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State of the Art on Small-Scale Concentrated Solar Power Plants

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Abstract

Many efforts have been spent in the design and development of Concentrated Solar Power (CSP) Plants worldwide. Most of them are for on-grid electricity generation and they are medium or large plants (in the order of MWs) which can benefit from the economies of scale.
Nevertheless, several potential applications for Small-Scale CSP plants (< 1 MW) can be relevant in the industrial sector as well as for off-grid purposes (i.e. in rural contexts).
This paper presents the technologies suitable for off-grid applications, for electricity or cogenerated production. Major characteristics are illustrated and advantages and drawbacks for each configuration identified and discussed.

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Keywords: Concentrated Solar Power Plant, Off-grid electricity, Organic Rankine Cycle, Dish-Stirling engine, Solar Micro Gasturbine, Solar cogeneration plant

1. Introduction

Concentrated Solar Power Plants (CSPPs) are seen as an interesting alternative to produce electricity in large scale from renewable energy.Even if their growth has not been as fast as expected [1] and some relevant projects are on hold or have been cancelled as in Australia [2],an overall relevant increase of solar thermal electricity capacity can be counted in the last years[3].

By 2050, in an optimistic "high-renewable" outlook, solar thermal energy could represent about 11% of total electricity generation worldwide (about 4300 TWh), shared among USA, MENA (Middle East-North Africa), China and India [3-9].

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Even if CSPPs are usually developed in large scale, as a supplement to traditional energy playersfor the base loaddemand [10] (storage systems allow a levelized or shifted electricity production), they could be applied also in some particular “market niches”.

Relevant applications for Small Scale (SS) CSPPs (<1 MW) have been identifiedin [11]. Many industrial sectors require process heat [12] and the replacement of traditional primary sources (coal, oil, etc.) with solar energy can be a promoter for the local development and can have a great impact on the reduction of environmental degradation (e.g. deforestation) and human health problemsin emerging countries [13, 14]. In such a sector SS-CSPPs can be considered proven technologies with over 100 installations worldwide. Some barriers have to be removed yet, especially low awareness among customers and unattractive payback periods [11] but the perspectives are substantially optimistic.

SS-CSPPs have also a potential market for off-grid applications in rural contexts with limited access to electrical grid and favorable environmental characteristics. In such contexts, SS-CSPPs could offer electricity, fresh water, process heat and coolingfor communities and local manufacturing. Nowadays, some promising technologies exist but the lack of support programs keep them, in the better cases, at demonstration level.

In the last years, several research projects have been financed to study suitable SS plant layouts based on different concepts. Their potential deployment is related to plant reliability, maintainability, good payback time and it is strongly affected by local environmental characteristics, specific cogeneration requirements as well as by national policies (economic incentives, micro-credits etc.).

This work presents such technologies for electricity or cogenerated production, suitable for off-grid applications, highlighting the major points of strength and weakness and, finally, discussing future perspectives of development.

2. Small-Scale Concentrated Solar Power Systems

Several methods for the collection and conversion of solar radiation are currently available for CSPPs: Parabolic Through Collectors (PTCs), Compound Parabolic Collectors (CPCs), Linear Fresnel Reflectors (LFRs), Parabolic Dish Collectors (PDCs), Heliostat Field Collectors (HFCs), widely described in literature [15-20].

In CSPPs the solar system section (collectors, tracking system, receivers etc.) represents a relevant amount of the total plant installation costs [21]. Such costs strongly depend on plant configuration and size.Therefore, in SS-CSPP design great efforts are spent to make the solar section cheaper (i.e adopting low-technology single-axis PTCs[22]) and, consequently, reducing the expected overall plant efficiency, or decreasing the total plant footprintand enhancing plant performance (i.e. adopting high-technology PDC systems). In such a case, even if the cost per square meter is higher, the high concentration ratio and, therefore,the higher maximum temperature of the heat transfer fluid (HTF) leads to an increase of the engine section efficiency, making the plant more compact.Thus, plant layouts suitable for off-grid SS-CSPPs can be divided in two main categories based on HTF maximum temperature:

- Medium Temperature Plants (up to 500 °C): reference thermodynamic cycles for power plants are Organic Rankine Cycles (ORCs). However, in the last years, some noticeable applications of Stirling Cycles have been implemented. The plant solar section is typically based on PTC or LFR technologies;
- High Temperature Plants (above 500 °C): Stirling and, recently, Brayton-Joule are the thermodynamic cycles of reference. For SS applications the power plant is usually coupled with PDCs (up to 25-30 kWe each module) or with HFCs (mini-towers) for plant size in the order of 100 kWe or above.

The following sections will describe such arrangements, presenting the major advancements achieved in the last years.

