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Thermodynamic Cycles for Solar Thermal Power Plants: A Review

Solar Thermal Power Plant; Rankine Cycle; Brayton Cycle; Integrated Solar Combined Cycle; Supercritical CO_2 Cycle; Advanced Organic Cycles

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Abstract

Solar thermal power plants for electricity production include, at least, two main systems: the solar field and the power block. Regarding this last one, the particular thermodynamic cycle layout and the working fluid employed, have a decisive influence in the plant performance. In turn, this selection depends on the solar technology employed. Currently, the steam Rankine cycle is the most widespread and commercially available power block option, usually coupled to a parabolic trough solar field. However, other configurations have been implemented in solar thermal plants worldwide.

Most of them are based on other solar technologies coupled to a steam Rankine cycle, although integrated solar Combined cycles have a significant level of implementation. In the first place, power block configurations based on conventional thermodynamic cycles -Rankine, Brayton and combined Brayton-Rankine- are described. The achievements and challenges of each proposal are highlighted, for example, the benefits involved in hybrid solar source/fossil fuel plants. In the second place, proposals of advanced power block configuration are analyzed, standing out: supercritical CO_2 Brayton cycles, advanced organic cycles and innovative integrated solar combined cycles. Each of these proposals show some advantages compared to the conventional layouts in certain power or source temperature ranges and hence they could be considered attractive options in the medium term. At last, a brief review of proposals of solar thermal integration with other renewable heat sources is also included.

1 INTRODUCTION

The thermal use of solar radiation has two main applications: on the one hand, it can be used directly as heat, both at a domestic and an industrial level (Solar Heat for Industrial Processes, SHIP); on the other hand, it can be used in Solar Thermal Power Plants (STPPs) for electricity production. The total capacity of STPPs worldwide is 9,267 MW_e at the end of 2020 according to (SolarPACES, 2021), divided in turn into 6,128 MW_e of operational power, 1,547 MW_e under constructions and 1,592 MW_e, under development.

A STPP includes, at least, two main systems: the solar field and the power block. There are basically four concentrating solar technologies that can be coupled to a power cycle: Linear Fresnel Collector (LFC), Parabolic Trough Collector (PTC), Central Receiver (CR) systems and Parabolic Dish (PD) (Zarza-Moya, 2018). The selection of a particular type of thermodynamic cycle and the configuration for the power block depend on the solar technology employed. It is common knowledge that the cycle performance is directly affected by the maximum cycle temperature, improving as that temperature increases. Nevertheless, the solar field efficiency is lower as the working temperature increases, as the heat loss also increases. So, a thermal optimization is necessary to optimize the global efficiency of the STPP (Breeze, 2016). Besides that, there are several technological challenges associated with high working temperatures: materials, the working fluid (degradation in oils or corrosion in molten salts) and limitations due to solar technology itself, as it will be seen below (Mehos, 2017).

Solar thermal power plants powered only by solar energy, regardless the concentrating technology used, show several important drawbacks: the need of large extensions for the concentration mirrors, due to the low energy density of the solar irradiation; lack of dispatchability due to the discontinuous nature of solar radiation; and usual requirement of an intermediate medium to transfer the thermal energy to the working fluid of the power block (except in direct absorption receivers). The last drawback leads to a limitation on the maximum working temperature due to the maximum allowed temperature in the material, which is lower compared to temperatures reached in combustion.

Regarding dispatchability, STPPs usually include a third important component, a Thermal Energy Storage (TES), that allows the energy surplus to be stored for its subsequent management thanks to the solar multiple (oversizing of the solar field). There are several storage technologies: thermocline tank, dual-tanks with a high density fluid (for example, molten salts), Phase Change Materials (PCM), or solid storage in bedrocks, this latter one suitable when the working fluid is a gas (Steinmann, 2015).

Another possibility to improve the dispatchability is to arrange a hybrid layout with auxiliary boilers, natural gas or biomass (Powell et al., 2017). The hybridization involves a double benefit: the improvement in the management and the possible increase in the working temperature at the solar field outlet and before the power block inlet and, therefore, the STPP global efficiency. If the hybrid configuration is based on a biomass boiler, the renewable nature is kept.

In summary, the main advantage of the STPPs is its sustainability and renewable nature, while the main drawbacks are the requirement of large land area for the concentrating mirrors, the dispatchability and the high cost of the technology compared to other energy sources.

Solar thermal power plants can be classified according to different criteria, mainly the type of thermodynamic cycle or combined cycle the power block is based on and the solar field technology or the type of heat transfer fluid employed. This work focuses on the analysis of different configurations of the power block, describing the state of the art and its evolution over time and putting forward advanced proposals. Section 2 is devoted to a brief description of the four concentrating solar technologies usually employed in STPPs. In section 3, the conventional configurations in operational plants are described and classified according to the basic thermodynamic cycle employed: Rankine, Brayton or combined Brayton-Rankine. Finally, some advanced proposals are described in section 4, in search of solutions to increase efficiency and achieve lower generation costs. These proposals are either in a conceptual development state or in a prototype phase, but preliminary research studies show some advantages over the conventional configurations under certain conditions, and hence they could be considered attractive options in the medium term.

2. CONCENTRATING SOLAR TECHNOLOGIES FOR SOLAR THERMAL POWER PLANTS

As said in the introduction, there are four concentrating solar technologies usually employed in STPPs, which are, from lower to higher concentration ratio: Linear Fresnel Collector (LFC), Parabolic Trough Collector (PTC), Central Receiver (CR) systems and Parabolic Dish (PD). A brief description of each technology is given in this section, paying special attention to the maximum temperatures that they can provide, since it is the input variable to the power cycle.

The Parabolic Trough Collector technology is the most common option in the commercially developed STPPs (Fernandez-García et al., 2010). PTCs are linear collectors with one-axis solar tracking and medium-high concentration factor (between 50: 1 and 100: 1) that allows to reach a maximum temperature as high as 600ºC approximately. The Heat Transfer Fluid (HTF) in the solar field, which transfers the solar heat to the power cycle, is usually synthetic oil, although it can also be molten salts, water-steam (DSG, direct steam generation) or even air. The maximum working temperature of PTCs are limited by the HTF degradation temperature - 400ºC in the case of Therminol VP1-, or the selective coating of the absorber tube - 550ºC in advanced tubes - (Montes et al., 2008). This technology is very mature and there are multiple collector's designs, as well as different technologies for the absorber tube in the receiver.

Central Receiver (CR) plants consist of a field of heliostats with two-axes solar tracking that concentrate solar radiation onto a receiver (Romero et al., 2002) that can be designed as: (i) direct-absorption receiver on solid particles or a fluidized bed; (ii) atmospheric or pressurized volumetric receiver; (iii) or indirect-absorption receiver by means of an intermediate surface to transfer the thermal energy to the working fluid. The concentration factor is higher than in PTC, between 200:1 and 1000:1, yielding to higher temperatures in the receiver, thus a lower thermal efficiency in the receiver and a higher energy conversion efficiency in the power cycle; the optimum temperature must take into account the global STPP efficiency. The study of different HTFs to work at high temperatures is a remarkable research field in this technology: advanced molten salts (Benoit et al., 2016; Turchi et al., 2018), pressurized gases (Avila-Marín, 2011; Ho et al., 2014), liquid metals (Pacio & Wetzel, 2013) and solid particles (Ho, 2016).

A Lineal Fresnel Collector (LFC) system consists of linear mirrors with one-axis solar tracking, with maximum concentration values similar to those of a PTC, but lower yearly-average value. These systems were developed later than the PTC and CR technologies. LFC presents some advantages related to the land requirements and robustness. Lower investment, operation and maintenance costs can lead to savings of 11% in the electricity production (Morin et al., 2012). In addition, LFC technology has many degrees of freedom in both the optical and thermal designs, which can be optimized (Montes et al., 2016). For a time, while the number of plants under construction was lower than that of PTC and CTR technologies, the number of studies was higher, due to the clear economic advantages of LFC. However, the promising potential of CR technology has reduced again the interest on LFC, which has remained in a marginal niche compared to the CR (Wang, 2019).

