High-temperature solar energy technologies: from laboratory curiosity to the current implementation at power, thermal and chemical markets

Energie solaire à haute température : de la curiosité de laboratoire à son implantation actuelle dans le marché de l'électricité, la thermique et la chimie

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1. INTRODUCTION

Solar thermal power plants, due to their capacity for large-scale generation of electricity and the possible integration of thermal storage devices and hybridization with backup fossil fuels, are meant to supply a significant part of the demand in the countries of the solar belt [1] . Nowadays, the high temperature thermal conversion of concentrated solar energy is rapidly increasing with many commercial projects taken up in Spain, USA and other countries such as India, China, Israel, Australia, Algeria and Italy. This is the most promising technology to follow the pathway of wind energy in order to reach the goals for renewable energy implementation in 2020 and 2050.

Spain with 2,400 MW connected to the grid in 2013 is taking the lead on current commercial developments, together with USA where a target of 4,500 MW for the same year has been fixed and other relevant programs like the "Solar Mission" in India recently approved and going for 22 GW-solar, with a large fraction of thermal [2] .

Solar Thermal Electricity or STE (also known as CSP or Concentrating Solar Power) is expected to impact enormously on the world's bulk power supply by the middle of the century. Only in Southern Europe, the technical potential of STE is estimated at 2,000 TWh (annual electricity production) and in Northern Africa it is immense [3] . Worldwide, the exploitation of less than 1% of the total solar thermal power plant potential would be enough to meet the recommendations of the United Nations' Intergovernmental Panel on Climate Change for long-term climate stabilization [4] One MW of installed concentrating solar thermal power avoids 688 tons of CO_2 compared to a Combined Cycle conventional plant and 1,360 tons of CO_2 compared to a conventional coal/steam plant. A 1-m^2 mirror in the primary solar field produces 400 kWh of electricity per year, avoids 12 tons of CO_2 and contributes to a 2.5 tons savings of fossil fuels during its 25-year operation lifetime. The energy payback time of concentrating solar power systems is less than one year, and most solar-field materials and structures can be recycled and used again for further plants.

But in terms of electric grid and quality of bulk power supply, it is the ability to provide dispatch on demand that makes STE stand out from other renewable energy technologies like PV or wind. Thermal energy storage systems store excess thermal heat collected by the solar field. Storage systems, alone or in combination with some fossil fuel backup, keep the plant running under full-load conditions. This capability of storing high-temperature thermal energy leads to economically competitive design options, since only the solar part has to be oversized. This STE plant feature is tremendously relevant, since penetration of solar energy into the bulk electricity market is possible only when substitution of intermediate-load power plants of about 4,000-5,000 hours/year is achieved.

The combination of energy on demand, grid stability and high share of local content that lead to creation of local jobs, provide a clear niche for STE within the renewable portfolio of technologies. Because of that, the European Commission is including STE within its Strategic Energy Technology Plan for 2020, and the US DOE is launching new R&D projects on STE. A clear indicator of the globalization of such policies is that the International Energy Agency (IEA) is sensitive to STE within low-carbon future scenarios for the year 2050. At the IEA's Energy Technology Perspectives 2010 [5] , STE is considered to play a significant role among the necessary mix of energy technologies needed to halving global energy-related CO_2 emissions by 2050, and this scenario would require capacity additions of about 14 GW/year (55 new solar thermal power plants of 250 MW each).

STE systems consist of a large reflective surface collecting the incoming solar radiation and concentrating it onto a solar receiver with a small aperture area. The solar receiver is a high-absorptance radiative/convective heat exchanger that emulates as closely as possible the performance of a radiative black body. An ideal solar receiver would thus have negligible convection and conduction losses. In the case of a solar thermal power plant, the solar energy is transferred to a thermal fluid at an outlet temperature high enough to feed a heat engine or a turbine that produces electricity. The solar thermal element can be a parabolic trough field, a linear Fresnel reflector field, a central receiver system or a field of parabolic dishes, normally designed for a normal incident radiation of 800-900 W/m². Annual normal incident radiation varies from 1600 to 2800 kWh/m², allowing from 2000 to 3500 annual full-load operating hours with the solar element, depending on the available radiation at the particular site [6]

