Archimede's mirrors and the parabolic dish

Archimede Solar Plant and the parabolic dish with micro gas turbine: two milestones of ENEA's research on concentrating solar energy aiming for the future

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Concentrating solar power (CSP) plants produce electricity just as the conventional power stations, i.e. using high-temperature steam or gas to drive a turbine. However, in the CSP plants, the hot fluid is produced by concentrating the solar radiation instead of burning a fossil fuel.
The CSP technology is also referred to as solar thermal electricity (STE), or even concentrating solar thermal (CST) if the solar heat is used for other applications such as industrial and residential heating and cooling, production of solar fuels, or water desalination.
There are four main types of commercial technologies (Figure 1): parabolic troughs (PT), linear Fresnel (LFR), central receivers towers (CR) and parabolic dishes/engine systems (PD). These technologies differ with respect to optical design, shape of receiver, nature of the transfer fluid and capability to store heat before it is turned into electricity. The first two systems concentrate the solar radiation along a line (the axes of the receiver), about 100 times with temperatures of up to 600 °C, while the other two ones concentrate the solar radiation into a point (the focus) as far as 1000 times, with operating temperatures of more than 1000 °C. The thermal energy is then converted into electric power by means of conventional systems such as steam turbine Rankine cycle.
In 2016, the total worldwide installed capacity reached 5 GW. Around 45% of the operational plants are in Spain, whereas 37% are in the United States. However, over the past three years, the market interest has shifted away from the traditional ones to emerging ones like South Africa, Morocco, Chile, and China due to their high solar resources and political commitment to solar energy.
Most (90%) current plants are based on trough technology, but tower technology is increasing and linear Fresnel installations emerging. Trough technology can be considered "mature" since several manufacturers are available for erecting entire plants or subsystems. There is good experience in engineering procurement and construction and 20-year operating experience allows for good confidence on the operation. Commercial CSP plants in operation are between 5 and 392 MW in size, with efficiency in the range of 14%-

18% and capacity factor from 20% to 50%, depending on technology, configuration and solar resource. By 2020 the efficiency is expected to increase of 2 absolute points.

Parabolic trough systems are suited to a hybrid operation called integrated solar combined cycle (ISCC), where the steam generated by solar is fed into a thermal plant, which also uses fossil-fuel generated steam, generally from natural gas. Examples of operational ISCC CSP plants are 25 MW-Hassi R'mel in Algeria, 20 MW-Al Kuraymat in Egypt, and 20 MW-Ain Beni Mathar in Morocco.

Linear Fresnel systems are based on solar collector rows or loops as the PT technology. However, the parabolic shape is achieved by almost flat linear facets. The radiation is reflected and concentrated onto fixed linear receivers mounted over the mirrors, combined or not with secondary concentrators. Water flows through the receivers and is converted into steam. Since the steam is the working fluid, LFR technology is usually fitted with steam storage system, but molten salt and phase changing material (PCM) storage systems are currently demonstrated at pilot plant scale. LFR technology has lower optical performance compared to other technologies, but this is offset by lower investment and operation and maintenance costs.
Compact LFR technology uses a design with two parallel receivers for each row of reflectors. This configuration minimizes blocking of adjacent reflectors and reduces required land area. Another advantage is that, depending on the position of the sun, the reflectors can be alternated to point at different receivers, thus improving optical efficiency.
Increasing the overall efficiency depends on superheating the steam. Superheated steam at about 380 °C has been demonstrated, and there are proposals for producing steam up to 450-500 °C to enable higher power-cycle efficiency.
There are almost 200 MW plants in operation and around 200 MW under construction. After a first pilot scale application in Australia, a few new pilot plants have been tested in Spain and in the United States. In 2012, the first commercial 30-MW Puerto Errado 2 plant started its operation in Spain. While, in 2014, 125 MW of the total 250-MW Dushar project, were connected to the grid in India; and is by far the largest CSP plant using LFR technology.
In addition to electricity generation, linear Fresnel technology is quite useful for direct thermal applications such as heating/cooling or industrial process heat.

