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Concentrating Solar Thermal Technologies – Status, Cost and Research Trends

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1. Abstract

This article presents an overview of the status of CST technologies, their cost, and their future trends. The information regarding the trends in CST technologies is based on the informed opinion of the authors, many of which have decades of experience in the CST field in academia and industry. Thus, it does not pretend to be an exhaustive list of all lines of research and commercial innovations being explored around the world, but a summary of the lines of research that the institutions and groups that the authors belong to are exploring.

2. Introduction

CST systems are characterized for the direct transformation of solar radiation into useful heat. Once this transformation is carried out, the heat can be:

- Used to drive any high-temperature thermal process of interest, such as a power block for electricity generation, any high-temperature industrial process heat, or any high-temperature chemistry reaction.
- Stored as thermal energy to be used when needed during the day or the night,
- Combined or hybridized with heat from other sources, and either used directly to drive a thermal process, or stored as thermal energy to be used when needed.

Typically, a CST system is composed of the following subsystems:

- Light Collection and Concentration (LCC), in charge of collecting the direct solar radiation and concentrating it on the active surface of the receivers, where the thermal conversion will take place.

- Radiant to Thermal Conversion (RTTC), in charge of transforming the concentrated solar radiation in the active surfaces of the receiver into thermal energy, typically as an enthalpy increase in working fluid that circulates through the receiver.
- Thermal Energy Storage (TES), in charge of storing the thermal energy provided by the RTTC subsystem and by any other potential heat source, such as fossil fuel or biomass.
- Thermal Process (TP), driven by the thermal energy provided either by the RTTC subsystem or by the TES.

Traditionally, the CST systems are classified according to the technology used to collect and concentrate the solar radiation. The main concentrating technologies are: Parabolic Trough (PT), Linear Fresnel (LF), Parabolic Dish (PD), and Solar Tower (ST) [1]. While PT and LF concentrate around a line, PD and ST concentrate around a point, achieving substantially higher concentration ratios and temperatures.

Because of their characteristics, CST system can provide a very large range of energy service options, such as electricity generation, heating and cooling, heat process at high temperatures, solar fuels, and other solar chemistry applications. They can be easily hybridized with other sources of thermal energy and can integrate thermal energy storage. When hybridized with biomass they can provide a continuous 24/7 clean and renewable heat process or electricity production operation. When combined with a TES they can provide the heat for the heat process application or for the delivery of electricity when is most needed or most economically profitable. When deployed with a conventional power block, CST systems deliver dispatchable clean and renewable electricity and provide ancillary services to the grid. Furthermore, since the technical expertise needed to deploy CST systems is available in many countries, there is a high potential for conversion or expansion of existing manufacturing capabilities in a country to serve the CST sector, which in turn, can ensure a high local content of CST projects, and a positive impact on employment, tax revenues and contribution to the GDP.

In countries with appropriate levels of direct solar radiation, CST systems have all the attributes needed to become the backbone of the highly decarbonized energy system of the future. In the electricity sector, CST power plants are fully dispatchable and do not need any conventional backup. They can play any role needed from base-load to peaking plants, and they can provide critical grid stability to increase the penetration of non-dispatchable renewable energy technologies. In the industrial and transport sectors, CST systems can provide process heat, fuel and solar chemistry solutions needed to highly decarbonize these sectors. Thus, because of its excellent value proposition, CST systems are called to play a very significant role in the necessary Energy Transition to a greenhouse-emissions-free, sustainable, and environmentally friendly world energy system from the current fossil-fuel based system, which is damaging the planet in many different aspects and contributing to worsening the Climate Crisis.

This article provides a succinct overview of their status, costs, and trends. The information regarding the research trends in CST technologies is based on the informed opinion of the authors, many of which have decades of experience in the CST field in academia and industry. Thus, it does not pretend to be an exhaustive list of all lines of research and commercial innovations being explored around the world, but a summary of the lines of research that the institutions and groups that the authors belong to are exploring.