The first generation of commercial STE projects is mainly based on technological developments and concepts that matured after more than two decades of research. Nevertheless, the current solar thermal power plants are still based on conservative schemes and technological devices which do not exploit the enormous potential of concentrated solar energy. Commercial projects use technologies of parabolic troughs with low concentration in two dimensions and linear focus, or systems of central tower and heliostat fields, operating with thermal fluids at relatively modest temperatures, below 400ºC [7] . The most immediate consequence of these conservative designs is the use of systems with efficiencies below 20% nominal in the conversion of direct solar radiation to electricity; the tight limitation in the use of efficient energy storage systems; the high water consumption and land extension due to the inefficiency of the integration with the power block; the lack of rational schemes for their integration in distributed generation architectures and the limitation to reach the temperatures needed for the thermochemical routes used to produce solar fuels like hydrogen.

In the first commercial projects involving parabolic trough technology some improvements are being introduced such as the use of large molten salt heat storage systems able to provide high degrees of dispatch for the operation of the plant, such as the plants Andasol 1 and 2 in Guadix, Spain, with 7.5 hours of nominal storage, or the use of direct steam generation loops to replace thermal oil at the solar field. Central towers are opening the field to new thermal fluids like molten salts (Gemasolar tower plant in Seville, Spain) and air, and new solar receivers like volumetric absorbers.

In parallel a new generation of concentrating solar thermal power systems is starting deployment. This new generation is characterized by its modularity and higher conversion efficiencies. The design strategy is based on the use of highly compact heliostat fields, using mirrors and towers of small size, and looking for integration into high temperature thermodynamic cycles. There are currently some initiatives with prototypes at an experimental stage and announcing large commercial projects like the one proposed by BrightSource with a prototype of 6 MW_{th} at the Neguev desert in Israel, the 100 kWe prototype promoted by the AORA company and researchers of the Weizmann Institute in Israel, and the 5 MWe prototype built by the company eSolar in California.

2. SOLAR THERMAL POWER PLANTS: SCHEMES AND TECHNOLOGIES

Four Concentrating Solar Power technologies are today represented at pilot and commercial-scale [8] : parabolic trough collectors (PTC), linear Fresnel reflector systems (LFR), power towers or central receiver systems (CRS), and dish/engine systems (DE). All the existing pilot plants mimic parabolic geometries with large mirror areas and work under real operating conditions (Figure 1).