CR, or *central receivers towers*, or solar power towers, or simply tower systems use a field of distributed mirrors – heliostats – that individually track the sun over two-axis and focus the sunlight onto a receiver mounted on the top of a tower. A heat transfer fluid in this central receiver absorbs the highly-concentrated radiation reflected by the heliostats and converts it into thermal energy that is used to generate superheated steam to drive a conventional turbine.
The temperature level of the primary heat transfer fluid determines the operating conditions (i.e. subcritical, supercritical or ultra-supercritical) of the steam cycle in the conventional part of the power plant. Depending on the primary heat transfer fluid and the receiver design, maximum operating temperatures may range from 250-300 °C (using water-steam) to 390 °C (using synthetic oil) and up to 600 °C (using molten salt). Temperatures above 1000 °C can be obtained using gases, which in turn can be used to directly replace natural gas in a gas turbine. This application makes use of the excellent efficiency (60%) of modern gas and steam combined cycles. Direct steam

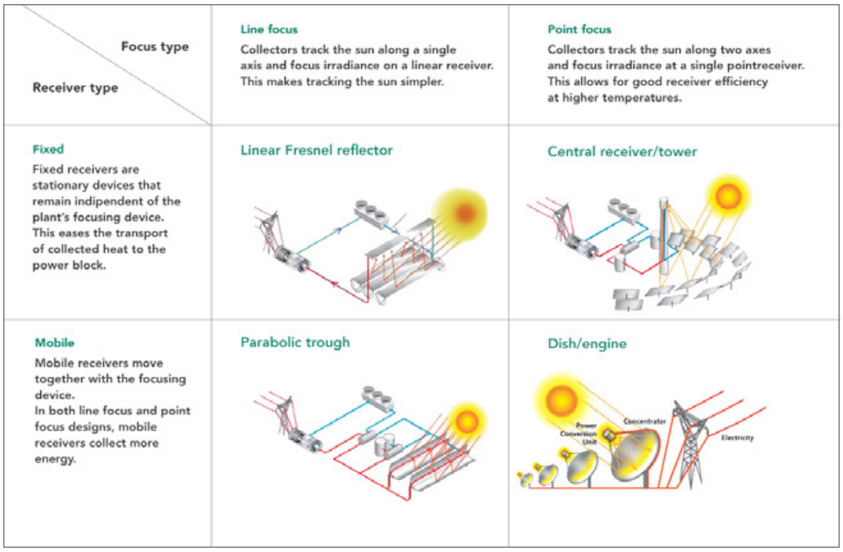
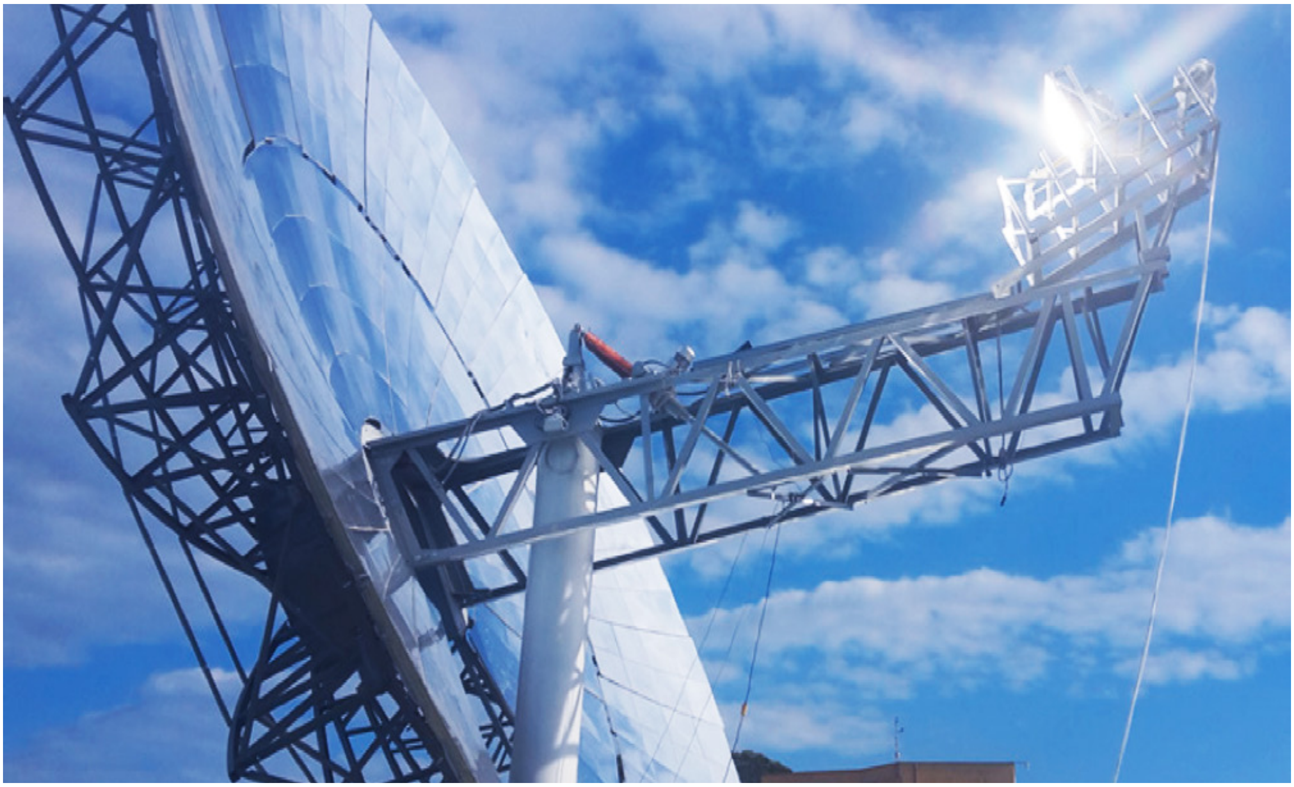


