European Commission

LOW CARBON ENERGY OBSERVATORY

SOLAR THERMAL ELECTRICITY
Technology development report

Joint Research Centre

EUR 30501 EN

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FOREWORD ON THE LOW CARBON ENERGY OBSERVATORY

The LCEO is an Administrative Arrangement executed by DG-JRC for DG-RTD, to provide top-class data, analysis and intelligence on developments in low carbon energy technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use of private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind Energy
- Photovoltaics
- Solar Thermal Electricity
- Solar Thermal Heating and Cooling
- Ocean Energy
- Geothermal Energy
- Hydropower
- Heat and Power from Biomass
- Carbon Capture, Utilisation and Storage
- Sustainable advanced biofuels
- Battery Storage
- Advanced Alternative Fuels

In addition, the LCEO monitors future emerging concepts relevant to these technologies.

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. In some cases, external experts are contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main deliverables?

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Report on Synergies for Clean Energy Technologies
- Annual Report on Future and Emerging Technologies (this information is also systematically updated and disseminated on the online FET Database).

Techno-economic modelling results are also made available via dedicated review reports of global energy scenarios and of EU deployment scenarios.

How to access the deliverables

Commission staff can access all reports on the Connected LCEO page. These are restricted to internal distribution as they may contain confidential information and/or assessments intended for in-house use only. Public versions are available on the SETIS website**.**

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Author

Nigel Taylor

1 INTRODUCTION

Solar thermal electric or concentrated solar power plants[1] generate electricity by converting solar energy to heat, which is then used to generate electricity in a thermal power block. When combined with a thermal storage system, STE provides dispatchable, renewable electricity. This can help achieve the EU's energy transition [1 2], support EU jobs and promote economic growth [3].

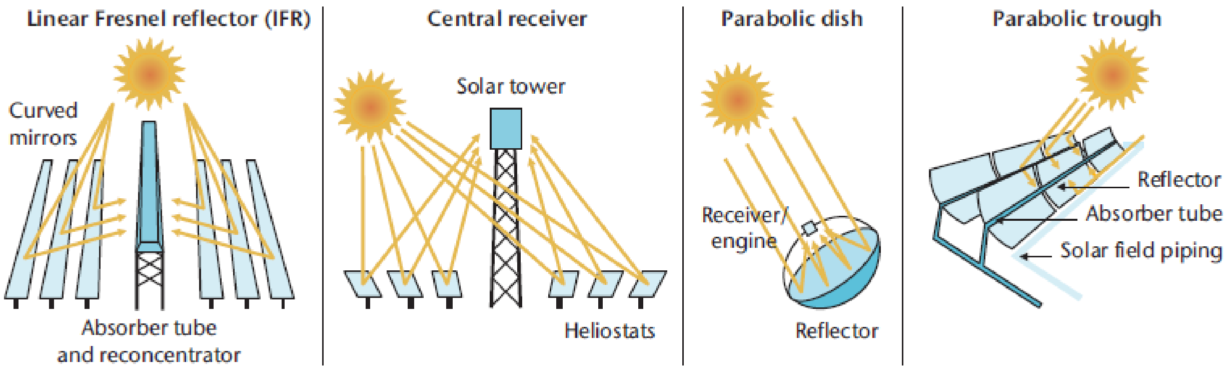
This LCEO Technology Development Report aims to provide an unbiased assessment of development trends, targets and needs, of technological barriers and of techno-economic projections for STE until 2050. Particular attention is given to how EC funded projects are contributing to technology advancements. It follows the structure and methodology set out in the updated LCEO Work Programme (as revised in 2017). It is noted that the 2019 LCEO Technology Market Report [4] covers medium and long-term perspectives for CSP technology markets, highlighting the role of EU stakeholders.

1.1 Main Characteristics of the Technology

Figure 1 shows a schematic of the main design concepts. The two major designs used today are p*arabolic trough* power plants and central receiver or p*ower tower systems*. Both can include a heat storage system, which allows electricity generation in the evening and night. Systems with linear Fresnel receivers (essentially a variation on the power trough concept, but using flat mirror elements to concentrate the light) are also in commercial operation. Systems using a parabolic dish receiver with a Stirling engine are also researched, but there are no plants in commercial operation.

STE systems comprise the following main elements:
- solar field
- receiver or absorber, and heat transfer system
- thermal storage system
- power conversion unit (heat to electricity) and balance of plant.

Figure 1 Main solar thermal electricity generation concepts: most current CSP plants are based on trough technology, but tower technology deployment is increasing and linear Fresnel installations emerging. No parabolic dish systems are in commercial operation



(source IEA [5])

In terms of capital costs, the solar field is presently the largest single element, accounting for about 40% of the total. STE plants are rated in terms of the maximum power output in MW (AC electricity output). The annual load capacity factor for a plant without storage is approximately 27% i.e. 2,300 to 2,400 MWh/yr/MW.

[1] This report uses the term solar thermal electricity (STE) interchangeably with concentrating/ed solar power (CSP). In principle STE also includes non-concentrating solar technologies - the solar chimney (solar updraft tower) is the main example. The term CSP also covers generation of solar heat for industrial processes. Regarding the use of the term concentrat<u>ed</u> or concentrat<u>ing</u>, the SET-Plan uses concentrated while the IEA uses concentrating solar power.

The capacity factor can be increased substantially by increasing, the size of the solar field and adding thermal storage, to allow operation also after sundown.

STE plants require high levels of steady, direct normal insolation (DNI > 1900 kWh/m^2/year). This limits the range of potential locations in the first instance, as shown in Figure 2. Only southernmost Europe offers suitable (but not good) locations. Applying further site exclusion criteria such as land slope > 2.1 % and land cover such as permanent or non-permanent water, forests, swamps, agricultural areas, shifting sands, salt pans, settlements, oil or gas fields, mines, etc., leads to an even more restricted range of potential locations [6]. On the other hand, the available resource is still enormous and points to the possibility for export of electricity from areas with high resource to areas with high electricity demand, or for producing "green" hydrogen by electrolysis..

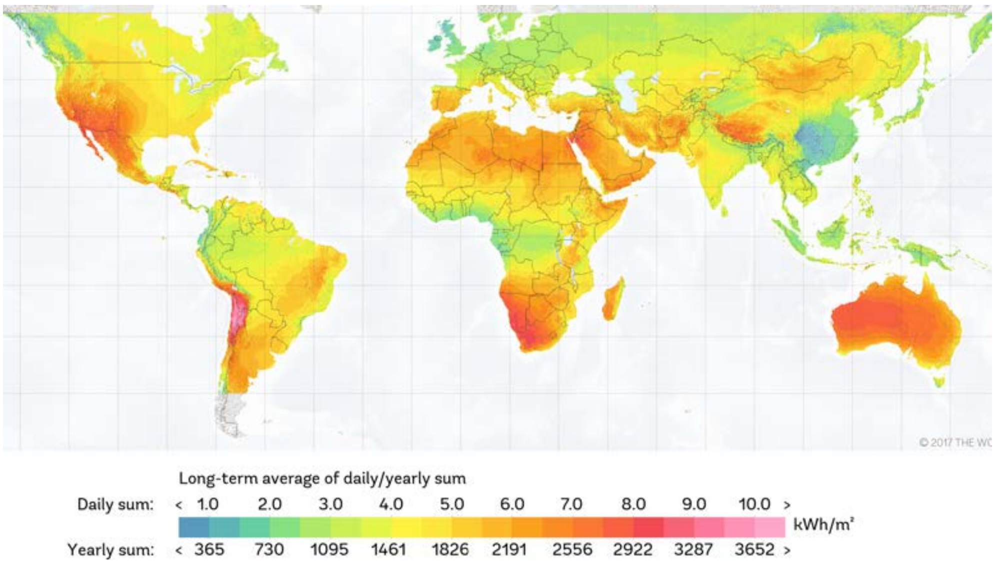
STE can also be combined with other power generation technologies, either for solar-assisted power generation (where the solar heat is used to boost performance of a high-availability fossil plant) or in hybrid configurations. There is a growing interest for plants combining CSP (with substantial storage) with a PV field to generate during sunshine hours and provide power for the plant ancillary power[2] for heat transfer pumps, tracking and control systems etc., a load that amounts to around 5% of rated CSP power. Some prototype CSP and biomass plants are already operating. The use of CSP to support steam raising in conventional fossil plants has also been proposed.

Thermal storage is increasingly the key selling point for STE/CSP technology. The current generation of plants with 150 MWac rating and 10 hours storage effectively offer a storage capacity an order of magnitude above large battery units, and at about 50% less cost per MWh.

Concentrated solar systems can also provide heat for enhanced oil recovery or industrial processes. Fuel synthesis is a further option, as demonstrated by EU supported projects[3] on the feasibility of using concentrated solar radiation for thermochemical splitting of H_2O and CO_2 into hydrogen and carbon monoxide, precursors to kerosene and other liquid fuels.