Finally, the parabolic dish technology, with the highest concentration ratio, is suitable for driving small engines, commonly Stirling or Micro - Gas Turbines, using air as the HTF. These systems allow large-scale generation (hundreds of MW_e) by replicating the low power unit: concentration collector with its engine (Hafez et al., 2016).

3. SOLAR TOWER POWER PLANTS BASED ON CONVENTIONAL POWER CYCLE CONFIGURATIONS

3.1 Rankine Solar plants

3.1.1 Steam Rankine Solar Plants

Steam Rankine cycles, in several regenerative and reheating layouts, have been widely used in fossil or nuclear thermal plants; the steam at the turbine inlet is usually superheated in the first ones and saturated in the second ones. These cycles generally work with pressures below the critical pressure. The first STPPs were based in this conventional scheme, coupling a PTC solar field to a steam Rankine cycle. SEGSs (Solar Electric Generation Systems) plants, built in California in the 1980s, are included in this type of scheme. Figure 1 shows the layout of SEGS-VIII and SEGS-IX plants, that is very similar to actual PTC plants. The power block is a regenerative steam Rankine cycle with reheat. Superheated steam at the turbine inlet is at 371 ºC and 100 bar, and the reheating conditions are 17.2 bar and 371 ºC (Lippke, 1995).

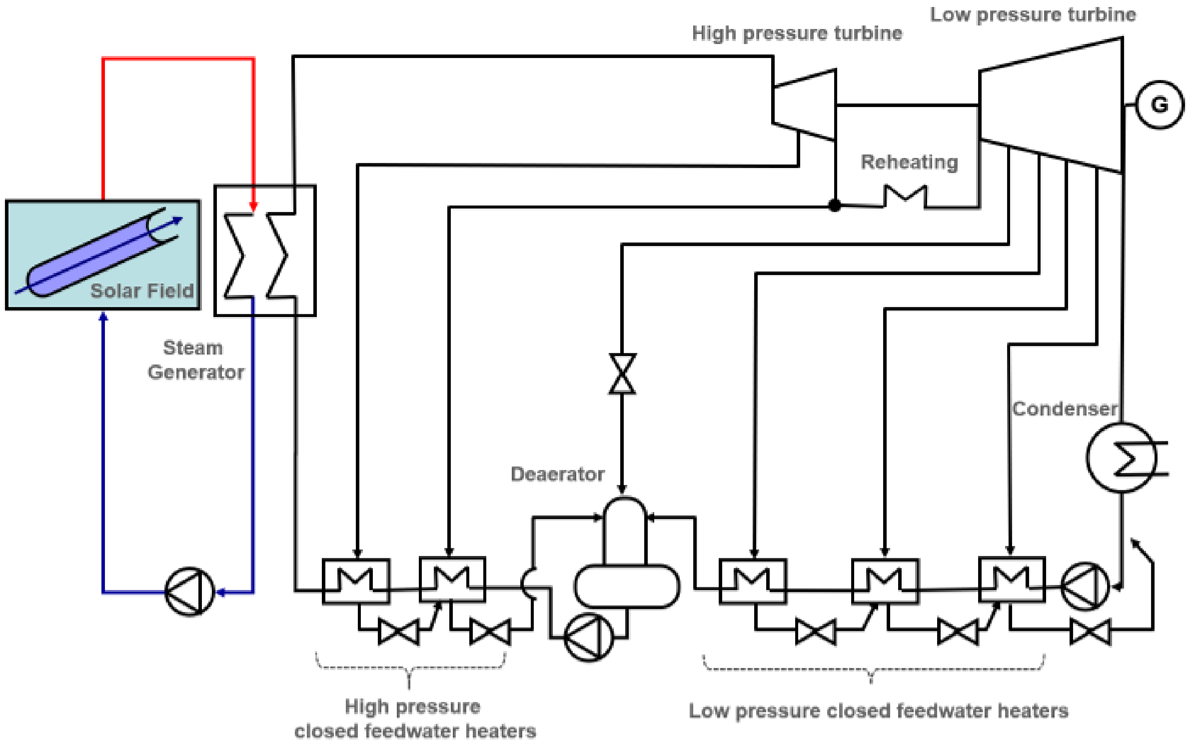

Figure 1. Simplified scheme of the steam Rankine cycle coupled to a parabolic trough solar power plant. This layout is similar to SEGS-VIII, SEGS-IX and current plants (Montes et al., 2009)

During the first years of STPPs implementation, the research was focused on improving the solar field performance (Montes et al., 2009), while keeping a conservative power block configuration, although there were some optimization studies, i.e. the optimal number of extractions or the influence of different cooling options in the condenser (Blanco-Marigorta et al., 2011; Deng and Boehm, 2011). Currently, the steam Rankine cycle is the most widespread and commercially available power block option, usually coupled to a PTC solar field working with oil, in which case, the inlet turbine conditions are 370 ºC – 390 ºC and 100 bar; or it can be coupled to a CR solar field, in which case, the thermal conditions at the turbine inlet are 550 ºC – 600 ºC and 180 bar.

In this type of STPPs, solar-to-electricity efficiencies are around 25%, since the power block is limited and its thermal performance is in a range between 35% - 38% and the solar field efficiency is around 65%.

3.1.1 Organic Rankine Solar Plants

When the available heat source temperatures are in a low-to-moderate range (90ºC < Tmax < 300ºC), Organic Rankine Cycles (ORCs) are regarded as a suitable option. Organic fluids can condense at pressures above the ambient, have low boiling points and critical point conditions that make them specially adequate to operate at low temperatures and pressures, either in subcritical or transcritical cycles, depending on the specific organic fluid selected.

ORC installations are smaller than conventional steam Rankine cycles, due to the higher working fluid density of the organics fluids, compared to water; and simpler, as a consequence to the thermodynamic behaviour of numerous organic fluids, that show a positive gradient of the saturated vapour curve in the temperature-entropy diagram (dry fluids), as seen in Figure 2. This thermal behavior implies that the ORC expanders can operate with saturated conditions at the inlet, ensuring that the expansion proceeds and finalizes in the vapour region. And this property involves a double technological benefit: from one side, superheating is not always required to avoid humidity in the expander; from the other side, the thermal heat associated to the expander outlet is used to the regenerative preheating of the liquid, without the need of more complex steam bleedings from the turbine, as it is the case of the steam Rankine cycle (Figure 1). Therefore, compared with water, the selection of dry organic working fluid brings significant benefits in terms of a reduction of costs, bound to absent humidity. The lack of liquid droplets increaes the turbine thermal efficiency and reduces its maintenance costs (Desai & Bandyopadhyay, 2016).

However, keeping in mind the decisive influence of turbine inlet temperature over cycle efficiency, ORCs have an important limitation compared to steam Rankine, namely, there is not availability of dry isentropic fluids with critical temperatures above 400ºC, without degradation and maintaining a suitable condensation pressure and density. In consequence, ORCs have been generally proposed to be coupled to low-temperature (from 80 ºC to 300 ºC) renewable sources (Braimakis & Karellas, 2017), like biomass, geothermal, heat recovery and non-concentrated solar systems (Zhai et al., 2016). Manufacturers have been present on the market since the beginning of the 1980s, with many plants installed worldwide that use the low-medium temperature heat sources mentioned above. Currently, this technology is being proposed as well for concentrated solar systems, although its share is still very low, with less than 1% of the total installed power. According to (SolarPACES, 2021), there are three commercial grid-connected plants, located in Arizona (1 MW_e), Morocco (3 MW_e) and Denmark of (12 MW_e) (Macchi & Astolfi, 2017; Rodriguez et al., 2016).

