CETP-SRIA Input Paper

Thematic Cluster 1: Renewable Technologies

Concentrated Solar Thermal Energy

Contents

1 Introduction

Heat production using solar energy is based on photo-thermal conversion; the photo-thermal effect is produced by a) photoexcitation due to absorption of solar photons using an optical absorber surface (black surface), b) energy release by photons to the absorber surface (heat production) and c) transfer of the produced heat using a thermodynamic fluid [1]. The photoexcitation can be observed in inorganic materials, such as noble metals and semiconductors, as well as inorganic materials such as carbon-based materials, dyes and conjugated polymers [2]. The efficiency of photon-thermal conversion can be very high (> 60 %). For this reason, this kind of conversion is the most efficient method to convert solar energy into usable energy. Solar collectors are devices that enable efficient photo-thermal conversion by reducing infrared losses. To increase the solar collector efficiency, concentrating collectors such as compound parabolic collectors (CPC), Linear Fresnel Reflector (LFR), Parabolic Trough Collector (PTC), Solar Tower and Solar dish can be used. The optical concentration is crucial because the heat losses are proportional to the absorber area and not to the solar collector aperture. In Concentrating Solar Thermal (CST) technologies, there is a decrease in the absorber area and an increase in the aperture area, allowing an efficient collection of solar light [3]. The CST technologies can reach a concentration factor from 5 to more than 1000. Changing the concentration factor is possible to realise a solar plant that can work at a temperature from 60°C to more than 1000°C. This technological flexibility allows the adaption of CST technologies to several industrial processes, like water desalination, or the emerging green applications related, as example, to solar chemistry and material processing. The use of CST technologies for electricity production, traditionally known with the acronym CSP (Concentrating Solar Power) and more recently with STE (Solar Thermal Electricity) to distinguish between solar concentration for PV plants and solar concentration for solar thermal power plants, have been already tested solutions, relatively cheap and available at high TRL. For these reasons, CSP is among the most important sustainable technologies that can reduce the fossil fuel consumption of processes and their corresponding carbon footprint. Unfortunately, CST technologies are still gathering a slow pace of commercial deployment. In addition, to facilitate the penetration of CST technologies in the industrial and emerging green sectors it is crucial to: i) identify strategic applications for CST energy (e.g. green chemistry, drying, desalination or production of electricity); ii) identify solutions to improve the solar system efficiency; iii) identify solutions to reduce CAPEX and OPEX; iv) identify solutions to increase the durability of the solar plant; v) promote the use of CST systems.

2 Technology status

Technology status of CST technology, for electricity production, can be summarized on Table 1, which indicate the baseline technological characteristics for the currently most common CST systems: parabolic trough and central receivers (also known as solar towers) systems. In 2019, 8150 MW of CSP commercial projects were either in operation or in advanced construction, worldwide. The majority of these projects (around 5840 MW) were related to trough designs, due to being normally considered as most bankable for project financing. Tower projects (around 1890 MW) allow to higher maximum temperature and hence increased efficiency for power generation and thermal heat storage, reason why it could achieve lower electricity costs in locations of low attenuation of the light between the mirrors and the receiver. Linear Fresnel technology, another CST line-focusing system, has much lower commercial deployment (415 MW, also in 2019).

Table 1 Main current characteristics of State-of-the-Art commercial CST technologies [4]

	Parabolic Trough	Central Receiver (Tower)
Receiver	Line absorbers with high absorptivity (>95%) and low emissivity (<10%/400ºC)	Metallic point receivers
Heat Transfer Fluid	Thermal oil at max. 395 ºC	Molten salt or steam; max. working fluid temperatures of 570 ºC
Thermal energy storage	Two-tank molten salt	
Power cycle	Rankine with superheated steam (ORC for small facilities)	Rankine with superheated steam
Capacity factor (2050 DNI location)	27%, or greater with TES	26%, or higher with TES
Land area required	2.4 – 3.2 hectares/MW (direct area, including TES)	
Water consumption	3.5 m^3/MWh (with wet cooling, as for fossil plants) 0.05 m^3/MWh (dry cooling option)	
CO2 footprint	22 gCO_2/kWh	

Besides Tower projects were less common than Parabolic Trough ones, the first have higher efficiency as the temperature of the Heat Transfer Fluid (HTF) is typically also higher (570 ºC against 395 ºC, considering the reference fluids used as HTF in both technologies). Reference Parabolic Trough specifications, considering the existing HTF and TES (Thermal Energy Storage) possibilities are [5, 6, 7]:

- If thermal oil is used as HTF (most common situation), normal temperature is 390 ºC, and the flux on the receiver is about 42 (peak)/25 (mean) kW/m^2. TES hot temperature is 390 ºC, being 290 ºC the cold one (two-tanks nitrate molten salt systems). The standard condenser temperature for heat rejection is 40 ºC.
- If molten salts are used as HTF, the receiver temperature is 500 ºC, with a flux of about 42 (peak)/25 (mean) kW/m2. In this case, the hot and cold storage of TES is 500 ºC and 300 ºC, respectively (two-tanks system).
- If water/steam is used as HTF, a typical receiver temperature is 500 ºC, with the same previous values of solar flux. In this case, there is no commercial TES available.

