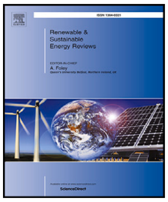
Renewable and Sustainable Energy Reviews xxx (xxxx) xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



High temperature central tower plants for concentrated solar power: 2021 overview

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ARTICLE INFO

Keywords:
Concentrated solar power
Solar power towers
Technologies Overview
High Temperature Receivers
Thermal Energy Storage and Hybridization
Power Cycles
Thermo-economic Data

ABSTRACT

Among the diverse technologies for producing clean energy through concentrated solar power, central tower plants are believed to be the most promising in the next years. In these plants a heliostat field collects and redirects solar irradiance towards a central receiver where a fluid is heated up. Afterwards, the same fluid or eventually another one heated in a heat exchanger develops a thermodynamic cycle that produces a mechanical power output, transformed in electrical energy through an electrical subsystem. Quite high temperatures can be reached in the solar receiver, above 1000 K, ensuring a high cycle efficiency. This review is focused to summarize the state-of-the-art of this technology and the open challenges for the next generation of this kind of plants. An actualized review of the plants working nowadays as well as the plants under development and research projects is presented. Updated thermo-economic data are collected in a comprehensive way. Each of the subsystems of a typical plant are surveyed, putting the emphasis on the more relevant research lines and the issues to be solved in the next years. Heliostat field margin of improvement, high temperature receivers and the most suitable thermodynamic cycles to take advantage of high temperature heat are detailed. Thermal storage and hybridization concepts are also surveyed. It is stressed the importance to design the plant as a whole, optimizing subsystems and their coupling to improve overall plant performance. Finally, a prospect for future R&D in this field is performed.

1. Introduction

Current anthropogenic intensification of climate change, energy demand growing and fossil fuel exhaustion have made imperative the necessity of a new energy generation paradigm looking for an increase of generated power, but from cleaner sources reducing pollutant emissions. Among the different renewable energy sources, Concentrated Solar Power (CSP) technology constitutes a very interesting option that employs solar radiation as main energy source. This technology stands out thanks to its ability to produce reliable, safe, efficient and clean power reducing, or even fully removing, pollutant greenhouse effect emissions associated with conventional fuel combustion [1]. In Concentrated Solar Power systems, direct solar radiation is concentrated in order to obtain (medium or high temperature) thermal energy that is transformed into electrical energy by means of a thermodynamic cycle and an electric generator. Main advantage of concentrated solar power technology against other conventional renewables as photovoltaic or wind energy is its potential for hybridization and also to store solar energy as heat. These possibilities allow to produce electric energy when desired and to rectify the inherently variable solar contribution, thus helping to stabilize and to control power output [2].

By 2013, there was about 3.4 GW of installed CSP operating capacity worldwide. Global CSP capacity grew 11% in 2019 to 6.2 GW. This is below the average annual increase of the past decade (about 24%), but CSP spread to new markets as France, Israel, Kuwait, China and South Africa. For the first time as much tower capacity as parabolic trough capacity was completed during 2019 [3]. According to the 2014 technology roadmap for Solar Thermal Electricity [1], the solar thermal electricity will represent about 11% of total electricity generation by 2050. In this scenario, called hi-Ren (High Renewables scenario), which is the most optimistic one, the global energy production will be almost entirely based on free-carbon emitting technologies, mostly renewables in 2050. As a consequence, the annual emissions from the power sector would fall from 13 $GtCO_2$ in 2011 to a mere 1 $GtCO_2$ in 2050. Thermosolar technology will be responsible for emissions reduction of 2.1 $GtCO_2$ and 9% cumulative emissions reduction over the entire scenario period, which is about half the contribution from photovoltaic electricity (20%).

One of the first prototypes for obtaining usable energy from concentrating solar radiation was developed by Augustin Mouchot, who presented it at the Universal Exhibition in Paris in 1878. That prototype

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https://doi.org/10.1016/j.rser.2021.111828
Received 23 March 2021; Received in revised form 10 September 2021; Accepted 26 October 2021

Please cite this article as: R.P. Merchán, *Renewable and Sustainable Energy Reviews*, https://doi.org/10.1016/j.rser.2021.111828

Abbreviations and acronyms

ASTRI	Australian Solar Thermal Research Initiative
CRS	Central Receiver System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrated Solar Power
DLR	German Aerospace Center
DNI	Direct Normal Irradiance
EES	Engineering Equation Solver
HTF	Heat Transfer Fluid
HYGATE	Hybrid High Solar Share Gas Turbine Systems
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LCoE	Levelized Cost of Electricity
LFR	Linear Fresnel Reflector
MENA	Middle East and North Africa
MS	Molten Salts
NREL	US National Renewable Energy Laboratory
OMSoP	Optimized Microturbine Solar Power system
PCM	Phase Change Material
PDC	Parabolic Dish Collector
PEGASE	Production of Electricity from Gas and Solar Energy
PPA	Power Purchase Agreement
PTC	Parabolic Trough Collector
PV	Photovoltaic
SAM	System Advisor Model
sCO_2	Supercritical CO_2
SHGT	Solar Hybrid Gas Turbine
SOLGATE	Solar Hybrid Gas Turbine Electric Power System
SOLHYCO	SoLar Hybrid Power and Cogeneration plants
SOLUGAS	Solar Up-scale Gas Turbine System
SPT	Solar Power Tower
SolarPILOT	Solar Power tower Integrated Layout and Optimization Tool
SS	Saturated Steam
SUNSPOT	Stellenbosch University Solar Power Thermodynamic cycle
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TRNSYS	Transient System Simulation Tool
UAE	United Arab Emirates
UC	Under Construction
UD	Under Development
USD	US Dollar

was made up by a parabolic reflector working together with a vapor turbine that obtained ice from concentrated solar heat [4]. More than one hundred years later, in the 1980s, CSP started its commercial development as an industry thanks to the construction of nine parabolic trough operational plants (*SEGS I-IX* plants) in California [5]. USA continued leading CSP market until 2010, when Spanish installed capacity overtook USA [6]. Since then, a very fast development both at a commercial and at a research stage of CSP has been performed. Actually, CSP has been proposed by the International Energy Agency (IEA) as key for the future of power generation [1,7]. Nowadays, other countries are making big efforts in order to increase their CSP installed capacity, especially China, India, UAE, Morocco and South Africa [6].

1.1. CSP working principle and geometry types

Sun radiation that reaches the Earth is denominated global radiation. It has two components: direct and diffuse solar radiation. Direct Normal Irradiance (DNI) is the most important component for solar concentrating energy generation and it accounts for the amount of solar irradiance that reaches a normal or perpendicular area. Therefore, best places in the Earth for CSP generation are those with higher DNIs levels, namely, regions approximately between 15° and 40° both north and south latitudes and also places with higher elevations. As a result, regions like Chile, Peru, north of Mexico and south west of USA in America; western Australian areas; south and north Africa; some Mediteranean regions; Middle East; or north west of India and western China in Asia have a big potential for CSP [1,8]. Kabir et al. [9] have provided a global scenario of solar energy technologies with respect to their potential, prospects, limitations and policies. Dowling et al. [10] have particularly reviewed the economic assessment of concentrated power technologies by 2017. Mehos et al. [11] have analyzed CSP markets and market requirements in terms of the technology status in a report for National Renewable Energy Laboratory (NREL), USA.

The working principle of concentrated (or concentrating) solar power is very simple: direct solar radiation is concentrated in order to obtain high temperature (approximately between 500 and 1000 °C) thermal energy that is transformed into electrical energy [12]. Although there exist different arrangements, CSP systems are basically formed by the same elements [2,13]:

- A solar reflector (or a system of reflectors), which gathers and concentrates the Sun radiation.
- A solar receiver, where the solar radiation is concentrated and absorbed.
- A power conversion system, which turns the concentrated solar heat into mechanical energy.
- An electric generator, which transforms that mechanical energy into electricity.

Currently, four broadly accepted types of Concentrated Solar Power systems can be distinguished. They are differentiated by the way of concentrating the Sun radiation onto the receiver, as it can be observed in Fig. 1 [12,14].

- Parabolic Trough Collectors (PTC) are made up of a parabolic mirror which concentrates the Sun radiation on a focal line.
- Linear Fresnel Reflectors (LFR) focus sunlight on a linear receiver too, but, in this case, through an array of linear planar mirrors, behaving as a Fresnel lens.
- Parabolic Dish Collectors (PDC) consist of a parabolic mirror which reflects and concentrates the Sun heat on the focal point of the dish.
- Solar Power Towers (SPT), also denominated Central Receiver Systems (CRS), are set up by a heliostats field which reflects solar radiation into a central receiver located atop a tower. These heliostats track the Sun with two axis. They are also considered as point focus collectors.

He et al. [15] have very recently presented a review on the perspectives of concentrating solar power. Fig. 2 summarizes very well the main characteristics of the past and eventual future generations of CSP power plants.

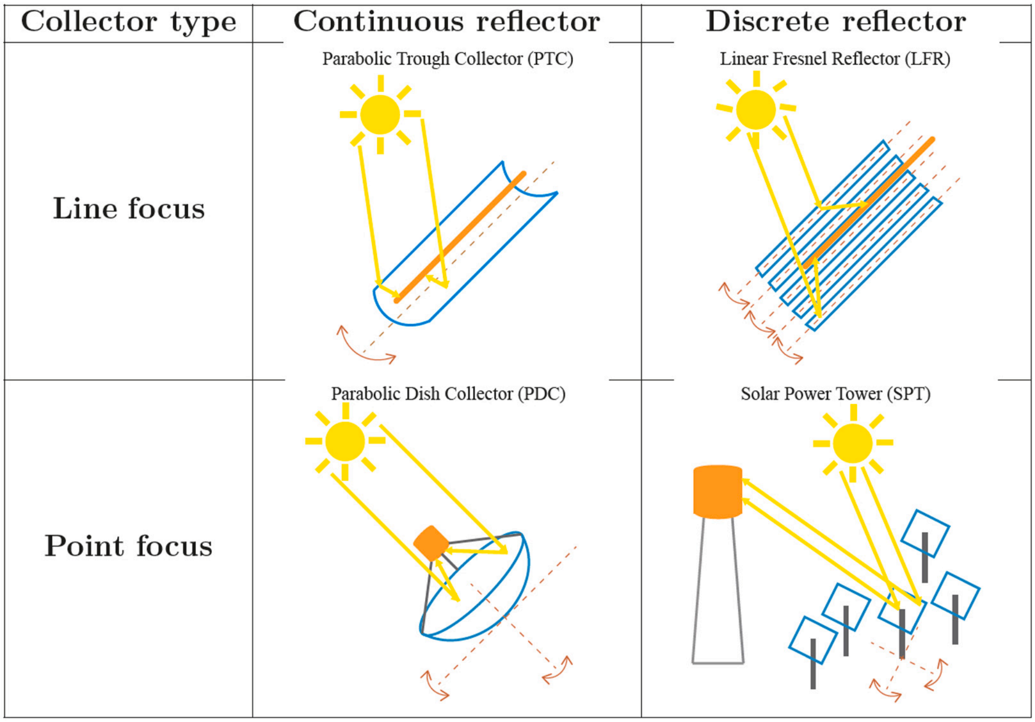
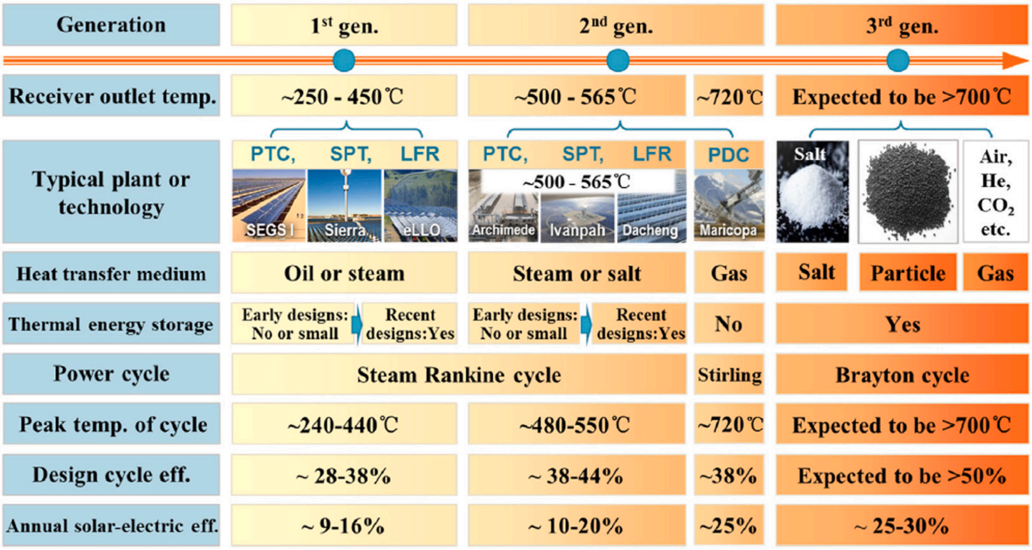


Fig. 1. Classification by reflector geometry of the commonly accepted CSP systems. Yellow arrows represent Sun radiation, orange structures symbolize solar receivers, blue structures correspond to solar reflectors and brown arrows with dashed lines show reflectors rotation axis.



Generation	1st gen.	2nd gen.		3rd gen.		
Receiver outlet temp.	~250 - 450℃	~500 - 565℃	~720℃	Expected to be >700℃		
Typical plant or technology	PTC, SPT, LFR SEGS I, Sierra, eLLO	PTC, SPT, LFR ~500 - 565℃ Archimede, Ivanpah, Dacheng	PDC Maricopa	Salt		Air, He, CO_2 etc.
Heat transfer medium	Oil or steam	Steam or salt	Gas	Salt	Particle	Gas
Thermal energy storage	Early designs: No or small → Recent designs: Yes	Early designs: No or small → Recent designs: Yes	No	Yes		
Power cycle	Steam Rankine cycle		Stirling	Brayton cycle		
Peak temp. of cycle	~240-440℃	~480-550℃	~720℃	Expected to be >700℃		
Design cycle eff.	~ 28-38%	~ 38-44%	~38%	Expected to be >50%		
Annual solar-electric eff.	~ 9-16%	~ 10-20%	~25%	~ 25-30%		

Fig. 2. Scheme of the main characteristics of past and foreseen future generations of CSP plants as reported by He et al. [15].