Finally, an aspect of potential strategic importance is that the locations most favourable for STE are also amongst those for which water supply is either already a major issue or at risk in the future. This offers a role for STE combined with water desalination, although a broad range of cost and environmental factors need to be taken into account [7].

Figure 2 Map of direct normal solar irradiation: CSP needs 1900 kWh/m^2 or more to be viable (effectively the orange/red areas)



(source: © 2017 The World Bank, Solar resource data: Solargis)

[2] In general STE plants include an auxiliary fossil heat source for the heat transfer circuits at night and in early morning, or in periods when there is a lack of solar heat.

[3] See the sites for the FP7 SOLAR-JET Project and its H2020 follow-up SUN-to-LIQUID.

1.2 Market Status

The worldwide capacity of solar thermal electricity plants at the end of 2019 was approximately 5.6 GW, which represents <<1% penetration in the overall electricity market. This corresponds to 83 operational plants in 11 countries. Growth is modest; the annual market has generally been well below 1 GW. Overall, the deployment of this technology remains far behind that of the wind, solar photovoltaics and bioenergy. The IEA tracking report June 2020 [8] notes that CSP produced 15.6 TWh electricity in 2019, below the trend foreseen in its sustainable development scenario.

While Spain and the USA are the traditional deployment leaders, the latest developments are taking place elsewhere, in China, the Middle East, Morocco, South Africa and Chile. There has also been a move to larger plants, >100 MW, which can bring economies of scale and reduced capital costs. Up to now, operating experience with the new generation of large-scale central receiver plants is limited.

Storage systems with capacities to allow full-capacity generation for at least 8 hours after sundown have become an essential part of the STE package. In terms of technology, more than 80% of existing CSP power plants use parabolic trough designs. However, central receiver (power tower) concepts represent approximately half of the projects under construction or in development. Developing a track record for reliable operation of these new larger plant designs is important to reduce financing costs. There is also scope for reduction of construction and commissioning times.

Concerning the value chain, the last five years have seen the emergence of Chinese suppliers, engineering companies and finance houses as major players in the market. Nonetheless European companies continue to play an important role in the latest international developments, both for overall plant engineering as well as for specialised solar field components (Rioglass, Flabeg, TSK Flagsol). Siemens is a major supplier of the steam turbine power block.

Globally the IEA envisages a modest role for CSP in the long-term, with installed capacity rising to 267 GW by 2040 under its sustainable development scenario [9]. The IRENA ReMAP analysis is more ambitious [10], with a 2050 scenario including 633 GW of CSP (contribution 3.7% of electricity generation).

In the EU, the National Energy and Climate Plans submitted by the Member States in 2020 indicate 6.1 GW of new capacity by 2030, with the bulk in Spain[4].

1.3 Methodology and data sources

The methodology for the technology development reports is based on three pillars:

- JRC peer review and expert judgement;
- Monitoring, data compilation; definition and use of indicators, for which the focus is the technology readiness level (TRL) parameter, using the guidelines set out in the 2017 study contract for DG-RTD [11].
- Modelling of long-term deployment trends, using the JRC-EU-TIMES model.

The data sources are divided as follows:

i) R&D projects
ii) Patents statistics, for patents filed on technologies/sub-technologies
iii) Scientific publishing statistics from the JRC's TIM (Tools for Information Monitoring) software
iv) Existing scientific overviews and compilations

[4] NECP values for 2030: Spain, 7.3 GW, Italy 0.88 GW, Greece, 0.1 GW, Cyprus, 0.05 GW, Portugal, 0.3 GW.

2 STATE OF THE ART

2.1 Technology Status

2.1.1 Commercial System Performance

Table 1 sets out the technology characteristics of current commercial STE systems. As mentioned above, parabolic trough designs are the most widely deployed and are considered most bankable for project financing. Nonetheless several recent developments have opted for central receiver designs (also known as or solar towers), which allow a higher maximum temperature and hence increased efficiency for power generation and thermal heat storage. On the other hand, they can be more sensitive to site climatic conditions due to attenuation of the light between the mirrors and the receiver.

Table 1 Main characteristics of commercial parabolic trough (PT) and central receiver (CR) plants (source: 2015 KIC InnoEnergy report [12] and other as indicated).

ITEM	PARABOLIC TROUGH	CENTRAL RECEIVER
Receiver	Line absorbers with high absorptivity (>95%) and low emissivity (<10%);	Metallic point receivers
Heat Transfer Fluid	Thermal oil at max. 395 °C	Molten salt or steam; max. working fluid temperatures of 570 °C
Thermal energy storage	Two-tank molten salt	
Power cycle	Rankine with superheated steam (ORC for smaller facilities)	Rankine with superheated steam
Capacity factor[5] (2050 DNI location)	27%, or greater with TES	26%, or greater 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[6], as for fossil plants)	
CO2 footprint	22 gCO/kW h [13]	

2.1.2 Standards

The IEC/TC 117: "Solar thermal electric plants" was set up in 2011 and currently has 8 working items with publication expected in 2021/2020

- PNW 117-120 Code of solar field performance test for parabolic trough solar thermal power plant
- PNW 117-121 Thermal insulation for solar thermal electric plants
- PNW 117-122 Solar thermal electric plants - Part 4-2: Technology specification for solar field control system of solar tower power plant
- PNW 117-123 Solar thermal electric plants - Part 4-3: Inspection specification for solar field control system of solar tower power plant
- IEC TS 62862-2-1 Solar thermal electric plants - Part 2-1: Thermal energy storage systems - Characterization of active, sensible systems for direct and indirect configurations
- IEC 62862-3-1 Solar thermal electric plants - Part 3-1: General requirements for the design of parabolic trough solar thermal electric plants
- IEC 62862-4-1 Solar thermal electric plants – Part 4-1: General requirements for the design of solar tower plants

[5] since the nominal power output of the generator in a CSP plant is fixed, the capacity factor can be increased by increasing the size of the solar field and adding a thermal storage system, so the power generator can run after sundown; values up to 60% are proposed.

[6] Dry cooling designs can reportedly reduce the water consumption by 90%, but with a 10% cost penalty on the electricity generated due to the higher plant costs and reduced cycle efficiency.

- IEC 62862-5-2 Solar thermal electric plants - Part 5-2: Systems and components - General requirements and test methods for large-size linear Fresnel collectors

From the European side, the Spanish Association for Standardization, Subcommittee CTN 206 / SC117 "Solar thermal electric plants" is particularly active in supporting standards work.

2.1.3 Sustainability

Sustainability should minimise negative environmental impact, conserve energy and natural resources and be economically sound and safe for the community. The IPCC 2011 report cites life cycle carbon emissions 22 gCO2eqv/kWh [13]. A more recent 2017 literature review [14] found that most studies arrive at values well below 40 gCO2eqv/kWh and with an energy payback time of less than 1 year. .A new study for the H2020 PreFlexMS project [15] estimated 24.3 gCO2eqv/kWh for a 100 MW central tower receiver with 8 hours storage in a location with 2,900 $W/m^2/a$. In broad terms, the emission associated with the construction and operation phases are similar. Recycling of materials at end of life was credited with some negative emissions.

The water consumption value in Table 1 assumes wet cooling as in conventional thermal fossil plant. Several H2020 projects address dry cooling and other measures to reduce water consumption. The US Sunshot programme considers dry cooling to be an intrinsic part of its 2030 vision for a high performance and cost effective plant.

It appears that CSP plants do not use (or not significantly) materials from the EU's critical raw materials list [16]. The IPCC report [13] only notes the use of silver for mirrors in the solar field, in relation to materials sustainability.

Regarding the social dimension, IRENA reports that the CSP provides 34,000 jobs, of which approximately 5000 in Europe [17]. More detailed breakdown is not available. However, the PreFlexMS study [15] did address both the distribution of working time in seconds per country and the statistical occurrence of lethal and non-lethal accidents.

No studies have been located so far regarding methodologies for assessing impact of CSP on biodiversity or on the natural environment at production sites. For central receiver plants, in the US some environmental groups raised concerns about the potential impact of the concentrated light beams on wildlife

2.1.4 Technology development options

There are a wide range of options for improving the performance and cost effectiveness of STE plants [5, 12, 18]. Ultimately, higher working fluid temperatures and heat storage density are key. CSP is uniquely placed to provide high input temperatures in the solar receiver, but use of molten salt-based systems seems limited by factors such as corrosion problems with high temperature ternary salts. Hence the interest in various air, supercritical CO2 or liquid metal concepts, coupled with high temperature and economic heat storage methods Gauché et al [19] summarise the issues for future developments at different time scales (Table 2).

