CONCENTRATING SOLAR THERMAL SYSTEMS IN GREECE: CURRENT STATUS AND FUTURE POTENTIAL

V. Drosou[1], R. Christodoulaki[1], E. Kyriaki[2], A.M. Papadopoulos[2]

[1]Solar Thermal Systems Department, Center for Renewable Energy Sources and Saving, Pikermi, Athens 19009 (Greece)

[2]Process Equipment Design Laboratory, Department of Mechanical Engineering, Aristotle University, 54124 Thessaloniki (Greece)

Abstract

It is a truism that renewable energy sources (RES) facilitate countries to address their objectives regarding a secure, clean, reliable and affordable energy. Greece has committed itself to achieving a renewable energy share of 35% in its aggregate energy mix by 2030, up from 31% presently, which is planned to come mainly from wind, solar and hydroelectric power plants. Concentrating solar thermal (CST) systems have the ability to provide dispatchable power to the grid, due to their inherent thermal storage capacity. Therefore, they are expected to play an important role in the European energy transition plan. Furthermore, CST systems can deliver high temperature process heat for industrial applications. This research work addresses the CST technology and discusses the current status, the national strategy and policy measures, as well as the future potential in the electricity and the industrial sector of Greece.

Keywords: Concentrating solar thermal systems, concentrated solar power, industrial process heat.

1. Introduction

Solar energy is a form of renewable energy which can be converted into useful thermal or electrical energy for use in the residential, commercial and industrial sector. The conversion of solar energy in thermal energy is made with the use of solar thermal systems. The main component of a solar thermal system is the solar thermal collector. Solar thermal collectors may be classified in two categories: with or without sun tracking mechanism. Sun tracking mechanism is used to adjust the collector orientation in a sun-following solar collector system. For low-medium temperature applications, stationary, non-tracking solar thermal collectors are usually used, whereas for medium and high temperature applications, collectors with solar concentration through tracking mechanisms are indicated. Solar concentration is the re-direction of solar radiation to enhance the irradiance received by the absorber or the receiver. Concentrating Solar Thermal (CST) systems use mirrors or lenses with tracking systems to focus a large area of sunlight onto a smaller area.

Solar thermal systems may produce fluid of low ($T < 100\ ^oC$), medium ($100^o < T < 400\ ^oC$) and high ($T > 400\ ^oC$) temperatures that can be used directly or be transformed into other forms of energy as mechanical, electrical and chemical.

The most common applications of solar thermal systems are:

- Sanitary hot water production
- Hot air production for space heating and drying
- District heating
- Space heating / cooling
- Solar desalination
- Industrial process heat
- Electricity production

CST systems use a combination of mirrors or lenses to concentrate direct solar radiation to produce heat, electricity

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or fuels. In CST technologies there is a decrease in the absorber area and an increase in the aperture area, allowing an efficient collection of solar light (Mortazavi and Maleki, 2019). Unlike flat plate solar thermal collectors and photovoltaics, CST systems are not able to use diffuse radiation. The most common CST commercial systems configurations are Linear Fresnel Reflector (LFR) and Parabolic Trough Collector (PTC) with linear focus (Fig.1) and Solar Tower and Solar Dish (Fig.2) with point focus mechanism.

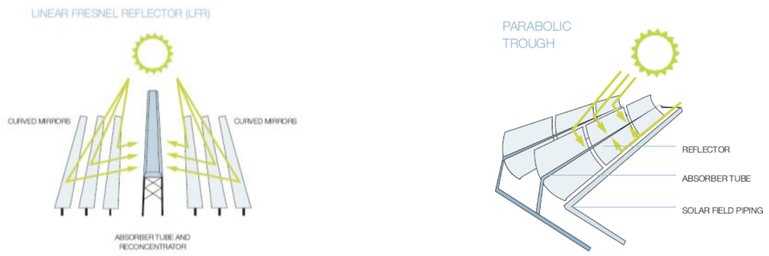

Figure 1: Linear focus CST technologies. Linear Fresnel collectors (left) and Parabolic trough collectors (right)

Figure 2: Point focus CST technologies. Solar tower (left) and Parabolic trough collectors (right)

CST technologies can reach a solar concentration factor from 5 to more than 1000. The increase of the concentration factor from 5 to 1000 increases the operating temperature of the solar plant from 60°C to more than 1000°C, respectively. This technological flexibility allows the adaption of CST technologies to several industrial processes and other emerging applications, such as water desalination, solar chemistry and material processing. The use of CST technologies for electricity production is traditionally known as Concentrating Solar Power CSP or more recently, as Solar Thermal Electricity STE, with the view to differentiate from the concentrating PV plants. These are already tested solutions, relatively cheap and available at high Technology Readiness Levels; for these reasons, CSP is among the most important sustainable technologies that can reduce the fossil fuel consumption of industrial processes and their corresponding carbon footprint (CETP-SRIA, 2020).