In the case of Central Receiver projects, typical reference specifications also depend on considered HTF and TES availability, as follows [7, 8]:

- For molten salts as HTF, the receiver temperature is 565 ºC; the peak flux on the receiver is 1,000 kW/m^2 and the typical mean flux around 750 kW/m^2. TES temperatures are 565/290 ºC (hot/cold), and the condenser temperature is 40 ºC.
- In power plants using water/steam as HTF, the typical top temperature is 550 ºC with flux values on the receiver around 600 kW/m2 (peak) and 350 kW/m2 (mean). No TES available in this case.

The weighted average LCOE of these commercial CST plants fell by 47% between 2010 and 2019 [9], with a wide range of options for still widely improving the performance and cost-effectiveness of the technology [10, 11, 12].

3 Ongoing research, expected impact and the challenges addressed

Cost reduction of the energy produced is the main objective of ongoing research in the field of CST technologies. This overall objective is based on three specific challenges:

- Investment cost reduction
- Operation & maintenance cost reduction and
- Efficiency increase

Although significant progress has been achieved during the last two years in the priority R&I activities defined in the Implementation Plan for the CSP SET-Plan (hereinafter referred to as “the IP”), there are still nowadays many innovative ideas for technology improvements and cost reduction. However, stakeholders have pointed out that the significant lack of public funding at European level is slowing down the development of more technology improvements that have been identified, and sometimes even unsuccessfully proposed to the reduced number of public calls for CST technologies.

Some innovative ideas to reduce optical losses in linear Fresnel concentrators are now under development to increase the overall plant efficiency. It is also worth mentioning that commercial plants with linear Fresnel concentrators using molten salts in the receivers have been implemented in Europe (Sicily) and China (Dacheng Dunhuang), thus proving the industrial engagement in this technology. The main challenge at present in the field of linear Fresnel concentrators is the efficiency increase to become more competitive with parabolic trough plants.

Concerning parabolic trough collectors, current research is aimed at using molten salt as heat transfer fluid, thus increasing the solar field nominal temperature and therefore the overall plant efficiency. Novel evacuated collector tubes (ECTs) covered with infrared (IR)-reflectors on the partial area of glass envelope are being investigated to effectively reduce the heat loss and enhance the performance of the receiver tubes. The expected impact is a relative heat loss reduction of up to 43.8%. Intensive testing of the critical components is required to evaluate degradation and failure mechanisms and to develop mitigation measures. This testing will be performed as soon as the required funding is available.

There is also a significant R+D effort in Europe for the use of silicone based heat transfer fluid (HTF) in parabolic trough collectors. A new grade of silicone based HTF was introduced in 2019, with a vapour pressure similar to that of the thermal oil currently used as HTF in commercial parabolic trough plants. Current R+D effort is devoted to evaluate the technical aspects of this new silicone-based oil (i.e. ageing tests, fire tests at small and full scale and hydrogen accumulation, mainly). Non-technical aspects (qualification guideline, market barriers, cost analysis, etc.) are being also investigated.

The main target in the field of open volumetric receivers is a gain in thermal efficiency of more than 3%-points with large commercial receivers (80 – 125 MWth). Together with other improvements, a total receiver efficiency increase from 70% to 85% seems feasible at commercial scale, as well as a significant improvement in load change capability (from 10% to 90% in less than 300 s). Current R&D activities in this field are also devoted to the evaluation of new porous structures that have shown promising results in preliminary tests at lab scale. The detailed design of the receiver and the air duct of a pre-commercial plant of about 10 MWe is well advanced and an alternative design for this plant as a CSP/PV hybrid concept is being developed.

Strong research activity is ongoing concerning solar thermal power plants with the molten-salt central receiver. Improvements to increase the efficiency and safety of the receiver are being investigated, and some of them have been already implemented in commercial plants. The main challenge related to the molten salt receivers is the increase of the solar flux density without jeopardizing their lifetime and reliability. Additionally, innovative receiver designs with a target of a 50% CAPEX reduction for similar performance have been proposed and they are under study. Technical improvements of the molten salt hot tank are also being investigated to avoid the problems found in the first commercial plants. There are also R+D activities related to the steam generator to increase its lifetime and reduce maintenance costs.

The high impact of the atmospheric attenuation on the efficiency of central receiver plants, independently of the working fluid used in the receiver, is motivating ongoing research to develop accurate and reliable measurement systems for atmospheric attenuation. Although outstanding results have been already achieved (a prototype is working on-line efficiently since two years ago in Spain) there are nowadays several R+D groups working on this topic. There is also a significant research effort devoted to improve the operation and maintenance of the heliostat field. Cheaper heliostats provided with a self-calibrating system are being developed in current R+D projects, and they could be commercially available in a short term. The target in this topic is a specific cost of less than to 90 €/m^2. Additionally, to water-less heliostat prototypes currently under evaluation, there are many proposals (i.e., design of sCO_2 cycles, innovative heliostat field lay-out and multi-tower approaches) to accomplish the target of LCOE reductions in the range of 7-12 % for central receiver plants.