Table 2: from P. Gauche' et al – "Near, mid and long term CSP commercialisation map" [19]

Technology area	Near-term (5 year)	Mid-term (5–15 years)	Long-term (15–30 years)
Reflector materials	• Lower lifecycle cost for solar mirrors	• Advanced solar mirrors • Reflector film	• Smart reflector surfaces
Concentrators	• Wireless heliostats • Increase use of sensors and autonomy • Very low cost parabolic trough for molten salt • Modular CSP units	• Resurgence of Linear Fresnel and/or Linear mirrors • Autonomy for most services • Beam down towers	• Micro paraboloid (dish) • Lifecycle autonomy
Receivers	• Selective coatings • Air receivers • Improved experience	• Particle receivers	• Receivers for micro paraboloid concentrators
Storage	• Advanced molten salt • Thermoclines • Concrete (lower temperature) • Target 10+ hours of storage	• Particle storage • Lower cost thermoclines • Initial thermo-chemical • Thermal storage graduates from CSP as renewable system balancing technology • Target 15 h storage	• Thermo-chemical for seasonal storage (fuels) • Target: Transportable fuels enable crossing the diurnal (24 h) cycle
HTF	• Advanced molten salt • Early potential for Sodium and air	• Liquid metals • Particles • Air	
Working fluids	• Air	• Supercritical CO_2	• Some abandonment from direct CSP
Generators	• CSP optimized steam generators for daily thermal cycling, which requires different thinking to conventional power generation	• Breyton and combined cycle • Supercritical CO_2	• "Solid state" (thermoelectric, thermovoltaic, CPV with storage) • Separation from CSP with generation from solar thermal generated fuels
Water consumption	• Improved and optimized dry and hybrid cooling	• Completely "dry" cycles and water reduction for mirror washing	• Continued improvements in reflector washing

2.2 Global and European Research and Innovation Trends

2.2.1 Scientific Publications

Approximately 300 research articles (excluding reviews, books, conference proceedings etc) on CSP/STE are published annually. Figure 3 shows the geographical breakdown in terms of author affiliation for the previous five years (2015 to the present) according to a search[7] performed with the Clarivate Web of Science search tool. It identified 1811 articles, and organisations from EU countries are involved in 47%. The USA is also a leader in this area and there is a significant (and increasing) contribution from China The most prolific organisations include the US DoE, DLR, the Helmholtz Association, CNRS, Chinese Academy of Sciences and the University of Seville. The most frequent topics are thermal heat transfer and thermal storage.

A separate analysis in Scopus of the 20 most cited articles for the same time period found that EU organisations were involved in 40%, the USA in 15%, China in 10% and other countries in 50%. Table 3 shows the top-20 list of papers ranked by number of citations.

Figure 5 looks at the inter-organisation links as evidenced by shared publications using the JRC's Technology Innovation Monitoring Tool. The main clusters are:

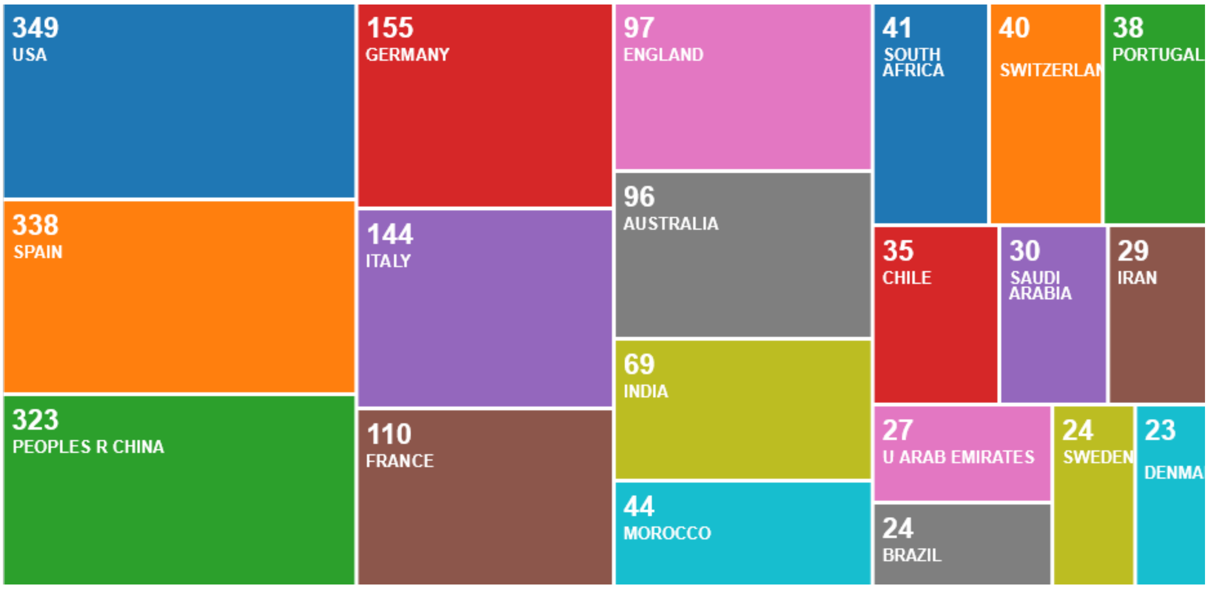
- CIEMAT – DLR, focussed around the Plataforma Solar de Almería[8]
- NREL + others (USA)
- Chinese Academy of Sciences and the North China Electrical Power University
- Xi'an Jiaotong University
- CNRS – U. Perpignan
- Abengoa - U. Lleida – Tecnalia – U. Barcelona + others
- U. Seville – CENER – Abengoa + others

[7] Search string: TOPIC: ("concentrating solar power" OR "concentrated solar power" OR "solar thermal electricity") DOCUMENT TYPES: (ARTICLE); Publication Years 2020 (285), 2019 (392), 2018 (374), 2017 (298), 2016 (261)

[8] Shown as Solar Research in Figure 5. PSA is located in southeastern Spain and is the largest concentrating solar technology R&D centre in the world. It receives a direct annual insolation of more than 1900 kWh/m^2/year.

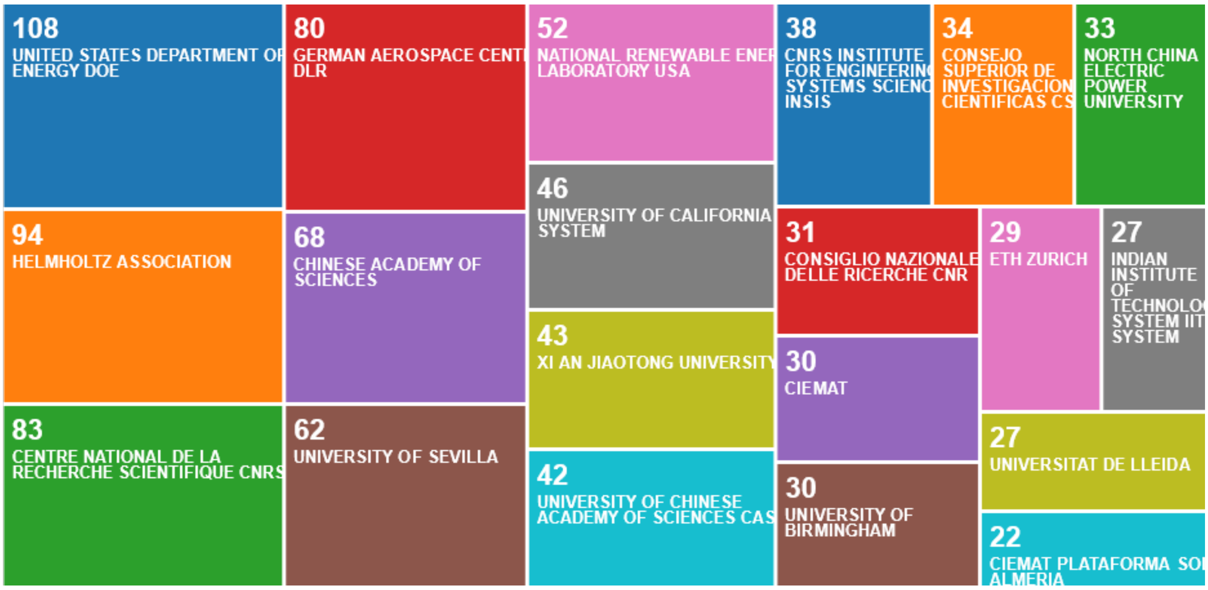
There are also links between the clusters, and indeed European organisations have collaborated intensively over the last 20 years, aided by support from EU projects such as SFERA-I, SFERA-II and the EU-SOLARIS Research Infrastructure initiative.

Figure 3 Geographic distribution of the top-20 countries with organisations that published CSP research articles (excluding reviews) from 2015 to the present.



Source: JRC analysis using Clarivate Web of Science search tool

Figure 4 Most prolific organisations for CSP research articles (excluding reviews) from 2015 to the present.



Source: JRC analysis using Clarivate Web of Science search tool

Figure 5 TIM tool analysis of the clustering of organisations involved in scientific publications in 2019 on CSP.