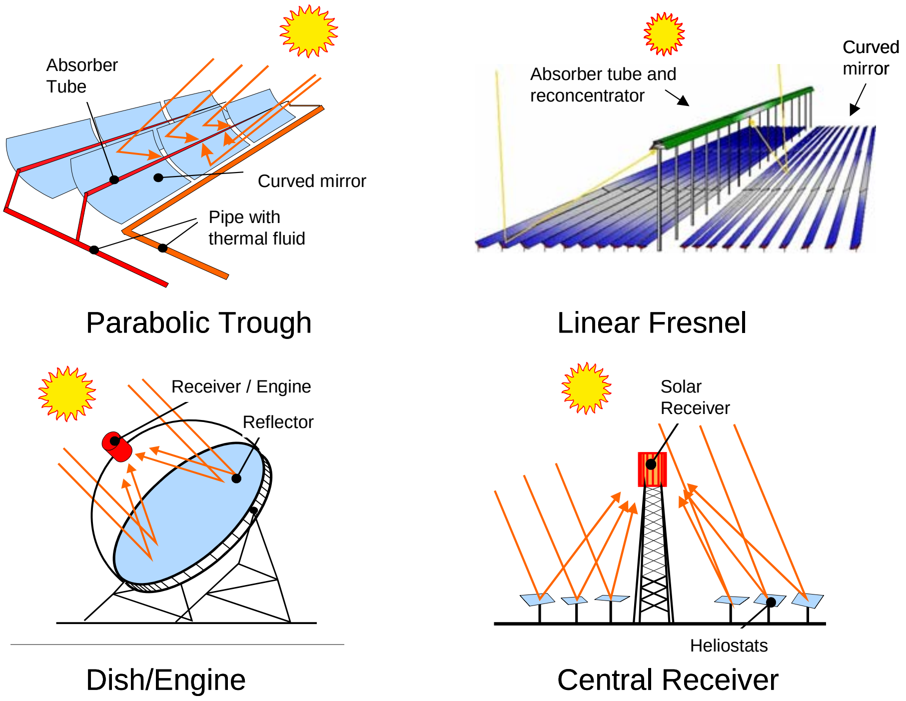

Figure 1: Schematic diagrams of the four STE systems currently scaled up to pilot and demonstration sizes.

PTC and LFR are 2-D concentrating systems in which the incoming solar radiation is concentrated onto a focal line by one-axis tracking mirrors. They are able to concentrate the solar radiation flux 30 to 80 times, heating the thermal fluid up to 450ºC, with power conversion unit sizes of 30 to 80MW, and therefore, they are well suited for centralized power generation at dispatchable markets with a Rankine steam turbine/generator cycle. CRS optics is more complex, since the solar receiver is mounted on top of a tower and sunlight is concentrated by means of a large paraboloid that is discretized into a field of heliostats. This 3-D concentrator is therefore off-axis and heliostats require two-axis tracking. Concentration factors are between 200 and 1000 and unit sizes are between 10 and 200MW, and they are therefore well-suited for dispatchable markets and integration into advanced thermodynamic cycles. A wide variety of thermal fluids, like saturated steam, superheated steam, molten salts, atmospheric air or pressurized air, can be used, and temperatures vary between 300ºC and 1,000ºC. Finally, DE systems are small modular units with autonomous generation of electricity by Stirling engines or Brayton mini-turbines located at the focal point. Dishes are parabolic 3D concentrators with high concentration ratios (1,000-3,000) and unit sizes of 5-25 kW. Their current market niche is in both distributed on-grid and remote/off-grid power applications.

Typical solar-to-electric conversion efficiencies and annual capacity factors are listed in the table below [6] . The values for parabolic troughs, by far the most mature technology, have been demonstrated commercially. Those for linear Fresnel, dish and tower systems are, in general, projections based on component and early commercial projects and the assumption of mature development of current technology. With current investment costs, all STE technologies are generally thought to require a public financial support strategy for market deployment. At present direct capital costs of STE and power generation costs are estimated to be 2-3 times those of fossil-fueled power plants, however industry roadmaps advance 60% cost reduction before 2025 [7] . In fact governments at some countries like Spain are already accelerating the process of drastic tariff reduction with the goal of STE, PV and wind energy becoming tariff-equivalent in less than one decade.

Table 1 Characteristics of Solar Thermal Electricity System (adapted from [10]).

Fresnel systems are not included since performance data available are not conclusive for a comparative assessment.

	Parabolic troughs	**Central Receiver**	**Dish-Stirling**
Power Unit	30-80 MW*	10-200 MW*	5-25 kW
Temperature operation	390 ºC	565 ºC	750 ºC
Annual capacity factor	23-50 %*	20-77 %*	25 %
Peak efficiency	20 %	23 %	29.4 %
Net anual efficiency	11-16 %*	7-20 %*	12-25 %
Commercial status	Mature	Early projects	Prototypes-demonstration
Technology risk	Low	Medium	High
Thermal storage	Limited	Yes	Batteries
Hybrid schemes	Yes	Yes	Yes
Cost W installed			
$/W	3.49-2.34*	3,83-2,16*	11.00-1.14*
$/Wpeak**	3.49-1.13*	2,09-0,78*	11.00-0.96*

* Data interval for the period 2010-2025

** Without thermal storage.

Every square meter of STE field can produce up to 1200 kWh thermal energy per year or up to 500 kWh of electricity per year. That means a cumulative savings of up to 12 tons of carbon dioxide and 2.5 tons of fossil fuel per square meter of CSP system over its 25-year lifetime [9] . After two decades of frozen or failed projects, approval in the past few years for specific financial incentives in Europe, the US, India, Australia and elsewhere, is now paving the way for launching of the first commercial ventures. Spain with 2,400 MW connected to the grid in 2013 is taking the lead on current commercial developments, together with USA where a target of 4,500 MW for the same year has been fixed and other relevant programs such as the “Solar Mission” in India has been recently approved for 22 GW-solar, with a large fraction being thermal [2] .