Concerning “Pressurized air cycles for high efficiency solar thermal power plants”, only the R&D activities of the current European project POLYPHEM are related to that topic. An advanced pressurized air solar receiver is being developed to drive a Brayton cycle. The project will validate a prototype with a 40 kWe topping Brayton cycle with a stated ending TRL of 5. No other project aligned with this R&I topic has been identified. The use of particles as new heat transfer fluid for high-temperature cycles (>700°C) is studied in the framework of the European Project Next-CSP. Fluidized particles flowing inside a tubular solar receiver are also used as heat storage medium. A 3 MWth solar receiver and associated components (storage tanks, heat exchanger and gas turbine) will be tested in 2020-2021. Open particle receiver demonstration to provide heat and power to pasta manufacturer in Italy in the MW scale is under preparation in the European Project HIFLEX (2021-2022)

Ongoing research activities related to “Beam Down” technology is mainly focussed on the use of dense suspensions of solid particles as direct absorption solar receivers, thus identifying some requirements to select good candidates. It is expected that the implementation of the Yumen Xinneng 50 MW commercial Chinese CSP/STE plant, which is the first large-scale commercial CSP/STE plant in the world using innovative beam-down molten salt tower technology, will boost the R&D effort on Beam Down technology. There are at present several European R&D projects developing several innovations related to thermal storage (SOCRATCES, ProMS, VESUW). Nevertheless, the technical progress so far achieved in this field during the last two years is very limited. A significant R&D effort is being devoted to develop cost-effective thermal storage systems for temperatures greater than 565ºC. Another priority topic in the field of thermal energy storage is the development of phase change materials (PCM) with a melting point in the range 200ºC-300ºC. The efforts devoted to this topic so far have been unsuccessful.

In spite of the great interest that development of specific turbomachinery for the requirements of solar thermal electricity plants has for this sector, a very little R&D effort has been devoted in the last two years. Various turbine manufacturers have showed their interest on developing advanced concepts for improved flexibility of turbines in CSP/STE plants and development of air Brayton turbine combined with sCO_2 systems. However, the lack of public funding to support this effort (no related H2020 call has been issued since the publication of the IP) has been a significant barrier to enable such R&D activities.

4 Technical potential

According to IEA, the historical production of commercial CST technology in 2019 was 15,6 TWh and the organization forecasts a worldwide contribution, in the Sustainable Development Scenario, of 53,8 TWh in 2025 and 183,8 TWh (around 60 GW of installed power) in 2030, from this technology [13]. However, the technical potential of CST, just for electricity production, is much higher; if we also add the capability of provide thermal energy for industrial heat applications, such potential multiply due to the distributed potential contribution and a large number of industrial applications suitable of fitting CST technologies. The yearly world thermal energy consumption of the industrial sector is higher than 23600 TWh, and a significant portion of this energy consumption can be delivered with CST technologies [14], thus increasing their potential.

Thanks to the thermal storage capability, the power generated by CST power plants is fully dispatchable and, therefore, these plants can perform the role of base load and also making possible the penetration of very high rates of renewable electricity in sunny countries (complementing the non-dispatchable technologies like PV and Wind). In Southern Europe the DNI (Direct Normal Irradiation) is around 2000-2100 kWh/m^2/yr, and with these solar values, the technology is fully viable as already has been demonstrated in Spain. In other world locations, with higher DNI values (2400-2600 in North Africa and Middle East countries, 2800-3000 in South African countries, or even 3300 kWh/m^2/yr in Chile), the potential is also significantly higher as the performance and power cost of these plants could be up to a 50 % lower than in the case of European plants.

Another important technical factor that could strongly promote the deployment of CST technology for electricity production in scenarios close to 100% of renewable energy generation, is the necessity of a specific amount of synchronous electricity generation to guarantee system inertia levels above the current critical ones and, as a consequence, sufficient grid stability. Advances in electronics and converters will certainly reduce the current inertia levels limit but the eventual feasibility of full disappearance of synchronous electricity generation from power grids is still unknown [15].

5 Economic potential

Recent estimations provide LCOE values starting from 142 USD/MWh in current CST project development in China (country with the highest current activity in this technology) at locations with DNI above 1,800 kWh/m^2/yr [16]. As the local policies and conditions, added to the climatic ones, could be very different from one country to another. Lowest bidding price for dispatchable CSP power reaches 73 USD/MWh (DEWA project case in Dubai). Up to 2019, around 80% of all worldwide commercial deployment of CST technologies has been made by European companies. Assuming a conservative 50% share in the future developments up to 2030 and the previous estimation of 60 GW worldwide installed to that year, a business market of around 100 billion Euros (considering an average investment of 3-3.5 million Euros per nominal installed MW) to the European CST industry, is estimated.