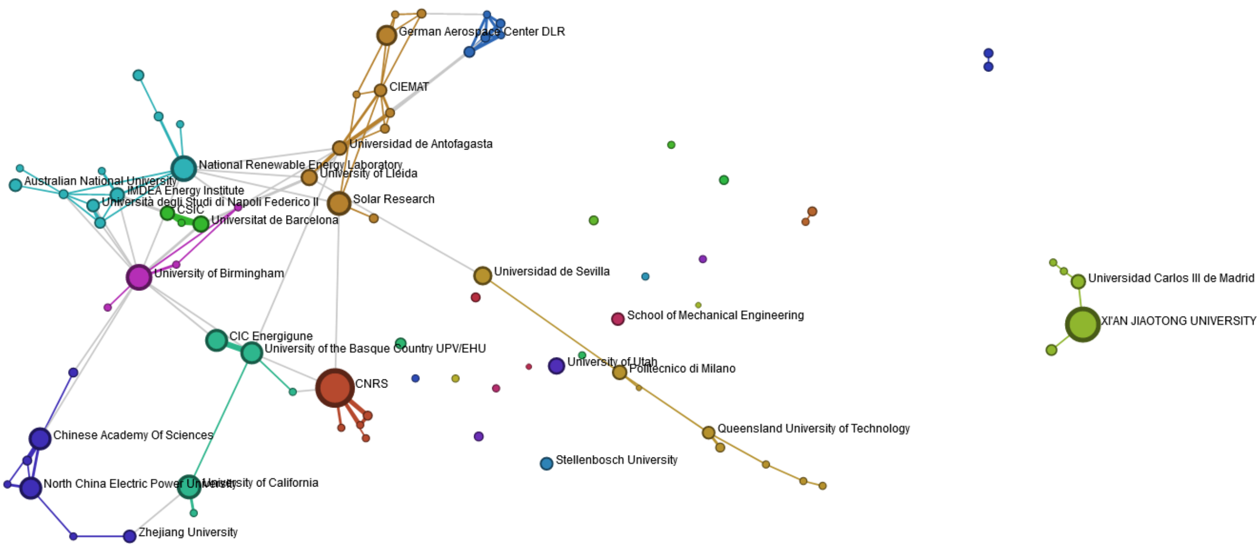


Table 3 Twenty most cited scientific articles for STE/CSP from 2015 to present, from 1616 total publications (Scopus analysis & JRC elaboration)

AUTHORS	TITLE	YEAR	JOURNAL	CITATIONS
Padilla R.V., Soo Too Y.C., Benito R., Stein W.	Exergetic analysis of supercritical CO2 Brayton cycles integrated with solar central receivers	2015	Applied Energy	139
Wang X., He Y., Liu X., Cheng G., Zhu J.	Solar steam generation through bio-inspired interface heating of broadband-absorbing plasmonic membranes	2017	Applied Energy	132
Al-Sulaiman F.A., Atif M.	Performance comparison of different supercritical carbon dioxide Brayton cycles integrated with a solar power tower	2015	Energy	129
Chacartegui R., Alovisio A., Ortiz C., Valverde J.M., Verda V., Becerra J.A.	Thermochemical energy storage of concentrated solar power by integration of the calcium looping process and a CO2 power cycle	2016	Applied Energy	100
Colangelo G., Favale E., Miglietta P., Milanese M., de Risi A.	Thermal conductivity, viscosity and stability of Al2O3-diathermic oil nanofluids for solar energy systems	2016	Energy	92
Al Garni H., Kassem A., Awasthi A., Komljenovic D., Al-Haddad K.	A multicriteria decision making approach for evaluating renewable power generation sources in Saudi Arabia	2016	Sustainable Energy Technologies and Assessments	87
Reyes-Belmonte M.A., Sebastián A., Romero M., González-Aguilar J.	Optimization of a recompression supercritical carbon dioxide cycle for an innovative central receiver solar power plant	2016	Energy	86
Behar O., Khellaf A., Mohammedi K.	A novel parabolic trough solar collector model - Validation with experimental data and comparison to Engineering Equation Solver (EES)	2015	Energy Conversion and Management	85
Desai N.B., Bandyopadhyay S.	Thermo-economic analysis and selection of working fluid for solar organic Rankine cycle	2016	Applied Thermal Engineering	84
Wang X., He Y., Liu X., Shi L., Zhu J.	Investigation of photothermal heating enabled by plasmonic nanofluids for direct solar steam generation	2017	Solar Energy	81

AUTHORS	TITLE	YEAR	JOURNAL	CITATIONS
Myers P.D., Jr, Goswami D.Y.	Thermal energy storage using chloride salts and their eutectics	2016	Applied Thermal Engineering	79
Parrado C., Girard A., Simon F., Fuentealba E.	2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile	2016	Energy	78
Palenzuela P., Alarcón-Padilla D.-C., Zaragoza G.	Large-scale solar desalination by combination with CSP: Techno-economic analysis of different options for the Mediterranean Sea and the Arabian Gulf	2015	Desalination	78
Cao F., Kraemer D., Sun T., Lan Y., Chen G., Ren Z.	Enhanced thermal stability of W-Ni-Al2O3 Cermet-based spectrally selective solar absorbers with tungsten infrared reflectors	2015	Advanced Energy Materials	77
Zanganeh G., Pedretti A., Haselbacher A., Steinfeld A.	Design of packed bed thermal energy storage systems for high-temperature industrial process heat	2015	Applied Energy	77
Ju X., Xu C., Hu Y., Han X., Wei G., Du X.	A review on the development of photovoltaic/concentrated solar power (PV-CSP) hybrid systems	2017	Solar Energy Materials and Solar Cells	73
Desai N.B., Bandyopadhyay S.	Optimization of concentrating solar thermal power plant based on parabolic trough collector	2015	Journal of Cleaner Production	72
Fornarelli F., Camporeale S.M., Fortunato B., Torresi M., Oresta P., Magliocchetti L., Miliozzi A., Santo G.	CFD analysis of melting process in a shell-and-tube latent heat storage for concentrated solar power plants	2016	Applied Energy	71
Daabo A.M., Mahmoud S., Al-Dadah R.K.	The effect of receiver geometry on the optical performance of a small-scale solar cavity receiver for parabolic dish applications	2016	Energy	69
Myers P.D., Alam T.E., Kamal R., Goswami D.Y., Stefanakos E.	Nitrate salts doped with CuO nanoparticles for thermal energy storage with improved heat transfer	2016	Applied Energy	69

2.2.2 Patents

This analysis looked at the Patstat (European Patent Office) data for the period to 2016[9] (JRC update: December 2019 – for details on the processing methodology see [20, 21, 22]). The CPC codes relevant to CSP are as follows:
Y02E 10/40 - Solar thermal energy
Y02E 10/41 - Tower concentrators
Y02E 10/42 - Dish collectors
Y02E 10/43 - Fresnel lenses
Y02E 10/44 - Heat exchange systems
Y02E 10/45 - Trough concentrators
Y02E 10/46 - Conversion of thermal power into mechanical power, e.g. Rankine, Stirling solar thermal engines
Y02E 10/465 - Conversion of thermal power into mechanical power, thermal updraft
Y02E 10/47 - Mountings or tracking

Figure 6 shows the trend in counts of patent families[10] per year from 2000 to 2016. Overall filings grew strongly from up to 2012, slightly decreased to 2014 and have since started increasing again. The main application areas are the generic solar thermal energy category (Y02E 10/40)[11], heat exchange systems (Y02E 10/44) and mounting and tracking (Y02E 10/44). The overall volume of patents (>3000 per year) precludes a detailed analysis of content.

[9] There is a time lag of 3 years to obtain complete data for a given year.
[10] Patent documents are grouped in families, under the assumption that one family equals one invention.
[11] Regarding the high proportion of patents under the generic solar thermal codes, it seems that detailed codes (subcategories) are only given when the examiners (or the algorithms they use) are completely certain that a patent application strictly relates to that specific application area, otherwise it goes in the general basket.

Figure 7 shows the global regional breakdown for 2016, considering all patent family applications (2762) and those considered of high value (138) i.e. with international[12] recognition. For the former, China is dominant with an 82% share. The situation is very different for the high value patent applications where the EU is leader with a 37% share.

Figure 6 Global trends in patenting under the main CSP application groups for 2000-2013.