Fig. 1 The main CSP technology families

generation in the receiver eliminates the need for a heat exchanger between the primary heat transfer fluid and the steam cycle, but makes thermal storage more difficult. Tower plants can be equipped with thermal storage systems whose operating temperatures also depend on the primary heat transfer fluid. Today's best performance is obtained using molten salt at 565 °C for either heat transfer or storage purposes. This enables the use of efficient supercritical steam cycles. In addition, the TES may be less than half the cost of salt TES in commercial trough plants because the larger temperature range across the storage system enables more energy to be stored per mass of salt. The combination of salt density, salt specific heat, and temperature difference between the two tanks allows economic storage capacities of up to 15 hours of turbine operation at full load. Such a plant could run 24 hours per day, 7 days per week in the summer and part-load in the winter to achieve a 70% solar-only annual capacity factor.

Early test plants were built in the 80s and 90s in Spain (Planta Solar 10 and Planta Solar 20) using water as HTF. By far the biggest solar power plant in the world is the Ivanpah Solar Electric Generating System, with a total capacity of 392 MW. It gathers three separate units, each with its own turbine, based on direct steam generation technology, without storage. The first molten-salt power tower is the 20-MW Gemasolar plant in Spain, designed for 15 hours of thermal storage; while the 110-MW Crescent Dunes Solar Energy plant, located in Nevada, is the biggest utility-scale plant to feature advanced molten salt as both heat transfer fluid and heat storage medium. The plant delivers 500 GWh/yr and has a storage capability of 10 hours (2-tank direct molten salt), thus resulting in a capacity factor of 52%.



Dish/engine CSP systems use a collection of reflectors assembled in the shape of a parabolic dish to concentrate sunlight onto a receiver cavity at the focal point of the dish. Within the receiver, the heater head collects this solar energy and runs an engine-driven generator to produce electricity. Like heliostats, all dishes rotate along two axes to track the sun for optimum capture of solar radiation. The three major types of engines, used at the core of dish/engine technology, are kinematic Stirling engines, free-piston Stirling engines, and Brayton turbine-alternator-based engines. Dishes have also been proposed with air receivers that feed hot air to a steam generator. Both kinematic and free-piston Stirling engines harness the thermodynamic Stirling cycle to convert solar thermal energy into electricity by using a working fluid such as hydrogen or helium. Brayton systems use turbine-alternator engines with compressed hot air to produce electricity. Dish/Stirling systems generate 3–30 kW of electricity, depending on the size of the dish and type of heat engine used. Dish/Brayton systems have been proposed at sizes up to 200 kW.

Dish/engine systems are cooled by closed-loop systems, like an automobile engine; this type of cooling, combined with the lack of a steam cycle, endow these systems with the lowest water use per megawatt-hour among all the CSP technologies.

As a modular technology, dish/engine systems are built to scale to meet the needs of each individual project site, potentially satisfying loads from kilowatts to gigawatts. This scalability makes the dish/engine technology applicable for both distributed and utility-scale generation.

The technology is still under demonstration and investment costs are still high.

Several prototypes have successfully operated over the last ten years with capacities ranging from 10 to 100 kW. Thermal storage systems for dish technology are still under development.