Besides, it should be noticed that electricity generation by CST technology with thermal energy storage can be more competitive when the comprehensive net costs of these plants are compared to other renewable energy sources, like wind or PV (Net Cost = Levelized Cost of Energy + Transmission Cost + Integration Cost – Energy Benefits – Ancillary Service Benefits – Capacity Benefits) [17]. Typically, in today competitive power markets, the value of energy is determined in advance taking into account that real-time energy imbalances, mainly as a consequence of load forecast errors, constitute only a few percent of total energy market financial settlements. The addition of variable wind and solar production to these markets may increase the quantity of balancing energy transacted in real-time, and possibly the volatility of prices, providing more value to operational flexibility. This is why the energy storage development will be the key element which will probably determine the final contribution of different generation technologies to the grid systems. And this is a unique advantage of CST enabling dispatchable power supply on demand thanks to the integration of low-cost thermal energy storage.

The size of the CST system with storage can be designed to fulfil specific demand profiles, even full load operation for 24h is possible (e. g. Cerro Dominador plant in Chile). With this load-shifting capability, CST is perfectly suited for the delivery of power during the evening, night and morning when PV cannot deliver (much) power. To obtain high shares of renewables even in these time periods, battery storage is the main alternative solution. However, CST can provide this at significantly lower cost, even when predicted cost reductions for both technologies are taken into account. Current cost for thermal storage systems in CST plants are in the range of 20-26 USD/kWh, being in the case of batteries around 350-450 USD/kWh; the expected achievement by 2025 of both technologies is around 16-18 USD/kWh and around 200-325 USD/kWh, respectively (one order of magnitude gap, at least) [18, 19].

To illustrate this difference more clearly, one should keep in mind that just the depreciation[1] of a battery system that costs 300 USD/kWh and is used for one cycle every day equals 82 USD/MWh. This number does not include neither the cost of O&M of the battery system, nor the cost of the renewable electricity and inherent losses of battery system, that adds another 30–50 USD/MWh to the overall electricity cost.

[1] At an annuity rate of 10% that equals 15 years of lifetime at an interest rate of 5,5%

The situation of CSP is particularly favourable for medium and long-term storage capacity. This fact guarantees the economic viability of CST technology for the coming future and its necessity to the achievement of a full decarbonized energy sector by 2050.

Finally, it should be also considered the additional important contribution of CST projects to local inclusive growth, job-creation, manufacturing, construction and rural development, as already demonstrated in countries like South Africa and Morocco.

6 Challenges and the components in the challenges

6.1 Central Receiver plants with lower LCOE

Central receiver solar plants need to reduce their electricity cost (LCOE) to become more competitive with other renewable technologies (i.e., wind and PV) or develop hybrid solutions in combination with other renewables. At present, the most mature technology for commercial plants is based on molten-salt receivers. However, other technologies that are still less developed should not be disregarded and further R+D effort should be devoted to assess their commercial potential. The challenge proposed is not technology-specific, so that any innovative idea related to central receiver technology aimed at reducing the current LCOE would be eligible (e.g. new working fluids, new heliostats, new receiver materials and designs, etc.) without limiting the R+D effort to molten-salt tower technology. Innovative plant field designs (e.g. multi-tower approaches or beam down), volumetric receivers, particle receivers or pressurized receivers would be eligible if the ideas proposed clearly show that they would lead to a LCOE reduction, which is the key overall challenge nowadays.

- Targeted/expected impact from proposed R&I
  - LCOE[2] reduction of tower technology to 0,09 EUR/kWh in Southern Europe locations (without any additional constraint), by 2025, targeting 0,08 EUR/kWh by 2030, providing competitive dispatchable solar power (e. g. during night). These cost targets imply that the industry does not face additional constraint in Europe regarding the size/type of the plant, the financial conditions, a radiation of 2050 kWh/m2/year (conditions in Southern Europe) and within Power Purchase Agreements (PPA) with a duration of 25 years.
  - Solar Rankine cycles with the same efficiency than conventional fossil fuels ones.
  - Feasible commercial solar Brayton cycles validated experimentally.
- Specific challenges to achieve targeted impact
  - Receivers for mean solar fluxes >1MW/m2
  - Receiver thermal efficiencies higher than 85 percent for temperatures above 600 ºC
  - Working fluids with T > 600ºC for Rankine cycles
  - Working fluids with T > 750ºC for unfired Brayton cycles
  - Self-calibrating and cheaper heliostats, below 90 EUR/m2 (installed)

[2] LCOE calculation methodology, assumptions and parameters according to IRENA definitions in the Annex 1 of [26]

- Mirrors with anti-soiling coatings
- High precision heliostat field and automated control for long focal distance and/or high temperature applications up to 1200°C
- Innovative plant configurations achieving better use of solar energy resource and technologies
- High degree of automation of condition monitoring of all relevant plant parameters to optimize O&M, including virtualization of plants, augmented reality and remote supervision.