1.2. CSP against other renewable or conventional technologies

The key advantage of CSP against other renewable energies like photovoltaic (PV) energy, or wind power is its ability to store heat for producing electric energy when desired. Hence, CSP can be coupled with Thermal Energy Storage (TES) [5], but also with a combustion chamber burning some conventional fuel or some biogas constituting hybrid plants. Nowadays, other hybridization schemes are being investigated, as the coupling with photovoltaic, wind, biogas, or geothermal systems [16–19]. Both these hybrid and TES systems allow for high dispatchability and for stabilizing power output. Therefore, the generation can be shifted to non-Sun shining times, as cloudy periods or even nighttime [20]. In this way, CSP plants can be designed for covering baseload or demand peaks, a major advantage with respect to PV or wind facilities [17]. Köberle et al. [21] presented in 2015 a very complete comparative analysis on the techno-economic potential of CSP and PV technologies.

As stated by Pietzcker et al. [22] during the last years PV has undergone a very rapid growth, associated to a significant cost decrease. Nevertheless, the deployment of CSP is being quite slower. Even International Energy Agency (IEA) [1] recognizes that PV rapid deployment has been a barrier causing a delay in the deployment of CSP. Partly this can be associated to the fact that CSP is more dependent on the quality of the solar resource, direct solar irradiance over 5 kWh/m^2 per day is usually considered as the minimum in order to be economically interesting. On the contrary PV can work with diffuse

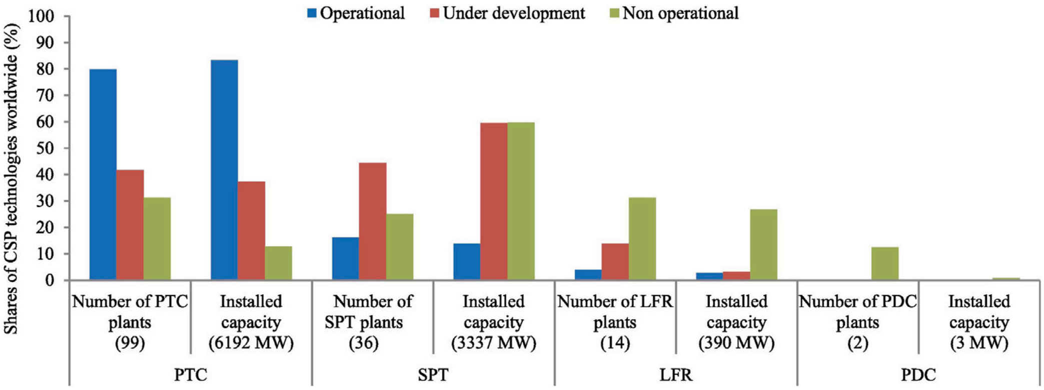


Fig. 3. Shares of worldwide CSP plants by technology, as they were in 2020, by Achkari and El Fadar [6]. Number of plants and their installed capacity are detailed in accumulated terms.

irradiance. But CSP flexibility to be combined with thermal storage and co-firing in order to meet demand requirement is considered a key advantage. It is expected that PV (or wind) technologies should complement each other with CSP in the future [8]. CSP can contribute to meet production necessities in those moments when PV has less possibilities. Thus, actually the increasing electricity production by means of PV can boost CSP deployment. A detailed analysis of the future interrelationships between PV and CSP was developed by Pietzcker et al. [22]. Hernández-Moro and Martínez-Duart [23] have investigated the future evolution of production costs of PV and CSP in a review.

As commented by del Río et al. [8] CSP has also positive records in three main local environment impacts of any renewable or standard technology: land requirements, water availability and landscape impact. One km^2 of arid land can generate electricity as a conventional 50 MW plant working with coal or gas. The area required by CSP to generate 1 MWh is in the same order of magnitude that wind or biomass. Also, the water requirements of CSP are not large, even below that fossil or nuclear plants. This is specially relevant for high temperature cycles as gas turbines where the working fluid is not water vapor and water is only required in certain refrigeration processes. Finally, visual impact of CSP plants, as for instance central tower ones, can be actually unavoidable, but these plants are usually installed in arid zones without much population or touristic value.

1.3. CSP worldwide global data

Overall installed capacity of CSP worldwide reached 6.3 GW in 2019 [24]. Regarding concentration ratio (the ratio between the area of reflecting surface and that of the receiver), PDC can achieve the highest values, in the range of 1000–3000 and SPT intermediate ones (300–1000) [25], while PTC and LFR present relatively lower values: between 60 and 80 [2]. Right now, Parabolic Dishes are the only technology recommended for small scale generation, in the range [0.01–0.4] MW, whereas the other three systems are preferred for medium or high scale generation ([10–200] MW) [25].

Currently, most mature technologies are parabolic trough collectors, which constitute 80% of operational plants [6], as it can be observed in Fig. 3. Since the development of *Andasol* plants at Spain in 2011, which have significant TES, and of *Solana* plant at USA in 2013, other interesting projects have been recently carried out worldwide and some are under development. Among already operating commercial plants, *Noor II* at Morocco (2018), *Shouhang Dunhuang 100 MW Phase II* at China (2018) and *Kathu Solar Park* at South Africa (2019) stand out thanks to their installed capacity and innovative concepts.

Solar power towers, which constitute about 15% of operational plants [6] (see Fig. 3), are the second most mature technology. Taking into account that this review is focused on SPTs, further details about real SPT plants are gathered at Section 2. Linear Fresnel reflectors and parabolic dish collectors represent just a very small percentage of installed capacity. Regarding LFR, *Puerto Errado 2* in Spain (2012) and *Dhursar* in India (2014) are among the few commercial plants and *Zhangjiakou* project is presently under development in China. Finally, two parabolic dishes plants were built in USA, *Maricopa* in 2010 and *Tooele Army Depot* in 2013, but currently they are non-operational [26].

However, this trend is already changing since the amount of under development SPT plants (45%) and their installed capacity (60%) is higher than those of PTC [6], as illustrated by Fig. 3. In 2018, worldwide and operational solar power tower gross installed capacity was 618.42 MW and, in the following years, it will finish achieving 995 MW [27]. The overall capacity of under construction and development solar power towers reached around 5383 MWh$_e$ in 2019, with an average power capacity of 207 MWh$_e$ [5]. The reason of that growth is the capacity of SPT to achieve higher temperatures in comparison to PTC [6] and, thus, greater solar to electric efficiencies [25]. Moreover SPT plants admit thermal storage and hybridization strategies, *i.e.* a certain control on energy production, a key element for the commercial development of future renewable energy technologies.

Thus, the main objective of this review is to present an actualized survey on this technology that is called to be key in the next years in the search for clean and renewable electric energy production sources. The main novelty of this review is that it is focused on high temperature SPT technologies, including their present status, active research lines, and future prospects. A comprehensive compilation of data, technological options and open investigations is exposed with the aim to be interesting for expert and also non-expert researchers, professionals, or other readers.

2. Current central tower plants and R&D projects

2.1. Solar power towers operation and sorts

Depending on the characteristics of each plant component, there exist a big variety of solar power tower plants both at a commercial and at a research stage. As it was previously mentioned, solar power towers, also denominated central receiver systems, are composed of a heliostat field, in which a varying number of heliostats reflect solar radiation, redirecting it towards the central receiver. Regarding heliostat field symmetry, there are basically two types of commercial plants: surround and polar fields. In surround fields, heliostats are placed around a central tower in a nearly circular shape, covering 360° or almost. On the other hand, polar fields are set up by heliostats located on a sector of a circle, thus the field has a wedge shape. In low latitudes, close to the equator, a surround field is the best option for reducing land use as well as tower height. As latitude increases, a field more concentrated to the polar side of the tower becomes better in order to improve performance. Therefore, at higher latitudes, a north/south polar field depending on the hemisphere is preferred. In the case of a north field, all heliostats are placed in the north side of the tower since the Sun is towards the south during all the year [1,28–30].

In the top of the tower, concentrated solar radiation reaches the solar receiver. Nowadays, according to their geometry, receivers can be external or have a cavity aperture. External receivers are suitable both for surround fields, in case they have a cylindrical shape, or for polar fields, if they are made up by a flat-plate panel. Alternatively, cavity receivers present a small aperture through which concentrated solar radiation enters. Due to its constrained geometry, they are normally employed for polar fields [28,29]. Therefore, heliostat field depends also on the receiver type or *vice-versa* [30].

This solar receiver acts as a solar radiation absorber too. At a commercial stage, most of the absorbers are made by tubes that can be placed to form a cylindrical or a billboard absorber, hence they are denominated tubular absorbers [28,31]. Thus, both external and cavity receivers could employ tubular absorbers [32]. In volumetric absorbers, solar heat enters within the structure or volume, where it is absorbed by a porous material, though currently they are not mature enough to be fully commercial [28,33]. As a general rule, tubular receivers are employed for high temperatures or high pressures, but not both at the same time; meanwhile, volumetric concepts are adequate for higher temperatures with limited pressures [28]. Most employed materials for the receivers are ceramics and metals stable at high temperatures [27]. In the next section more details and figures about heliostat fields and solar receivers types will be shown and commented.

Then, in the solar receiver, a Heat Transfer Fluid (HTF) absorbs concentrated solar heat and it can either transmit it to the thermodynamic cycle working fluid (through some type of heat exchanger) or it can act itself as this working fluid. The function of the heat transfer fluid can be performed presently by water/steam or by molten salts. Moreover, the use of air as HTF [27] and even solid particles [34] or nanofluids are being researched nowadays in the search for larger operation temperatures in the receivers. Maximum operating temperature of HTF is a very important parameter for receivers, clearly conditioning their design [5].

Therefore, high temperature heat is achieved and employed for running directly a power block or indirectly by storing this energy in advance. All commercial and operational central receiver plants employ steam for running a Rankine cycle; although some research projects about air as working fluid running a gas turbine are being conducted. With respect to thermal energy storage, right now, almost all commercial plants accumulate energy through two tanks of molten salts. Thus, most of current commercial SPT plants employ two working fluids: molten salts as HTF and for TES, and superheated steam for the Rankine cycle [12]. The research lines under way on these fields will be detailed later on.

2.2. Current and under-development solar power tower plants

Table 1 summarizes, by countries, the operating SPT plants as well as some plants under development. Spanish *PS10* plant, the first purely commercial solar power tower system providing electricity to the grid in the world, started operation in 2007 and two years later, in 2009, the very similar *PS20* plant was already operative too [26,27]. Both of them employ a cavity receiver, a saturated steam turbine and a pressurized water thermal storage with 1 h of capacity as main technology systems [30,40]. Then, in 2011, *GEMASOLAR* plant [41], which utilizes a 19.9 MW steam turbine, was already working in Spain too. This plant was pioneer due to an innovative up to 15 h storage system, which uses molten salts as the heat transfer fluid and storage medium [30].

After that Spanish SPT boost, United States began its contribution thanks to the construction of three key central receiver plants which were operative in 2009, *Sierra*, in 2014, *Ivanpah*, and in 2015, *Crescent Dunes* (Tonopah). *Ivanpah* project, with a net turbine capacity of 377 MW, was at that moment the largest solar thermal power tower system in the world [26,27]. *Crescent Dunes* plant used an external cylindrical receiver with molten salts as HTF and incorporated a 10 h storage. Nevertheless, it is not currently operational because of some ongoing issues [42,43]. Along the same lines, *Sierra Tower*, which employed water as HTF and is made up by two towers and, thus, two receivers (a dual cavity receiver and an external rectangular one), is currently non-operational [26,30]. At least other three projects are now under development in USA: *Rice* (Mojave) with 150 MW of capacity, *Palen* and *Hidden Hills*, both with 500 MW planned capacity [5].

China constitutes another major SPT driver with several operational plants in the last years. From 2013, when *SUPCON 10 MW* plant started operation at that country, passing through the development of *Shouhang Dunhuang I* in 2016, up to the last two years, when those growth has been intensified due to the development of five chinese operative plants: *SUPCON 50 MW* and *Shouhang Dunhuang II* in 2018 and *Qinghai Gonghe*, *Hami* and *Luneng Haixi* in 2019 [6,26]. *Golmud 200 MW* plant is currently being constructed and other two plants are under a development process (*Golden* and *Shangyi*) [6,26].

Three years before, in 2016, South African *Khi Solar One* plant began to operate its 50 MW Rankine turbine. The same year, *Sundrop* project commenced heating greenhouses, desalinating seawater and running a steam turbine in Australia. Apart from that project, other two Australian non-commercial plants have been set up. In 2011, the demonstration *Lake Cargelligo* project, currently non-operational, tested a very interesting graphite solar receiver, which acts also as a boiler and storage system. Moreover, pilot *Jemalong* plant has been operational since 2017 [26].

Another region that has promoted this sector is the so-called Middle East and North Africa (MENA) area with different projects. The commercial *NOOR III* plant, located in Morocco in the Ouarzazate complex, was launched in 2018, with 7 h of storage capacity. While *Ashalim Plot B* project, with the tallest tower worldwide (240 m) [39], started operation in 2019 at Israel [26].

One of the best locations regarding solar radiation in the world is sited on Chilean deserts. As a consequence, Chile is trying to take advantage of its natural resources and stands out as one of the most promising countries regarding SPT according to their four planned plants. *Cerro Dominador* project is already being constructed [26]. It will have more than 10600 heliostats and 17.5 hours of storage capacity for producing 110 MW [44]. Additionally, *Copiapó*, *Likana* and *Tamarugal* are being developed in 2020.

Furthermore, the construction of *DEWA Tower* has already started in United Arab Emirates and other plants are currently under development worldwide as *Redstone* in South Africa, *MINOS* in Greece, *Aurora* in Australia, and *TuNur* in Tunisia, which stands out due to their 2000 MW of capacity [26]. Although, *Aurora* project has recently (December, 2019) changed to a fully different kind of project and now it will be supposed to become a photovoltaic facility [45,46].

2.3. Thermo-economic data

Regarding efficiency values and as a general overview, it can be highlighted that thermal efficiency (solar to mechanical) is estimated between 30% and 40% for solar power towers. This kind of systems presents overall plant peak efficiency (solar to electric) values in the interval [23–35]%, while its annual solar to electric efficiency varies from 20% to 35% [27]. In the case of *PS10*, a real plant that has been operational for 13 years, the mean annual efficiency is about 15.4% [29].