3. Medium-temperature cycles

PTCs and LFRs make available thermal power at medium temperature (up to 400 °C for synthetic oils, 600 °C for molten salts, about 500°C for direct steam generation) [18, 23, 24]. It means that in no co-fired solar plants, the engine cycle maximum temperature is limited at 370 °C for synthetic oiland 500°C for molten salts. Moreover, molten salts require a higher plant complexity to avoid salt solidification, high-tech collector configurations and, therefore, high plant investment costs.

To overcome such drawbacks, in the last decades, a wide research activity on ORCs coupled with synthetic oil PTCs has been carried out [25-29].

Many organic fluids are available on the market [26, 30,31]. Such fluids can be divided in isentropic, wet and dry on the basis of the saturated line slope in the T-S diagram. As explained in [26] dry and isentropic fluids are the favorable candidates for ORC plants.

Recently, cycle modifications have been analyzed in order to improve the efficiency, working fluid superheating or reheating [32] or arranging recuperated cycles [26,33, 34]. In any case, ORCs show low efficiency due to intrinsic thermodynamic reasons (small gap between hot and cold cycle thermal sources). Furthermore, the more the cycle complexity is, the higher investment and maintenance costs are and the lower the plant robustness is.

Other drawbacks in SS-ORC plantsare related to the expander choice. ORC manufacturers are present on the market since the 80’s providing solutions for ORC fueled by industrial waste heat, geothermal primary source or biofuels [34, 35, 36]. Most of the machines commercially available can cover mainly a power range from 0.2 MWe to 2MWe. Few solutions are available for power in the order of 50-200 kWe, and under 50 kWe just some prototypes have been developed modifying volumetric compressors [31, 33, 37, 38]. Obviously, the efficiency is quite low because of the machine size and because the expander is not optimized yet.

Nowadays, despite ORC simple concept, common application in other fields and great interest of the Research Community for its application to CSP, just a few plants already exist. They are based on PTC-ORC concept and developed for electric power production:

- The Saguaro Power Plant: 1MWe system supplied by Solargenix/ORMAT and installed in Arizona in 2005.The design solar to electric efficiency is 12.1% (design point) and 7.5% (annual).Although such a plant can be considered a SS-CSPP, it was born as demo plant for future scaling up (50 MWe), announced but not realized yet [39-43];
- A 2-MW plant, supplied by Sopogy/Electratherm, inaugurated in 2009 in the Kona Desert (Hawaii) [44, 45];
- A 1-kWe installed in Lesotho (South Africa) as demo plant for rural electrification. The demo plant is based on a simple cycle without regeneration and it is designed to be robust and cheap but with a low overall efficiency (about 5%)[33, 34, 37, 38, 46].

Starting from these examples, Solar ORCs have been studied also for poly-generation (electricity, fresh water, heating and cooling).Such systems can be of great interest for remote rural areas because the same plant can satisfy small community needs, enhancing the quality of life [47].

Part of the SS-CSPP power could be usedfor the production of pure water from brackish or seawater. An interesting work is [48],where the Authors investigate a 700 kWth PTC-ORC plant coupled with a reverse-osmosis system. Recently, some projects have been financed to demonstrate the feasibility of SS-CSPP electricity/pure water production. As an example, one of the aims of the EU Project POWERSOL [49,50] was the development of a 5 kWe (PTC-ORC and then LFR-ORC) pilot plant for the production of electric power or, alternatively, for water desalination.

Moreover, Solar ORCs are interesting for Combined Heat and Power (CHP) applications. Evaluations have been conducted by the ISE FraunhoferInstitute [51, 52] and, in the last years, some projects on such a topic have been launched. As an example, the EU Project EFISOL [53] was focused on the development of LFR-ORC plants (size around 100 kWe) for CHP production. Smaller Solar CHP plants based on ORC technology are under development in the EU Project REEL-COOP [54, 55]: propotypes of 6 kWe hybrid CPC-ORC systems and 60 kWe PTC-ORC plants will be installed in North Africa.

Furthermore, medium temperatures available by means of PTCs and LFRs make the Stirling engine a viable alternative to ORCs for SS-CSPPs. Recently, a PTC-Stirling demo plant for CHP has been developed under the EU Project DiGeSPo[56-59].A Stirling engine prototype for medium temperature heat source (250-350 °C) has been developed and a demo plant for the production of 3kWe and 3-9 kWthwas successfully tested giving an electric efficiency of 12-15% [58].

4. High-temperature cycles

PDCs and HFCs make available a heat source at high temperature (up to 1000-1500°C) concentrating the solar rays in a focal spot [17].Therefore, they could be coupled with high-performance cycles for electricity production. In particular, PDCs fit well with SS-CSPP needs. In the last decades, they have been principally developed to be coupled with Stirling engines in modules up to 25 kWe. In [60-62] the historical development of such systemsis reported. There was a great interest and many prototypes were built up. Some products were marketed: e.g. theInfinia 3.2 kWe system, having a declared engine efficiency of 32%, net concentrator reflectivity 86% and net system efficiency 24% [63]. Before 2010, about 100 units were installed worldwide. Alsomicro-CHP units were marketed like InnovaTrinum[64]. Such a system can provide 1-kWe and 3-kWth with 13.8% of declared electrical efficiency and 41.4% of thermal efficiency (based on a 725 W/m^2 DNI).