In operating ORC plants, the fluids commonly employed are, for instance, Toluene, R134a, R245fa, Solkatherm, Pentane or Octamethyltrisiloxane (OMTS); other initially promising fluids were discarded due to their high inflammability (Desai & Bandyopadhyay, 2016).

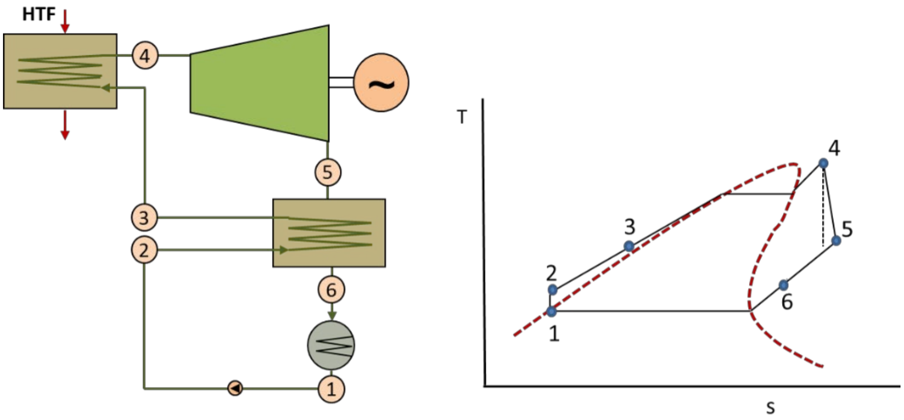

Figure 2. Layout of a recuperative Organic Rankine Cycle and T-s diagram

The research on the performance of ORCs coupled to a concentrating solar technology as heat source has been very active lately. In (Astolfi et al., 2017) authors highlight its suitability for low-moderate temperatures. Petrollese and Cocco (2019) also evaluate a recuperative ORC of 630 kW_e, conected to a LFC solar field and operating under different scenarios of HTF mass flow and temperature. Subsequently, in (Petrollese et al., 2020), they study a STPP based on an ORC coupled to a LFC and a Concentrated PhotoVoltaic (CPV) solar field.

There are also several current studies addressing the study of ORC plants with powers similar to those of plants based on the Rankine steam cycle. For example, in Desai & Bandyopadhyay (2016), a thermo-economic evaluation model is developed to analyze the behavior of a 30 MW_e ORC coupled to two different solar technologies, namely, PTCs and LFRs. The use of several working fluids (i.e. natural hydrocarbons, siloxanes, R245fa and R113) is analyzed, including water as fluid for comparison purpose. In this study, when using PTC as solar field, the organic working fluid that results in the lower LCOE, is R113, while the use of Toluene implies the highest cycle efficiency

(31.2%). However, the former presents environmental problems, whereas the latter costs are still significantly high. The LCOE results for water compete closely with those of R113. In the case of selecting LFC, Toluene presents as well the highest efficiency (28 %) and LCOEs are slightly higher for all 12 fluids analyzed. To sum up, it is concluded that ORCs are a good option in the case of low-medium power plants (less than 2 MW_e) and distributed generation. Within that power range, steam Rankine plants lose the advantage of its higher efficiency, characteristic of high power steam Rankine plants, coupled to an increase in the capital cost per kW.Therefore, ORCs working with dry fluids, offer higher nominal and off-design efficiencies at temperatures lower than 400 °C, in small-medium power scale applications, compared to steam Rankine cycles.

3.2. Brayton Cycle Solar Plants

The coupling of solar energy to Brayton cycles is relatively new, compared to Rankine-based cycles, and less mature. The main advantage of Brayton cycles is the simpler installation, while steam Rankine facilities are complex, with equipment such as the bulky condenser. However, the Brayton cycle presents lower efficiency operating with medium temperature heat sources, as it is the case of PTC solar technology with syntetic oil. Really, to attain a competitive performance, the maximum temperature should move from 400 °C up to 1000 °C.Therefore, they are generally proposed for high concentration systems: CR or parabolic dish (Semprini et al., 2016; Meas & Bello-Ochende, 2017), where the combustion chamber is replaced by the concentrated solar receiver. Hybrid configurations fosil-solar have been proposed as well, requiring systems of lower solar concentration ratios, as the solar contribution may be employed to preheat the combustion air, adding up to the regenerative contribution, as shown in Figure 3.

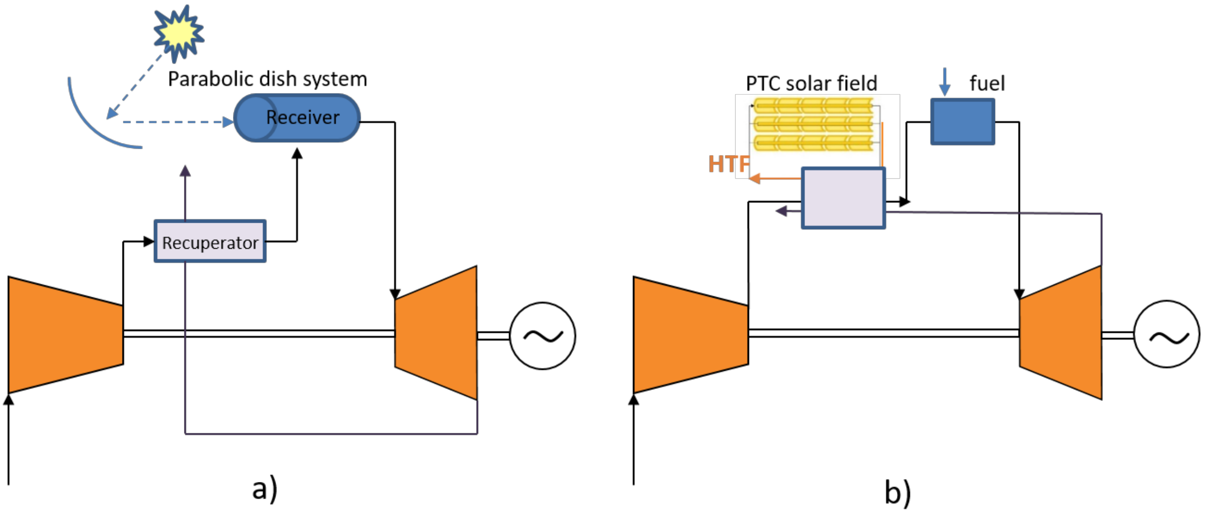

Figure 3. (a) Solar Brayton cycle (a) and (b) Solar preheating Brayton cycle.

While Brayton solar plants coupled to CR systems are intended for medium-high power levels, parabolic dish concentration systems are focused on distributed electricity generation. In this way, the integration of a micro gas turbine with a solar dish has been analyzed as a promising option for several end use applications, within a power range between 100 kW_e and 1 MW_e (Al-attab & Zainal, 2015).

Finally, there is another configuration based on a Brayton cycle, characterized by the use of CO_2 as working fluid, which has also been proposed for CSP applications (Kumar & Srinivasan, 2016), among others. Since this option is still in a less readiness technological level, a detailed description of its special features will be included in section 4, devoted to innovative advanced configurations.

3.3 Solar Combined Cycles

Combined Cycle Gas Turbine (CCGT) technology had an important development and implantation, that began in the 90s decade, in high power thermal generation plants. The heat recovery from the gas turbine exhaust to generate steam in a Rankine bottoming cycle entails a high global energy conversion efficiency. From the beginning of its commercial deployment, the possibility of solar integration has been analyzed, either the solar-only option or with fossil hybridation. However, as the fossil heat source is introduced in the topping gas turbine cycle, the solar-only alternative entails the replacement of the combustion chamber by the solar receiver, and the use of high concentration solar systems, as explained in the previous section. Therefore, the option of hybrid partial integration has been preferred.

There is a wide consensus in the technical literature regarding the synergies between fossil and solar technologies, since the production of conventional combined cycle plants decreases those days of high solar radiation due to the higher ambient temperature, which it is just when the solar field performs best (Zhu et al., 2015; Rovira et al., 2016). Thus, the yearly operation comes up with higher values of solar-to-electric efficiency.