Recent data from January 2020 indicates that the world total capacity of CSP plants, either in operation or in advanced construction, is 9267 MW (Fig 3). Parabolic trough collectors hold the greatest share of this figure, as they considered the most bankable for project financing. On the other hand, solar tower designs can reach higher maximum temperatures and hence, increased efficiency for power generation and thermal heat storage. Linear Fresnel technology, another CST line-focusing system, has much lower commercial deployment (415 MW, also in 2019).

In 2019, the commercial CST systems under operation produced 15.6 TWh. This energy production is expected to undergo an exponential increase in the upcoming years; under the Sustainable Development scenario, IEA forecasts that the worldwide energy production from CST will be 53.8 TWh in 2025 and 183.8 TWh (around 60 GW of installed power) in 2030 (IEA, 2020).

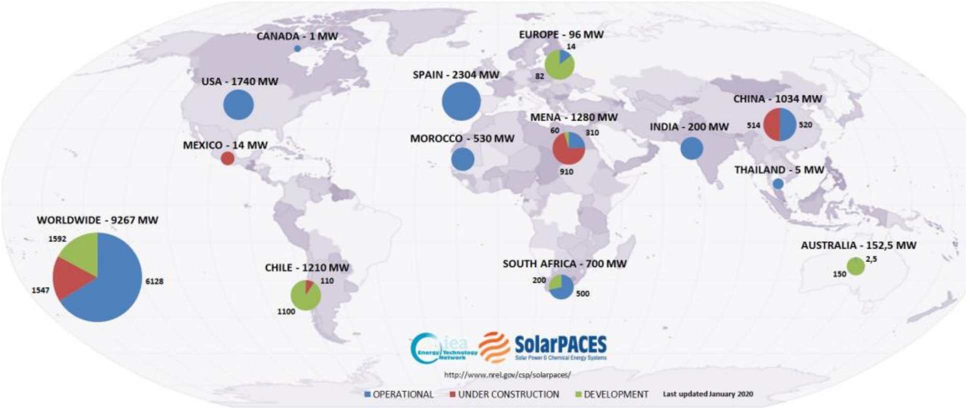

Fig. 3 CSP projects worlwide (SolarPACES, 2020)

The technical potential of CST is much higher, firstly due to its capability to supply industrial heat. According to the International Energy Agency (IEA, 2019), the amount of thermal energy required worldwide by industry was 86 EJ in 2017, which represents about 73% of the total industrial energy consumption. CST can supply most of this heat, since approximately 52% of that heat demand lies in temperatures below 400^{o}C (SolarPayback, 2018). Several industrial sectors can be identified as intensive heat consumers within these temperature ranges. These industries include chemical synthesis, food and beverage, textile, wood processing, pulp and paper, mining and machinery; in processes like evaporation, distillation, pasteurization, cleaning, washing and drying.

Secondly, CST, in contrast to other renewable technologies, can employ heat storage systems efficiently. Following sufficient studies and simulations, the integration of storage technologies can be techno-economically optimized, enabling the matching of the variable solar heat source and the variable load profile. The use of storage concepts further increases the technical potential of the CST technology.

2. Current status in Greece

In this framework, Greece with its inexhaustible solar radiation could not miss out. Today, there are two Greek projects, namely “Maximus” and “Minos”, which have been selected for funding in the first round of EU's NER300 programme, there are other projects waiting for unlocking administrative procedures and there are smaller projects installed in the industrial sector.

“Maximus” project is a large-scale Stirling dish power plant with a total installed capacity of 75.3 MWe, located in the north west of Greece, in the region of Florina. The plant consists of 25160 Stirling dish units, each with 3kW rated power output. The plant is composed of 37 small power plants of modular design, built on different land plots, which will be connected to the grid via a single connection point. The Stirling dish unit consists of a cavity receiver that captures the concentrated solar irradiation from the parabolic-shaped reflector, a free-piston Stirling engine that converts the solar energy to electricity and a closed loop air driven cooling system. The concentrator is mounted on a structure with a two-axis tracking system to follow the sun. This project is on-hold situation.