6.2 Line-focus solar power plants with lower LCOE

Although central receiver solar plants usually have higher efficiencies than line-focus plants in areas with clear-sky conditions, because of their higher temperature and thermodynamic cycle efficiencies, there are many sunny places with a significant atmospheric attenuation where large tower plants are not the best option. The shorter focal length of line-focus concentrators makes these technologies more attractive for sunny places with atmospheric attenuation. Therefore, improvement of line-focus solar power technologies to reduce their costs should be included within the R+D priorities for this sector. The use of working fluids thermally stable at temperatures higher than 425ºC would increase the power block efficiency. Also, the improvement of the environmental footprint of the thermal oils currently used in parabolic trough plants, as well as the LCOE reduction through hybridization concepts, should be eligible within this challenge. There is still margin to reduce the solar field cost and the maintenance effort demanded by some key components at present, like the receiver tubes and the elements used to connect the receiver tubes of adjacent parabolic-trough and linear Fresnel collectors. Any innovative idea clearly showing a good potential for LCOE reduction in line-focus solar power plants would be eligible within this challenge

- Targeted/expected impact from proposed R&I
  - LCOE[2] reduction of line-focusing technology to 0,09 EUR/kWh in Southern Europe locations (without any additional constrain), by 2025, targeting 0,08 EUR/kWh by 2030, providing competitive dispatchable solar power (e. g. during the night). These cost targets imply that the industry does not face additional constraint in Europe regarding the size/type of the plant, the financial conditions, a radiation of 2050 kWh/m2/year (conditions in Southern Europe) and within Power Purchase Agreements (PPA) with a duration of 25 years.
  - Solar Rankine cycles with the same efficiency than conventional fossil fuels ones.

- Specific challenges to achieve targeted impact
  - Advanced heat transfer fluids with lower environmental footprint for working temperatures higher than 450ºC
  - Cheaper collector designs
  - Mirrors with anti-soiling coatings
  - More efficient, cost-effective and reliable receiver tubes
  - More cost-effective and reliable flexible connections
  - Higher degree of automation of plant control by condition monitoring and AI
  - Innovative plant configurations achieving better use of solar energy resource and technologies

6.3 Turbo-machinery developed for specific conditions of solar thermal power plants

Turbine manufactures have pointed out that the use of turbo-machinery specially designed taking into consideration the technical and operational constraints of solar thermal power plants could increase the overall plant efficiency, which in turn would increase the competitiveness of solar thermal power plants. Turbomachinery specially designed for the specifics of highly competitive solar thermal power plants would enable higher overall plant efficiencies, improved operational flexibility and reduced first-time and maintenance costs. The European turbine manufactures must be the key players in the accomplishment of this challenge, because they would also be the main beneficiaries from a commercial stand-point.

- <u>Targeted/expected impact from proposed R&I</u>
  - Increase of 3 points in the overall plant efficiency
  - Improved performance (cycle and turbine efficiency)
  - Improved operational flexibility
  - Reduced first-time, maintenance and service costs
- <u>Specific challenges to achieve targeted impact</u>
  - Optimized steam turbine developed for the specifics of a modern and very competitive CSP with improved efficiency, operational flexibility, as well as reduced first-time and service costs.
    [Note: Although the required steam turbine designs and technologies do exist in principal from large power output generation applications, the development need arises for adopting these to considerably smaller power output ranges in CSP applications (<200MW)].
    - Steam turbine with elevated steam pressures (e.g. supercritical) and high steam temperatures (≥600°C)
    - Compact steam turbine design with thin walled components, lower weight and optimized speed
    - Upgraded steam turbine technologies adopted for the specifics of CSP applications – e.g. advanced 3D airfoils, quasi-hermetic seals, advanced bearings (e.g. magnetic bearings)
    - Robust large last stage blades to maximize efficiency and operational flexibility - e.g. number of starts, steam purity requirements, etc.
    - Cost-effective and oxidation resistant alloys by extending the application of steel to higher temperatures (e.g. up to 650°C)
    - Advanced concepts for improved flexibility in CSP applications using state-of-the-art technologies (e.g. artificial intelligence, machine learning, digitalization)
  - Supercritical CO2 turbine (design, operational concepts, rotordynamics, etc.) for high cycle efficiencies and more compact turbomachinery.