3.3.1 Combined cycles with solar integration into the Rankine bottom cycle

The term ISCC (Integrated Solar Combined Cycle) generally refers to the particular configuration of Combined Cycles (CCs) with solar integration into the Rankine bottom cycle, as shown in Figure 4. This configuration was initially proposed by the company Luz Solar International and took advantage of the previous expertise gathered by the commercial operation of the SEGS plants, being nowadays the most used solar combined cycle configuration. Early studies proposed an ISCC plant with two gas turbines and a steam cycle. The solar energy was incorporated in parallel to the boiler by means of heat exchangers that evaporated the preheated water before its return to the steam drum (Allani et al., 1997). These studies discussed the advantages of the system, established the parameters of the boilers, designed the heat exchangers in the Heat Recovery Steam Generator (HRSG) and the solar generator and carried out one of the first economic analysis. Finally, the economic unfeasibility of the layout in its contemporary cost scenario was highlighted and, therefore, it was concluded that there was need for economic incentives (Kane & Favrat 1999; Kane et al., 2000).

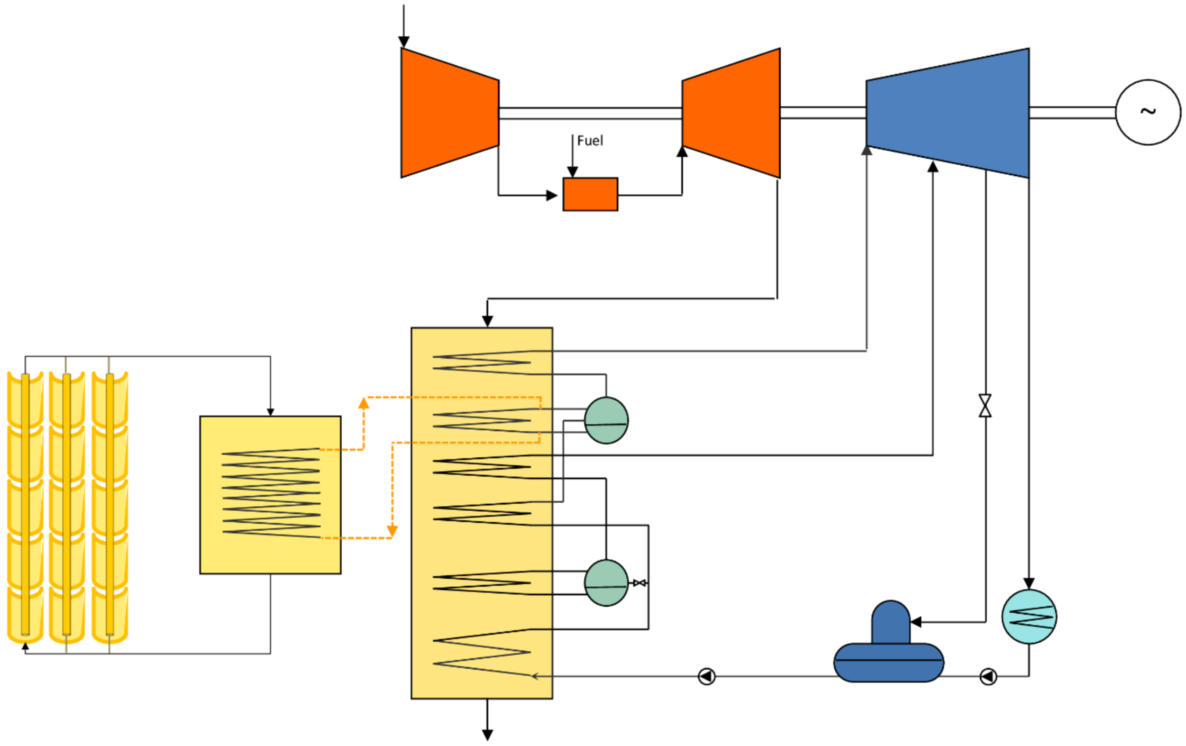

Figure 4. Layout of Integrated Solar Combined Cycle based on PTC (Rovira2020a)

At the beginning of this century, the research in ISCCs increased, mainly due to the installation of some facilities in developing countries such as Argeria, Egypt or Morocco, granted by the Global Environment Facility Agency. These studies were focused on the economic feasibility and the production cost of different layouts.

Nowadays, several ISCC plants have been installed, some of them thanks to the above-mentioned grants. Among them, stand plants installed in the Aïn Beni Mathar (Morocco), Hassi R'mel (Algeria), Kuraymat (Egypt), Martin Next Generation Solar Energy Center (USA), Archimede (Italy) and Yazd (Iran). There are other plants planned or under construction, such as Agua Prieta II in Mexico, Al-Abdaliyah in Kuwait or Duba 1 and Waad Al Shamal, both in Saudi Arabia.

Most of the plants built or projected consist of configurations with a solar field that provides heat in parallel to the HRSG, as mentioned before. PTC technology is the most used in ISCCs (Dersch et al., 2004; Franchini et al., 2013), and the solar energy is transferred to the water/steam using an additional steam generator fed by synthetic oil coming from the solar field (T_{max} = 390 ºC), except for

Archimede, in which the HTF is a molten salt (T_{max} = 550º C) (Falcheta et al., 2009). Therefore, solar energy contributes to evaporate water, like in Hassi R'Mel and Yazd plants (Behar et al., 2011), although in some plants, solar heat provides a certain degree of steam superheating (Aïn Beni Mathar and Kuraymat) and water preheating (Archimede).

Other solar concentration technologies have been also considered in theoretical studies, namely, CR (Reyes-Belmonte et al., 2019) or LFC (Rovira et al., 2016). For example, Manente et al. (2016) compare ISCC plants using PTC, LFC and CR, concluding that it is not necessary a solar concentration as high as in CR, to achieve 30% solar-to-electric efficiency. Although the use of a HTF is more realiable compared to DSG, due to the difficult of controling the two-phase fluid in the solar field, DSG has been also studied, considering the advantage of not requiring an additional steam generator. For example, Rovira et al. (2018) compare the annual performance of ISCC cycles using the three solar concentration technologies, PTC, LFC and CR, in every case with DSG in parallel with the high pressure evaporator of the heat recovery steam generator. Results show better performance in the case of PTC for both locations analyzed, with solar-to-electric efficiency up to 37%.

When the plant includes a HRSG with 2 or 3 pressure levels, as conventional CCGT plants, a very important issue is the selection of optimal point in the cycle to integrate the solar energy. Many works have been dedicated to this analysis; for example, Calise et al. (2018) carry out a dynamic study of an ISCC with solar integration in the low-pressure level of the HRSG. Brodrick et al. (2017) study the behavior of the ISCC layout with integration in the intermediate-pressure level, and Li & Xiong (2018) working with DSG, propose to incorporate the solar heat simultaneously in paralel to both evaporators, at the high-pressure and the low-pressure levels. Similarly, Bonforte et al. (2018) analyze the case of integration at the three pressure levels, including a management system to distribute the solar heat source between the three evaporators. They conclude that the installation cost increase significantly, whereas the fuel saving of the proposal is negligible. Rovira et al. (2013) compare four different layouts of integration in a dual pressure HRSG, considering preheating and superheating as well as evaporation, both with HTF and DSG. They work out that a lower HRSG irreversibility is reached when solar heat is used for evaporation at the high-pressure level, compared to water preheating. Finally, Mabrouk et al. (2018) design a solar boiler in parallel to the HRSG, to analyze in which of the heat exchangers of all pressure levels the integration of solar heat contribution provided some benefit. They gather, as well, that the integration in high temperature exchangers is more favorable, being the high-pressure evaporator the best option.