“Minos” project concerns the implementation and operation of a CSP plant based on central tower technology with a nominal installed electrical capacity of 52MWe that will be built in the southeast of Crete. The project intends to use heliostat mirrors to concentrate the sun irradiation on a solar receiver placed on the top of a tower. The tower system will be based on innovative superheated steam technology in order to increase the efficiency of the present plants with tower technology and saturated steam. The project will be located adjacent to the existing power plant of Atherinolakkos. The planned site has a size of approximately 143 ha, only 1500m from the sea, at an elevation between 50 and 100 m above sea level. It is foreseen 5h thermal storage system with 2 tanks molten salt system. Currently the EPC Engineering – Procurement – Construction selection process has been completed and the EPC contract signing is being finalized. The project construction is expected to start early 2021 with expected operation start in 2023.

Currently, a pilot plant of smaller capacity, namely 0.5MW_{th}, has already been constructed and has operated in the area of the ‘MINOS’ project (Fig. 4). The pilot plant size with an installed electrical capacity of 50kW_e consists of 1200m^2 of heliostat area. The pilot plant produces superheated steam of 350^{0}C at approximately 3MP_a. The expected net annual electricity production is estimated at 100kWh_e. In Fig 5 the allocation of pilot plant in relation to the "MINOS" project is seen.

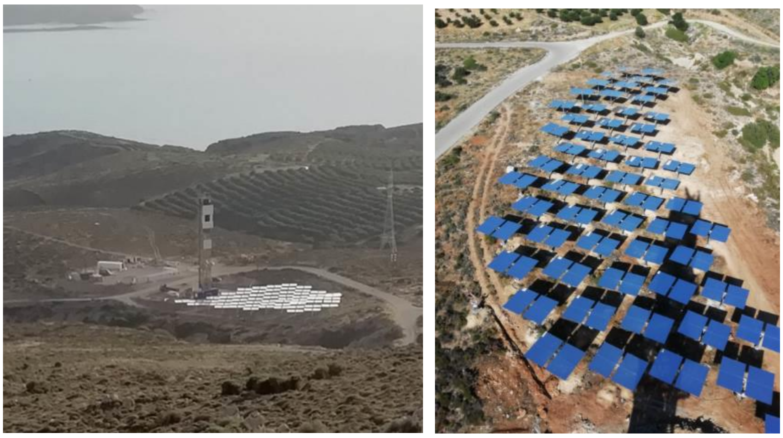

Fig.4 Pilot plant in the area of MINOS project, in Crete.

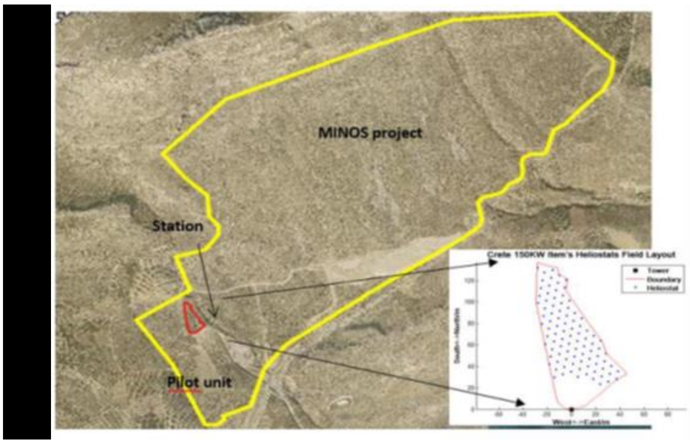

Fig.5 Mapping of the pilot plant, in relation to the 'MINOS' project, in Crete.

A new CSP project, entitled "YPERION-1" has also received approval decision from the Greek Ministry as officially announced on July 2017, with a license of 2+2 years. The owner is the company SOLAR POWER PLANT LASSITHI EPE. It concerns a CSP plant with 70MW installed capacity, with estimated energy production of 168GWh/y. This amount accounts for approximately 10% of the total Crete's energy needs, the total population of which is 630000. The foreseen technology is parabolic trough collectors with oil and molten salt storage. The solar plant will consist of 552552 solar collectors in 138 loops and will occupy about 0.452 km^2. 6 biogas burners of total capacity 186MW for the preheating of heat transfer fluid & molten salt are also foreseen. Fig. 6 indicates the location of YPERION-1, in relation with MINOS project in Crete.