3. CSP Status

As indicated in Table 1, there are 119 commercial CST systems in operation worldwide with a total nominal power capacity of 6.8 GW, and a total TES capacity of 27 GWh. Figure 1 presents the deployment of these CST systems, in terms of installed nominal capacity, as a function of time, grouped by technology. While most of the operational plants are of PT technology, there is a clear tendency in recent years towards ST plants.

Table 1. Commercial CST systems currently in operation worldwide (Source: CSP Guru[1]).

Country	Systems	Nominal Power (MW)	TES (MWh)
Spain	50	2,304.90	8,046.00
USA	15	1,726.00	2,636.00
China	15	696.00	6,641.00
Morocco	5	533.00	2,945.00
South Africa	6	500.00	2,315.00
India	6	242.50	0.00
Israel	2	231.00	495.00
United Arab Emirates	2	200.00	1,500.00
Chile	1	110.00	1,925.00
Saudi Arabia	2	93.00	0.00
Kuwait	1	50.00	450.00
Algeria	1	20.00	0.00
Egypt	1	20.00	0.00
Mexico	1	12.00	0.00
France	2	9.30	27.08
Italy	3	6.10	39.31
Denmark	1	5.50	0.00
Thailand	1	5.00	0.00
Australia	2	2.60	3.00
Turkey	1	1.40	4.06
Canada	1	1.10	0.00
Total	**119**	**6,769.40**	**27,026.44**

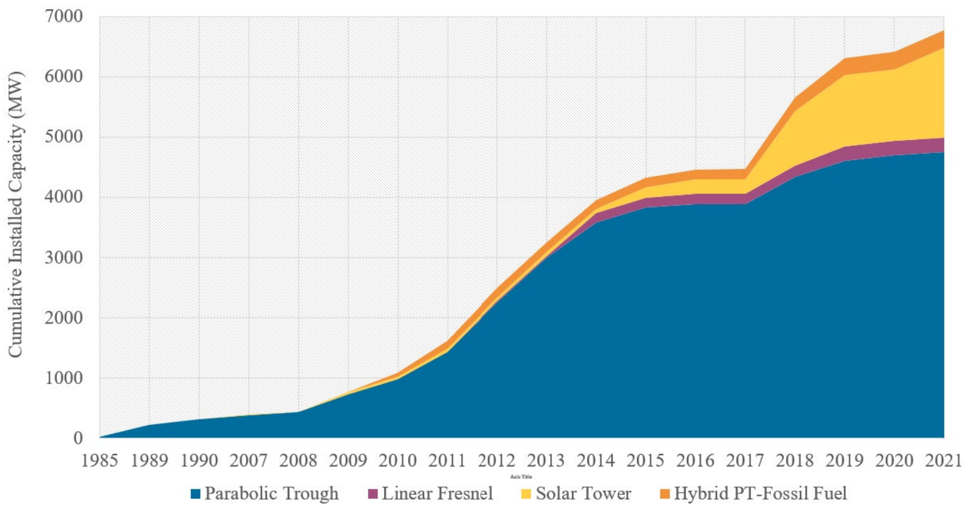

Figure 1. Evolution of the install capacity of CST systems in operation, grouped by technology (Data source: CSP Guru).

[1] https://csp.guru/

Figure 2 shows the temporal evolution of the TES capacity of CST power plants, grouped by technology. Since none of the hybrid PT-fossil fuels plants have storage, this category is not shown in the figure.

A clear trend in recent years is the increase in TES capacity per plant. Currently, the CST power plant with the largest thermal energy storage facility in the world is the Noor Energy 1 plant, formed by a 100 MW solar tower, a field of 600 MW parabolic trough receivers and 250 MW of photovoltaic panels, which is about to enter commercial operation. It has two thermal storages able to keep the solar tower segment operating at its nominal condition of 100 MWe for 15 hours and able to keep the parabolic trough segment operating at its nominal condition of 600 MWe for 11 hours. In terms of equivalent electricity storage capacity, the TES of this plant can store 8.1 GWhe, which is 736 time more than the electricity storage capacity of the TES of the first commercial plant ever entered operation in Europe (the PS10 plant that started operating in Spain in 2007), which has electricity equivalent energy storage capacity of 11 MWhe.