If the ISCC is specifically designed for the maximum steam mass flow rate production (solar plus heat recovery), the turbine, as well as the superheaters and economizers of the HRSG, must be oversized. That design would imply a lower turbine efficiency during non-solar irradiation periods, partially compensated by a higher steam production in the oversized heat exchangers; besides that, lower ambient temperatures that could occur during non-irradiation periods benefit gas turbine performance, also mitigating the previous effect. However, if the plant is designed to operate in a fuel-saving mode, this oversizing would not be necessary. This issue must be accounted when comparing conventional CCGT and ISCC performance, to perform a consistent analysis.

3.3.2 Combined Cycles with solar integration into the gas turbine.

Although the most common scheme of solar integration in CCs is the solar heat incorporation into the steam cycle at the high-pressure level, the option of integration into the gas turbine, has been explored as well. Some layouts regarding the integration into the Brayton cycle have been already described in section 3.2. In the case of CCTG, for example, Amelio et al. (2014) propose to heat up the combustion air by passing it through PTCs, managing without an intermediary HTF. Thus, the pressurized air coming out of the compressor is sent to the solar field where is preheated up to 580 ºC, prior to enter the combustion chamber. As expected, the fuel required to achieve a predetermined turbine inlet temperature is reduced. The authors estimated a fossil fuel saving of 22% at design conditions and 15.5% evaluating the annual performance. Duan et al. (2017) propose a configuration that integrates solar contribution to preheat the combustion air but with the peculiar feature of a prior use of the air exiting the compressor to preheat water that is then incorporated to the HRSG. Although the air is thus previously cooled, the temperature achieved, by means of the solar contribution, is finally higher, which results in a greater power generation and fossil fuel saving. Other designs propose to integrate the solar heat source, coming from a CR, to heat the air coming from the compressor (Okoroigwe & Madhlopa, 2016).

Rovira et al. (2018) compare the annual performance of a reference CCTG with the performance of two ISCC layouts that differ in the solar heat integration options: a conventional ISCC scheme, in which solar heat is used to directly evaporate water at the high pressure level of the steam cycle, and a second scheme in which the solar heat is used to preheat the combustion air. In both cases, three different solar concentration technologies (LFC, PTC, CR) are analyzed. Results show that ISCC with combustion air preheating suffer a reduction in yearly energy produccion in comparison to the reference CCTG, as a consequence of the pressure drop in the heat exchanger, whereas DSG, on the contrary, increases the yearly production. Nonetheless, the former option entails notable higher solar-to-electricity efficiencies, with values above 40% in the case of PTC and CR.

4 SOLAR THERMAL POWER PLANTS BASED ON ADVANCED CYCLE CONFIGURATIONS

4.1 Innovative organic cycles

4.1.1 Balanced Hybrid Rankine-Brayton cycle

Rovira et al. (2015a) proposed a configuration named Balance-Hybrid Rankine-Brayton (B-HRB) cycle for moderate temperatures heat sources in a range between 350 ºC - 400 ºC, as it is the case of moderate concentration factor solar technologies. In that study, the propose cycle was compared to several other cycles and/or different working fluids, among them, different configurations of steam Rankine cycles, ORCs (Acetone, R125) and sCO_2 cycles. As can be observed in Figure 5, the configuration implies the hybridization of a transcritical Rankine and a Brayton cycle, combination that allows a low and constant temperature of heat rejection and a high mean temperature of heat supply; this configuration also includes a single recuperator and a compressor to divert a fraction of the total mass flow, in order to achieve a quasi-balanced behavior of the recuperator and very low irreversibility. These features lead to a potentially high cycle efficiency, as well as a simpler facility, but require the use of a working fluid with specific properties. For example, dry organic fluids, such as isobutane, propane, and R125 fulfill those requirements, namely: high critical temperature, that allows condensation at adverse high ambient conditions, as well as low critical pressure, roughly below 25% of the maximun fluid pressure, that implies a more constant specific heat during the heating process (Rovira, 2015a). As a consequence, the B-HBR cycles, working with either isobutane, acetone or R141b, reach higher efficiencies than the transcritical ORCs analyzed, under the boundary conditions of the study. In comparison with SRC, efficiencies are very much alike, but with the considerable advantage of being a less complex facility that includes a single recuperative heat exchanger instead of the typical regenerative SRC layout (figure 1). In (Muñoz et al, 2017), the study is extended to analyze off-design operation, assuming that heat supply comes from a PTC solar field, with a maximum temperature of 397 ºC. The annual performance simulation is based on hourly meteorological data corresponding to Almeria (Spain). Among the various working fluids analyzed, the study concludes that propane and R125 are the most suitable, even under adverse conditions. In the case of propane, cycle efficiency varies along the year between 41.37 and 30.2%, whereas in the case of R125 cycle, efficiencies are slightly lower.

As seen the temperature-entropy diagram of this cycle in Figure 5, the resulting working fluid temperature at the inlet of the heat source exchanger is quite high, which in turn implies a high HTF return temperature, that is just what is desirable to work with so-called closed sources. That is the case of the PTC solar fields, that require an oil return temperature above a minimum value to guarantee high solar field thermal efficiency.

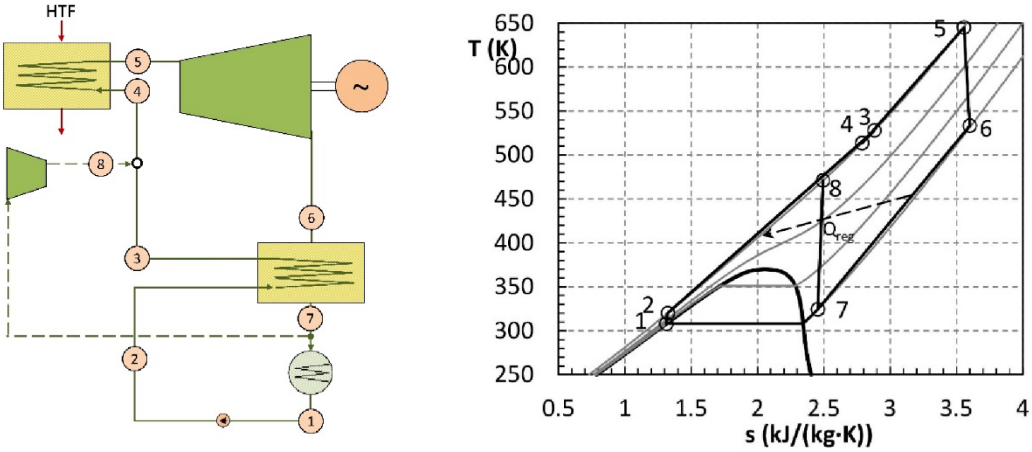

Figure 5. Balanced Hybrid Rankine-Brayton cycle configuration and corresponding T-s diagram (Rovira2020b)

4.1.2 Unconventional Rankine organic cycles (RDE & DRDE)

The B-HRB cycle described in the previous section is not adequate to be used as power block in heat recovery applications (open heat sources), where it is desirable to reduce as much as possible the temperature of the heat transfer fluid associated to the waste heat source to recover as much residual thermal energy as possible. Having this in mind, Rovira. et al. (2020b) propose a new configuration, derived from the previous B-HRB, more suitable for this kind of application, and that may have a role in solar plants configurations, as will be explained in the following section. Figure 6 presents the layout and temperature-entropy diagram of the proposal that consist of a Rankine cycle with two heating lines, owing to the split of the flow exiting the pump in two streams. The main one is heated by the heat source and then proceed to the expander or turbine. Given that the inlet fluid temperature to this stream is very low, it is possible to recover a large percentage of the thermal energy from the source. A secondary stream makes use of the thermal energy associated to the main expander exhaust, by means of the recuperator. Since the fluid leaving this recuperator at supercritical pressure has a high thermal energy, a secondary expander is incorporated downstream, thus increasing the power generation. Considering that this layout includes a single recuperator and two expansors, it will be referred to as Recuperated and Double Expanded (RDE) cycle. Propane has been identified as a very good option as the working fluid in this cycle.