6.4 Reliable and cost-effective medium and high-temperature thermal storage systems

Dispatchability is the main benefit of solar thermal electricity when competing with wind or PV. This dispatchability is provided by the thermal energy storage systems. The working temperature of the storage systems commercially implemented at present in solar thermal power plants is either 390ºC or 565ºC, depending on storage media (diathermic oils/molten salts). This already commercial solution can be improved in terms of energy density storage and cost-effectiveness through innovative storage configurations and the use of combined sensible/latent heat systems. Anyway, the current storage temperatures are not high enough for supercritical steam Rankine cycles or Brayton cycles with supercritical CO2 (sCO2), which would have higher efficiencies. Development of thermal storage systems for T > 600ºC is needed to allow the implementation of supercritical steam Rankine cycles, while thermal storage for T > 750ºC are required for tower plants with a sCO2 or Brayton cycles. The nature and storage medium for these two temperature levels are likely to be different and the technical constraints will be different too, e. g. solid materials promise cost-effective solutions for high temperatures.

Thermal storage systems are also highly relevant to industrial process heat applications as specific developments are needed for different temperature ranges. Specifically, the development of suitable thermal storage systems based on latent heat (phase change materials, PCM) or the enthalpy of reversible chemical reactions (thermochemical energy storage, TCS) have the potential to substantially boost the commercial deployment of these solar systems in the industrial sector, thus contributing to its decarbonisation [20]. Availability of cost-effective and reliable PCM thermal storage systems for the medium temperature range (200-300ºC) would make the use of direct steam generation (DSG) feasible for solar heat industrial process applications, thus contributing to a wider commercial implementation of these solar systems, while improving the environmental footprint due to the replacement of thermal oil by water in the solar field.

- <u>Targeted/expected impact from proposed R&I</u>
  - Feasibility of novel material approaches via validation in lab or demonstration in relevant environment (liquid, solid, PCM or TCS media).
  - More sustainable and environmental friendly novel materials for thermal energy storage
  - Cost-effective sensible-heat thermal energy storage for T>600ºC
- <u>Specific challenges to achieve targeted impact</u>
  - Thermal storage systems and materials for T < 550°C with improved cost effectiveness
  - Suitable thermal storage systems and materials for T > 600ºC
  - Suitable thermal storage systems and materials for T > 750ºC
  - Suitable and cost-effective PCM thermal storage systems and materials for the 200–300ºC range, with investment cost lower than 40 EUR/kWh (thermal) of storage capacity
  - Target for cost of sensible-heat thermal storage system lower than 15 EUR/kWh (thermal) of stored energy for temperatures higher than 600ºC, including heat exchangers.
  - Low cost thermal storage materials, in particular, obtained through a circular economy approach

6.5 Cost-effective and highly autonomous medium- and high temperature systems for industrial solar heat applications

Decarbonisation of the industrial sector is one of the priorities of the EU to achieve a carbon-neutral energy system. Since the industrial sector is responsible for 32% of the total World energy consumption and 74% of the energy consumption in this sector is heat, development and implementation of renewable energy systems to supply thermal energy for industrial heat processes is essential to achieve the objectives of the EU. About 40% of the thermal energy consumption in the industrial sector is within the range 60–300ºC. These systems are often relatively small, which result in the demand for a robust and highly automated system to reduce O&M cost and to increase the efficiency of the solar system for industrial processes. However, the sector still needs the development of highly autonomous solar fields to further reduce maintenance requirements and to increase the amount of thermal energy delivered to the industrial process. Also, significant cost reductions may be additionally achieved by the use of direct steam generation, which has many advantages over the use of thermal oil or pressurized liquid water as working fluid in line-focus solar fields. For high-temperature industrial heat applications with temperatures up to 1000°C the development of suited receiver materials, technologies and autonomous solar fields promise to provide low-cost thermal energy reducing the release of CO_2 significantly to the atmosphere.

- Targeted/expected impact from proposed R&I
  - Application of concentrated solar to industrial processes/synergies of the solar thermal industry. with existing industrial processes achieving a 10% of heat consumed in industrial processes in Europe delivered through concentrated solar technologies, by 2030.
  - Thermal energy cost ≤ 0.03 EUR/kWh (thermal) for temperatures lower than 400ºC, in small scale applications.
  - Thermal energy cost ≤ 0.02 EUR/kWh (thermal) for temperatures higher than 600ºC, in large scale applications.
- Specific challenges to achieve targeted impact
  - Autonomous and smart solar fields, e.g. fail detection software, active & predictive management of the solar plant.
  - Suitable high temperature (600-1000°C) receivers adapted to industrial processes
  - To achieve specific investment cost lower than 400 EUR/m2 of solar collector surface for small line-focus solar fields
  - Materials for increased robustness and durability
  - More reliable and cost-effective receiver tubes (even non-evacuated)
  - Low melting point heat transfer fluids to reduce operating costs
  - Solutions to satisfy 24h operation
  - Development of software tools for predictive design and test a solar plant in an industrial environment
  - Materials and functional materials for increased robustness, efficiency and durability
  - Hybridization by integrating power generation from the produced industrial heat or from waste heat

6.6 Reliable and cost-effective solar fuels production

Concentrated solar energy systems can be employed in the production of “solar fuels” (any chemical compound that can react with oxygen releasing energy), using two possible approaches: in the so-called solar thermochemical processes they can supply high-temperature process heat as the necessary energy source for the performance of endothermic chemical reactions for the production of chemical substances that can be used downstream in the chemical industry for the synthesis of liquid hydrocarbon fuels or ammonia, or stored/transported and used for off-sun electricity production when and where needed.