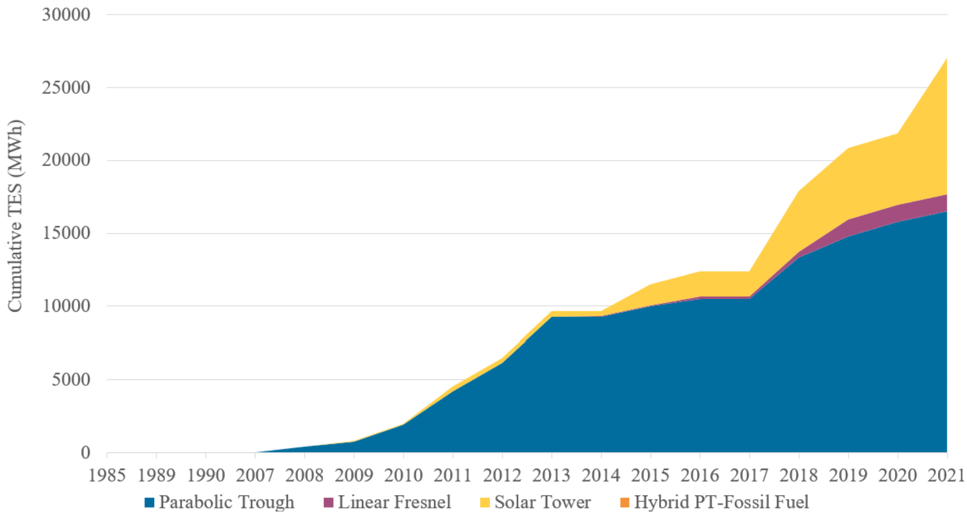

Figure 2. Evolution of the TES capacity of CST systems in operation, grouped by technology (Data source: CSP Guru).

The CST power plant with second biggest storage system in operation – totaling 1.9 GWh – is installed at the Cerro Dominador project in Chile. This plant can generate 110 MW of electricity for up to 17.5 hours from stored heat and together with the co-located 100 MW PV plant. The complex is designed to provide around the clock solar electricity. Because storage increases the utilization of components, especially the power block, the Levelized Cost of CST electricity decreases with larger storage if the load factor increases.

Globally, the accumulated electricity storage capacity of the TES of the CST systems that are either currently operational or expected to be operational within 2022 is 34,48 GWh. This is of the order of five times greater than the worldwide installed capacity of utility-scale battery storage.

4. Cost

As shown in Figure 3, CST technologies experienced dramatic cost reductions in the last decades, equaling or exceeding in percentage terms the cost reductions experienced by PV technologies, even though the installed capacity of CST systems is orders of magnitude smaller than the installed capacity of PV systems.