When the thermal heat of the secondary expander exhaust is significant, a secondary recuperator could be used to preheat the main stream before entering the source heater; configuration that could be more convenient to prevent excessively low HTF exhaust temperatures that may entail, for instance, acid condensation problems. That configuration is named Double Recuperated and Double Expanded cycle (DRDE), and it has been proposed as the bottoming cycle in the configuration shown in Figure 9, that will be explained in section 4.3.3.

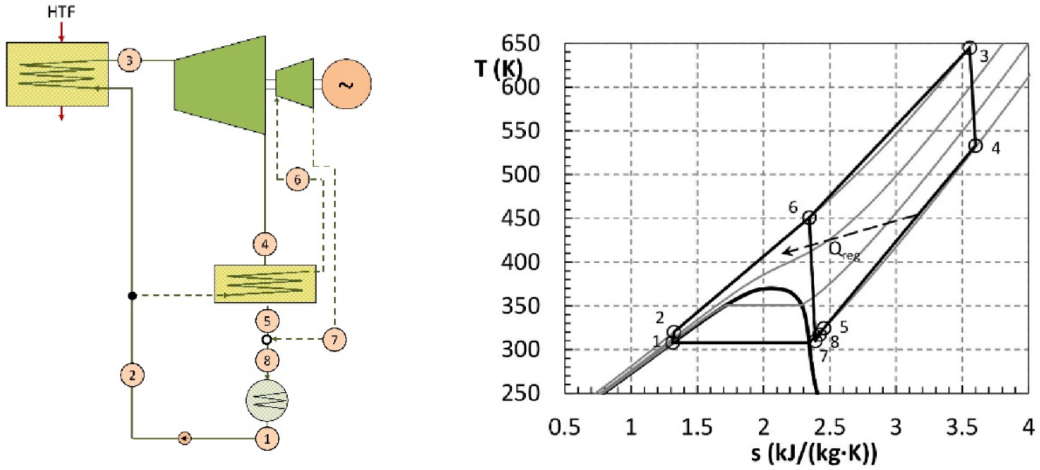

Figure 6. Recuperative Double Expansion cycle (RDE) and T-s diagram (Rovira et al., 2020a)

4.2 Supercritical CO_2 Brayton cycle

In recent years, the use of supercritical CO_2 as working fluid in recuperative closed Brayton cycles, has gained notable consideration for power generation. This may be imputed to the specific characteristics of CO_2, with relatively low values of both temperature and pressure at supercritical conditions (30.98 ºC, 73.77 bar) and its very high density, that implies a much smaller size of the equipment involved. In the case of the compressor, if the inlet conditions are selected near the critical point (for instance, pressures between 75 bar - 90 bar and temperatures between 35 ºC - 55 ºC) the power required for compression is very low in comparison to the power generated by the turbine expansion. This characteristic, together with a recuperative configuration, allows to achieve values of thermal cycle efficiency, even higher that those obtained with conventional superheated steam Rankine cycles, with a simpler configuration. Two important drawbacks must be mentioned: on the one hand, the lack of proven-commercially available technology for equipment working with supercritical CO_2 (turbomachinery and heat exchangers); and on the other, the peculiar behavior of CO_2 specific heat near the critical point, very dependent both on pressure and temperature. This latter feature makes it difficult to design the intermediate recuperator because the specific heat of the two streams, the high temperature-low pressure and the low temperature-high pressure, are very different. This problem is overcome by means of the use of a second recuperator and an auxiliary compressor (re-compressor), splitting the flow at the exit of the High Temperature Recuperator (HTR) by diverting a fraction through the re-compressor. The lower mass flow that circulates through the higher pressure-lower temperature side of the Low Temperature Recuperator (LTR) allows the balance of the specific heat capacities of both streams. Figure 7 presents the layout and temperature-entropy diagram of the recompression supercritical CO_2 (sCO_2) cycle.

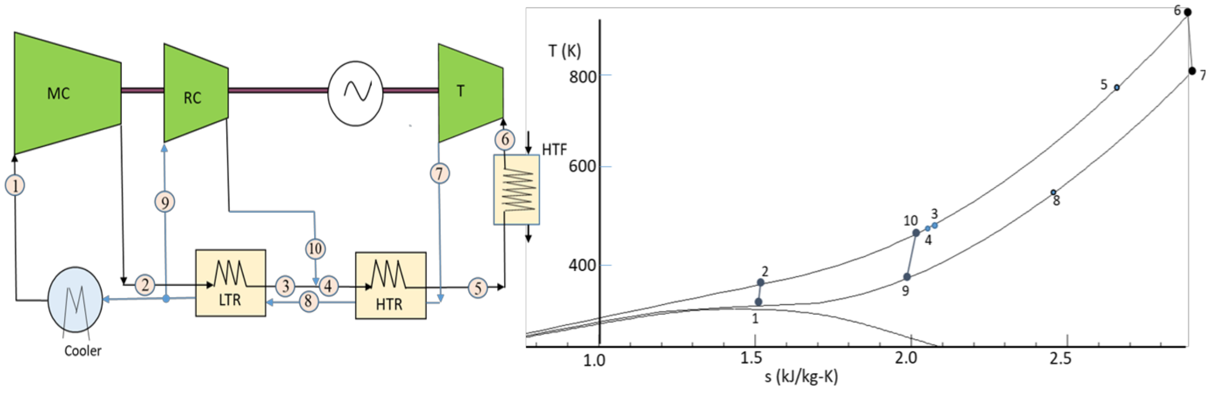

Figure 7. Recompression sCO_2 cycle layout and corresponding T-s diagram

It can be said that the recompression sCO_2 is one of the most studied cycle lately. As the maximum temperatures of the working fluid are in a range from 500 °C up to 1000 °C, this cycle achieves thermal efficiencies that can compete advantageously with other conventional options (Wang & He, 2017; Rovira et al. 2014; Kumar & Srinivasan, 2016). Apart from CPS, this technology has been proposed for nuclear plants, geothermal systems, fuel cells and high temperature heat recovery systems.

In relation with different sCO_2 Brayton configuration options, Zhu et al. (2017) analyze the recompression configuration together with other sCO_2 layouts that do not include the bypass recompressor, instead they incorporate a pre-compressor or partial cooling. Coco-Enríquez et al. (2017) compare the performance of a solar plant based on a steam Rankine cycle with four solar sCO_2 cycles configurations, all of then with reheating: the basic regenerative cycle, and three recompression layouts: the standard, the partial cooling and the intercooling. In this work, several cycle parameters are optimized by means of multivariable algorithms, for example: the bypass fraction, the main compressor total pressure ratio and the intercooling pressure. The study concludes that a considerable efficiency enhancement is obtained if a recompression sCO_2 cycle is selected as power block, compared to the conventional Rankine option. Other studies carry out an optimization analysis of the recompression cycle parameters, aiming to increase the cycle efficiency, for specific solar technologies, mainly CR. In this line, Wang et. al (2017) optimize a recompression cycle with reheating; Binoti et.al (2017) optimize and compare additional layouts, considering main compressor intercooling, partial cooling, and the conventional recompression cycle; and (Monjurul et al., 2020) study the off-design and the annual performance, comparing dry and water cooling.