Alternatively, in electrochemical processes, CST systems with their function as electricity providers can supply (in addition to other renewable sources like photovoltaics or wind power) the renewable electricity for electrolysis of steam; obviously CST systems can provide both the electrical and thermal energy required for a number of hybrid processes which use electricity as well as thermal energy. Up until now, such CST-driven processes for solar fuels production involve reforming and gasification of carbon-containing feedstocks, or thermochemical water/carbon dioxide splitting cycles employing either sulphuric acid (for water splitting only) or redox oxides. With respect to the latter, currently, technical solutions based on reactors without high-temperature moving parts, incorporating the maximum possible redox material quantity per volume and integrating at the time being the most efficient schemes of (only) gas-phase heat recovery, seem to offer the easiest way to scale-up beyond the lab-scale level and significant progress in such solar reactor design has been made. Indeed, the full process value chain from CST-driven syngas production via water and carbon dioxide splitting to liquid hydrocarbon fuels has been shown to be technically feasible at a pilot solar field/reactor level, but nevertheless, no such process has been so far demonstrated at the several hundred kW level and relatively long-term operation.

- Targeted/expected impact from proposed R&I
  - Demonstration of hydrogen production cost potential comparable to that from fossil fuels or alternative RE-based process routes like, e.g. PV/Wind-driven electrolysis (target cost of 3 €/kg H2 by 2030).
  - Demonstration of potential benefits of future CST plants if co-producing electricity and solar fuels as a new business opportunity in the field.
- Specific challenges to achieve targeted impact
  - Solar-to-fuel conversion efficiencies ≥ 15 %, with the integration of heat recovery.
  - Proof-of-concept operation of solar fuels production reactors, comparable to “traditional” chemical industrial plant operation.
  - Materials that can perform reliably at process temperature levels that will not require shift to expensive overall plant infrastructure.
  - Use of materials that do not exhibit toxicity and/or corrosion issues especially under the extreme conditions that many thermochemical cycles require.
  - 1 MW scale demonstrator with at least 500 hours of operation time.
  - Development and construction of custom-made solar fields capable of achieving the high temperatures required on high-efficiency receivers/reactors.

7 Relation to cross-cutting issues

- **Hybridization with other renewable energies for power production**. Efficient and competitive hybridization of solar thermal electricity, especially with PV, bring significant benefits as it can increase the penetration of intermittent renewable energy technologies. This hybridization not necessarily should be at plant level neither at grid connection point; it can also be done at system level. CSP with capabilities of Thermal Energy Storage, decoupling energy capture and power dispatch and displacing production precisely when the resource is not available, can be then used as a complementary solution to overcome intermittency issues of other renewables such as solar Photovoltaic panels (PV) and Wind turbines. Both of these technologies are greatly influenced by the unpredictability and instability of environmental conditions, placing their reliability, as power generation solutions, rather limited. Therefore, PV can generate during the day while CSP is capturing energy to be dispatched at night. However, there are still issues to be solved to optimize this integration to overcome problems such as PV ramp rate control and temperature-decreasing efficiency of PV modules, being therefore needed specific research activities.

Cross cutting topic related to the challenges #1 (Central Receiver plants with lower LCOE) and #2 (Line-focus solar power plants with lower LCOE)

- **Integration into the grid at large scale**. Grid Integration of variable renewable energies is an issue concerning the grid management, and mainly affecting wind, PV and solar thermal electricity. Here is where CSP can provide the most valuable insight. In order to achieve large penetration rates of intermittent renewables, you need both (i) fast-response storage (i.e. batteries to guarantee supply during small gaps) and (ii) massive storage for planned dispatch (i.e. CST). Here targeted support can be provided CSP, for example via auctions for sliding feed-in premium, in accordance with technology- or even site-specific requirements. This can be a useful and cost-effective alternative to high carbon prices. One of the most important features of auctions to facilitate CSP market uptake is that they value dispatchability of electricity generation [21]. This can be achieved by requiring firm power with a specified generation profile which is complementary to fluctuating RES generation which will be mainly characterised by PV in places with rich solar resources. Other possibilities for CSP to receive the right market signals are higher remuneration levels at times of higher demand or a required minimum storage time for RES projects. Research is needed to design these CSP targeted support mechanisms.