Apart from efficiency, another interesting parameter is the capacity factor, which is defined as the ratio between the actual output of a power plant and its maximum over a year (including nights) [6]. Capacity factors over 50% indicate that a significant amount of storage is employed [5]. For instance, the annual capacity factor for a tower

Table 1

Current (operational and non-operational) and Under Construction (UC)/Under Development (UD) solar power tower plants in the world by country according to [2,5,6,26,27,30,35–39]. In brackets the commissioned start year of the plant for the operational, currently non-operational plants, and — if not available.

Country	Non-operational	Operational	UC/UD
Australia	*Lake Cargelligo*[a] (2011)	*Solar Field (1+2)*[a] (2010)/*Sundrop* (2016)/*Jemalong*[a] (2017)	*Aurora* (UD)
Chile			*Cerro Dominador* (Atacama) (UC)/*Copiapó, Likana, Tamarugal* (UD)
China	*Huanghe Qinghai Delingha* (2017) / *Yumen 100 MW*[a] (–)	*Dahan*[a] (Yanqing), *Badaling*[a] (2012)/*SUPCON 10 MW* (2013)/*Shouhang Dunhuang I* (2016)/*Shouhang Dunhuang II, SUPCON 50 MW* (2018)/*Hami, Luneng Haixi, Qinghai Gonghe* (2019)	*Golmud, Yumen 50 MW*[a] (UC)/*Golden, Shangyi* (UD)
France	*Themis*[a] (1983)		
Germany		*Jülich*[a] (2008)	
Greece			*MINOS*[a] (UD)
India		*ACME*[a] (2011)	
Israel		*Ashalim Plot B* (2019)	
Italy			*Mazara* (UD)
Morocco		*NOOR III* (2018)	
South Africa		*Khi Solar One* (2016)/*Redstone* (2018)	
Spain	*SOLUGAS*[a] (2012)	*PS10* (2007)/*PS20* (2009)/*GEMASOLAR* (2011)	
Tunisia			*TuNur* (UD)
Turkey		*Greenway Mersin*[a] (2012)	
UAE			*DEWA Tower* (UC)
			Noor Energy 1/DEWA IV (UC) (CSP+PV) (UC)
USA	*Solar One*[a] (1981)/ *Solar Two*[a] (1996)/*Sierra* (2009)/*Coalinga*[a] (2011)/*Crescent Dunes* (Tonopah) (2015)	*Ivanpah* (2014)	*Rice* (Mojave), *Palen, Hidden Hills* (UD)

[a] R&D, pilot and demonstration plants.

Table 2

A few Solar Power Tower Projects, some of their features and their PPA data [26,29,35,47]. PPA data are taken from [26] and currency exchanges to USA dollars (USD) according to start year have been applied in order to unify units. Commiss. corresponds to Commissioned, SS means saturated steam, MS, Molten Salt, UC stands for Under Construction and UD, for Under Development.

Project	Heliostat Field	Receiver	Net Turb. Capacity	TES	Comm. Year	PPA/Tariff Rate (USD/MWh)
PS10 (Spain)	Polar	Cavity	11 MW	4 tanks (SS), 1 h	2007	352
PS20 (Spain)	Polar	Cavity	20 MW	4 tanks (SS), 1 h	2009	377
SUPCON I (China)	Surround	External	10 MW	2-tank direct (MS), 2 h	2013	193
Crescent Dunes (USA)	Surround	External	110 MW	2-tank direct, salt, 10 h	2015	135
Huanghe Qinghai (China)	Surround	External	135 MW	2-tank indirect (MS), 3.7 h	2017	166
Shouhang Dunhuang II (China)	Surround	External	100 MW	2-tank direct (MS), 11 h	2018	177
SUPCON II (China)	Surround	External	50 MW	2-tank direct (MS), 7 h	2018	177
NOOR III (Morocco)	Surround	External	134 MW	2-tank direct (MS), 7 h	2018	156
Redstone (South Africa)	Surround	External	100 MW	2-tank direct (MS), 12 h	2018	124
Hami (China)	Surround	External	50 MW	2-tank direct (MS), 8 h	2019	167
Luneng Haixi (China)	Surround	External	50 MW	2-tank direct (MS), 12 h	2019	167
Qinghai Gonghe (China)	Surround	External	50 MW	2-tank direct (MS), 6 h	2019	167
Ashalim Plot B (Israel)	Surround	External	121 MW	None	2019	212
DEWA Tower (UAE)	Surround	External	100 MW	2-tank direct (MS), 15 h	UC	73.0
Aurora (Australia)	Surround	External	135 MW	2-tank direct (MS), 8 h	UD	54.9
MINOS (Greece)	Surround	External	52 MW	2-tank indirect, 5 h	UD	312

plant with 10 h of TES is around 55% [27]. Hence, among other CSP systems, tower plants present the highest capacity factor [27].

A widely employed economic indicator is the Power Purchase Agreement (PPA). A PPA is a deal between a seller and a purchaser of electricity, in which all the commercial terms are defined [5]. Table 2 and Fig. 4 gather information about a few commercial tower projects with their PPA data [26]. PPA data are taken from [26]. In order to unify units, currency exchanges to USA dollars (USD) referred to each commissioning year have been applied. Highest tariff rates correspond to the earliest plants: *PS10* and *PS20* in Spain. On the other hand, *Aurora*'s project was associated with the lowest signed PPA among the analyzed plants, although, as it was previously mentioned, the project type has recently changed to a photovoltaic facility [45,46]. *DEWA* project has also a very low tariff rate for a duration of 35 years [24] and all considered PPAs signed in China are related to almost the same electricity prices. Therefore, tariff prices have decreased with

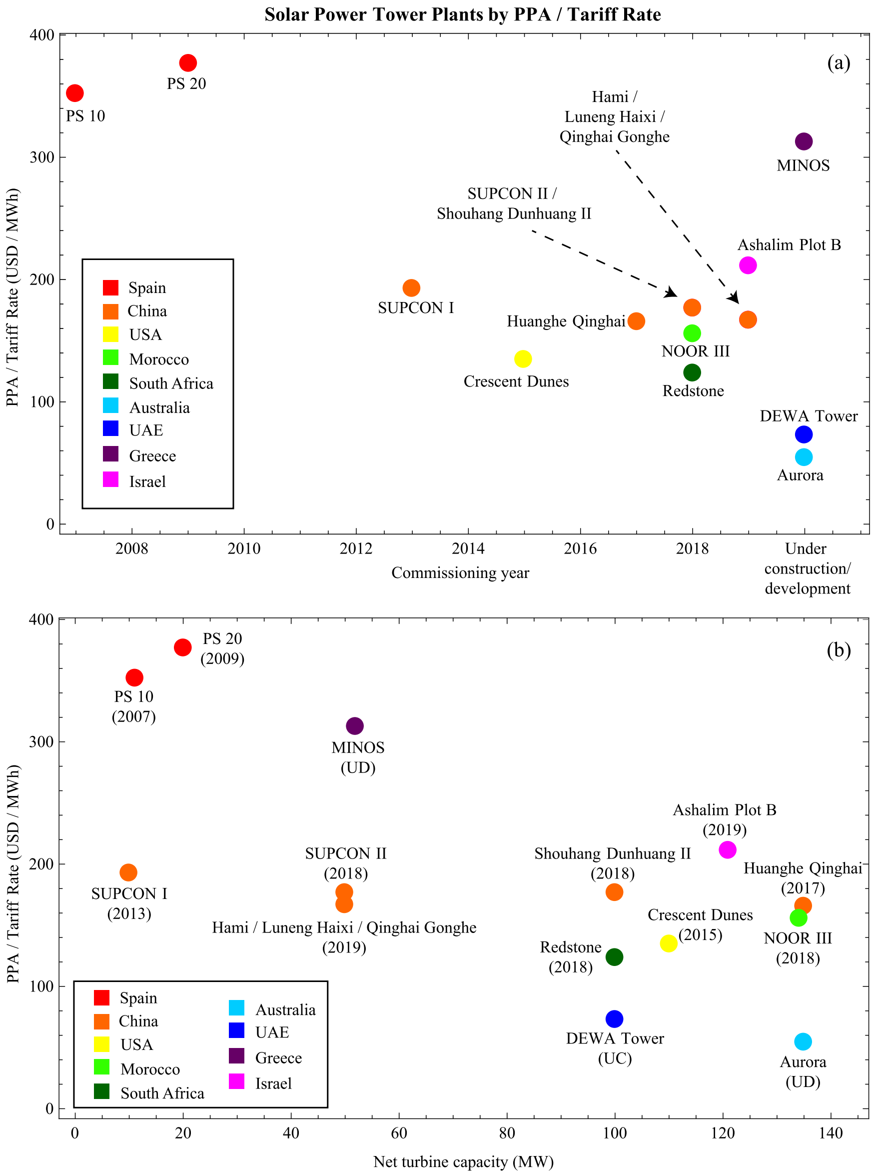


Fig. 4. PPA data in terms of plant commissioning year (a) and net turbine capacity (b) of a few SPT plants. Colors make reference to location country. PPA data are expressed in USA dollars (USD). Currency exchanges were applied according to the plant commissioning year [26].

time, as it can be observed in Fig. 4 [5]. The decrease in the last 10 years is very significant, proving the evolution of those technologies towards maturity [5]. In almost all those commercial plants, steam is the selected working fluid for performing a Rankine cycle and storage is usually associated with molten salts. In addition, a surround heliostat field pointing to an external receiver is the preferred option, except in *PS10* and *PS20* plants, which are set up by a polar field and a cavity receiver. Regarding future plants, average PPA tariff rate for CSP commissioned projects in 2020 and 2021 ranges between 75 and 94 USD/MWh, according to IRENA [24].

Another key economic indicator is the Levelized Cost of Electricity (LCoE). It indicates the price electricity should be sold for recovering the initial investment and the yearly running costs of the plant for an estimated period of operation [48]. Thus, it is employed in order to analyze the economic profitability of a power plant [6]. This levelized cost of electricity depends on TES capacity. If no storage is assumed, estimated LCoE in 2020 is around 145 USD/MWh. When 6–7.5 h of TES are considered, LCoE drops until 118–129 USD/MWh. And a further reduction is achieved when bigger TES is implemented (12–15 h TES), 112–121 USD/MWh [6]. Fig. 5 condenses the evolution of LCoE for several CSP technologies as a function of plant capacity and storage hours. It is clear that CSP levelized costs have suffered a decrease process, mainly and likely motivated by the higher levels of irradiance of recent plant locations [20] and by the lower total installed costs and by the larger storage systems and higher capacity factors [24].

Comparing CSP technologies from Fig. 5, it stands out the fact that the most recent solar power towers give the lowest LCoE [24,49]. SPT plants have a bigger potential for cost decrease and a better performance when employing TES. The room for improvement of this concept is higher and there are more under construction and development plants than for the rest of CSP technologies, due to their technical advantages [6,27]. In this way, among the four CSP types and for large scale generation, SPT are expected to lead the market and to be the most developed ones in the near future [1,2,35,39,50–52]. Even if eventually SPT plants have a higher cost in terms of installed power per unit area, they remain more profitable than PTC ones, because they require a smaller aperture area to meet the same energy needs [6].

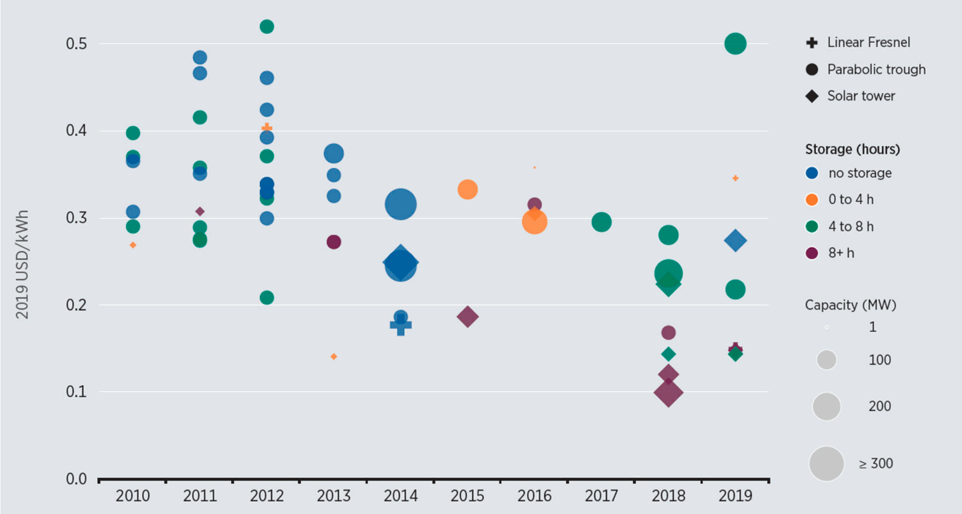


Fig. 5. Levelised Cost of Electricity (LCoE) versus commissioning year of a few CSP plants..
Source: Figure from IRENA ©IRENA2020 [24].

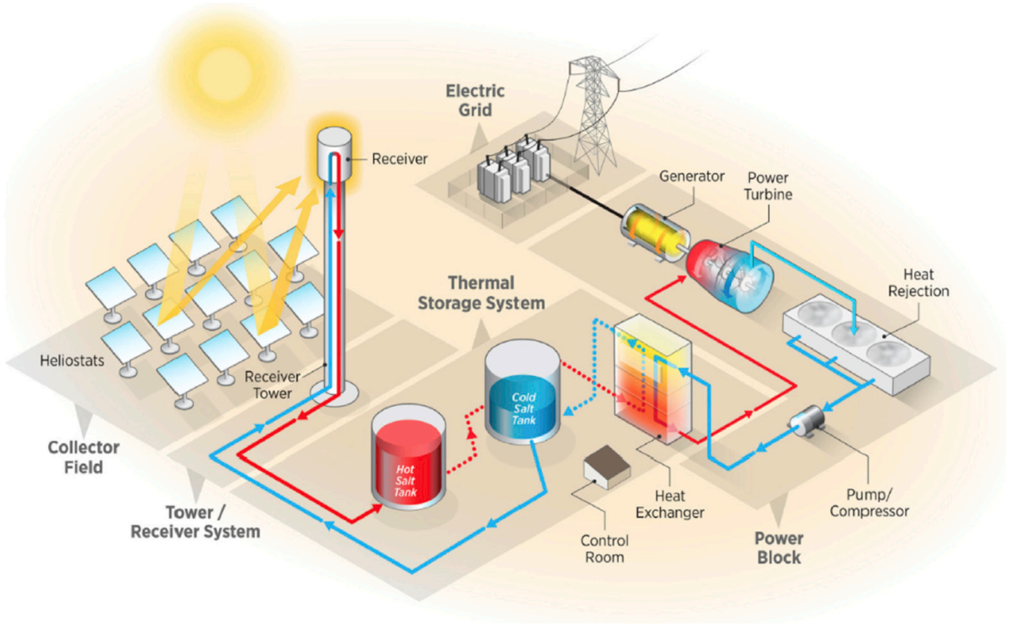


Fig. 6. Subsystems scheme for a SPT gas turbine power plant with thermal storage [5]. Main subsystems as solar field, receiver, heat engine (Brayton cycle in the example) and TES subsystems are shown.