An important issue to consider is the high value of the working fluid maximum pressure in sCO_2 cycles. The compression pressure must be higher than 2.5 to achieve an optimum cycle efficiency. That means pressures as high as 200 bar or even 300 bar, and heat exchangers that must work with a high pressure difference between both streams. For this reason, Printed Circuit Heat Exchangers (PCHEs), designed to support a high mechanical stress, are commonly selected. However, their design imply the flow through very small channels, so clogging problems can arise when using, for

example, molten salts as heat transfer fluid. To overcome this problem, Linares et al. (2020) propose a novel layout where the heat power is supplied downstream the turbine, therefore at the low pressure side (typically 80-90 bar). This option allows the use of a shell and tube design for the source heat exchanger, when molten salts are used, as it is often the case of CR solar systems.
Lately, important reseach programs, as the Solar Power Gen3 Demonstration Roadmap from the National Renewable Energies Laboratory (NREL) (Mehos, 2017) or the Australian Solar Thermal Research Initiative (ASTRI) (Gurgenci et al., 2014), have selected the recompression sCO_2 cycle for the power block of CR systems, with the objective of achieving efficiencies higher than 50% while using simpler facilities, thus lower LCOE values. To that aim, the integration of a bottoming ORC cycle to recover the sCO_2 rejected heat in the cooler has been explored, although the advantage of simplicity is compromised in that case. Along that research line, Song et. al (2018) explore the potential of adding a bottoming ORC in the sCO_2 cycle to improve its thermal performance, carrying out a parametric optimization of that combined cycle, and Singh & Mishra (2018) analyze a solar PTC plant feeding a combined cycle based on a recuperative sCO_2 – ORC configuration as power block. In both cases the sCO_2 cycle do not include recompression and the maximum temperature is lower than 400ºC.

Hou et al. (2018) carry out the optimization of a combined sCO_2 recompression cycle (T_{max} = 750º) with a regenerative ORC using zeotropic mixture fluid. On the other hand, Mohammadi et al. (2020) propose a layout for hybrid CR –gas turbine solar plant reaching high temperatures (1000 ºC). The gas turbine exhaust gases feed two sCO_2 cycles in series: a recompression cycle followed by a sCO_2 partial cooling cycle. This configuration yields to lower LCOE, because the sCO2 cycles include smaller components expected to entail lower costs than those required in other bottoming cycles, such as the steam Rankine cycle. However, the global thermal efficiency obtained was lower.

4.3 Innovative configuration proposals for integrated solar combined cycles

4.3.1 Integrated solar combined cycle using gas turbine with partial recuperation

The idea of CC with a recuperative gas turbine cycle has been explored in several works, always in search of layouts that would increase plant thermal efficiency (Carcasci & Facchini, 2000; Franco & Casarosa, 2002). However, this configuration has not been implemented in commercial operating plants, because the advantages are not particularly relevant. The improvement in gas turbine efficiency is balanced out by the lower temperature of the exhaust gases that feed the HRSG, that will entail a lower steam production, leaving aside the greater complexity of the layout. However, further studies follow this research line based on the concept of partial recuperation, extended it to integrated solar combine cycles (Rovira et al., 2015b; Rovira et al., 2017; Liu et al., 2018).

Concerning the high solar–to-electricity efficiency obtained with the integration of the solar heat in the gas turbine, Rovira et al. (2020c) propose a layout of ISCC plant where the gas turbine integrated a heat exchanger for Partial Recuperation (ISCC-PR). This layout, showed in Figure 8, aims to save an amount of fuel equivalent to the solar input, without requiring any variation in the turbine inlet temperature.

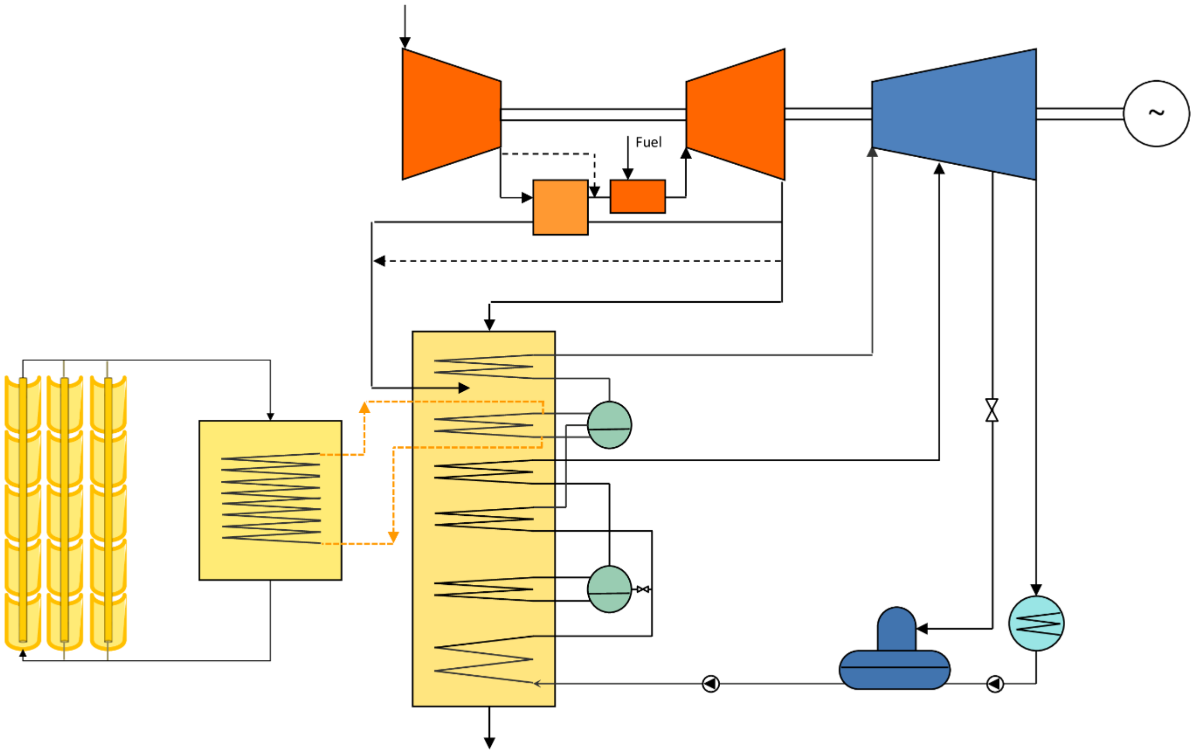

Figure 8. Layout of ISCC with Partial recuperation GT (Rovira et al., 2020c)

This proposal keeps the integration of the solar source in the bottoming cycle, as in standard ISCC, with the advantage of using this reliable technology that ensures a constant steam production. However, in this proposal the gas turbine exhaust is not sent in full to the HRSG. In periods of solar irradiation, when solar heat contributes to the high pressure water evaporation, a fraction of the exhaust gases is sent to the gas turbine recuperator, thus achieving a reduction of fuel consumption. That fraction reduces its temperature and must be introduced downstream in the HRSG, at the high pressure superheater inlet, where it is mixed with the main stream. When the partial recuperation takes place, the gas mass flow through the HRSG is affected and therefore, the fraction sent to the recuperator must be modified and selected in each case, to maintain the steam mass flow generated.as well as its temperature. This proposal achieves a solar-to-electricity efficiency above 50%, using a proven technology for solar integration in the bottoming cycle, as in conventional ISCC (Rovira et al., 2020c).

4.3.2 Integrated solar combined cycle configurations based on the organic Rankine cycle as the bottoming cycle

Among other alternatives for integrated solar combined cycle, it is worth pointing out the following. Chacartegui et al. (2009) propose a low temperature ORC as the bottoming cycle in medium and large power combined cycle plants. They conclude that, while modern conventional CCGT plants make use of gas turbines in the topping cycle with very high inlet temperatures, to achieve an efficiency close to 60%, combined cycle plants including a toluene ORC as bottoming cycle, may reach similar global efficiency with a more moderate turbine inlet temperature, that entails inferior values of NO_X emissions and lower manufacture and maintenance costs.

In this research line, Cao et al. (2016) study the coupling of a ORC cycle to a low power gas turbine (12 MW_e) and Shaaban et al. (2016) analyze the performance of a solar integrated combined cycle plant including two low temperature cycles: a steam Rankine cycle and a ORC. The steam Rankine cycle is fed in the conventional way, by both heat sources, the solar heat and the gas turbine exhaust. However, as in this proposal the gas turbine includes compressor intercooling, the ORC gets its heat source from the cooler rejected heat. In (Zare & Hasanzadeh, 2016), authors analyze a similar configuration with two low temperature ORCs and a recuperative gas turbine as topping cycle.