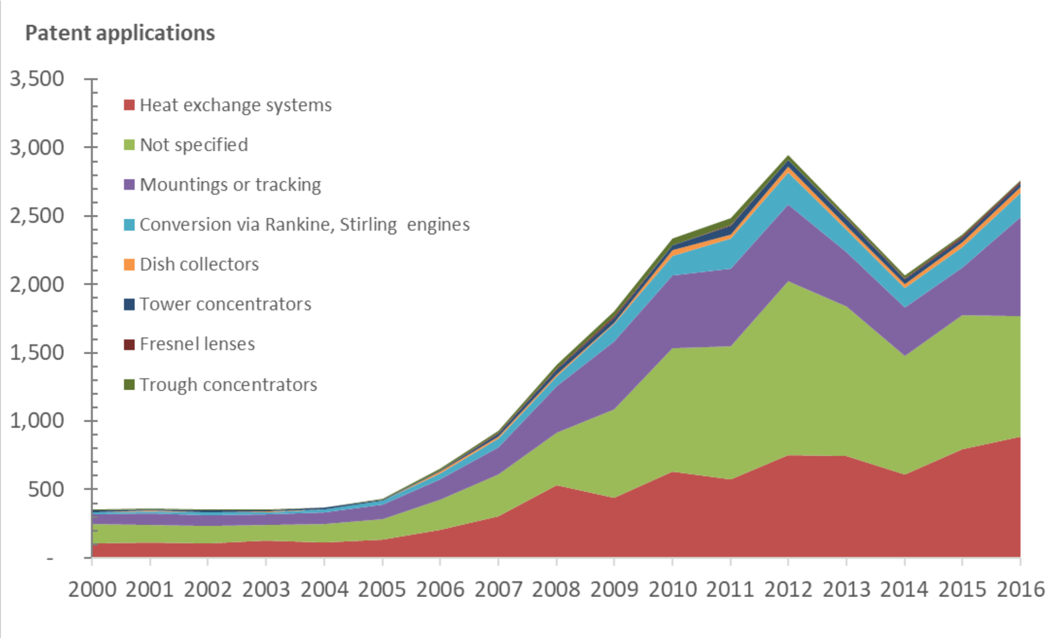
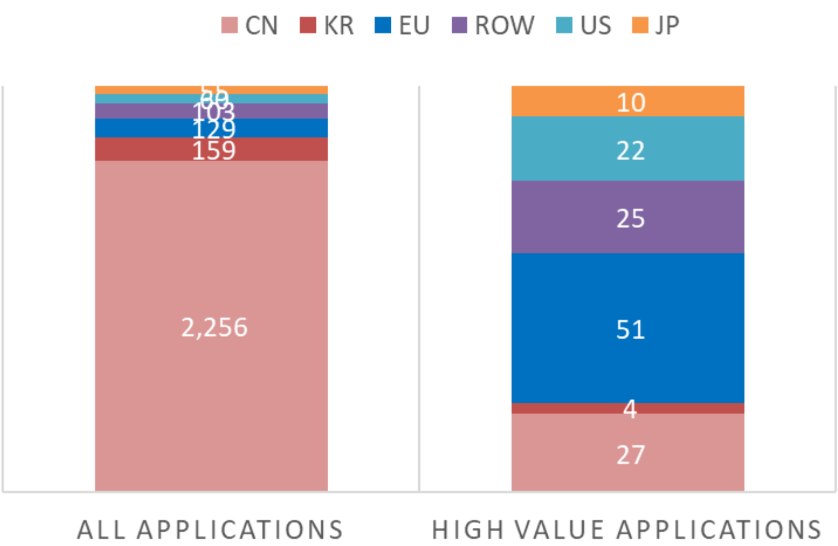


Figure 7 Regional breakdown of patent families for 2016 for all patent family applications (2761) and for so-called high value applications (138) submitted to multiple patent offices.



[12] International indicates that a patent family includes patent applications filed in more than one patent office; such patent families can also be termed "high-value", as it implies that the applicant foresees wide uptake.

2.3 EU programmes

2.3.1 Strategic Energy Technology Plan

The SET-Plan working group has developed a comprehensive planning for R&D and demonstration activities [23, 24, 25] based around the following two targets:

- Short-term: > 40% cost reduction by 2020 (from 2013) translating into a supply price[13] < 10 c€/kWh for a radiation of 2050 kWh/m^2/year (conditions in Southern Europe)
- Longer-term: develop the next generation of CSP/STE technology: new cycles (including supercritical ones) with a first demonstrator by 2020, with the aim to achieve additional cost reductions and opening new business opportunities.

The CSP Implementation Plan [25] established a ranking of research and innovation activities, as well as stressing the need for at least three first–of-a-kind (FOAK) commercial-scale plants in Europe. Table 3 lists these activities together with the targeted TRL increase to 2025.

Table 4 SET-Plan CSP Implementation Plan - Ranking of R&I Activities and expected improvement of TRL.

Priority	Proposed Activity	Targeted TRL Change by 2025
1	Improved central receiver molten salt technology	7→9
2	Parabolic trough with silicon oil (target 430 °C working temperature)	6→8
3	Next generation of central receiver power plants	6→8
4	Advanced Fresnel technology with direct molten salt circulation for HTF and TES	6→8
5	Parabolic trough with molten salt	6→8
6	Scale-up of open volumetric air receiver technology	6→8
7	Multi-tower central receiver beam down system	5→7/8
8	Thermal energy storage	4→7
9	Supercritical steam turbines for CSP	
	State-of-art max. temperatures	→7
	Max. Temperature > 650 °C	5→7
10	Advanced concepts for improved flexibility in CSP applications	
	Topic 1 improved steam turbine operation	→3
	Topic 2 Development of CSP plan analytics	3→6
11	Development and field test of CSP hybrid air Brayton turbine combined cycle sCO2 systems	3→6
12	Pressurized air cycles for high efficiency solar thermal power plants	5→7

[13] The targeted price for 25-year power purchase agreements

2.3.2 Horizon 2020

Based on data for 2014-2019, the EU has supported 26 CSP/STE projects with approximately EUR 161 m contribution and a total budget in excess of EUR 200m. This represents a substantial share (32%) of the overall budget for solar energy R&D, as indicated in Table 5. Within the CSP sector itself, projects on solar thermal electricity received the largest share.

Table 6 lists the STE/CSP projects. The majority (87% by funding) are R&D activities (IAs and RIAs), with one FTIPilot project (3% of funding). Annex 1 provides more details of the technical objectives, targeted TRL and progress to date. Chapter 4 below discusses the overall technical progress.

Table 5 H2020 funding for solar projects 2014-2019, with a breakdown for CSP,

SOLAR TECHNOLOGY AND SUB-TECHNOLOGY	FINISHED PROJECTS	RUNNING PROJECTS	TOTAL
Photovoltaics	82,785,217	183,213,168	265,998,385
CSP	49,058,269	111,512,694	160,570,963
STE	40,691,934	76,779,338	117,471,272
Process Heat	6,309,615	16,314,426	22,624,041
General	-	9,102,631	9,102,631
Heating and cooling	50,000	3,999,384	4,049,384
TES	895,922	420,389	1,316,311
Desalination	50,000	-	50,000
Solar Thermal (non-concentrating)	8,218,159	26,705,728	34,923,887
Heating and cooling	6,192,952	26,705,728	32,898,681
Process Heat	2,025,207	-	2,025,207
Photochemical	7,028,031	26,159,682	33,187,713
Coordination	2,980,095	14,953,181	17,933,276
Solar windows	1,264,438	995,935	2,260,372
Hybrid Technology	395,455	1,398,478	1,793,932
Grand Total	150,718,866	360,042,340	510,761,206

(Source: JRC analysis of COMPASS data)

Table 6 Horizon 2020 CSP project listing (for more details see Annex 1)

Acronym	Title	Type	EC Grant	Start Date	End Date
CySTEM	Cyprus Solar Thermal Energy Chair for the Eastern Mediterranean	CSA	2,500,000	01-07-2015	30-06-2020
NESTER	Networking for Excellence in Solar Thermal Energy Research	CSA	1,060,798	01-01-2016	31-12-2018
MUSTEC	Market uptake of Solar Thermal Electricity through Cooperation	CSA	2,396,526	01-10-2017	30-09-2020
HORIZON-STE	Implementation of the Initiative for Global Leadership in Solar Thermal Electricity	CSA	999,656	01-04-2019	31-03-2022
OCONTSOLAR	Optimal Control of Thermal Solar Energy Systems	ERC	2,500,000	01-09-2018	31-08-2023
ORC-PLUS	Organic Rankine Cycle - Prototype Link to Unit Storage	IA	6,249,316	01/05/2015	30/04/2019
PreFlexMS	Predictable Flexible Molten Salts Solar Power Plant	IA	14,362,194	01-06-2015	31-05-2018
RAISELIFE	Raising the Lifetime of Functional Materials for Concentrated Solar Power Technology	IA	9,291,723	01-04-2016	31-03-2020
MSLOOP 2.0	Molten Salt Loop 2.0: key element for the new solar thermal energy plants.	IA	2,243,085	01-11-2016	31-07-2019
IN-POWER	Advanced Materials technologies to QUADRUPLE the Concentrated Solar Thermal current POWER GENERATION	IA	4,998,928	01-01-2017	31-12-2020
NEXTOWER	Advanced materials solutions for next generation high efficiency concentrated solar power (CSP) tower systems	IA	4,981,304	01-01-2017	31-12-2020
SHIP2FAIR	Solar Heat for Industrial Process towards Food and Agro Industries Commitment in Renewables	IA	7,996,793	01-04-2018	31-03-2022
SOLWARIS	Solving Water Issues for CSP Plants	IA	10,812,504	01-05-2018	30-04-2022
HyCool	Industrial Cooling through Hybrid system based on Solar Heat	IA	5,818,972	01-05-2018	30-04-2021
HIFLEX	HIgh storage density solar power plant for FLEXible energy systems	IA	13,557,625	01-09-2019	31-08-2023
GLASUNTES	Innovative high temperature thermal energy storage concept for CSP plants exceeding 50% efficiency	MSCA	259,558	01/05/2016	30/04/2019
SESPer	Solar Energy Storage PERovskites	MSCA	195,455	13/11/2017	12/11/2020
THERMOSTALL	High Performance Seasonal Solar Energy Latent Heat Thermal Storage Using Low Grade, Low Melting Temperature Metallic Alloys	MSCA	195,455	01-11-2016	31-10-2018