The cost of CSP plants and STE electricity varies significantly depending on the technology, the size of the plant, the thermal storage system, the local labour and land cost, and the level of maturity (i.e. demo, pilot, commercial) of the project. The investment and financing costs account for more than 80% of the electricity cost; once the plant has been paid for, only operating costs, which are currently about 2-3 USD cents/kWh, remain. Investment costs range from 4000 to 9000 USD/kW and large differences exist in per kWh prices worldwide. STE projects in the US have executed PPA prices of 13 USD cents/kWh, while projects in Spain were paid a FiT price of 27 Euro cents/kWh. Estela estimates LCOE in the range of 8-10 Euro cents/kWh by 2025, while the US Department of Energy's SunShot Initiative is much more aggressive: 6 USD cents/kWh by 2020.

The breakdown of the investment costs depends on several factors, including the specific technology under consideration and the presence of thermal storage. Generally the solar field is the most important cost element followed by the thermal storage and the power block.

Innovations

The first commercial CSP project called SEGS (Solar Electric Generating Systems) was carried out in the 1980s in California, based on a synthetic oil as heat transfer fluid and without thermal storage system.

Since the 2000s several innovations are modifying CSP technology. The research and development effort aims at increasing economic viability by reducing investment and operating costs and increasing productivity by improving plant efficiency. Better performances can be achieved with higher temperatures for working fluids, scale factors, new materials, more efficient manufacturing processes and assembly activities on site.

The thermal energy storage improves the operational efficiency balancing short-term variations of the electric load or sudden cloud covers and mostly increases the dispatchability of the produced electric power and enhances the electric network stability.

The optimal size of storage depends on the role the plants supposed to play. Very large storage involves greater annual energy production and lower cost of energy (LCOE), but more investment cost because of the larger solar field and the storage system. The efficiency of the storage medium be very high: up to 98%.

We can distinguish three categories of storage systems that can be used in solar thermal power plants, but each category is at a different stage of maturity: Sensible heat storage systems, Latent heat storage systems, and Thermochemical storage systems.

Sensible heat storage systems are used in most state-of-the-art solar thermal power plants with "two-tank indirect molten salt storage" (two tanks with molten salts at different temperature levels). The development of new storage media with improved thermal stability will allow higher temperatures to be attained. Higher temperatures enable increased energy density to be achieved within the TES and lower the specific investment costs for the system. Improvements to TES systems would have the potential to reduce the investment cost and to improve efficiency.

Latent heat storage has not been implemented in commercial solar thermal power plants yet, but there are several research activities ongo-

ing to support the introduction and use of phase changing materials in TES technologies. The use of latent heat storage offers new possibilities for direct steam generation helping to achieve cost competitiveness with sensible heat technologies.
Since 2010, thermal storage has been used in 40% of Spanish plants, providing an average of five to ten hours storage, depending on the DNI.

Fig. 2 Test facility at the ENEA Casaccia Research Centre

ENEA's contribution

Since 2001, the Italian Agency ENEA developed an innovative CSP technology using parabolic trough collectors based on molten salt mixture as heat transfer fluid and heat storage media. Compared to diathermic oil, this innovation results in a higher thermodynamic conversion efficiency, elimination of the heat exchanger between the solar field and the thermal storage system, and lower storage tanks volume.
The use of molten salt as heat transfer fluid required a series of technological developments of key plant components, such as collectors, receivers and thermal storage systems. These innovative components have been developed and patented by ENEA, after being tested under operating conditions at the ENEA PCS (Prova Collettori Solari – solar collector testing) facility (Figure 2).
Of strategical importance, in the effort of innovation undertaken by ENEA, are the receiver tubes able to work at 550 °C thanks to a special coating developed to maximize the absorption of solar energy and minimize the heat losses by radiation. The latter are produced, using ENEA licenses, by the Archimede Solar Energy (ASE), a subsidiary of Angelantoni Industry Group.
The first industrial plant powered by the ENEA technology has been built by Enel in Sicily (Priolo Gargallo - Syracuse) – within the national Archimede Project – and is currently in the operational phase.
Thanks to its expertise, ENEA is the national reference centre for the concentrated solar thermal technology. The Agency has the ownership of several patents and exclusive competences, and collaborates with several companies within several national and international initiatives. Indeed, Italy has taken a leading role in the field of molten salt parabolic trough technology, industrial firms and research centres have created a fully integrated supply chain in the concentrated solar thermal technologies.
The main research areas where ENEA is presently involved are heat transfer fluids, innovative plant components, small- and medium-scale systems, thermal storage, new generation towers, parabolic dishes.
ENEA is studying novel salt mixtures and gas (CO_2) as heat thermal fluid, innovative collectors and tube receivers, Fresnel systems based on oil or salts as heat transfer fluid coupled with organic Rankine cycle (ORC) to produce electricity and heat, thermal storage systems based on solid (modified concrete) or phase changing materials, use of molten metals as very high temperature heat transfer and storage fluids and parabolic dishes combined with micro gas turbines. ENEA is also carrying out the development of a thermal storage system based on one thermocline tank with steam generator integrated inside the tank.
Relating to parabolic dishes, ENEA is carrying out the project OMSOP, funded by the European Commission, at Casaccia Research Centre, with the aim to develop and demonstrate technical solutions for the integration of the dish technology with the micro gas turbines to produce electricity from solar source in a small scale capacity range (5-30 kW_e). The test facility is based on a 12 m diameter parabolic dish concentrator, with 90 m^2 reflecting surface and a 5 kW electric micro gas turbines. Figure 3 shows the concentrator and the frame to support the micro gas turbine to be installed.