3. Solar power towers subsystems state of the art

In this section a brief summary of the state of the art of the research on the main subsystems that constitute solar power towers is accomplished. Heliostat fields, solar receiver advances, thermodynamic cycles and working fluids, thermal energy storage options and hybridization technologies will be briefly surveyed. As an illustrative example, Fig. 6 shows a diagram in which the main subsystems of a SPT power plant coupled to a hybrid gas turbine can be distinguished. Additionally, an extra subsection, Section 3.5, about subsystems integration state of the art is also added.

3.1. Heliostat fields

Heliostat field accounts for around 40–50% of the total SPT plant cost and can be responsible for up to 40% of energy losses. As a consequence, lot of efforts have been made for optimizing designs in order to reduce costs and improve efficiency [53,54].

Currently, commercial heliostat units have decreased their costs until 100 USD/m^2 and a target of 75 USD/m^2 is expected for the following years [53]. Several different designs are under development or test processes with the objective of obtaining low cost heliostat concepts, as the *STAGE-STE* European project or the Heliostat Cost Down Scoping Study from Australian Solar Thermal Research Initiative (ASTRI) [55]. Several issues related to heliostat units are currently being addressed like the study of wind loads, shaping and dimensioning, the canting, components, manufacturing and assembly, and the qualification or the heliostat cleaning [53]. Regarding heliostat materials, nowadays the most adequate option for reflectors are mirrored glasses and reflective films [55]. The optimal size of a heliostat is currently an open research subject, compromising both optical and cost issues [38,53,56–58]. Small heliostats have the advantage of high optical quality, lower shading and blocking in the field, feasible mass production, easily handling and installation and they are associated with smaller wind loads [30,38]. Conversely, large heliostats can raise up concentration ratio, while decreasing their number and control requirements. Nevertheless, they have to suffer higher wind loads [30]. Belaid et al. [59] have recently reported a general analysis of the influence of heliostat shapes in respect to shadowing and blocking effects.

Among current commercial heliostats, some designs can be mentioned like the *CSIRO* one, which is a small heliostat made by a single facet; the Stellio heliostat, with a pentagonal shape for reducing shadowing and blocking; or designs from SENER, eSolar and Abengoa [53]. Other designs that are being researched nowadays comprise a rim drive and a carousel heliostat from DLR, a pitch/roll heliostat from Amrita University, a small sized *EASY* heliostat from IK4-TEKNIKER and CENER, and other two designs from USA National Renewable Energy Laboratory (NREL) and Stellenbosch University. All of these and possibly others constitute the next generation heliostats [53].

Optimal arrangement of heliostats in a field is not trivial; therefore, current research is also focused on looking for optimum optical efficiencies in heliostat fields layouts [60,61]. Nowadays, two different types of field layouts are being researched in SPTs: radial staggered and biomimetic, but some other configurations are also possible [60]. In radial staggered fields, the most common ones, heliostats are placed in circles with some offset with respect to the heliostat immediately in front [30,60]. Nevertheless, cornfield configurations, where heliostats are placed one just directly behind the other, were also tested, like in *Sierra* and *Jülich* projects [30]. More recently, biomimetic layouts have been proposed by Noone et al. [62], in which heliostats follow a spiral pattern. Examples of a radial staggered, both surround and polar, and of a biomimetic layout are shown in Fig. 7.

A major conclusion from Barberena et al. [60] is that similar heliostat field efficiencies are found for different layout generation algorithms if they are optimized. However, for North fields, Zhang et al. [65] found that biomimetic spiral field is associated with a higher efficiency than radial staggered field, but the opposite for circular fields. It can be also highlighted that hybrid layouts combining both methods have a promising potential. The implementation of those methods to large heliostats is already proved, however it is not tested for small ones [60].

Specific software packages are valuable tools that can be used to simulate and analyze heliostat field designs in order to test their performance under different conditions and to generate new field designs focused on certain constraints and objectives. Optical efficiency, annual power output, cost of the produced energy and investment cost are some usual (but non-exclusive) optimization objectives. It is interesting to note that proposing new approximated ways of evaluating the optical performance of heliostat fields is a very active work area. It is specially focused on reducing the computational cost of evaluating shading and blocking relations among heliostats, which is one of the most computational demanding processes. This area has been under development since the first generation of codes appeared at late seventies.

Nowadays, a big amount of software tools for generating, analyzing and optimizing heliostat fields have been or are being developed. Two basic categories can be distinguished: ray tracing software packages, also denominated statistical or Monte-Carlo software, and convolutional methods, called Hermite polynomials expansion methods too [38,53]. In ray tracing software tools, specific and random solar rays are traced from the Sun to the target through heliostat reflection [53]. They are precise analysis tools suitable for computing accurate optical performance of a particular heliostat field [54]. On the other hand, convolutional methods compute solar flux distribution on the target from a mathematical perspective: the convolution of Sun shape together with mirror distribution errors [53]. They are often optimization-orientated tools that give an optimum heliostat field configuration taking into account different objectives as deployment costs or land usage [54]. The main advantage of random ray tracing methods is its lower associated computational time. Convolutional methods were developed before, but now ray tracing is probably dominant [53]. Interpolation methods have been proposed in order to accurately estimate annual field efficiency at real meteorological conditions [66].

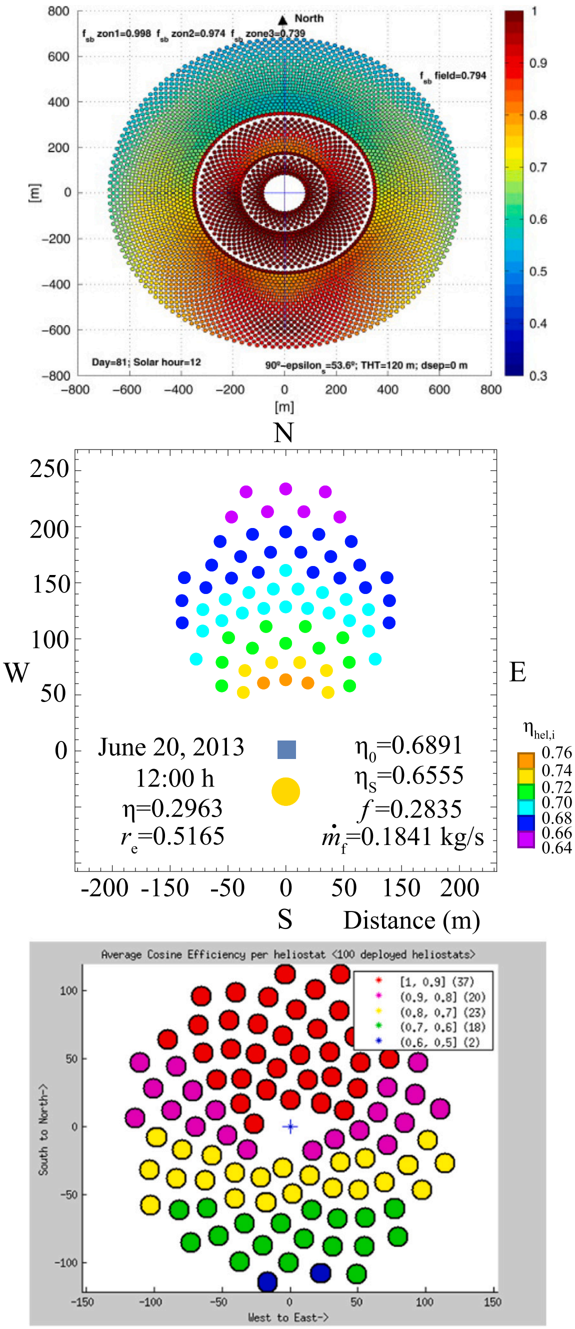


Fig. 7. Examples of a dense radial staggered surround layout from *campo* code by Collado et al. [63] (top), of a radial staggered polar heliostat field by Merchán et al. [64] (middle), and of a biomimetic surround heliostat field from Biomimetic software by Cruz et al. [54] (bottom).

Tonatiuh is a very good example of ray tracing methods. It is open source and it is continuously being improved [54]. Nonetheless, codes like MIRVAL [67], SolTRACE [68], and more recently, SoFiA [69] and SPRAY [70] employ Monte-Carlo ray-tracing methods too [38].

With respect to convolutional methods, *campo* code [71,72] stands out because of its effort in reducing blocking and shadowing calculation time, thus it is employed for quick and precise field optimizations [54]. It is based on the regular radial staggered pattern [73] and tries to improve it, starting by the densest field since losses (except from blocking and shadowing) are small [60]. Then, the field is expanded, so blocking and shadowing are reduced, but the rest of losses grow, until the optimum is achieved [53]. Regarding annual optical efficiency, *campo* code layout and biomimetic pattern presented very similar performance [38,74]. *Campo* code has been also used to estimate the flux over the receiver [75]. Other examples of convolutional methods are DELSOL/winDELSOL [76,77], HFLCAL [78] and UHC/RCELL [38,73]. Algorithmic field optimization may help reduce environmental impacts and required ground leveling work while maximizing output. Larger fields tend to be more circular to limit the maximum receiver heliostat distance and minimize atmospheric attenuation [1].

Coupling between heliostat field and solar receiver is a key factor in SPTs. Multi-aiming strategies are a good alternative in order to not surpass receiver technical limits, as it can happen in single aiming [79]. Regarding this issue, several techniques have been presented, like the novel method developed by Sánchez González for receiver aiming based on the allowable flux density limit [79]. Hu et al. [80] have recently presented a deep analysis on solar flux distribution in solar towers. A new methodology for estimating the yearly averaged flux on the receiver is due to Cruz et al. [81].

3.2. Solar receivers

Many efforts have been devoted to solar receivers design and optimization since receivers are the key component that links heliostat field and power conversion cycle [39,82]. Innovative receiver concepts have been proposed, operating at high temperatures with the aim of looking for more efficient receivers [28]. Nevertheless, just a few receiver tests have been fully performed to date in demonstration plants [32], therefore more proof-of-concept tests should be performed under real weather conditions for new designs [83].

Tubular receivers (usually formed by vertical pipes meeting the concentrated solar flux from the heliostats), working both with gas or liquid, are the most common receiver concepts, specially the ones employing liquid as heat transfer medium [32,39,84]. In fact, tubular liquid receivers constitute the only concept used in large scale commercial plants [39]. In those cases, normally molten salts are employed. Its temperature operating range is relatively narrow since they decompose at temperatures higher than 600 °C and solidify below 220 °C, respectively [34]. Concerning those receivers, innovative fluids have arisen in the last years, namely, fluoride, chloride or carbonate salts [32]. Their performance as working fluids have still to be tested [32,85]. The performance of tubular receivers operating with supercritical CO_2 has been investigated in [86]. Other open research area deals with tubes coatings for receivers that could improve their efficiency [82,87].

Alternatively, tubular gas receivers can withstand higher solar fluxes, which is translated to more compact receivers, and are associated with lower metal temperatures and pressure drops, but potentially higher costs [32]. In an illustrative way, Fig. 8 shows a basic scheme of both an external and a cavity tubular receiver [32] and Fig. 9 displays a basic diagram of different tubular receiver concepts: from billboard to cylindrical and cavity [39]. *SOLUGAS* receiver, whose scheme is shown in Fig. 10(a) [36], constitutes a real example of a cavity tubular receiver. Some researchers have developed a new method for the determination of the thermal efficiency of those cavity tubular receivers [88]. Samanes and García-Barberena have developed a detailed model to analyze heat losses and transient behavior of cavity tubular receivers [89].

An advantage that a surrounding heliostat field has over a polar field is a more stable solar field optical efficiency over the course of the day, while a polar heliostat field has a higher noon performance. Hence, employing a surrounding receiver system can allow for an increased optical efficiency of the heliostat field. For large scale plants the polar field becomes unviable, as the distance of the farthest heliostats grows too large for efficient operation [31].

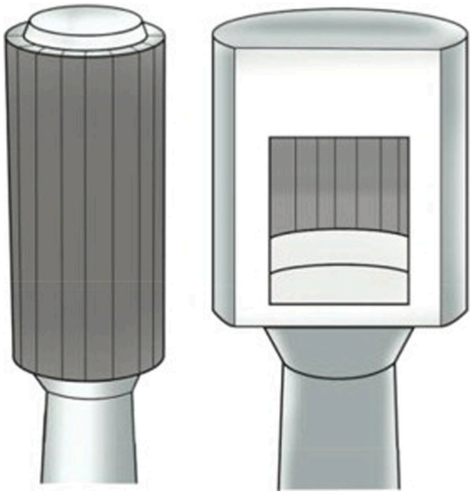


Fig. 8. External (left scheme) and cavity (right scheme) tubular receiver concepts by Ho et al. [32].

Nowadays, the best alternative to tubular receivers are volumetric receivers since volumetric effect (a trap for radiation) lessens thermal radiation and reflection losses and efficiencies higher than 75% can be achieved [31,33,92,93]. In addition, they could be simpler, cheaper and more flexible than tubular designs [33]. Lot of efforts for developing volumetric air receivers that can operate both in atmospheric pressure open cycles and in gas turbines closed cycles with higher pressures have been carried out in Europe and Israel [31,33]. According to Ávila-Marín [33], four kinds of volumetric receivers can be distinguished: open-loop with metallic (*Phoebus-TSA* type) or ceramic absorber (*SOLAIR* type), and closed-loop with metallic (*REFOS* type) or ceramic absorber (*DIAPR* type) volumetric receivers. Those efforts are being devoted because of the key advantages of receivers operating with air, namely, air is a non-toxic fluid with obvious availability and low heat capacity and it allows for highest operating temperatures [32,33]. The use of air could also lead to other advantages: improved absorber durability and efficiency, less potentially unstable flow (because of temperature dependent air properties as viscosity and density) and non-uniform heating, and possible windowed designs for pressurized concepts [32,33]. Those temperature dependent instabilities could be reduced if low-porosity absorber materials are employed [32]. Moreover, the usage of graded porosity materials for air volumetric absorbers has been demonstrated to have potential for reducing costs [94]. A recent review by Ávila et al. [95] summarizes modeling strategies for porous materials as solar receivers.

