installation	Operation	Total
Non-tracking PV system	360	100	460
2-axis-tracked PV system	450	135	585
Parabolic trough power plant	270	108	378

In 10 years, the break-even irradiation for the generation costs of non-concentrating and solar thermal systems move to higher irradiation values. In South Europe both technologies can produce with costs below 20 Euro-cents/kWh. Solar thermal power plants remain the best-cost solution in South Europe and North Africa with possible generation costs below 10 Eurocents/kWh. Tracked PV systems have little costs advantages in North Africa (see figure 10).

In 20 years, full market competitiveness to conventional fossil power plants can be achieved even if external costs are not considered.

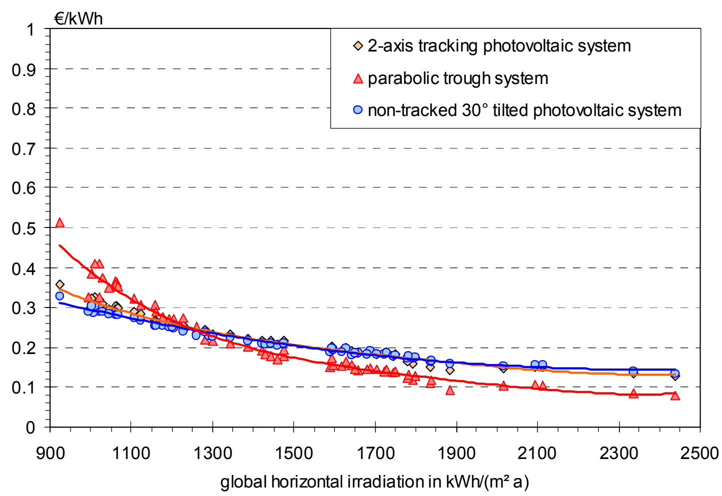

Figure 10. Levelised electricity generation costs in 10 years for photovoltaic systems and 1-axis tracked concentrated parabolic trough systems as function of the global horizontal irradiation

POTENTIALS AND OUTLOOK

Resource assessment for solar power has recently become very easy, in fact much easier than for fossil or nuclear fuels: the solar radiation intensity on the ground can be measured by remote sensing technologies using weather satellites and orbiting satellites around the world. With very high spatial (up to 1 km) and temporal (up to 1h) resolution and accuracy, those technologies provide a reliable data base for the engineering and economic assessment of solar power projects, considerably lowering costs and risks in comparison to other energy prospecting activities.

The technical potential of solar power generation in Northern Africa exceeds the present world electricity demand by more than one order of magnitude (see figure 11).

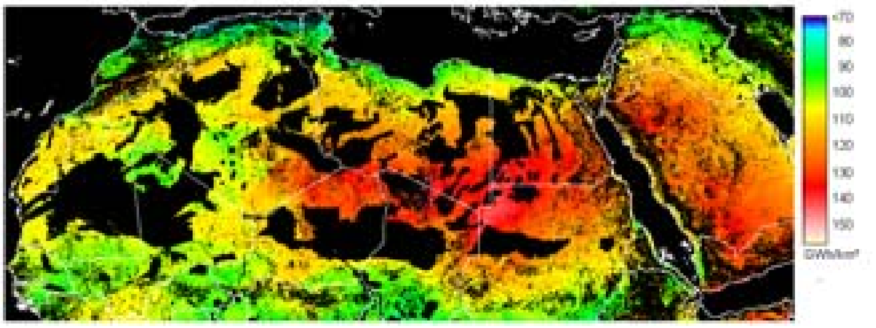

Figure 11. Annual Solar Electricity Yield of Solar Thermal Power Plants (200 MW_e SEGS) in Northern Africa. The total potential of $13 \cdot 10^6$ TWh_e/year can theoretically cover about 1000 times the world electricity demand

This huge potential can be activated only to a very small portion, as the regional demand for electricity is very limited, although growing steadily. In addition to that, solar electricity could be exported to the centres of demand in Europe, by high voltage direct current transmission lines (HVDC) or by means of solar hydrogen production. In this context, the generation of electricity and of desalted water for electrolysis is of particular importance.

With electricity transportation costs below 2 cents/kWh_e using high-voltage DC transmission solar generated electricity from solar thermal power plants in Northern Africa may be available for 5 to 9 cents/kWh_e in Europe until the year 2020. For the long term, clean electricity from North Africa can generate a significant share of the Central European demand. Therefore, new high-voltage electricity transmission lines are needed and should be planned already today.

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