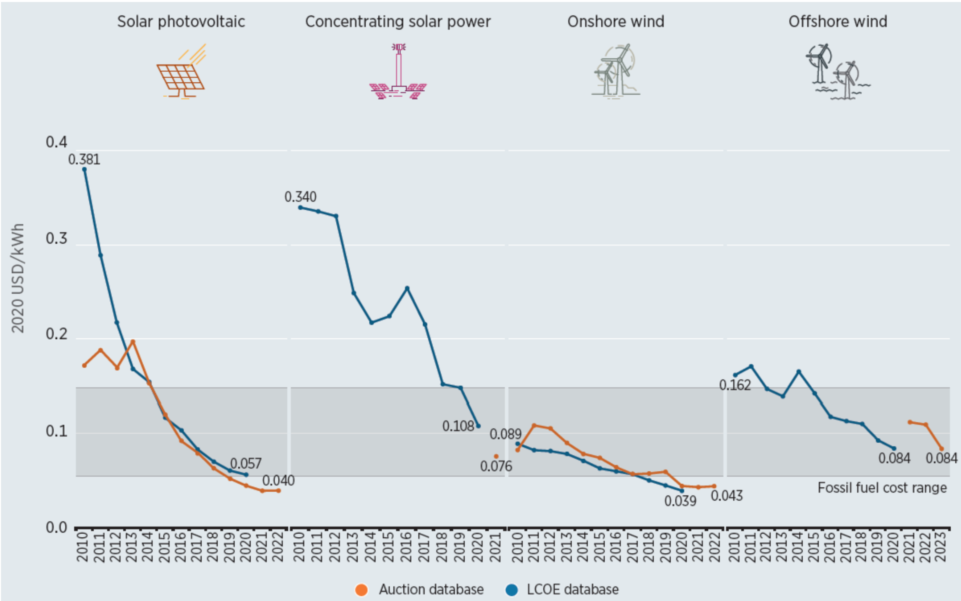

Figure 3. The global weighted-average LCOE and PPA/auction prices for solar PV, onshore wind, offshore wind and CSP, 2010-2023 (Source: IRENA[2])

A DLR study published in December 2020 [2] estimated the LCOE of PT and ST power plants for 2018 and 2030 for all G20 countries, assuming a gross nominal electrical output of the plants of 150 MW and a TES of 7 hours for the 2018 plant configurations and of 10 hours for the 2030 plant configurations and considering the solar field optimized for each country to obtain the minimum LCOE for the latitude and meteorological conditions of the country.

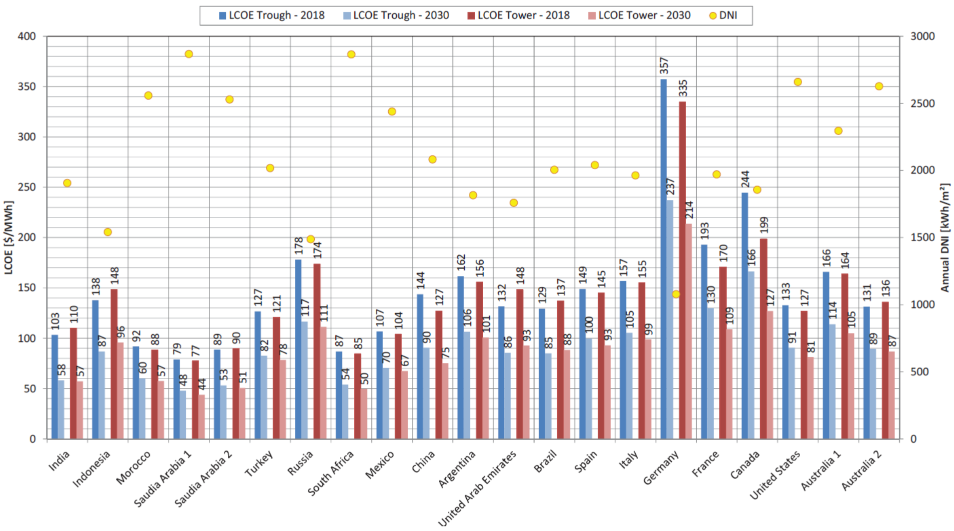

Figure 4. DNI resource and calculated LCOE for all CST power plants in G20 states as well Morocco and UAE sorted by price index (Source: DLR [2]).

The results obtained are presented in Figure 4. This figure shows that for the countries with an Annual DNI equal or greater than 2000 kWh/m^2 the LCOE could vary between 70 and

[2] IRENA Renewable Power Generation Costs in 2020. ISBN 978-92-9260-348-9.

149 $/MWh for 2018, and between 44 and 100 $/MWh for 2030, depending upon the country, the latitude of the location and the annual DNI, with higher DNI resulting in lower LCOEs.