Despite the perspectives, there was not a great spread of such a technology because it was consideredtoo expensive in comparison with other CSP and PV technologies. Some Companies downfallen [65], thecontracts for new installations were cancelled [66, 67]and the existing 1.5 MWe Maricopa Solar Plant, based on PDC-Stirling 25–kWe modules, was acquired by a Chinese group and dismissed [68].

Although the interest fallen down for large and medium on-grid applications, the system can be consideredtechnologically mature and it can be an interesting alternative in the SS-CSPP panorama. It could be applied for stand-alone off-grid applications improving reliability and availability, reducing maintenance costs and providing a storage system.

Another PDC application to SS-CSPPs is its coupling with Micro Gas Turbines (MGTs). While the PDC-Stirling Engine can be considered a proven technology, the PDC-MGT was born in the last years due to the development of new small high-temperature solar receivers [79-71], which can allow HTF maximum temperatures up to 850-900 °C. Nowadays, the aim of some projects is to lead the technology to a demonstration level. A first project was carried on by Capstone Microturbine&Heliofocus Solar Thermal Solutions [72]. On the basis of a 65 kW MGT, they arranged an open recuperated MGT system to be coupled with the Heliofocus Solar System [20]. The prototype did not reach the expected design targets due to the low collector efficiency [72]. Solar power entering the receiver was about 175 kW instead of the required 265 kW and the engine gave roughly 29 kW instead of 40 kW. However, it has to be noticed that before this tentative, MGTs had been taken into consideration only for medium-large CSP-hybrid applications [73]. The prototype was able to demonstrate the technical feasibility of the system and it opened new perspectives.

Within the EU project SOLHYCO [74] in 2008-2009 was successfully tested a hybrid mini-tower HFC-MGT system (about 100 hours of operation were accumulated detecting necessary improvements in the receiver design). The solar receiver should pre-heat the air up to 800°C before entering in a combustion chamber.In 2013 was launched another EU project, OMSOP [75], for the demonstration (before 2017) of a 5-10 kWe PDC-MGT recuperated system for electricity production. The primary project challenge is to enable the production of SS units cheaper, more reliable and easier to maintain than PDC-Stirling Engine systems.

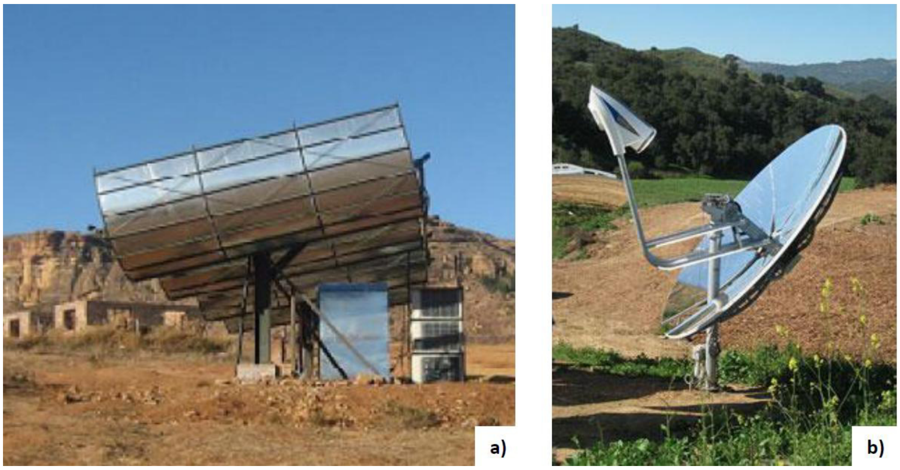

Fig. 1. (a) Lesotho PTC-ORC plant [33]; (b)Infinia CPD-Stirling engine [63]

5. Conclusions

Presently, SS Solar Plants for off-grid applications are seen as promising technologies to be applied in remote areas. Some countries, like Australia, decided of investing, above all, on solar hybrid mini-grids based on PVs [76]. However, CSPPs remain an interesting alternative to PV based small plants even if the technologies cannot participate in the market at competitive conditions yet. Among them, some SS-CSPP are based on technologies at medium-temperature, like PTC-ORC plants. They can be designed also in low-technology, robust and cheap arrangements like the demonstrator installed in Lesotho. Obviously, performance of such plants are quite low as reported in chapter 3.

On the contrary, SS-CSPPs based on technologies at high temperature, like PDC-Stirling engines,reach high-performance (up to 30% efficiency) and reduce the overall plant footprint. However, system reliability and maintainability have to be improved to make them more attractive for installation in rural areas.

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