The design of a solar receiver depends on the heliostat field layout, its capacity, the HTF and its operating temperature. For instance, Brayton power cycles employ very high temperatures (up to 1350 °C) and are associated with high pressures [31]. Thus, a receiver which transmits effectively the solar heat to the pressurized air with low pressure drops is mandatory [31,96]. Current pressurized air receivers employ a sealed window in order to keep pressure constant, but still have some limitations [31]. In those cases, cavity receivers are proposed since external concepts are related to higher heat losses. State of the art research of those receivers started a few years ago with demonstration projects like *REFOS*, *SOLGATE* or *SOLTREC* [90], whose receiver concepts can be observed at Fig. 10(b). *SOLTREC* receiver was made by a quartz glass window, a SiSiC ceramic foams porous absorber and a second concentrator, allowing to achieve up to 1000 °C [31,90,97].

Moreover, other alternative designs denominated particle receivers comprise small particle air concepts, which can transmit heat to pressurized air for high temperature pressure cycles, and falling solid

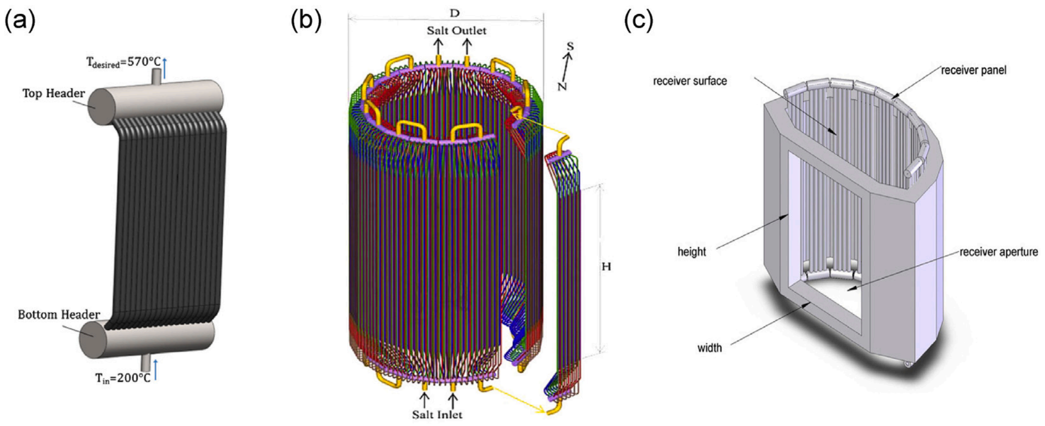


Fig. 9. (a) Billboard, (b) cylindrical, and (c) cavity tubular receiver concepts by Conroy et al. [39].

particle receivers [32]. A recent review on the field is due to Jiang et al. [34]. A similar concept, but regarding liquid receivers, has been proposed: falling film receivers that account for gravity-driven fluid motion [32,91]. Falling solid particle receivers work with solid particles that fall meanwhile are being heated by solar radiation. Once these particles are heated, they can be stored for transmitting the energy to the power cycle [98]. This is illustrated by Fig. 10(c), which shows a scheme of a free falling solid particle receiver [91]. Reached temperatures are above 1000 °C, temperature differences can be of hundreds of degrees and higher concentration ratios than in tubular concepts could be achieved and so, higher thermal efficiencies and lower costs [34,98].

As commented by Mahian et al. [99,100] solar collectors are a particular kind of heat exchangers that transform solar radiation energy into internal energy of the heat transfer medium. Nanofluid-based solar collectors are being investigated from at least two viewpoints: the efficiency in the energy transfer process and from economical and environmental aspects. Hussein [101] defines nanofluids or suspensions of nanoparticles in liquids as mixtures of fluids such as water, oil, ethylene glycol of molten salts with a small amount of solid metallic or metallic oxide nanoparticles or nanotubes. It is considered as a new type of heat transfer fluids in very different applications. Very briefly, among their main advantages it is noteworthy that nanoparticles can increase the thermal conductivity of the suspension and so, improve its heat transfer possibilities. Thermal conductivity and other properties as viscosity, specific heat or density can be modified by changing mixture concentration. Heat transfer is also enhanced due to the increase in the heat transfer area between the particles and fluids. They also can reduce friction and wear in pipelines and pumps. All these advantages and others, as well as, applications in solar collectors are detailed in the reviews by Hussein [101] and Elsheikh et al. [102].

3.3. Thermodynamic cycles and working fluids

The next generation of high temperature receivers will allow power cycles to work with higher operating temperatures, and so, likely higher efficiency power blocks. This is expected to lead to better overall plant efficiencies and reduced costs. In this search for better efficiency power blocks, Brayton and combined cycles have been proposed and tested to work with several fluids such as air, carbon dioxide or helium and operating in different thermodynamic conditions (subcritical, supercritical and transcritical) for their use in central receiver systems [103]. In addition, different configurations as recompression, recuperation or partial cooling Brayton cycles have also been proposed in the literature. Some of those cycle possibilities are shown in Fig. 11(a) within the framework of a pressure-enthalpy diagram [104].

In order to perform power block simulations, commercial packages as TRNSYS® [105–107], Thermoflex® [108], SAM® (System Advisor Model) [109], SolarPILOT® [110] or Ebsilon® [111] are usually employed. Nevertheless, other possibility is to develop an in-house software, based on a simplified theoretical model, in some programming language with the objective of keeping control on all involved parameters. This strategy allows to discern the most important variables and to perform optimization analysis in a computationally affordable manner [112].

In the next few years actual commercial steam Rankine cycles are intended to be replaced by other innovative configurations. Reyes-Belmonte et al. [114] have proven that an optimized subcritical Rankine cycle working together with a dense particle suspension solar receiver can maximize power plant efficiency, achieving values of 41% for power block efficiency.

Among all CSP types, the most proven technology for hybridization with gas turbine are SPTs [115] and this interest is becoming bigger mainly because of lower water requirements and higher efficiency rates [116]. Madhopa [117] has recently presented a monograph on solar gas turbines. Fig. 6 represents the main blocks of a SPT plant running a simple recuperative hybrid Brayton cycle as an example of a high temperature power block. Another example is represented in Fig. 12 where the thermodynamic cycle is a closed multi-stage Brayton cycle for supercritical carbon dioxide that includes thermal storage and reheating/intercooling between turbines/compressors [118]. The turbines operate at inlet temperatures between 750–850 K. System optimization leads to efficiencies about 21% and maximum power output about 1.6 MW.

Concerning the coupling of SPTs with gas turbine power cycles, several projects have been performed. Most of these experimental plants and prototypes have been developed in Spain during the last decades. Regarding hybrid solar tower gas turbine systems, project *SOLGATE* [119] was the first of a series of quite interesting prototypes in Spain. It was developed between 1999 and 2003 and it showed the technical feasibility of the combination of a pressurized air volumetric solar receiver and a small scale hybrid gas turbine with a combustion chamber [119]. Afterwards, *SOLHYCO* project [120] was carried out from 2006 to 2010. Its main innovation was the cogeneration system based on a micro-turbine (about 100 kWe) that could operate both with varying solar power input and fuel in parallel [120]. Finally, from 2008 to 2014, *SOLUGAS* [121] project was performed for demonstrating the solar tower hybrid gas turbine concept in a larger scale (about 5 MW). Expected efficiency for the open cycle was about 27% at ISO conditions [121]. Although plant operation lasted less time than expected because of different reasons, its novel hybrid gas turbine idea has been the basis of a few quite interesting research works. All those projects have a common interesting outcome: technology is feasible, however, if competitive electricity prices are desired, a longer R&D effort is needed [112].

Taking advantage of *THEMIS* facilities in France, other two interesting projects have been and are being developed at that place. First,

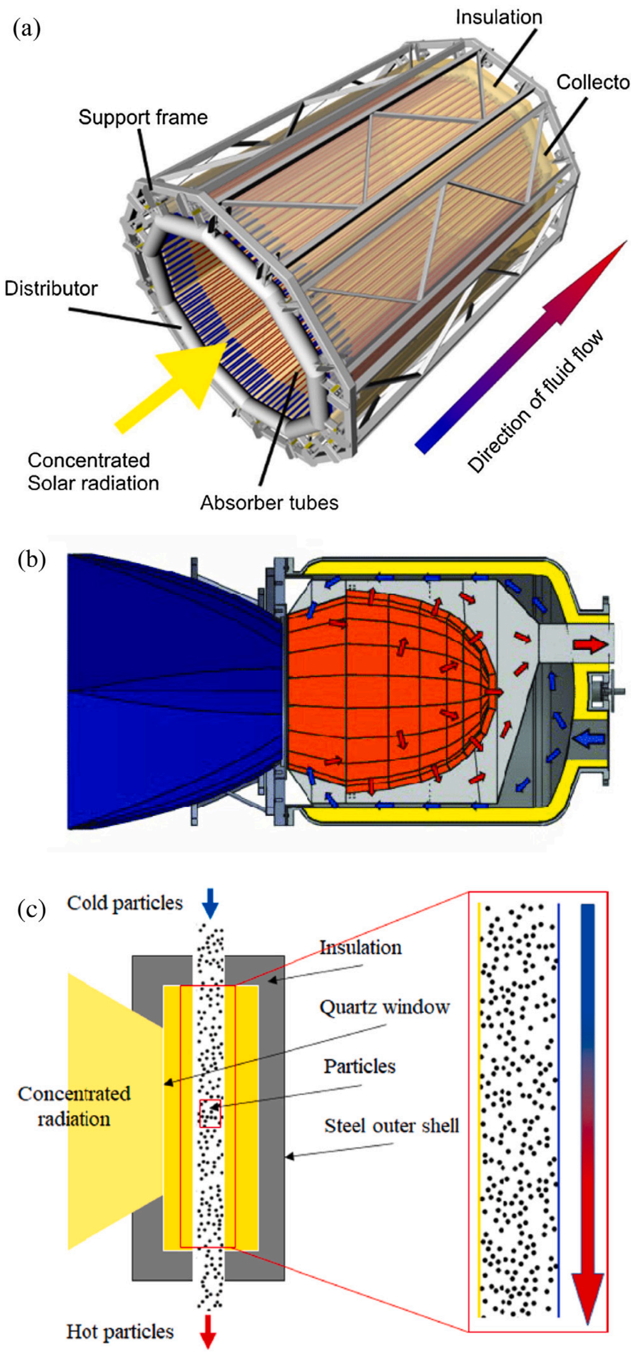


Fig. 10. Schemes of examples of different solar receivers. (a) *SOLUGAS* pressurized air tubular receiver by Korzynietz et al. [36]. (b) *SOLTREC* volumetric air receiver concept by del Río et al. [90]. (c) Solid particle receiver by Wang et al. [91].

French *PEGASE* project (Production of Electricity from Gas and Solar Energy) coupled hot air from a receiver directly to a gas turbine. In this context, a thermodynamic simulation model for a hybrid gas turbine system coupled with thermal energy storage and a metallic cavity receiver was elaborated [107]. The stabilization of the air temperature at the inlet of the combustion chamber thanks to the integration of TES was demonstrated. Solar share was also risen due to the inclusion of TES [107], that allows for a higher and stable electrical production [116]. Thermodynamic efficiencies around 30% are estimated for a simple Brayton cycle [116]. With this objective, an innovative intercooled unfired recuperative closed air Brayton cycle linked to a pressurized air receiver has been proposed [122]. It allows for a flexible electricity dispatch for solar and power demand fluctuations as a result of its pressure regulation system [122]. Afterwards, *NEXT-CSP* European project (high temperature concentrated solar thermal power plant with particle receiver and direct thermal storage) started at 2017. This project aims to integrate a SPT with a tubular receiver, high temperature particles as HTF and storage medium, a fluidized bed heat exchanger able to transfer heat from the particles to pressurized air, and a gas turbine [123].

Gas turbines can operate either in open or closed cycles, so admit different working fluids in closed configurations [124–126]. Other working fluids apart from air have also been proposed for developing Brayton cycles for CSP plants both at supercritical and subcritical conditions. An example of the outcomes from the former studies is depicted in Fig. 13, that shows the necessity to adjust the optimal pressure ratio of the turbine to the selected working fluid.

Probably, supercritical carbon dioxide is one of the most surveyed fluids. A review on supercritical CO_2 (sCO_2) technologies for power generation has been recently published by White et al. [127]. It includes an historical background and the reasons for the renewed interest in sCO_2 for different technologies of power production. It has been demonstrated that CO_2 Brayton cycles are competitive against conventional cycles from efficiency and cost viewpoint [51,128], as recently pointed out by Huixing et al. [129]. In Fig. 11(b), pressure–temperature states of CO_2 are represented together with its critical point beyond which CO_2 behaves as a supercritical fluid [130]. Supercritical carbon dioxide cycles (sCO_2) are expected to improve efficiency of gas turbines SPT systems [2], being able to reach 50% of thermodynamic efficiency [51]. The reason of these higher efficiencies lies in the behavior of CO_2 when compressing it near its critical point. In this case, a fast variation of its properties takes place and compressor power consumption is decreased [51]. Furthermore, sCO_2 Brayton cycles present other advantages, as illustrated by its low molecular leakage, its stability and its non-toxicity. Additionally, CO_2 is an easily available fluid with a low cost too and ambient temperature water could be employed as a coolant [51]. According to [131], sCO_2 has a better potential than subcritical and transcritical CO_2 for closed recuperative Brayton cycles. And it presents also higher potential than helium for Brayton cycles and superheated and supercritical steam cycles in terms of thermal efficiency [132]. Liu et al. [133] showed that higher overall efficiencies are found when CO_2 is employed in Brayton cycles instead of conventional steam Rankine cycles [51]. Furthermore, it has been demonstrated that sCO_2 turbomachinery can deal with short period solar fluctuations [134]. Experimental tests on transient analysis and control developed at Brunel University London have been recently reported by Marchionni et al. [135]. sCO_2 Brayton cycles have been researched from different perspectives, as illustrated by the energy and exergy analysis performed by Atif et al. [51]. From an experimental viewpoint, *Solar Field* (1 + 2) demonstration plant from *CSIRO*, in Australia, is testing supercritical and Brayton receiver cycles concentrating solar heat until temperatures above 1000 °C [39,136]. The effect of real meteorological conditions (particularly the effect of high ambient temperatures) on recompression Brayton cycles with sCO_2 and thermal storage has been investigated by de la Calle et al. [137,138] within Australian *ASTRI* initiative and by Yang et al. [139] in China.