5. Research Trends

Practically, there still substantial room for improvement in almost all aspects, subsystems, and components of all CST technologies. Many research groups around the world are working on instantiating those improvements, in a cost-effective way, to increase the cost-competitiveness of CST technologies. In this page-limited article is, therefore, futile to attempt carrying out a comprehensive review of all research lines of interest being pursuing around the world. Thus, we have limited the scope of this section to briefly summarize in one or two paragraphs a sample of research lines currently being explored by the authors of this article or by other members of their research groups.

ST Receivers. Particle and sodium receivers that can achieve higher temperatures than the traditional molten salt receivers at high thermal efficiencies are high priority research topics. They are needed to enable the integration of ST technology with supercritical CO2 power cycles, and the achievement of temperatures needed to thermally dissociate water and produce green H2 or to decarbonize very relevant and high temperature industrial processes [3],[4]. In relation to the above-mentioned receiver as well as in the case of the molten salt receivers, aside from the need as with any other receiver of optimizing its design coupled with the heliostat field, an adequate material selection is of paramount importance. Recent studies have demonstrated that materials currently used in tubular receivers with solar salt perform very poorly in terms of creep damage if the receiver operates at greater temperatures compatible with the projected third generation of SPT plants (i.e., 700 ºC or above). One way to overcome this problem is the use of functionally graded materials (FGMs) in which both the microstructure and the composition of the material constituents (e.g., ceramics and metals) can be spatially tailored, being useful in those applications where the service conditions vary with location, and therefore the material requirements also vary with it [5]. There is a lack of sufficient knowledge concerning the temperature and thermal stresses of the receiver in real-time for transient and partial load operation (i.e., startup, cloud passing), which leads often to over conservative designs and a relatively inflexible operation of the plant. Filling this knowledge gap is of interest. The integration of a ST Receiver with the TES is another research topic of interest [6]. Such integration may result in maximum thermal coupling with the volume of the storage medium, alleviating operational disadvantages of the traditional two tank CST configurations (e.g., pumping and the associated thermal and pressure losses, salt freezing, thermal fatigue, and thermal shocks under cloud conditions, etc.).

CST-PV Hybridization. The exploitation of the synergies between PV and CST technologies may play a significant role in the transition from fossil fuels to 100% renewable electricity [7]. This hybridization, in which the thermal energy storage of CST power plants is essential, may take different forms, from optimally operated side-by-side PV and CST power plants to the development and integration of hybrid devices that take advantage of the spectral characteristics of PV cells.

CST-centered multi-RES integration and polygeneration systems. Appropriately combining CST with TES along with photovoltaic, wind and battery storage could result in an innovative, polygeneration smart microgrid. Current research is focusing on the optimal integration of the systems at the microgrid scale, on active demand management and on how this integration can be scaled-up and deployed efficiently at large scale. Moreover, the enhanced flexibility of the microgrid enables research on optimally coupling the generation of electricity with other services such as process heat, sea water thermal desalination, high temperature green hydrogen production, etc.

Multi-aiming multi-tower central receiver systems. Current solar thermal (ST) tower technology has a clear limitation in terms of the optical performance of the heliostat field and current commercial plants are approaching these limits. The annual optical efficiency of large solar tower systems is in the 60% to 70% range even for tower heights between 200 and 300 meters[3]. The underlying reason for the relatively low optical efficiency of commercial scale CST tower systems is the concept itself. Current technology is mono-tower and mono-receiver. This means that all heliostats in the heliostat field must aim to the same region of space during the whole day and every day of the year. When this is the case, geometrical optics dictates that cosine, transmissivity and blocking losses will increase with heliostat field size. Higher towers are not expected to substantially improve optical performance [8]. Thus, current mono-tower and mono-receiver solar tower technology is intrinsically limited in their optical performance particularly for large heliostat sizes and, therefore, particularly for large powers. Losing between 30% to 40% of the energy of the direct solar radiation reaching the solar tower system just in the heliostat field, drastically limits the possibilities to substantially increase the cost competitiveness of solar tower technologies in the future. To overcome these limitations and radically improve the optical efficiency of CST tower systems of any size, the current trend is to move to multi-tower systems, in which several tower/receiver subsystems are present and sharing a heliostat field in such a way that, at every instant of time, every heliostat in the heliostat field aims to the receiver that will maximize its instantaneous optical efficiency [9]. This implies that for a multi-tower technology to be technically feasible, multi-aiming heliostats with adaptive optics is required as the key-enabling technology. Adaptive optics heliostats should be able to continuously adapt their focal length and aiming strategy to ensure that, at every instant, all heliostats in the field are maximizing their optical efficiency and, thereby, the optical efficiency of the heliostat field.