Fig.5 YPERION-1 CSP plant, in relation with 'MINOS' project in Crete

This project is an indicative example of the possible implications that social acceptance has; its installation has been put on hold due to reactions from citizens and local organisations, two years ago. The project now is in marginal timeline position. Recently, an updated Environmental Impact Assessment was submitted for evaluation and acceptance by regional authorities. In the EIA, the project is described to employ parabolic trough collectors by Flagsol GmbH, type SKAL-ET150, in 138 loops and 2 tanks molten salt thermal storage of 2h in nominal load. The project was highlighted by the Prime Minister of the country on September 2019, who stated *"Energy and environment are of particular importance to our country. Energy production must now be combined with the protection of natural resources. The country needs to get on the path to carbon independence; the next inter-ministerial committee on strategic investments will approve a new project solar thermal power generation project* *in Crete, which will cover 10% of the island's needs"*. This clear statement from the Greek Prime Minister, in line with the Greek National Energy and Climate Plan (Hellenic Republic, 2019), is expected to accelerate the construction procedure in the shortcoming period.

To begin with the industrial sector, a small CST plant has been installed in a dairy industry, Koukaki farm. The plant consists of $10m^2$ solar concentrating collectors with 7 kW_{th} nominal thermal power. The plant is installed in the roof of the company and it is used for the production of process hot water. It is located in Kilkis region, Northern Greece.

Fig.6 CST in Koukaki farm

Another small CST project has been installed in Colgate-Palmolive, employing parabolic trough collectors from Absolicon Company (Absolicon, 2019). The CST plant consists of a solar field of 100 m^2 T160 Absolicon collectors, for the production of process heat (Absolicon 2018).

Fig.7 CST in Colgate Palmolive Company

3. Potential in electricity sector

At the end of the 2020s, the Greek electricity market is characterized by four main features:

1) The use of lignite, which has been the main fuel for electricity generation since the 1950s and the only indigenous resource, is dramatically shrinking, accounting in 2018 for 33.94% of the total generation, whilst the use of natural gas is respectively increasing, accounting for 33.85%. The use of RES, in the form of wind and PVs, has reached an all-time high of 21.5%, whilst big hydroelectric plants provide another 10.6% (EnExGroup, 2019). RES technologies have become an integral part of the Greek electricity sector: from no more than 300 MW in 2000, 3576 MW of wind generators and 2835 MW of PVs were operational by the end of 2019. Throughout this period, the interest in CST plants was rather marginal, being limited to the aforementioned two projects. And this, despite an attractive Feed in Tariff rate of 284.85 €/MW, provided the CST ensures a storage capacity of 2 hours. The implementation of the Target Model in Greece, in July 2020, is expected to alter the whole renewables market significantly, along with the introduction of Power Purchase Agreements in 2018. The latter may be more suitable to promote a number of CST plants, which would provide the dispatchable capacities that PVs and wind cannot ensure. The ongoing propagation of renewables and natural gas is expected to alter both market structure and electricity generation and transmission costs, but it will impose new burdens on managing the electrical systems and transmission network, especially given the need for keeping reserves and/or storage.

2) The Public Power Corporation PPC still dominates the market, covering in 2019 still 83.9% of the consumers with a market share of 78.5%, with 4 private producers covering another 17.5% of the market and the rest being covered by smaller providers (EnExGroup, 2019). The liberalization of the market, which has begun in the mid-2000s, is based on the use of gas-fired power plants by the 4 main producers.

3) Greece has some of the highest electricity prices in Europe for commercial and industrial clients. In 2018 the average price was 110 €/MWh, with 25% of the price being taxes and another 25% being transmission and

distribution costs. Only Denmark due to its environmental policies and, for entirely different reasons Malta and Cyprus, have more higher tariffs. Even the low voltage tariffs for commercial clients like SMEs and small hotels, was in 2018 on average 175 €/MWh, again with 50% of the price being attributed to taxes and distribution and transmission (HAEE, 2019). Although this price is lower than the respective tariffs in most Northern European member states, it is still placing a considerable burden on the food processing SMEs and the tourism sector, in comparison with competitive Mediterranean countries.