3. TECHNOLOGY DEVELOPMENT NEEDS AND MARKET OPPORTUNITIES FOR SOLAR THERMAL ELECTRICITY (STE)

From the seventies to the nineties the development of solar thermal electricity technologies remained restricted to a few countries and only a few, though important, research institutions and industries were involved. The situation has dramatically changed since 2006 with the approval of specific feed-in-tariffs or power purchase agreements in Spain and the US. Both countries with more than 6 GW of projects under development and more than 1 GW in operation at the end of 2010 are undoubtedly leading the commercialization of STE [2] . Other countries such as India, China, Australia and Italy adopted the STE process. Subsequently a number and variety of engineering and construction companies, consultants, technologists and developers committed to STE are rapidly growing.

A clear indicator of the globalization of STE commercial deployment for the future energy scenario has been elaborated by the International Energy Agency (IEA). This considers STE to play a significant role among the necessary mix of energy technologies for halving global energy-related CO_2 emissions by 2050 [5] . This scenario would require capacity addition of about 14 GW/year (55 new solar thermal power plants of 250 MW each). However, this new opportunity is introducing an important stress to the developers of STE. In a period of less than 5 years, in different parts of the world, these developers of STE are forced to move from strategies oriented to early commercialization markets based upon special tariffs, to strategies oriented to a massive production of components and the development of large amounts of projects with less profitable tariffs. This situation is speeding up the implementation of second generation technologies even though in some cases still some innovations are under assessment in early commercialization plants or demonstration projects. The projected evolution of Levelized Electricity Costs of different STE technologies is depicted in Figure 2. LEC value may be reduced an additional 30% when moving to future sites with very high Direct Normal Irradiance.

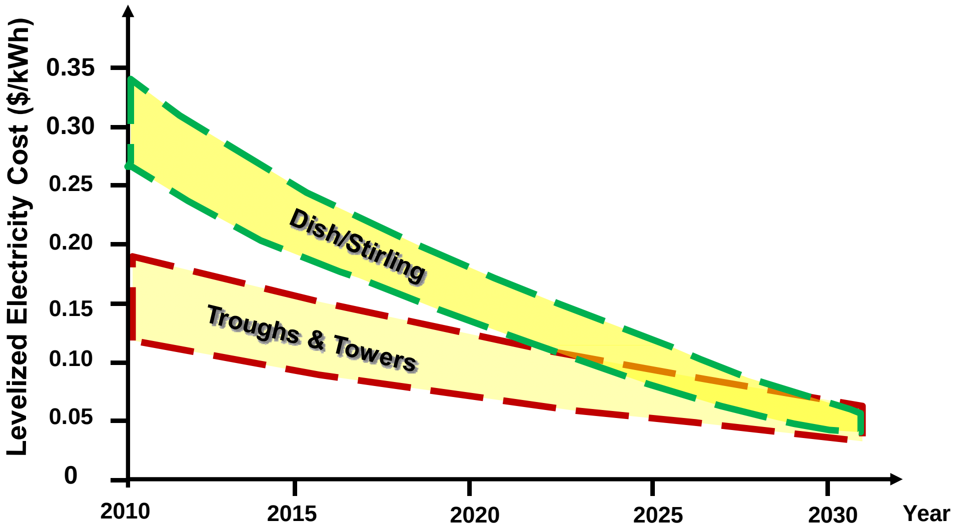

Figure 2. Evolution of Levelized Electricity Cost for STE technologies based upon technology roadmaps and industry.