Temperature at the outlet of gas turbines coupled to SPTs are usually very high, thus trying to recover its associated exhaust heat results essential. This can be done by means of a recuperator or/and by coupling a bottoming cycle. The most proven combined cycle configuration is a topping Brayton cycle and a bottoming Rankine one. Besides water, several organic fluids can be employed in the Rankine cycle as R123, toluene, cyclohexane, isobutane or R245fa [140,141]. A combined cycle made up by a helium closed Brayton cycle and two organic Rankine cycles was proposed by Zare et al. [140]. It has been proven that its performance is better than those of Rankine and sCO_2 cycles. The study also demonstrated that solar subsystem parameters

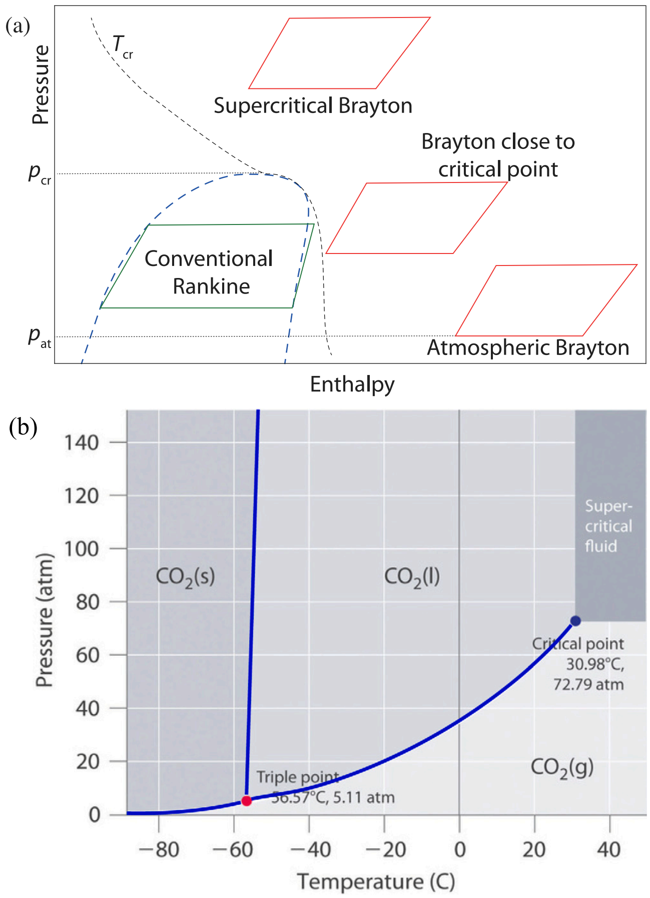


Fig. 11. Samples of power cycles diagrams suitable for SPTs. (a) Generic pressure-enthalpy diagram for different cycles by Muñoz et al. [104]. (b) Pressure–temperature phase diagram for CO_2 [113].

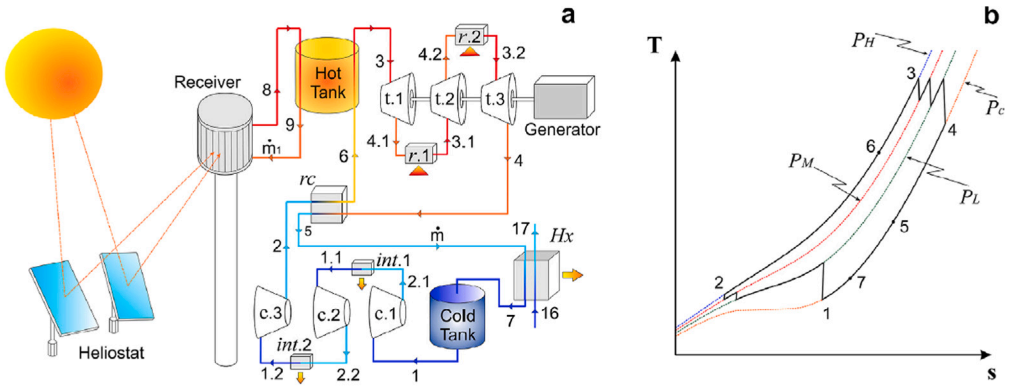


Fig. 12. (a) Scheme of the SPT plant analyzed by Osorio et al. [118] that includes a multi-stage Brayton cycle working with sCO_2 and TES. (b) $T-s$ diagram of the involved Brayton cycle.

are more important than power block parameters referring to the effect on overall performance [140]. At Stellenbosch University, the Stellenbosch University Solar Power Thermodynamic cycle (*SUNSPOT*) was developed. Air is the HTF being heated in a central receiver, then entering a gas turbine, and, finally, a steam turbine [142]. TES is also considered. A hybrid combined cycle plant based on *SUNSPOT* model was simulated in TRNSYS®, concluding that a reliable, stable and bankable tariff structure is a key factor for the development of solar electricity [143]. This kind of combined cycles could raise efficiency and lower cost with respect to single power block systems [31]; namely, thermal efficiency could rise from 30% to 60% [35]. In the case of *SOLUGAS* project, expected efficiency would increase from 27% to 46% ideally by implementing a bottoming cycle [121].

Additionally, combined cycles are related to better start-up and shutdown performance and improved yearly records [35]. Other configurations are also possible. However, at the moment, there are no SPT commercial facilities working with combined cycles due to some technological barriers added to the gas turbines issues themselves [26, 35]. Aspects that need further research are techno-economy of the plant in operation and tower height influence on LCoE [35]. The possibility to use in-cascade sCO_2 upper and bottoming Brayton cycles and sCO_2 Brayton-Rankine cycles have been surveyed by Mohammadi et al. [144] and Yang et al. [145] respectively. A review on the integration of

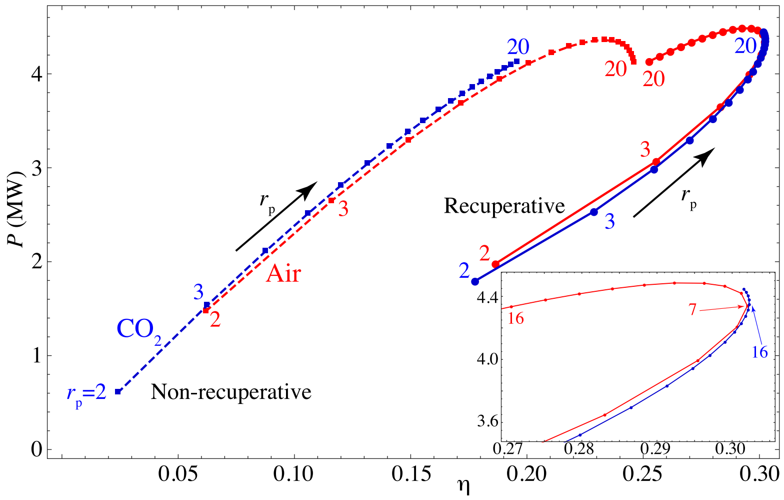


Fig. 13. Parametric curves of overall thermal efficiency (η) and power output (P) with pressure ratio (r_p) as hidden variable for air and carbon dioxide working at subcritical conditions in a hybrid gas turbine linked to a SPT [64]. Numbers refer to the pressure ratios for each fluid leading to those pairs of values for η and P.

different layouts between sCO_2 cycles and molten salts solar towers is due to Wang et al. [146].

3.4. Thermal energy storage and hybridization

With the objective of offsetting solar fluctuations in electric generation, different approaches can be adopted. Hybridization with fossil or renewable fuels and Thermal Energy Storage (TES) can be used separately or combined for producing energy when solar heat is not enough to run the thermodynamic cycle of the power unit [6,147]. To compete with conventional heat-to-power technologies, such as conventional thermal power plants, CSP must meet the electricity demand round the clock even if the sun is not shining. As mentioned by Palacios et al. [50], while PV is nowadays probably more cost-effective and efficient than CSP plants, CSP can supply supplementary energy and provide dispatchable power on-demand by using the heat stored in their integrated thermal energy storage systems (with low CO_2 emissions). It is expected that in the close future CSP technology could yield better economic records than photovoltaic technology, because lower LCoE does not imply in general higher revenue [148].

In general and so far, 45.5% of the operational CSP plants have TES [6]. As it was previously mentioned in Section 1.1, TES and hybridization allow solar power tower plants to work with higher capacity factors and dispatchability than other renewable energies [50]. Additionally, TES improves solar share [50]. The optimal sizing of SPT plants with TES is essential to increase system reliability, to balance investment costs and to reduce final electricity prices [149]. This could be translated into 11.3% of global electricity generated by CSP, from which 9.6% could be associated with solar energy and 1.7% with fuel energy, according to 2010 IEA [7]. Alternatively, the utilization of electric storage by means of batteries is not currently a feasible option for large scale PV or wind plants [50].

3.4.1. Thermal energy storage

Thermal energy storage intends to provide a continuous supply of heat over day and night for power generation, to rectify solar irradiance fluctuations in order to meet demand requirements by storing energy as heat. As a result, TES has been identified as a key enabling technology to increase the current level of solar energy utilization, thus allowing CSP to become highly dispatchable. Thermal energy storage systems for CSP plants have been investigated since the start of XXI century [150,151]. Solar power towers have the potential for storing much more heat than parabolic trough collectors [50]. Nevertheless, some key challenges must be addressed in order to become a real option for storing energy in large power capacity plants with low electricity costs in the near future [50]. Some alternatives to classical temperature limits should be found, allowing the plant to work with temperatures higher than 500 °C that could be translated into higher efficiency cycles [50]. Additionally, long term TES is required for further improving efficiency [6]. A review on materials for TES in the next generation of CSP plants was recently published by Sarvghad et al. [152]. It also includes a summary on the importance of materials requirements at different plants subsystems as receiver, Brayton cycles power units (including sCO_2 cycles) and heat exchangers.

Thermal energy storage systems are usually divided into 3 subgroups: sensible heat, latent heat and thermochemical storage. A comparison from the perspective of technology complexity and storage capacity is performed at Fig. 14, due to Carrillo et al. [153]. Among key desired features for TES systems, low cost, high temperatures able to couple with highly efficient Brayton cycles, stability and high energy density stand out [50,154,155].

Most of commercial plants employ sensible systems which require heating of a storage material (steam, molten salts, packed bed solids, etc.) and containing it in one or several insulated tanks. It is usual to use one tank for the hot medium and another for the cold one, the so-called two tanks configuration. In order to decrease costs, some systems are intended to employ just one tank for both hot and cold storage. In this case, the separation is performed thanks to the different densities (thermocline) [156].

Sensible heat can be stored by means of liquid materials, with a share of 95.6% of overall CSP plants employing it (and 99.8% of installed capacity) [6], especially molten salts, which constitute the most mature TES system [50]. Molten salts are commercially available essentially since they can store high energy density during more than 20 years and 10000 cycles. This technology has a maximum limit temperature of about 560 °C imposed by the molten salts themselves. Although they have been implemented in operational plants, some aspects can be further improved as revealed by operating temperatures, optimization and corrosion, which is currently under study [50]. In order to overcome temperature limits of molten salts, liquid metals could be a feasible alternative in the future, being able to achieve temperatures higher than 1000 °C. However, this technology constitutes the lowest developed TES. Thus, several key issues must be addressed for a promising future. Namely, water reactivity, in particular in the case of liquid sodium, corrosivity and material costs should be coped with for a safety and feasible operation [50]. Other possibility regarding liquid sensible TES consists in adding nanoparticles to molten salts (nanofluids). Those particles increase both thermal conductivity and

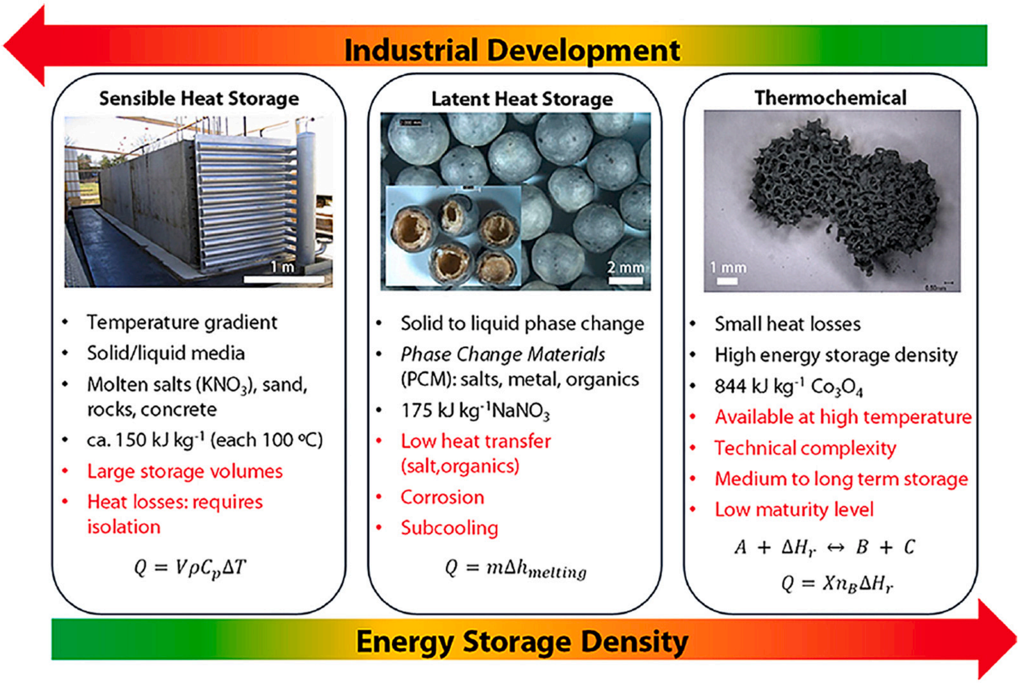


Fig. 14. Schematic representation of the main TES technologies due to Carrillo et al. [153]. The images represent, from left to right, a sensible heat storage concrete module, encapsulated phase change material, and a Co_3O_4-based foam for redox-bases thermochemical heat storage (see details in [153]). Disadvantages of each technology are shown in the items in red.