Thermal Energy Storage. Thermal energy storage (TES) is a key element for the effective and efficient generation and use of heat collected in the solar field. A specific feature of TES systems is that they are diversified with respect to temperature, power level and use of heat transfer fluids and that each application is characterized by its specific operation parameters. Thus, the availability of a broad portfolio of storage materials and design concepts is a need. Addressing technological gaps to increase the reliability of current molten salt storage systems is another need. In the case of the thermal storage with molten salt, which face the problem of molten salt leaks at the bottom of the hot tank, fundamental studies concerning better configurations and control strategies of the injection of injection of molten salt in the tank through the sparge ring are required to avoid the friction between the tank and its foundation, which causes deformation and salt leakage.

In addition, an interesting research path is related to working in higher energy density storage system based on latent heat. Latent heat storage based on phase change materials (PCMs) results in a promising alternative also for storing heat in new CST power plants with supercritical CO2 cycles. Additionally, the use of a PCM cascade concept has been highlighted as potential low cost and high energy TES systems [10]. Since the latent heat of fusion of a material is on average 2 orders of magnitude larger than the sensible heat capacity across a 100°C temperature change, the material cost of the system drops by the same degree. However, this total cost benefit is not necessarily realized due to the need for increased complexity. As shown in Figure 5, PCM storage under different system configurations has drastically different sensible and latent regimes. This results in higher system costs for non-cascaded systems. The cascade design significantly reduces solar salt inventory (by 50% or more) and in many cases also reduces the tank size versus the hot salt tank of the 2-tank system [11] and the use of PCM further increase the energy density and reduce the tank total volume. This configuration could potentially reach lower capital costs than a two-tank molten salt configuration [12].

3 https://solarpaces.nrel.gov/dewa-csp-tower-project

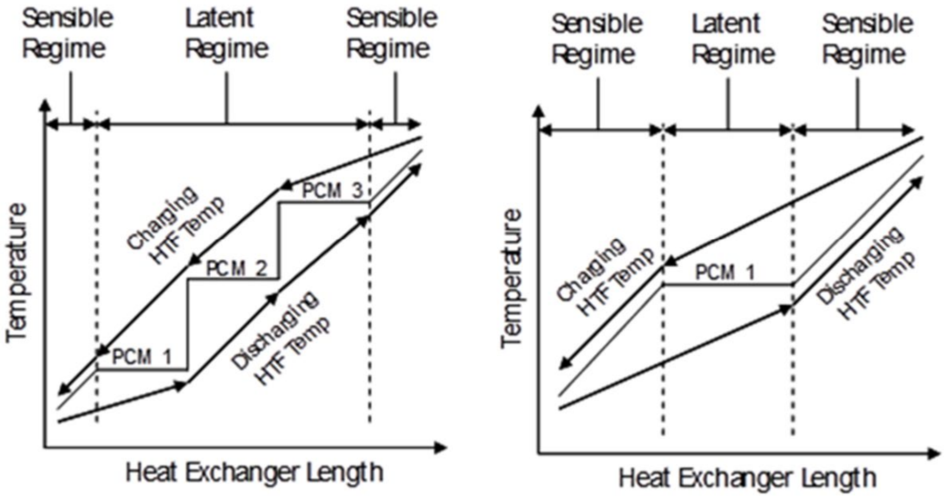

Figure 5. Comparison of 3 PCM cascaded storage system and 1 PCM storage system.