Next developments

As a consequence of wide efforts in research and demonstration, recently CSP technology has become more attractive to investors, presently through public incentives, but in a middle-long term perspective, also in free market condition. The IEA Solar Thermal Electricity Roadmap (2014 edition) suggests that by 2020 CSP deployment is expected to be sustained by policy incentives and emissions trading. From 2020 to 2030, CSP could become competitive with conventional base-load power due to cost reductions and the increasing prices of CO_2 and fossil fuels. Incentives to CSP will gradually disappear, and high voltage direct current (HVDC) transmission lines will reach a global extension of some 3000 km. The global installed capacity would reach 261 GW, by 2030 and 982 GW by 2050, providing about 11% the global electricity with an average capacity factor of 50%. The United States, Africa, China, India and the Middle East would be the largest producers and exporters, while Europe would be the largest importer from the Middle East-North Africa Region via HVDC transmission lines. In the long term, low-cost CSP electricity would compensate for the additional costs of electricity transmission.

For the next future, the CSP lines of development differ between large and small-medium facilities. The first ones, mainly power generating systems, would archive better performance increasing the solar energy caption and absorption efficiency, rising the operating temperature, using new thermal carrying fluids and improving the component reliability to reduce operating cost. The medium-small facilities, mainly multigenerating systems, would achieve a reduction of component costs through improvements of manufacturing processes, products standardization and utilization of new cheaper materials.

Another important CSP application area is the "solar chemistry" that mostly includes the production of solar fuels. A solar fuel is any chemical compound that can be reacted with oxygen to release energy, which has first been formed in part or in full by input of energy from solar radiation. There are a range of approaches for achieving this solar-to-chemical energy transformation. However, this case is primarily concerned with technologies that use concentrated solar radiation to store solar energy in a chemical form as a fuel via high temperature thermochemical reactions. Examples are conventional liquid hydrocarbons, alcohols and hydrogen, which can be oxidized by combustion to drive a heat cycle or to power an electric motor in a fuel cell.

Solar hybrid fuels combine solar energy with a carbonaceous fuel, such as natural gas or coal, to form a product that embodies both renewable and fossil energy. This is done by using concentrated, high temperature solar energy to provide the heat to drive endothermic chemical reactions that convert the fossil fuel into intermediate and final products, such as liquid transport fuels. In the longer term, however, there will be a need to develop technologies based on processes that are completely independent of any fossil fuel resources . In this context, the use of metal oxide redox cycles for water and carbon dioxide splitting is one promising route based on developments to date and the current scale of R&D devoted to this option. In fact, much attention is focused on the solar production of hydrogen and carbon monoxide, which form a synthesis gas (syngas) that can be further processed to liquid fuels such as methanol, diesel, and jet fuel.

Fig. 3 Parabolic dish receiver at the ENEA Casaccia Research Centre

Although hydrogen is a potentially clean alternative to fossil fuels – especially for transport uses – currently more than 90% of hydrogen is produced using process heat from fossil fuels, mainly natural gas. Generating hydrogen merely from water and solar energy would result in a completely clean fuel with no hazardous wastes or climate-changing by-products. This is the vision outlined in the European Commission's 'European hydrogen and fuel cell roadmap', which runs to 2050.

Another focus presently lies on the conversion of carbon dioxide into sustainable hydrocarbons. Like the thermochemical splitting of water into hydrogen and oxygen, carbon dioxide can be split into carbon monoxide and oxygen. Synthesis gas generated in this way can be further processed via conventional processes – e.g. Fischer-Tropsch synthesis – to liquid fuels, which will be indispensable for the following decades, especially for applications like air transportation.

For further information,
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