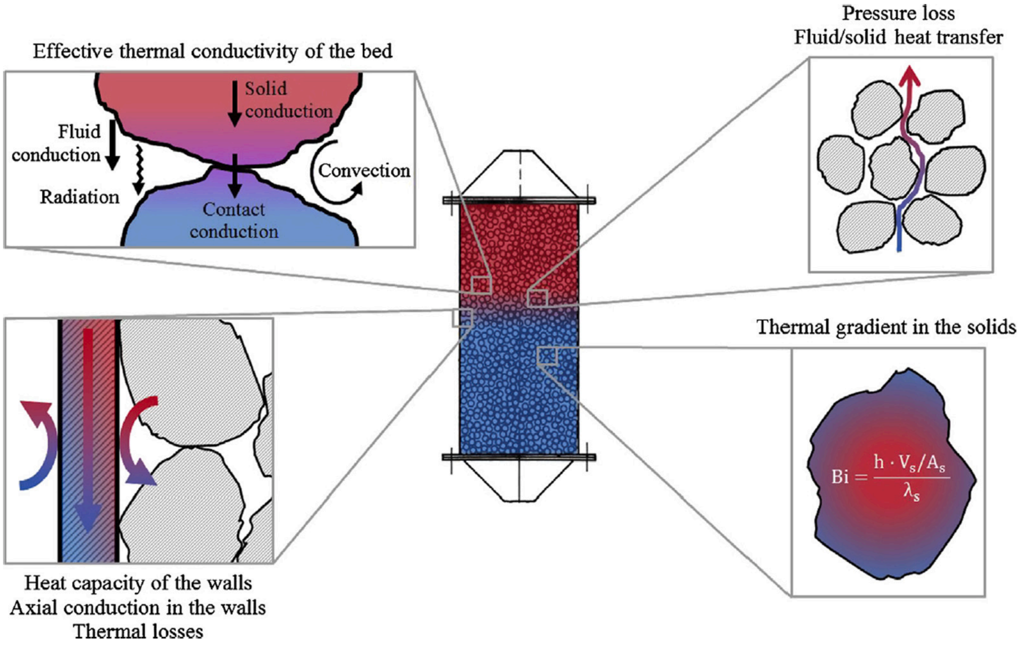


Fig. 15. Scheme of a packed bed TES system by Esence et al. [157] including the main physical phenomena involved in its behavior.

specific heat capacity, which implies higher energy density and lower storage volume [50,158]. On the other hand, viscosity, instability, pumping and material costs are also raised. Therefore, nanofluids are not currently commercially available and need more research [50]. Fernández et al. have summarized diverse possibilities to enhance molten salts capabilities in [5]. The reviews by Hussein [101] and Bhalla and Tyagi [159] summarize diverse applications of nanofluids in solar energy systems. Advantages and drawbacks are explained in detail and particularly possible utility in future CSP plants is stressed.

Nowadays, steam is the only sensible gas state system under research and it is stored as pressurized water [50]. It is commercially available for direct steam generation plants due to its high energy density, but it is attractive just for small scale generation from the economic point of view and there is no a great room for improvement in this area [50,160].

Moreover, sensible heat can be also stored in solid materials as packed bed, concrete and solid particulates [50,157], which represent 4.4% of operational CSP plants, although all of them are demonstration plants [6]. A main feature of packed bed rocks is the possibility of employing air as HTF entering in the porous media for charging and discharging. A basic scheme for understanding packed bed systems performance can be observed at Fig. 15. They stand out thanks to material stability and abundance, and because they can be employed in a large interval of temperatures [50,161]. There are some commercial plants that employ this kind of TES, but there are still some open issues as its stratification problems and some pressure drops that could appear [50]. Other possibilities combine a packed bed with phase change materials (latent heat) for increasing system efficiency [50,156]. A thermo-economic analysis of an air driven supercritical CO_2 Brayton power cycle with packed bed TES has been recently published by Trevisan et al. [162]. Gautam et al. have reviewed the technical and economic aspects of packed bed thermal energy storage systems in [163].

In the same vein, TES in concrete material could be a feasible alternative to molten salts. Within this TES feature, its low cost, its performance at ambient pressure, non-toxicity and easy design can be highlighted. On the other hand, concrete can present some undesired behavior as spalling and cracks or damage of pipes [155,164]. It has been already proved in some installations, but further demonstration tests regarding reliability should be performed [50].

Main advantages of solid particles are their low cost, stability, low thermal losses and high efficiencies at large temperatures [50,165]. Nevertheless, solid particles TES has not been implemented in any commercial facility up to date due to some technical challenges like sedimentation, design of fluidized bed, material stability control and particle conveyance. If those challenges are overcome, solid particulates could become a real alternative to molten salts [50]. An application of TES with particles to a closed Brayton cycle has been recently presented by Rovense et al. [122]

Furthermore, storing latent heat involves phase changes of materials and has the potential for storing about eight times more energy than sensible systems [50,166]. In the same way, technical complexity is not high [50]. Phase Change Materials (PCMs) could be organic or inorganic compounds and mixtures [167]. Currently, most mature latent systems include shell and tube PCM configurations [168]. But other layouts are being researched as cascaded, thermocline and sandwich systems [169,170]. Nevertheless, for latent systems to be commercial there is a necessity for improving high temperature PCM encapsulation and heat transfer, and to perform some parametric and optimization analysis together with pilot tests [50]. Rea et al. [171] have presented a detailed study of a medium size (below 1 MWe) SPT working with an Stirling engine and PCM storage.

Finally, thermochemical systems employ reversible chemical reactions for absorbing (endothermic) and releasing (exothermic) heat with the highest efficiency among mentioned systems. These systems are related to potentially high energy density and could capture atmospheric or industrial CO_2. On the contrary, they are so complex from a technical perspective that, at present times, they are not commercially available [50]. A recent review on TES technologies focused on the wide variety of geometrical configurations that are being surveyed is due to Suresh and Saini [172]. Aydin et al. [173] and Carrillo et al. [153] reviewed the state-of-the art of high temperature thermochemical storage, from a materials perspective.

3.4.2. Hybridization

As CSP plants employ conventional thermodynamic cycles, other energy sources can be integrated, usually, in order to run the same power cycles. Thus, hybrid CSP plants utilize two or more energy sources: usually solar and combustion of a conventional or a renewable fuel, but it could be others [174]. Hybridization could even substitute certain degree of competition among power generation technologies by synergies. These synergies between CSP and other technologies can be light, medium and strong, depending on the degree of solar share and the importance of CSP for the overall performance [174].

During the first stages of CSP development, to hybridize plants, especially with fuels, results essential, as a step forward before the complete deployment of CSP plants, as it has been performed with the automotive industry and hybrid cars. Apart from the already mentioned benefits, other reasons support hybrid plants: to decrease capital and electricity costs and financial and engineering risks, and to enhance reliability and flexibility of operation [27,143,174]. In other words, key desired features of hybridized CSP plants include an increment of efficiency and a decrease of LCoE regarding single plants, larger solar shares and lower emissions than conventional fossil plants [174].

Both coal and natural gas can be employed in CSP plants according to different approaches, but always producing reliable power. Nonetheless, natural gas is preferred since its combustion produces much less CO_2 and other pollutants [174]. Hybridization with natural gas is supposed to be the most promising hybridization technique for CSP [174]. A Solar Hybrid Gas Turbine (SHGT) [115] could currently reach operating temperatures up to 900 °C [176] and it has been demonstrated to be commercially and technically viable [177]. Most common layouts include open cycle gas turbines for peak power generation with efficiencies around 35–40% and combined cycle gas turbines, which account for higher efficiencies, about 55–60% [178]. Some concepts employ both TES and hybridization, as illustrated by the SPT air gas turbine hybridized with natural gas and employing a stone packed bed storage [179]. This system showed that an enhancement of 30% in solar to electric efficiency could be achieved when adding hybridization and comparing to a solar single plant [179]. A technical challenge has to be overcome when hybridizing the gas turbine: the fuel air ratio has to vary in a wide interval that must be accepted by the combustion chamber [116]. Moreover, in hybrid Brayton cycles CO_2 capture mechanisms should be implemented for avoiding combustion penalties [178]. According to Peterseim et al. [180], SPTs seem to be the preferred option for high temperature systems among hybrid CSP plants. Some already mentioned interesting projects include *SOLGATE* [119], *SOLHYCO* [120], *SOLUGAS* [121] and *HYGATE* [181], which proved that hybrid solar tower gas turbine systems are a feasible technology that requires more R&D for decreasing electricity prices [112].

Going further, fossil fuels can be replaced by biofuels from several biomass origins (as forestry residues, wood waste or stubble) that add to the already mentioned advantages the fact that generated energy is completely renewable and sustainable [174]. Those carbon-neutral fuels are still expensive to be feasible [178]. As interesting concept, the *HYSOL* project [182], a gas turbine hybridized with bio-derived gas, which is fully renewable, can be highlighted. Peterseim et al. [183] investigated the potential of some regions in Australia for CSP hybrid plants of 5–60 MWe using forestry residues, bagasse, stubble, wood waste and refuse derived fuels. It was concluded that the potential of this technology could be significant. Pantaleo et al. [184] have performed a thermo-economic analysis and a profitability assessment of the novel hybrid CSP-biomass combined heat and power plant for flexible generation.

Hybrid SPT plants could comprise not only fossil or renewable fuels, but also solar PV [27]. In some concepts, during solar hours, these former hybrid systems generate energy from PV and store energy to TES and then, during non-solar hours, TES is employed for generating electricity. Others employ CSP for cooling PV, which generates the electricity [174]. An interesting concept combining a hybrid SPT and PV facility together with both TES and large scale battery storage has been analyzed and it was concluded that a very big reduction (around 60–90%) of battery storage cost is needed for its integration in the hybrid plant to be feasible [19,175]. Fig. 16 summarizes this concept and some particular results. A recent project funded by European Union (SOLARSCO2OL) intends to check the viability of new technologies combining a central tower, molten salts storage, a gas turbine running with supercritical CO_2 and hybridization with a PV field [185]. Hybridization with geothermal and wind has also been proposed. Geothermal operates with low temperature, thus it has been already integrated into PTC plants, but not into SPTs [174]. Wind hybridization with CSP is not so common and normally they are only linked at grid level, improving demand fit [174].

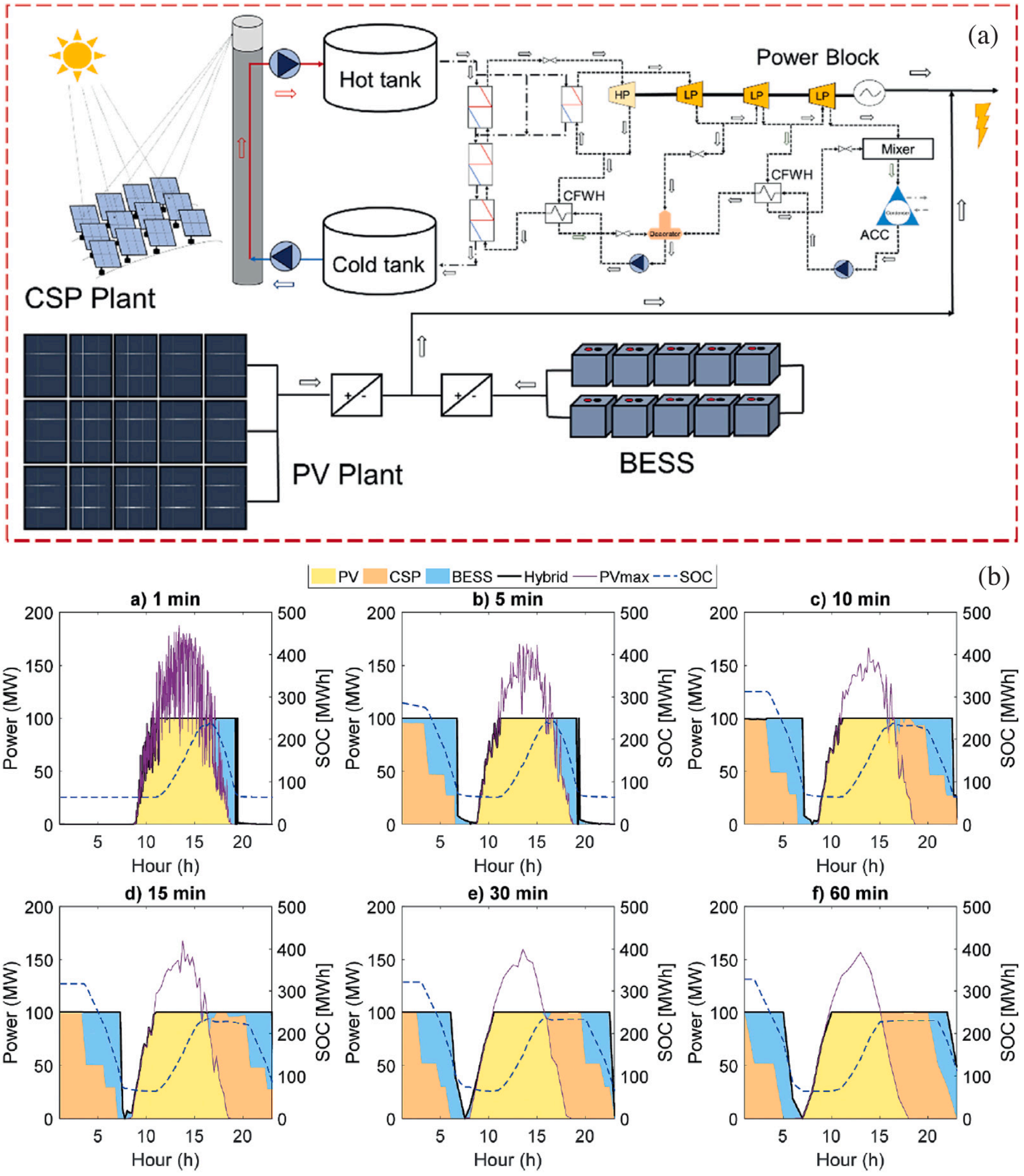


Fig. 16. Advanced CSP-PV hybridization concept by Zurita et al. [19]. (a) A SPT plant running a Rankine cycle with molten salts storage is coupled to a PV field with a Battery Energy Storage System (BESS). (b) Simulated production profile of the plant at Carrera Pinto (Chile) in a variable winter day for different time steps. DNI is represented by the purple curve (see [19,175] for details).