Acronym	Title	Type	EC Grant	Start Date	End Date
NPMSSES	Nanoparticle Enhanced Molten Salts for Solar Energy Storage	MSCA	195,455	01-03-2017	28-02-2019
Solar-Store	Solar Powered Thermochemical Heat Storage System	MSCA	195,455	01-07-2017	30-06-2019
Small-scale CSP	Numerical and experimental analysis of a novel thermal energy storage for a small-scale concentrated solar power plant	MSCA	212,195	01-06-2018	31-05-2020
THERMES	A new generation high temperature phase change microemulsion for latent thermal energy storage in dual loop solar field	MSCA	224,934	17-09-2019	16-09-2021
FRIENDS2	Framework of Innovation for Engineering of New Durable Solar Surfaces	MSCA	346,500	01-01-2015	31-12-2018
CAPTure	Competitive SolAr Power Towers – CAPTure	RIA	6,104,033	01-05-2015	30-04-2020
WASCOP	Water Saving for Solar Concentrated Power	RIA	5,941,608	01-01-2016	31-12-2019
MinWaterCSP	MinWaterCSP - Minimized water consumption in CSP plants	RIA	5,861,372	01-01-2016	31-12-2018
SOLPART	High Temperature Solar-Heated Reactors for Industrial Production of Reactive Particulates	RIA	4,366,563	01-01-2016	31-12-2019
Innova MicroSolar	Innovative Micro Solar Heat and Power System for Domestic and Small Business Residential Buildings	RIA	3,999,384	01-09-2016	31-08-2020
GRIDSOL	Smart Renewable Hubs for Flexible Generation: Solar Grid Stability	RIA	3,421,448	01-10-2016	30-11-2019
NEXT-CSP	High Temparature concentrated solar thermal power plan with particle receiver and direct thermal storage	RIA	4,947,420	01-10-2016	31-12-2020
PEGASUS	Renewable Power Generation by Solar Particle Receiver Driven Sulphur Storage Cycle	RIA	4,695,365	01-11-2016	31-10-2020
MOSAIC	MOdular high concentration SolAr Configuration	RIA	5,077,734	01-12-2016	30-11-2020
INSHIP	Integrating National Research Agendas on Solar Heat for Industrial Processes	RIA	2,498,661	01-01-2017	31-12-2020
SOCRATCES	SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage	RIA	4,994,153	01/01/2018	31/12/2020
POLYPHEM	Small-Scale Solar Thermal Combined Cycle	RIA	4,975,961	01-04-2018	31-03-2022
SFERA-III	Solar Facilities for the European Research Area - Third Phase	RIA	9,102,631	01-01-2019	31-12-2022
SCARABEUS	Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plants	RIA	4,950,266	01-04-2019	31-03-2023

Acronym	Title	Type	EC Grant	Start Date	End Date
TRANSREGEN	Portable thermal fluid regeneration system for Solar Thermal Plants	SME	50,000	01-03-2015	31-08-2015
helioSTEAM	A novel concentrated solar steam system for industrial applications with a high degree of pre-manufacturing at extremely low prices.	SME	50,000	01-07-2015	31-12-2015
TENCENT	The next generation of Hybrid Concentrating Solar Power Plants	SME	50,000	01-08-2015	31-10-2015
DIMONTEMP	Distributed Monitoring of HTF Temperature at Solar Thermal Power Plants	SME	50,000	01-02-2016	31-07-2016
HELITE	High precision and performance heliostat for variable geometry fields of Thermosolar Plants	SME	50,000	01-03-2016	31-08-2016
LIGHTHOUSE	LIGHTHOUSE: concentrated thermal solar power directly connected to the heating and cooling systems of buildings at the local level.	SME	50,000	01-08-2016	31-01-2017
HP-MOSES	Solar assisted high temperature heat pumps for molten salt energy storage applications.	SME	50,000	01-05-2017	31-10-2017
TurboSol	TurboSol: Turbo-Solar Thermal Power for Industrial Drying Processes	SME	50,000	01-03-2018	30-06-2018
SWCSP - Solar Water	Creating sustainable fresh water from desalinating seawater using Concentrating Solar Power (CSP)	SME	50,000	01-02-2019	31-05-2019
TANKRETE	A breakthrough concrete mega tank for thermal fluids storage over 500ºC in thermal solar energy generation	SME	50,000	01-05-2019	31-10-2019
HELIOtube	Inflatable solar collectors for a low cost CSP Plant with irreducibly small carbon footprint	SME	1,843,052	01-11-2015	31-10-2017
AUTO-RST	Flexible automated manufacturing of RST Facets: High Performance Solar Reflectors for CSP industry	SME	1,577,233	01-10-2019	30-09-2021

2.3.3 ERANET

ERA-NET is a funding instrument designed to support public-public partnerships. Over the period 2014-2018 the SOLAR-ERA.NET network funded both PV and CSP, with five CSP projects [19], as shown in Table 6 (the majority of the projects were on photovoltaics) [26]. This represents a total financing of approximately EUR 6.7 million, of which well over half comes from public funding.

Since 2019 CSP has its own dedicated ERA-NET. The first CSP ERANET call in January 2020 received seven proposals covering parabolic troughs with silicon oil and beam-down receivers.

2.3.4 Smart Specialisation

Smart specialisation is an innovative approach that aims to boost growth and jobs in Europe, by enabling each region to identify and develop its own competitive advantages. The interregional partnership for solar energy and smart specialisation has been running since 2015 its main objectives[14] are:

1. maintain the global leadership of the European industry in CSP/STE
2. focus on regional development, maintaining the competitiveness of the full value chain of the CSP European industry and strengthening its technological development;
3. maintain the EU's solar Industry's export opportunities by strengthening partnerships among national governments, industry and research actors;
4. focus on achieving significant cost reductions of existing technologies (in the short term), and to work towards the development of next generation technologies (in the longer term).

To date, much of the partnership's activity has focused on the development of the solar first of a kind (FOAK) project in Extremadura, but potentially exploiting cross-border collaboration mechanisms for funding and use of the electricity generated [27, 28].

2.3.5 NER 300

The aim of NER 300[15] is to establish a demonstration programme of CCS and RES projects involving the EU Member States. Table 8 shows the current status for CSP-related projects, which in general have struggled to find full funding (the NER 300 award covers only a percentage of the total costs).

2.3.1 Horizon Europe Clean Energy Transition Partnership

In preparation for the EU's 2021-2027 Horizon Europe research and innovation framework programme, the the CETP partnership is being developed strategy as Co-Funded European Partnership, meaning with Member States and Associated Countires funding topped with EC funding. A strategic research and innovation agenda (SRIA) is in development that includes STE/CSP.

[14] See https://s3platform.jrc.ec.europa.eu/s3-energy-partnerships-solar-energy for more infomation

[15] NER300 is a financing instrument managed jointly by the European Commission, the European Investment Bank and the EU Member States, that uses 300 million ETS allowances (rights to emit 1 t CO2) in a new entrants' reserve for subsidising installations of innovative renewable energy technology and carbon capture and storage. For the period 2021-2030 the Commission has proposed a new programme called Innovation Fund.