4) Greece has almost 6,000 islands, out of which 117 are inhabited. The non-interconnected islands, host approximately 15% of the Greek population, namely 1.5 million people, and account for 14% of the total electricity consumption. Furthermore, those islands host millions of tourists every year. Prior to the COVID-19 crisis in 2020, more than 18.5 million tourists had visited the islands in 2019 (SETE, 2020), leading to an extremely high seasonal variation of demand and consumption. Electricity generation costs in the non-interconnected islands varies from 120 €/MWh in big islands like Crete and Rhodes to more than 500 €/MWh in the very small islands like Kastellorizo (Papadopoulos, 2020). Although the projects of interconnecting Crete and the Cyclades, covering the overall cost for the islands remains an issue.

It is against this background that one should examine the use of CST and evaluate its feasibility, taking into consideration the increased need for spinning reserves and/or storage due to the increased propagation of RES in the interconnected system and the even more pressing need for meeting generation and demand in the not-interconnected one. As it can be seen in Figure 8, the weighted average cost is varying between 200 and 300 €/MWh, with China only achieving significantly lower values, and with auction prices on average being around 75 €/MWh. However, one has to consider the cost the electrical system operators, and eventually the consumers, have to cover to ensure ancillary services that include (a) Primary control and reserve, (2) Secondary control and range, (3) Tertiary control and spinning reserve, (4) Non-spinning reserve, (5) Standing reserve, (6) Voltage control and (7) Black-start services. This has been so far carried out over the Wholesale and Energy Capacity Assurance Market, which is working on the Day Ahead Scheduling base. The cost of the ancillary services varies on average from 8 to 15% of the system's marginal cost, which in 2019 varied between 45 and 85 €/MWh. However, in peak demand hours generation costs can exceed 125 €/MWh and the cost for replacing unavailable wind or PV plants is considerably higher (IPTO, 2020).

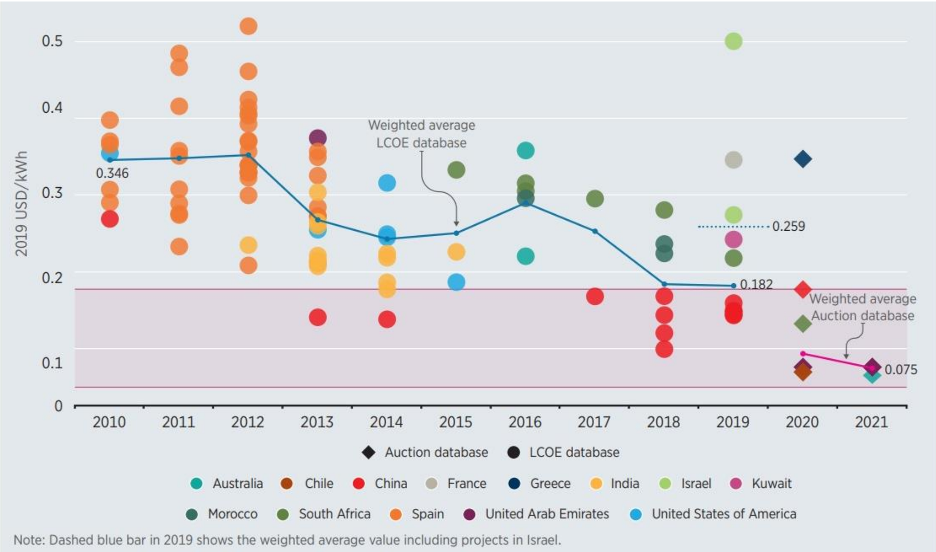

Fig.8 Levelised Cost of electricity and auction price trends for CSP, 2010-2021 (IRENA, 2020)

A CSP plant providing 2 to 6 hours of storage can in that sense be considered as a dispatchable power generation plant, and contribute to reducing the ancillary services costs of the system and this is something which has to be taking into consideration in the new market environment of the Target Model. In the case of non-interconnected systems, like the big islands of Crete and Rhodes, the significance of providing storage is even more important: one the hand there is the stronger impact of the fluctuations in the output of renewables and on the other the variation in the demand. The Value of Lost Load is an important parameter that determines to a great extent the feasibility of alternative energy generation technologies and of energy storage, which can exceed 400 €/MWh (Waterson, 2017; DiSomma et al, 2016). In that case, a CSP investment, which operates as a hybrid generation and storage plant, has a clear advantage over all other RES systems.

4. Potential in the Greek industrial sector

Industrial solar thermal installations with flat plate collectors, have been installed in Greece during the last years with a significant energy saving and environmental benefits. The thermal applications in the Greek industry vary from 60ºC to 200ºC, depending on the process. Flat plate collectors and evacuated tube collectors are ideal for temperatures below 90ºC, whereas for temperatures higher than 100ºC linear focus CST systems are more appropriate. This section discusses the possible configurations of CST systems in industrial process heat applications in Greece along with their technical characteristics and performance evaluation figures.