3.5. Subsystems integration and overall plant optimization

All these prototypes and studies demonstrate that there is a big amount of SPTs research projects with different perspectives. Nonetheless, most of them focus on particular subsystems of the whole Solar Power Tower plants and there are not so much research trying to analyze the overall plant as a whole and giving equal relevance to all subsystems. The importance of this subsystems integration methodology lies in the possibility of determining how certain subsystem parameters can affect other components and global plant performance in order to look for optimum designs [112,116,140]. These global studies can be differentiated in three groups according to the utilization degree of commercial software codes.

From a simulation approach, some studies analyze overall plant behavior detailing subsystems performance, which are all evaluated by means of different commercial software environments. Normally, these are very complex and realistic engineering surveys [52]. Despite being comprehensive and precise; however, this kind of approach has some disadvantages. Namely, these tools work with a big amount of parameters that are hardly managed [186]. In addition, dynamic meteorological data are not easily implemented, so just design point performance is usually evaluated [187]. Nevertheless, Barigozzi et al. [188] could predict dynamic performance of a SPT hybrid gas turbine by employing commercially available software tools. The solar field and the receiver were modeled using TRNSYS® [105,106] and they were coupled to a hybrid gas turbine model implemented in Thermoflex® [108].

A mixture between these former analyses and purely academic methodologies is also carried out in the literature when some components are modeled using commercial software packages and others with the help of in-house tools. This is perfectly illustrated by Behar et al. [52], who modeled a hybrid SPT combined cycle with TES employing different software codes. Although, fluidized bed TES heat exchanger and gas turbine have been studied thanks to different theoretical equations, heliostat field was modeled through SolarPILOT® [110] and linked to receiver geometry employing Solstice [189], a ray-tracing code [52]. This study proposed a complete approach that fills the gap between purely academic approaches and detailed engineering

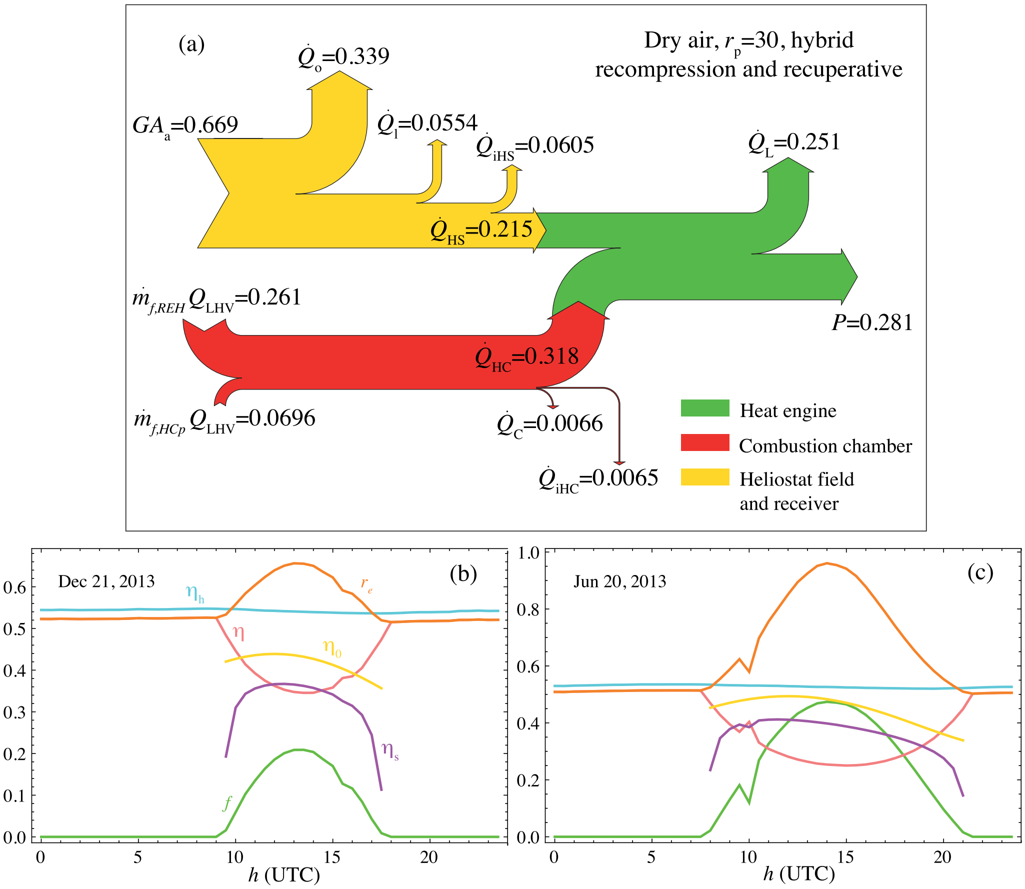


Fig. 17. (a) Simulated energy Sankey diagram of a SPT plant running a hybrid recuperative Brayton cycle with recompression [112] at design point. Total energy input is normalized to unity. Plant subsystems are denoted in different colors. P is the normalized power output and Q_L the heat release from the heat engine to the ambient. (b), (c) Daily and seasonal evolution of subsystems efficiencies: η, overall plant efficiency; η_h, heat engine efficiency; η_s, solar subsystem efficiency (including heliostat field and receiver); η_0, heliostat field efficiency; r_e, fuel conversion rate; and f, solar share. The plant is located at Seville, Spain and two particular days of winter and summer are shown. For details and notation see [112].

developments providing a realistic design tool that integrates comprehensive modeling of each component. Moreover, from the academic point of view, this work establishes a methodology for the analysis of complex solar thermal energy conversion systems that integrate components on the basis of optical, thermal science, and thermodynamic concepts [52]. Moreover, Zare et al. [140] studied an innovative combined cycle from a thermodynamic perspective via Engineering Equation Solver® (EES) [190] and proved that the effect on overall power plant performance of solar subsystem parameters have a larger impact than those of power cycle.

On the other hand and to the best of our knowledge, in-house simulations based on theoretical calculations and that deal with the global plant detailing each subsystem behavior are currently scarce. This other academic methodology presents some benefits, namely, the simplicity and flexibility, the total control of all plant variables, the reduced number of input parameters and the possibility of defining global optimization strategies [186,191]. In this way, Grange et al. [107] have emphasized the importance of models that couple TES with the rest of the plant in order to study the dynamic interaction of storage with other plant subsystems as the combustion chamber in a hybridized scheme. With this goal, they developed a simulation code for the overall plant, which is established via enthalpy, energy and mass balances [116]. Kalathakis et al. [192] have developed a toolbox in an object oriented environment that considers all plant subsystems including heat exchangers. The key importance of the heat engine efficiency in a hybrid SPT plant has been emphasized by Olivenza et al. [193] and Merchán et al. [64,112,187] in several works developed in the framework Mathematica® package. Fig. 17 displays some simulation results on a SPT working under a hybrid recuperative recompression Brayton cycle [112]. Upper panel (Fig. 17(a)) includes a Sankey diagram on energy showing, at design point, the energy inputs in the plant (solar and from the combustion chamber) and the normalized losses in each subsystem. It is noteworthy that the most important losses comes first from the solar subsystem (heliostat field and receiver) and second from the heat engine (heat release imposed by the second principle of thermodynamics). The lower panel (Fig. 17(b) and (c)) shows the hourly evolution of subsystems efficiencies and the overall plant efficiency for two particular days (winter and summer at Seville, Spain) at real meteorological conditions. Further details can be found in [112].

Probably, general thermodynamic models are to be developed first in order to select adequate plant concepts and the optimal intervals for the key parameters of each plant element and then detailed component-to-component simulations are required to solve technical issues and to get to very detailed predictions of plant performance. The optimization of overall plant design is a difficult task provided that plants are constituted by several complex subsystems. Each of them has a large amount of design parameters, that could be someway optimized at fixed design conditions, but are actually affected by sun position, meteorological conditions and other variables. Most optimization analyses are performed at particular design conditions, taking solar irradiance as a fixed parameter. Then, extrapolations for other realistic conditions or yearly averages are done. Design conditions optimization can be done with specific mathematical techniques as multi-variable multi-objective optimization techniques [194,195]. A sensitivity analysis to pre-select the most influential variables is done first and subsequently configurations that optimize the considered figures of merit are found. Objective functions can be purely thermodynamic [196–198] or thermo-economic [199–201]. For instance, Ma et al. [202] have recently presented a superstructure-based method to optimize the design of supercritical carbon dioxide for CSP power systems, including molten salts storage. Mahmoudimehr and Sebghati [203] have applied Dynamic Programming optimization methods in order to optimize the design of a plant with storage, assuming as objective functions the daily electricity generation and the daily revenues from selling electricity. These studies are capable to provide combinations of the most significant plant parameters, although afterwards particular engineering, business strategies, or even political conditions have to be considered for real plants development.

4. Open challenges overview

In this section it is intended to summarize the most relevant open challenges in high temperature SPT technology nowadays. As it has been previously mentioned, optimal heliostats dimensions constitute presently an active research topic in SPTs since a compromise between optical and cost issues is required. With respect to the distribution of heliostat in the fields, most usual heliostat field layouts are radial staggered where room for improvement is not high. However, hybrid layouts mixing radial staggered and biomimetic spiral field have a worthwhile potential. Another research field still open corresponds to innovative methods for calculating and analyzing heliostat field performance with the goal of lowering blocking and shadowing computational costs. Additionally, heliostats aiming to solar receiver strategies are still being investigated with the objective of uniformly distributing solar flux on the receiver.

Nowadays, one of the major active research fields in SPTs are solar receivers. The search for highly efficient solar receivers that can work at high temperatures, for coupling with highly efficient power cycles, is still open. Even tubular receivers, the most common ones, present margin for improvement. In particular, different heat transfer fluids are being tested in tubular liquid concepts. Alternatively, tubular gas receivers can deal with higher solar fluxes. This can be linked to more compact receivers, and lower metal temperatures and pressure drops, although probably higher costs. Different coatings for the tubes are being proposed for increasing their efficiency. On the other hand, volumetric receivers, which constitute the best alternative to tubular receivers, still need to cope with the main challenges related to air as heat transfer fluid. Those challenges are basically to improve absorber durability, efficiency, low heat capacity, potentially unstable flow and non-uniform heating, necessity of heat exchangers for TES, specific cost and windowed design for pressurized concepts. Lot of efforts for developing volumetric air receivers that can both operate in atmospheric pressure open cycles and in gas turbines close cycles with higher pressures are being performed. Furthermore, particle receivers have been proposed as other interesting alternative that still require further investigation. Many design options and materials have been proposed for next generation receivers, but just a few of them have been longly tested at real conditions. Thus, more experimental tests in demonstration plants are required, in particular paying attention to real weather conditions performance.

For power cycles, Rankine ones are highly mature, so room for improvement is scarce and research is focused on subcritical layouts and their application as bottoming cycles for residual heat recovery and supercritical CO_2 Rankine configurations. On the other hand, Brayton cycles can still enhance power plant performance thanks to their higher working temperatures. However, their actual development depends on the search of adequate solar receivers and these cycles still need to be tested. Different layouts and working fluids at different conditions, including supercritical CO_2, are being proposed through models or computer simulations. In the case of sCO_2, turbomachinery should be adequately developed and tested. Additionally, combined cycles are nowadays being researched and face the same challenges as Brayton cycles added to some others as the plant techno-economy in operation, thus there are no running commercial facilities.

The other major open research challenge is the development of efficient and reliable thermal energy storage systems. Lot of challenges must be dealt in order to become a real viable option in which refers to store heat at large scale for SPTs. Temperature limits should be enlarged with the objective of allowing highly efficient power cycles. Besides low costs, stability and high energy density should to be also achieved. Although being the most mature technology, molten salts can still be improved regarding operating temperatures limits, optimization and corrosion. Thus, new mixtures are being looked for with high temperature stability and lower solidification temperatures features. In general, liquid metals and nanofluids need to solve several issues, like material costs and instability, for increasing their maturity level. It deserves a special comment the foreseen importance of nanofluids, both as heat transfer medium in receivers and also as materials for storage. The possible control of parameters such as thermal conductivity, specific heat or viscosity in these fluids is very promising for enhancing the efficiency of collectors and the profitability of TES.

On the contrary, it seems to be scarce room for improvement regarding steam sensible TES. Alternatively, sensible TES with solid materials such as packed bed appears to be promising. It is necessary to cope with stratification issues and pressure drops. However, solid particulates are not going to be commercially available until some challenges as sedimentation and stability could be addressed. The same applies for concrete: spalling and pipes damage issues for long operation times should be surpassed. Regarding latent TES, high temperature phase change materials encapsulations and heat transfer have to be dealt with. Lastly, thermochemical storage has to face technical complexity as its main handicap.

Regarding SPT fuel hybrid plants probably its main advantage lies on their conceptual simplicity. Hybridization is easily integrated in existing fossil fuel plants. A wide interval variation of the fuel air ratio that must be accepted by the combustion chamber constitutes one of their main technical challenges as well as to minimize emissions. Additionally, diminishing electricity prices results also essential for commercial deployment. From this viewpoint, hybrid plants burning biofuels are still expensive. In addition, integration of both TES and hybrid technologies should be explored in order to get a flexible, reliable and ecological electricity dispatch. More experimental tests, especially for gas turbines coupled with high efficiency receivers working in hybrid mode and with TES, are required for SPTs further development.

From the methodological viewpoint, studies coupling all plant subsystems and analyzing how they are affected among them or how they influence overall plant parameters are still scarce from simulations perspective. Therefore, theoretical studies and simulations for global plant and particular subsystem behavior are still mandatory for evaluating intra- and inter-influence of all subsystems and the effect of the coupling of those subsystems. In addition, optimization of overall plant performance could lead to the expected and required efficiency improvement and costs reduction.

5. Conclusions

As concluding remarks from this review it can be said that on the whole, it is clear that there is still margin for innovation in concentrated solar power plants, particularly solar power towers. As quoted by del Río et al. [8] stable and reliable power production, deployment support, and expected decrease of electricity costs are the main factors that make CSP a future alternative among other renewable energies. Nevertheless, current higher electricity costs of CSP regarding other more conventional technologies and unsure policies are still a big handicap for its development.

All the issues commented above make solar power towers, among other concentrated solar power technologies, a promising technology with commercial possibilities in the mid term. Better performance and cheaper electricity compared with other options seems within reach. Levelized cost of electricity and other economic indicators are decreasing more rapidly than for other concentrated solar, paving the way towards its full availability among cost-effective and clean ways to produce electricity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Financial support from University of Salamanca and Banco Santander, Spain is acknowledged.

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