Table 7 SOLAR-ERA-NET projects for CSP

Acronym & Title	Coordinator	Status, Mid-2019
EDITOR - Evaluation of the Dispatchability of a Parabolic Trough Collector System with Concrete Storage	protarget AG (DE)	Running
SIMON - Silicone Fluid Maintenance and Operation	DLR, Deutsches Zentrum für Luft- und Raumfahrt (DE)	Running
SITEF - Silicon Fluid Test Facility	DLR, Deutsches Zentrum für Luft- und Raumfahrt (DE)	Completed
SLAGSTOCK - Low-Cost Sustainable Thermal Energy Storage Systems Made of Recycled Steel Industry Waste	Centro de Investigacion COOP de Energias Alternativas CIC (ES)	Completed
SolFieOpt - Optimal Heliostat Fields for Solar Tower Power Plants	TSK Flagsol Engineering GmbH (TSK Flagsol) (DE)	Completed

Table 8 NER-300 projects for CSP

Project/Plant	Country	Technology	Budget m€	Status
HELIOS POWER	Cyprus	Stirling dish	46,6	withdrawn in 2019
MAXIMUS	Greece	Stirling dish	44,6	withdrawn in 2020
MINOS	Greece	Solar tower	42,1	50 MW, In progress: developer: Nur-MOH Heliothermal SA, EPC consortium: China Gezhouba Group International Engineering Co., Ltd & Zhejiang Supcon Solar Technology
PTC50-ALVARADO	Spain	Solar tower	70,0	Cancelled
EOS GREEN ENERGY	Cyprus	Solar tower	60,2	50 MW, ongoing, should enter into operation by 30 June 2021
MAZARA SOLAR	Italy	Solar tower	40,0	withdrawn in 2017

2.4 Other R&D Programmes

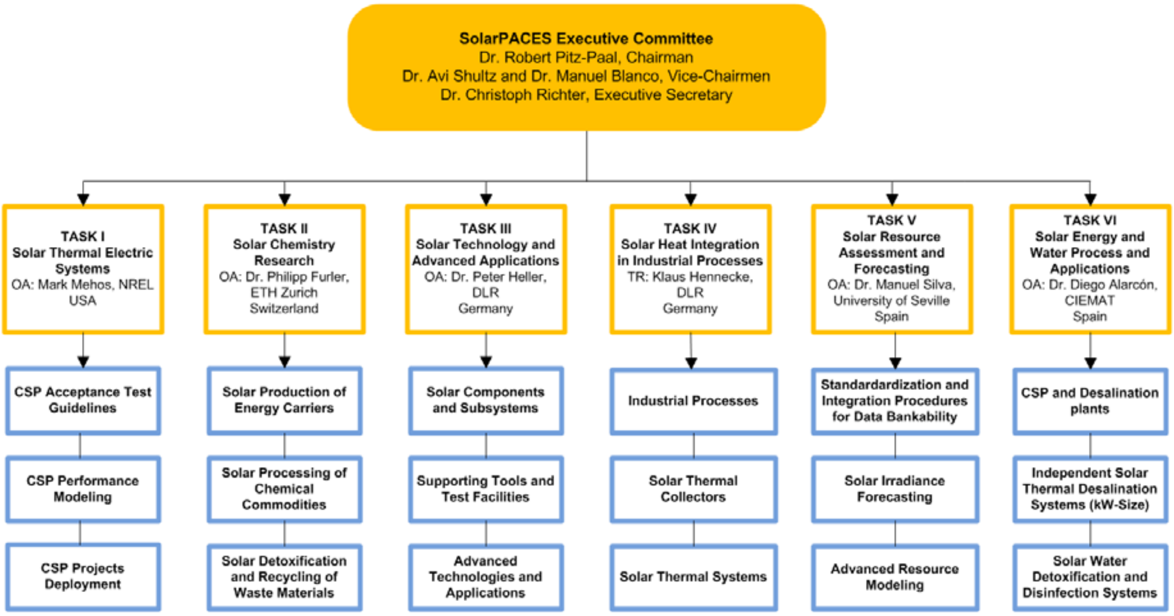
2.4.1 SET Plan Countries

The SET-Plan CSP Implementation Plan outlines the main national activities in each of the priority areas. Countries with significant efforts on CSP R&D include Spain, Germany, France, Cyprus, Portugal, Italy and Belgium. These countries also work together in ERA.NET network (see above). The 2019 SET-Plan progress report [29] indicates that the interim working group has endorsed 33 projects and that the funding is somewhat above 50% of the expected investment needs.

2.4.2 IEA Technology Collaboration Programme

The IEA oversees a technology collaboration programme for Solar Power and Chemical Energy Systems called SolarPACES. It reports to the Working Party on Renewable Energy Technologies (REWP). Currently SolarPACES has 19 members: Australia, Austria, Brazil, Chile, China, European Commission, France, Germany, Greece, Israel, Italy, Mexico, Morocco, Republic of Korea, South Africa, Spain, Switzerland, UAE and USA. Figure 8 shows the task structure and task leaders. European organisations play a very prominent role, providing the chair and five Operative Agents.

Figure 8 Current structure of the IEA technology collaboration programme for Solar Power and Chemical Energy Systems (SolarPACES)



2.4.2 USA

The US Department of Energy Solar Energy Technologies Office runs the Sunshot programme with the overall goal of making solar energy affordable. The new 2030 targets[16] recognise two distinct roles for CSP plants in the electricity market:

- $0.10 /kWh for peaker plants with no more than six hours of energy storage
- $0.05 /kWh for baseload plants with a minimum of 12 hours of energy storage

This reflects interest in the future US power market for peaking plants, in particular in view of the high daily power ramp as PV comes off-line and the evening load increases rapidly. This need could be addressed by modular, smaller (10-50 MW) CSP units with construction time < 1 year.

The SETO portfolio on CSP comprises 100 projects corresponding to a US$ 187 million budget. The technical breakdown is high temperature thermal systems $ 79 m, CSP systems $50 m, power cycles $28 m, desalination and other thernmal processes $ 16 m and solar collectors $ 14 m [30].

Gen3 CSP is the DoE's program for an innovative CSP system with thermal energy storage capable of providing heat at greater than 700 °C. A sCO2 Brayton cycle is seen as a likely successor to the current steam Rankine cycle due to its potential for high efficiency [31, 32] In 2018 DOE announced $72 million in funding for three technology pathways, as shown in Table 9. After two initial phases, in phase 3 one pathway will be developed as a full-scale test facility (1-10 MW_{th}) coupled to a sCO2 power block operating at 700°C-750°C. This should achieve a 10% efficiency gain and lead to a 20%-30% drop in LCoE.

The SETO is also running a Solar Desalination Prize to accelerate the development of low-cost desalination systems that use solar-thermal power to produce clean water from salt water. The prize was launched in April 2020.

[16] https://www.energy.gov/sites/prod/files/2018/05/f51/SunShot%202030%20Fact%20Sheet.pdf

Table 9 Heat exchange media for high temperature (> 700 ºC) STE cycles.[17]

PATHWAY	ADVANTAGE	DISADVANTAGE
Solid: sand-like particles	experimental particle receivers can operate up to 1,000°C	Particles must be circulated mechanically
New molten salts	Familiarity	Corrosion
Supercritical CO2	Easy to move the sCO2 gas/liquid	Hard to capture and store

2.4.3 China

In 2009 the Ministries of Science and Technology (MOST), of Finance and of Education, the State-owned Assets Supervision and Administration Commission of the State Council, the All China Federation of Trade Unions and China Development Bank established the Chinese National Solar Thermal Energy Alliance as a non-profit membership organisation. Its aim is to lead R&D innovation and promote the solar thermal development and application under the guidance of MOST. This has led to strong growth in R&D activities [33], and Chinese organisations are now leaders in terms of number of scientific publications and of patents.

In parallel, China has developed a series of commercial scale demonstration projects. A capacity of 1,35 GW was set out in the 1st round, for a FiT of 1.15 RMB/kWh (approximately 0.17 EUR/kWh). In 2018 the CGN Delingha project (a 50 MW parabolic trough plant with 8 hours TES) was connected to the grid. The most recent is the Dunhuang Dacheng 50MW molten salt linear Fresnel CSP project plant that began commercial operation in June 2020.
In parallel production capabilities for key equipment have been developed and is proving competitive internationally. The Chinese company SUPCON will be the equipment supplier to the Minos CSP plant in Crete, a project supported by NER-300.

2.4.4 Other countries

Other non-European countries with significant research publications in 2019 are India (17), Australia (15), South Africa (9), Morocco (7), United Arab Emirates (7), Chile (6), Pakistan (6), Brazil (5) and Malaysia (5).

Morocco also stands out for its role in hosting demonstration plants. The IRSEN Green Energy Park at Ben Guerir hosts the pilot plant for the H2020 ORC-Plus project. The Ouarzazate complex is hosting a 400 kW demo of an innovative US solar tower technology (called 24/7), which uses a hot air cycle (T_{max} over 900oC), thermal storage and a Brayton turbine.