The reduction in electricity production costs should be a consequence, not only of mass production but also of scaling-up and R&D. A technology roadmap promoted by the European Industry Association ESTELA [7] states that by 2015, when most of the improvements currently under development are expected to be implemented in new plants, energy production boosts greater than 10% and cost decreases up to 20% are expected to be achieved. Furthermore, economies of scale resulting from plant size increase will also contribute to reduce plants' CAPEX per MW installed up to 30%. STE deployment in locations with very high solar radiation further contributes to the achievement of cost competitiveness of this technology by reducing costs of electricity up to 25%. All these factors can lead to electricity generation cost savings up to 30% by 2015 and up to 50% by 2025, reaching competitive levels with conventional sources (e.g. coal/gas with stabilized Electricity Costs <10€c/kWh). Similar projections are published in another recent roadmap issued by the IEA [12] Other roadmaps coordinated by R&D centers expect larger influence of innovations (up to 25%) in cost reduction [13]

Some of the key general topics on medium to long-term R&D proposed by the STE community are [11] :

Build confidence in the technology through:

- pilot applications based on proven technologies;
- high reliability of unattended operation;
- increased system efficiency through higher design temperatures;
- hybrid (solar/fossil fuel) plants with small solar share.

Reduce costs through:

- improved designs, materials, components, subsystems and processes;
- exploitation of economies of scale.

Increase solar share through:

- suitable process design;
- integration of storage.

In all cases, R&D is multidisciplinary, involving optics, materials science, heat transfer, control, instrumentation and measurement techniques, energy engineering and thermal storage.

3.1 Trough and Linear Fresnel Power Plants

To further reduce costs and increase reliability in next generation PTC and LFR technology, the following are expected:

-Lighter and lower-cost structural designs including front surface mirrors with high solar-weighted reflectivity of about 95%.

-Development of high-absorptance coatings for tube receivers (96% and higher) able to work efficiently at over 500ºC.

-Development of medium temperature thermal energy storage systems (Phase Change Materials, molten salts, concrete) suitable for solar-only systems;

-Continued improvement in overall system O&M, including mirror cleaning, integral automation and largely unattended control;

-System cost reductions and efficiency improvements from substituting water for synthetic oil as the heat-transfer fluid (Direct Steam Generation technology)

3.2 Power Tower Plants

Power tower R&D in the United States, Europe, and Israel is concentrated in the two most relevant subsystems with regard to costs: heliostat field and solar receiver. The following improvements are expected:

Improvements in the heliostat field as a result of better optical properties, lower cost structures, and better control. Improvements in materials should be analogous to those for trough collectors. In general terms, optical performance and durability of existing heliostats is acceptable (95% availability and beam quality below 2.5 mrad), therefore R&D resources should focus basically on cost reduction.

Development of water/superheated steam and advanced air-cooled volumetric receivers using both wire-mesh absorbers and ceramic monoliths is the subject of various projects. Dual-aperture receivers for water/steam and volumetric receivers for air still need further development for scale-up, materials durability and thermal efficiency.

Heat storage is another key issue for CRS development. The new developments in air-cooled receivers have led to the development of advanced thermocline storage systems making use of packed-bed ceramic materials. This system has shown excellent performance for small units of a few MWh but pressure losses and design restrictions appear when size is increased.

Finally, more distributed control architectures, system integration and hybridization in high-efficiency electricity production schemes should be developed as already mentioned for trough systems.

3.3 Dish/Engine Power Plants

Several dish/engine prototypes have operated successfully during the last 20 years in the US and Europe, but there is no large-scale deployment yet. This situation may change soon with some existing commercialization initiatives. The use of dishes for stand-alone or grid-support installations will reach near-term markets as costs drop to less than 12¢/kWh. This lower cost can be achieved through:

- improvements in mirrors and support structures, improvements in hybrid heat-pipe and volumetric receivers coupled to Stirling and Brayton engines, and development of control systems for fully automatic operation; and
- improvements in system integration by reduction of parasitic loads, optimization of startup procedures, better control strategies, and hybrid Stirling-Brayton operation.

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