Presently, process heat applications are suited by a growing range of solar thermal concentrating technologies, all of them presenting products already in pre-commercial or commercial stage (INSHIP, 2018). Integrating solar heat is possible at several points in the heat supply and distribution network of an industrial production site. Nevertheless, the effort for identification of suitable integration points for solar heat as well as the complexity of possible solutions can vary significantly between industrial sectors and factories. The integration of CST in process heat systems must take into account the specificities of end-user´s framework and the development of standardized and modular Balance of Plant (BoP) concepts.

In order to design a solar field layout aimed at steam generation for a specific industrial process, some characteristic parameters should be determined. These parameters can be divided into three different groups depending on the particular subject they are related to: solar technology, location or industrial process. According to this classification, this section describes the main parameters and their effect on a proper design of the solar field layout focusing on medium temperature SHIP applications (150 to 400 ^{o}C) based on steam.

4.1 Solar Field Layouts

- Depending on the steam generation process: Depending on whether the steam is generated directly in the solar field or not, Direct (DSG) or Indirect (ISG) Steam Generation is considered. In the case of DSG, the heat transfer medium circulating through the solar field is water, employing two-phase fluid flow inside the collectors. In the case of DSG, three basic concepts can be considered depending on the specific configuration of the steam generation process in a solar collectors' loop, as seen in Fig. 9 (INSHIP, 2018a). For ISG case, the heat transfer medium is a liquid, typically thermal oil or pressurized water. The solar heat is then transferred to a secondary circuit by means of a heat exchanger an evaporator or a flash tank to generate the steam required by the industrial process.

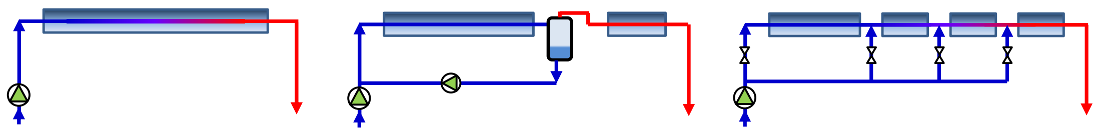

Fig. 9: Basic configurations of the DSG process in a solar collector loop: Once-Through (left), Recirculation (middle), Injection (right)

- Depending on the piping arrangement of the solar field: There are three different options, as seen below. Direct return is the simplest configuration but it involves a misbalance in pressure drop between collector loops because each row has a different pipe length. This results in the increase of the overall pressure loss through the solar field. In reverse return, a certain balance in pressure drop between rows is achieved. This configuration involves less pressure loss than the direct return; however, an extra length of pipe is required. Central supply layout requires regulation valves to balance pressure losses and mass flow rates between rows.

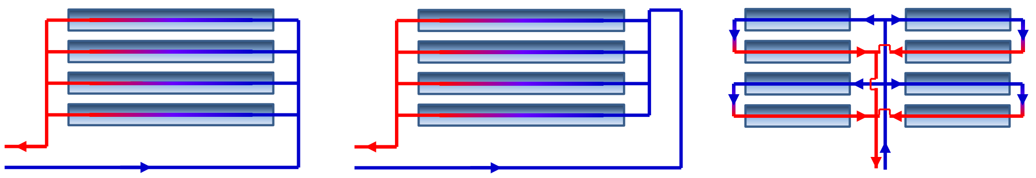

Fig.10 Typical configurations of distribution pipes in a solar field for SHIP applications: Direct return (left), Reverse return (centre), Central supply (right). (INSHIP, 2018a)

4.2 System Layouts

An example of the system layout for a solar ISG application including a storage system is shown in Figure 11 (INSHIP, 2018a). The solar field heats up the working fluid, which can be sent to the storage system or delivered to the industrial process via three-way valves. The heat transfer fluid at high temperature, obtained either from the solar field or the storage system, is used to generate saturated steam by means of a kettle-type evaporator. The steam is then injected into the conventional steam network via a valve, which represents the integration point to the industrial process.