Solar chemistry and fuels. The development of solar driven high temperature processes for thermochemical storage and to produce fuels, including hydrogen, is also essential for the transition towards a decarbonized energy system. Examples of this research line are the projects SOCRATCES[4] and CALGASOL[5]. The first one pursues demonstrate the feasibility and the scale-up capability of the Ca-Looping (CaL) process based upon the reversible carbonation/calcination of CaO for thermochemical energy storage, while the CALGASOL project explores the solar-assisted steam gasification of biomass to produce a H2 enriched-gas, together with a high-concentrated CO2 gas. The proposed concept is based on CaL gasification using CaO-based sorbent assisted by concentrated solar energy.

Automation using unmanned aerial vehicles (UAV) and Artificial Intelligence (AI). Cross-fertilization of current technological developments from sectors other than energy has the potential to unleash significant cost reductions in the operation and maintenance of CST systems. For example, from the aerospace industry, due to the current technological development of UAVs (e.g., drones) the technology has been already employed in various ways in the CST sector, while currently, a significant amount of research is focusing on incorporating the technology to even more applications in the field. Applications include the use of airborne drone-based systems/methods for heliostat field monitoring or for continuous, real-time characterization, assessment, and improvement of the heliostat's field optical behavior as well as characterization of the solar radiant field [13], [14], [15], [16]. Moreover, advanced plant high-end control systems based on the use of AI algorithms for continuous optimization of the economics of the plant operation, could enable the realization of fully autonomous CST systems, with the dramatic cost reductions that this will entail. Among others, these systems could include algorithms for developing advanced plant monitoring and control technologies for achieving optimal plant operation and control while meeting internal and external constraints and inputs from arrays of sensors within the field, the meteorological data and solar resource, etc.

Advanced software development for the integral design and optimization of CST plants. The current state-of-the-art in the design and optimization of CST plants is the use of relatively conventional software tools to design and analyze new types of systems and components, such as Monte Carlo ray tracers to analyze the optical behavior of heliostat field - receiver configurations,

4 SOCRATCES. SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage (SOCRATCES). Horizon 2020. Grant Agreement no.727348.
5 CALGASOL. Plan Estatal 2017-2020 Retos - Proyectos I+D+i. Producción de hidrógeno con captura de CO2 mediante termo-conversión solar de biomasa utilizando transportadores en lecho fluidizado cíclico.

dedicated CFD models to analyze the behavior of specific solar receiver designs, Finite Element Analysis (FEA) for structural design of components, etc. However, available software/tools to assist in the integral design and optimization of CST solar tower systems are yet in a primitive stage. In this context "integral" should be understood as complete and uncompromising. In the case of a CST tower system this translates into trying to optimize the complete set of parameters that define the system, and this set is usually huge. It includes the multiple parameters that define the position, size, and geometry of each one of the heliostats in the heliostat field; the multiple parameters that define the geometry of the receiver, its thermal properties, and its position and orientation with respect to the heliostat field; the multiple parameters that define the characteristics of the thermal energy storage, its relative positioning with respect to the receiver and the power block, etc.; the multiple parameters that define the power block and any other relevant subsystem, and many others. Having this said, the current developments and availability in the field of Artificial Intelligence, High Performance Computing, Semantic technologies, and interoperable Scientific Workflows are offering a very promising pathway from the perspective of integral CST optimization [17].

6. Conclusions

Because of its excellent value proposition, CST systems are called to play a very significant role in the necessary Energy Transition to a greenhouse-emissions-free, sustainable, and environmentally friendly world energy system from the current fossil-fuel based system, which is damaging the planet in many different aspects and contributing to worsening the Climate Crisis.

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For the countries with an Annual DNI equal or greater than 2000 kWh/m^2 a DLR study published in 2020 estimates that the LCOE of CST power plants of 150 MW of gross installed capacity and between 7 and 10 hours of TES could vary between 70 and 149 $/MWh now and between 44 and 100 $/MWh for 2030, depending upon the country, the latitude and the annual DNI.

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