  Cross cutting topic related to the challenges #1 (Central Receiver plants with lower LCOE), #2 (Line-focus solar power plants with lower LCOE) and #4 (Reliable and cost-effective medium and high-temperature thermal storage systems)

- **Flexibility provision**. At the policy level, a recent analysis of policy pathways [22] for the energy transition in Europe has shown that, regarding flexibility provision, there are no clear preferences or plans for flexibility provision, in any country or in any corner of the policy space. The main options – increasing dispatchable and carbon-free generation, deploying storage, or reinforcing grids and interconnections – are rarely specified by countries and, when they are, the deployment levels are almost always low. Recently published model-based assessment of the future market uptake of CSP is Europe have shown that CSP could be the fifth largest contributor to RES generation in Europe in 2030, serving as “gap filler” for the system flexibility to the EU power system that would rely on large shares of variable renewables. However, there is a need for dedicated support of CSP in the near to mid future. Therefore, CSP can be part of the solution, but political interest in CSP is weak. A part of the answer may lie on the European level where legal frameworks both for developing flexible technologies and ideas for further integration and cooperation on flexibility exist. Research is needed to evaluate the role that CSP can play in flexibility provision for the European energy union.

  Cross cutting topic related to the challenge #4 (Reliable and cost-effective medium and high-temperature thermal storage systems).

- **Advanced materials:** Innovative, advanced materials to be developed for CST are also of high interest in other technologies. High-temperature applications (CST, Fusion/Fission, high-temperature fuel cells, etc.) require metallic or ceramic materials that withstand the thermal load - often intermittent - over a long period. Some of these applications also operate in harsh climates or environments, i.e. elevated ambient temperatures or dusty or aggressive industrial or desert environments. Others use materials that may harm the surrounding structural materials, e.g. abrasive particles in particle receivers or fluidized bed heat exchangers. Also, innovative and cost effective structural materials need to be developed that are not only of benefit for concentrating solar thermal systems. In recent years there were first research projects developing fibre reinforced concrete of plastics as structural materials. Another area of common interest is on functional materials such as anti-reflective films, anti-soiling coatings for glass covers, solar selective coatings for absorbers (CST, low temperature collectors, PV) or nanostructured materials to enhance thermal conductivity. Metallic, ceramic foams used as high-temperature solar absorbers may also be additionally coated with catalytic substances which are then expanding their usage towards solar chemical reactor technologies for fuel production or towards fuel cell technology. <u>Research is needed to develop innovative structural or functional materials that help to lower cost, increase lifetime and be environmentally sustainable.</u>

  Cross cutting topic related to all indicated challenges.

- **RES cooperation between European countries**. Renewable energy cooperation is expected to play an important role as a way to ensure an effective and affordable low-carbon energy transition in the EU. One of the renewable energy technologies which may benefit from the use of the cooperation mechanisms is concentrated solar power. Recent research has shown that in the absence of RES cooperation support – i.e. when a “High Country Risk” is prevailing in many of the southern European host countries of expected future CSP developments – significantly higher specific support is required. At the aggregated EU level, a clearly positive impact of RES cooperation exists, specifically of the levelling of country risk in the financing, on RES-related support expenditures. This indicates that strong differences in financing conditions across EU countries as we still see them today are less preferential for the decarbonisation of the EU’s electricity sector. In this sense, EU’s RES and CSP cooperation mechanisms are fully consistent with EU’s energy transition and energy integration. Also, recent research [23] has identified the drivers and barriers to the use of cooperation mechanisms for CSP deployment. The most relevant drivers to the use of the cooperation mechanisms for CSP in the future – in descending order of importance- include: the dispatchability nature of CSP, new domestic jobs and industrial opportunities, complementarity with PV and policy ambition (renewable energy targets). Most relevant barriers, also in descending order of importance, are the higher costs of CSP compared to other renewables (on an LCOE basis), heterogeneous regulated energy prices and support schemes, resistance to lose sovereignty over energy market and existing interconnections capacities. <u>Research is needed to address barriers and potentiate drivers in order to materialise these CSP cooperation projects in Europe.</u>

  Cross cutting topic related to all indicated challenges.

- **Sustainability aspects, green growth and job creation**. Recent research [24] has also demonstrated that CSP deployment will create value-added and employment that will be mostly retained in Europe as opposed to investments in PV that will to a large extent be produce outside Europe particularly in China. CSP electricity has also a low environmental footprint. However, it seems that it could originate some social risks in their value chain mostly outside the European Union that should be minimized guaranteeing the social responsibility along the value chain of all the components. Research is needed to improve the sustainability performance of CSP power.

  Cross cutting topic related to all indicated challenges.

8 System level challenges that must be solved to realize the potential

- **Implementation of a European Electricity Market**. This should be based on the interconnection of European grid systems with common management rules and principles. This system-level challenge is somehow associated with the cross-cutting issue of "Integration into the grid at large scale", because such a unified European market would be of significant help for a far greater penetration of renewable energies due to the possibility of electricity transport between distant places, thus achieving better grid stability and more efficient use of power lines. To achieve this goal, current structural electricity market distortions should be removed, and the market transparency should be increased to make possible a fairer introduction of all renewables in the global European context. On top of permitting a high penetration of renewables, the implementation of a unique European electricity market could provide additional gains as high as €3.9 billion/yr, as some authors recently estimate [25].

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