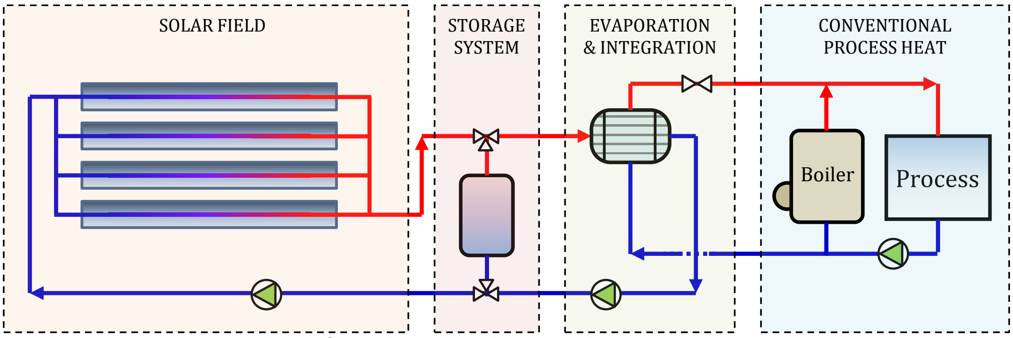

Fig. 11: System layout for a solar ISG application with a storage system (INSHIP, 2018)

Figure 12 shows an example of DSG in a solar field that feeds an industrial process working with superheated steam conditions (INSHIP, 2018a). It is based on the recirculation scheme by means of a common water-steam separator for the evaporation solar field (with 4 rows of solar collectors) and a separate field for steam superheating with 2 rows of solar collectors, including injection valves before the last collector in each row. A set of valves represents the integration point to the conventional steam network. A bypass is also foreseen to enable the stand-alone operation of the solar field for preheating purposes.

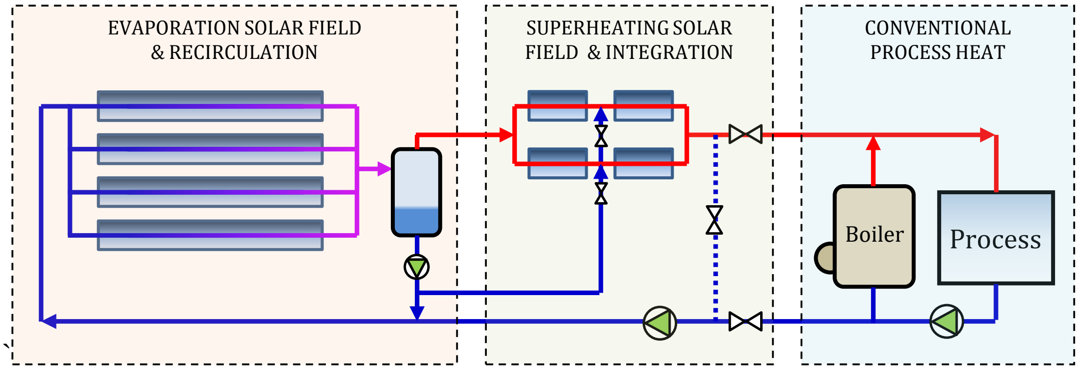

Fig. 12: System layout for a solar DSG application with superheating (INSHIP, 2018a)

Storage charging

Whenever the load profiles at the connected integration points require a storage concept, suitable storage charging and discharging strategies are applied. In SHIP systems, the most common concept is the storage charging via an external plate heat exchanger, because it offers high heat transfer rates.

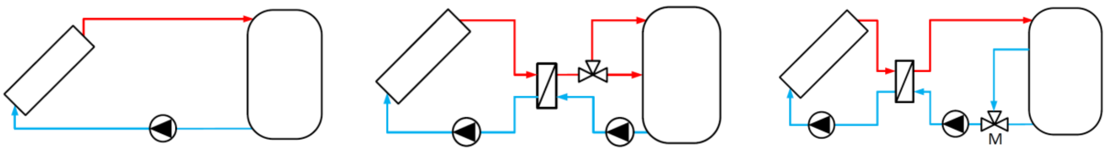

Fig. 13: Different charging concepts a) Direct charging without heat exchanger, b) External heat exchanger with stratification valve, c) External heat exchanger with mixed charging return flow (INSHIP, 2018b).

4.3 Integration point to the industrial process

A possible way for a classification is the distinction between supply and process level. The difference between the integration on supply level and on process level is shown in Fig. 14. Integrating solar thermal heat on supply level is the most common integration method, as it is the easiest possible and has minimum interference with the production process. Integration on process level is much more complex, but has the advantages of higher system efficiency and lower temperature supply.