4.3.3 Other integrated solar combined cycles

These proposals seek to obtain new and more advanced hybrid configurations to integrate and manage both heat sources, the solar source and the gas/biogas, in order to develop ISCC plants where, if possible, the solar contribution becomes more important than the gas contribution. In (Rovira et al., 2020a), different layouts with and without solar integration are analyzed and compared. This study includes a novel cycle that combines a topping recuperative gas turbine, aiming a reduction in fuel consumption, with an unconventional Rankine organic cycle (DRDE), as shown in Figure 9. The recuperative configuration of the gas turbine entails a drop of at least 100ºC in the turbine exhaust temperature, which in turn means a reduction of the bottoming cycle power. The annual performance of all the configurations considered is carried out in two different locations: Almeria and Las Vegas, because these two locations present different values of the mean annual ambient temperature (lower in Almería) and solar irradiation (higher in Las Vegas) and those parameters have a significant influence in the annual performance.

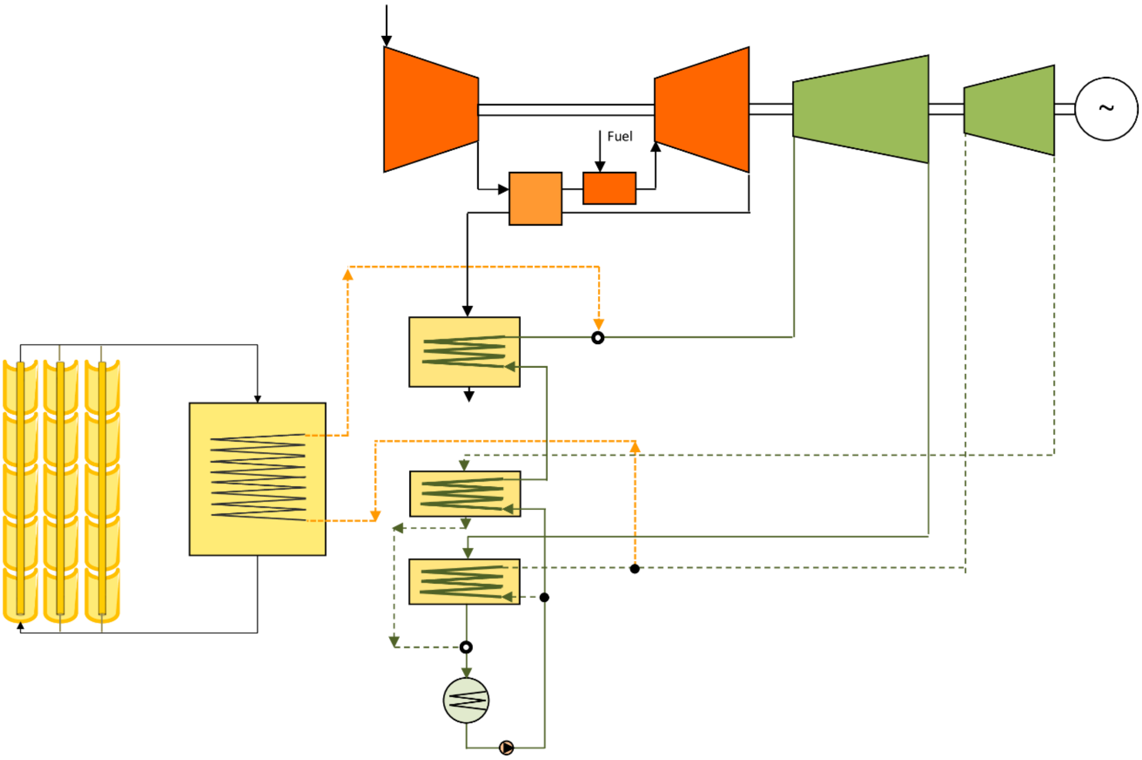

Figure 9. Layout of ISCC with Partial recuperation GT and Double Recuperation & Double Expansión (DRDE) bottoming cycle (Rovira2020a).

The ISCC-R-DRDE presents a superior performance compared to the state-of-the-art CCGT and ISCC, with a higher annual mean efficiency. The results show that the fuel saving is more important in the cooler mean temperature location (4%) versus (2.5%), whereas the solar irradiation solar level does not have significant effect. From the thermodynamic point of view, the authors conclude that the combination of a recuperative gas turbine and a Double Recuperative Double Expansion organic cycle shows promising results.

5 PROPOSALS OF INTEGRATION WITH OTHER RENEWABLE HEAT SOURCES

Several studies propose the integration of the solar source with other renewable sources. For example, Cakici et. al (2017) analyze the performance of a supercritical regenerative ORC that integrates a geothermal heat source with the heat from a solar field of PTCs. Jiang et al.(2017) consider those two renewable energy sources: geothermal and solar; each of them individually coupled to a sCO_2 recompression cycle, but with an integrated operation: the base-load power is supplied by the geothermal plant whereas the solar thermal plant generates supplementary power to cover the peak electricity demand. In relation to hybridization with biomass, Pantaleo et al. (2017) propose a combined cycle composed of a biomass external fired gas turbine and a superheated recuperative ORC. The novelty of this proposal is the use of a thermal storage between the topping and the bottoming cycle, and the integration of a solar field of PTCs connected in parallel to the thermal storage. Morrone et. al (2019) study a proposal of a transcritical organic Rankine cycle driven by a PTC solar field, with a conventional biomass boiler connected in series, that operates if the solar radiation does not satisfy the energy request. The study concluded that the biomass integration raises the annual net solar-to-electric efficiency. Finally, integration with waste heat that is generated in industrial processes, has been as well analyzed. For example, Bellos et al. (2018) study the performance of an ORC driven by a solar field of PTCs, with oil as HTF and an intermediate storage tank. In this proposal the waste heat of low-medium grade temperature (150º-300ºC) is supplied to the economizer of the ORC steam generator, but may contribute to the evaporation process, depending on the waste heat temperature and the working fluid employed.

Conclusion

This work has been focused on the analysis of different configurations of the power block in STPPs, describing the state-of-art and its evolution over time and putting forward advanced proposals, highlighting their drawbacks and their challenges. Currently, the steam Rankine cycle is the most widespread and commercially available power block option, usually coupled to a PTC solar field working with oil. The hybridization is a valuable option because it involves a double benefit: the improvement in the management of the discontinuous solar source, and the possible increase in the maximum temperature of the working fluid in the power block, yielding to higher STPP global efficiency. ISCC plants are good examples of these advantages, and several projects worldwide have chosen this configuration. In this review, several advanced alternative layouts of solar integrated combined cycle plants have been described (e.g. ISCC_PR, ISCC-R-DRDE), proposed to further increase the plant thermal efficiency with a better management of both heat sources, solar and fossil, and, if possible, increasing the solar source annual contribution. As CR technology is gaining prominence, other power block options that require high maximum working fluid temperatures have been considered, as it is the case of sCO_2 Brayton Cycles. This solar-only proposal presents the advantage of a high efficiency with a simpler facility compared to conventional options. Other configurations, suitable to operate with moderate temperature heat sources (ORCs, B-HRB) have been described as well, presenting promising results in specific ranges of temperature and power, showing cycle efficiencies comparable to the steam Rankine cycles but with the noteworthy advantage of being a less complex facility.

In summary, it can be stated that the current solar thermal electricity scenario consists of multiple alternatives available both for solar technologies and for power conversion and hybrid systems. An economic assessment and comparison of the different alternatives has not been addressed, because the results published in that regard, although promising, involve high uncertainties, as new technologies need to make use of some components still under development and not yet available on the market for the alternative working fluids, and operating conditions, that entail several of the advanced proposals described.

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