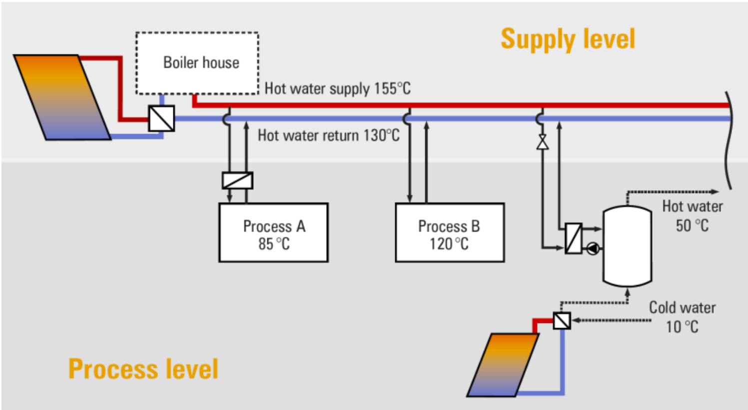

Fig. 14: Possibilities to integrate solar heat on supply level and on process level (Schmitt, 2017).

4.4 Proposed layouts

The authors have studied and simulated various solar heat for industrial processes systems and propose two typical configurations that can be used in most of the Greek industries, as shown in Fig. 15. The proposed system is an Indirect Steam Generation system, employing Parabolic-Trough Collectors with thermal oil as the heat transfer medium. The proposed solar field piping layout is reverse-return, since it involves less pressure losses compared to the other configurations. The evaporator is connected in-parallel and the integration type is on supply level. The two options refer to the presence of a storage tank.

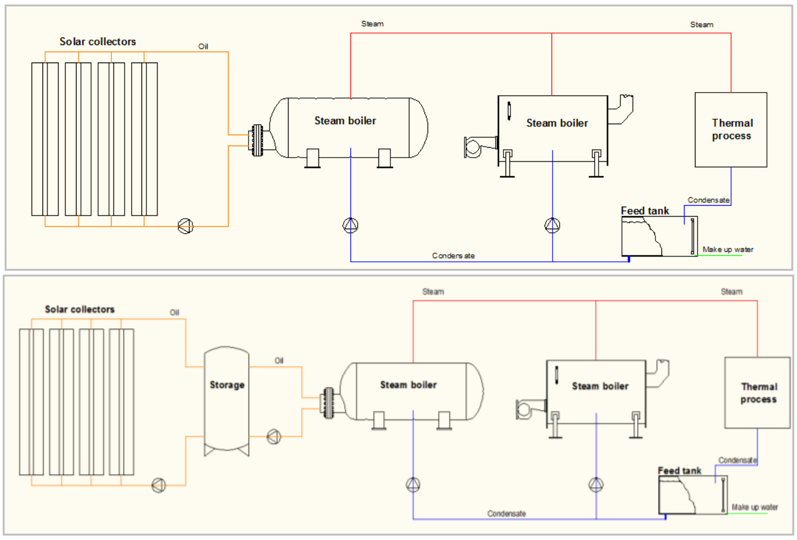

Fig. 15: Proposed SHIP configuration for Greek industries: Supply level, Indirect Steam Generation system, PTC collectors with thermal oil. Up: no storage. Down: with storage.

5. Future potential and Discussion

CST/CSP systems are much more than a highly promising technology. They have become a quite mature integrated energy generation and storage technology, which can provide solutions to a multitude of applications, both considering electricity generation and thermal power requirements. Still, and despite the significant reduction in their initial cost and the increase in their efficiency and reliability, their Levelized Cost of Energy remains high, compared to other renewables, as they are capital intensive investments. This however, is only one aspect, because one has also to consider the integrated storage they provide, which has otherwise to be covered by ancillary services provided by conventional generation plants, by over dimensioned RES systems, by storage or by a combination of all those options. It is against those options that the true feasibility of CST/CSP plants has to be evaluated. One has, however, to keep in mind that until there is a further reduction in these systems' initial cost, it will not be easy to foster their use without some form of incentives.

On the other hand, they are investments that call for a multifaceted evaluation and decision-making procedure that has to take into consideration macroeconomic factors, environmental aspects and eventually, the acceptability by local societies. All those parameters have to be part of an integrated energy and environmental policy that will lead to a regulatory framework for CST/CSP plants and to the elaboration of financial and/or non-financial incentives, which have to be provided in order to foster the energy transition and the de-carbonization of the Greek economy.

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