[17] https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp

3 IMPACT OF R&D WITH EU CO-FUNDING

Annex 1 provides a listing of all CSP-related projects so far in H2020, together with an assessment of progress to the end of March 2020, based on the progress reports from the projects. At this point 25 of the 49 projects has completed the contractual duration, although in some cases reporting is still ongoing. Almost all the SET-Plan R&I priorities are being supported to some extent. Several projects such as INPOWER, RAISELIFE and HIFLEX address multiple areas. The following sections briefly look at the progress and results of the larger projects under three groupings:

a) projects looking at optimisation of components and performance of designs with current steam temperatures (390ºC for oil HTFs and 570ºC for solar salt HTFs) and cycle efficiency limits;
b) Concepts going beyond current design in terms of maximum temperature and efficiency
c) Innovative thermal and thermochemical energy storage

3.1 Optimising Designs within Existing Cycle Efficiency Limits

There is a major focus on advancing the parabolic trough with molten salt combination. The FTiPilot project MSLOOP2.0 produced good results on molten salt additives, thermal monitoring and system engineering on a 500 m loop at the Manchasol plant in Spain. although full operational flow tests were not run. A large IA project PreFlexMS to demonstrate a molten salts system with a once-through steam generator (approximately 2 MWth rating) at Evora Molten Salt Platform in Portugal ended prematurely due to the bankruptcy of a partner providing a key component. The RAISELIFE IA project ended in March 2020 and has demonstrated improved anti-reflective coatings for mirror elements and for low temperature absorbers. The IN-POWER project (running to the end of 2020) is also working on advanced mirror and vacuum-free absorber technologies. The results are also relevant to Fresnel designs.

Concerning Fresnel systems, the MOSAIC project (2016- end 2020) is studying an innovative modular configuration based on a fixed hemispheric semi-Fresnel solar field and a high temperature mobile receiver, intended to bring substantial cost savings. The design is now changed to use mineral oil instead of molten salt as HTF (410 ºC). A full-scale prototype (313 kW) is under construction with testing to start mid-2020.
ORC-PLUS ((2015-2019) set out to improve an existing small-scale 1MWel CSP system with linear Fresnel collectors and an ORC power cycle system, A new TES facility with magnetite pebbles and providing 4 hours storage was completed in October 2019 at the IRSEN Green Energy Pak in Morocco. At the time of writing, no information is available on its operation.

For improved central receiver systems, RAISELIFE has also produced significant results on reflectors and on absorber coatings. The SME project AUTO-RST (2019-2021) is aiming to bring a patented solar reflector technology to commercialisation, with large-scale production of 2 m x 2 m facets. The technology is claimed to potentially reduce solar field costs by 15%.

Reducing water use has been addressed three projects:

- MinWaterCSP (2016-2018) brought several water saving measures including dry cooling techniques to TRL 4/5.
- WASCOP (2016-2019) achieved improvements in dust-barriers and other anti-soiling measures to reduce cleaning needs, as well as lower dry cooling temperatures by 5ºC.
- SOLARIS (2018-2022) aims bring water saving measures to TRL7, addressing cleaning water usage, wet and dry cooling designs and plant operation strategy. Plants in Spain and Israel will demonstrate the measures in a large-scale operation environment.

3.2 Designs for Higher Cycle Temperatures and Efficiencies

HIFLEX (2019-2023) is developing a prototype system using ceramic particle storage system (2.5x higher storage density than molten salts) and a particle to steam generator delivering at 620°C. The approach encompasses a solar field and tower particle receiver at up to 1000ºC, as well as the hot and cold storage tanks and particle circulation system. A prototype (TRL 7) will be installed to provide process heat for a food plant in Foggia, Italy, but project will also develop a plant for exploiting the technology in a 100 MW_{el} STE plant.

NEXTOWER (2017-2020) is working on a high temperature ceramic solar receivers with a maximum materials temperature of at least 800°C, to be exploited with a molten salt or. More radically, liquid lead heat transfer and storage system. The latter exploits work done for nuclear plants on liquid lead circuits. The target maximum lead temperature is 700ºC and will be demonstrated in the SOLEAD loop facility.

SCARABEUS (2019-2023) is working on supercritical CO2 cycles with a maximum temperature of up to 700°C, using blending with inorganic compounds and fluorocarbons to enable a more efficient condensing cycle.

Moving to Brayton cycles (gas turbine) and combined cycles:

- CAPTURE (2015-2020) studies an air receiver concept intended to operate at 1200ºC, The prototype receiver is being prepared for testing at PSA. The project also includes studies on system configurations and the economic viability.
- NEXT-CSP (2016-2020) aims to demonstrate a particle-in-tube concept with a 4 MWth receiver on the Themis facility solar tower, capable to heat particles up to 800°C, A particle-to-pressurized air heat exchanger would be coupled to a 1.2 MWel gas turbine. Demonstration of prototype is currently pending.
- POLYPHEM (2018-2022) studies a small-scale CSP concept in which a high temperature air receiver supplies a micro-gas turbine (top cycle); recovered heat is stored in a thermocline and used in an ORC bottom cycle. The project will build a 60 kW prototype plant with a 2 MWh thermal storage unit, to be validated to TRL 5.

3.3 Innovations for thermal and thermo-chemical energy storage

SOCRATES (2018-2020) looks at integration of the lime calcination process to provide thermo-chemical heat storage in a CSP system. The heat transfer from the receiver is via a CO2 and lime entrained flow, using solar heat to drive the calcination step (CaCO3 to CaO). This is reversed in the carbonator, providing heat for a steam or hgher temperature helium power cycle. The low cost of lime and possibility to use metallic rather than ceramic components in the solar receiver offers potential for lower costs than with other concepts. In the project's final phase wil demonstrated the thermochemical system (calcinator/carbonator) and the CSP-receiver will be separately (target is TRL 5). The SOLPART project (2016 to 2019) also addressed the use of CSP for calcination, but the application is decarbonisation of cement production rather than STE. The peak temperatures are considerably higher (950oC). At the time of writing, the final reports were not yet available.

PEGASUS (2016-2020) studies a sulphur particle heat transfer cycle that can be used for direct thermal energy storage (at up to 900oC) or with indirect thermochemical storage of solar energy in solid sulphur. The process can be coupled with a gas turbine for power production.

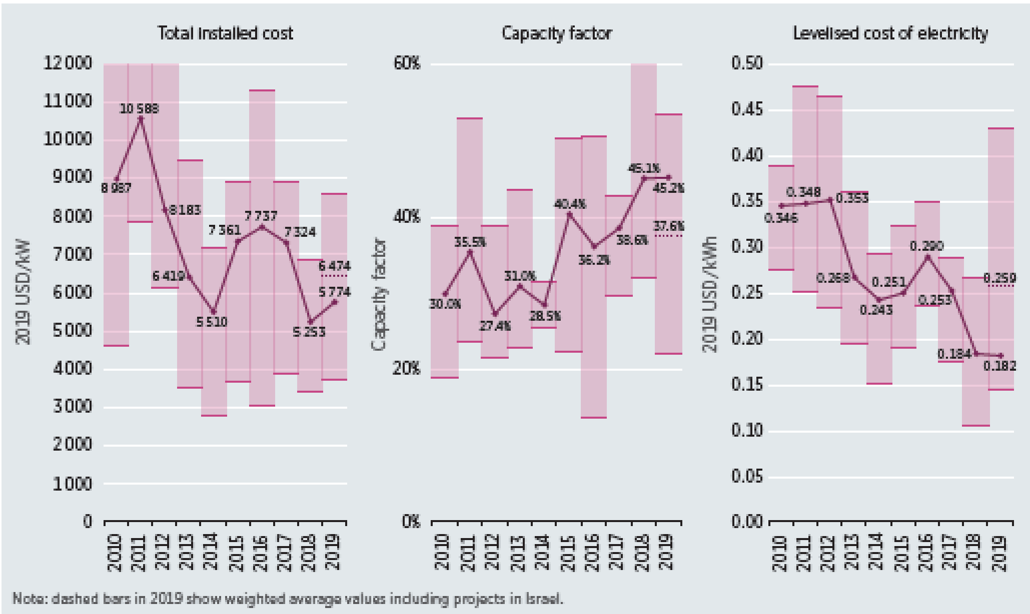
4 TECHNO-ECONOMIC OUTLOOK

4.1 Costs trends

While the marketability of STE electricity depends on several important non-technical elements, here the focus is on how technology development can influence capital investment and O&M costs. IRENA's compilation of CAPEX, capacity factor (reflected the amount of storage) and LCOE data for STE plants over the last 10 years [34] shows significant cost reductions have been achieved (Figure 9). However, as emphasised in the SET-Plan and Sunshot programmes, CAPEX for a large plant (100 MW or greater) with 8 hour storage needs to come down to the level of 3 EUR million/MW from a current level of over 6 EUR million/MW.

For this to happen cost reduction efforts need to address all the main sub-systems and be combined with gains in performance efficiency. The solar field (comprising here the reflecting systems themselves as well as the ground-work costs) represents c approximately 40% of the CAPEX and is an obvious target. A recent US analysis of measures to reduce the LCOE form a 2018 level of 98 USD/MWh to the 2030 Sunshot target of 50 USD/MWh come to similar conclusions: 44% of cost savings from the solar field, 14% from the power block, 23% from a higher efficiency cycle and 19% from low cost thermal storage [30].

Figure 9 Historical and projected CAPEX values for CSP parabolic trough and solar tower plants.



Source: IRENA Renewable Cost Database.

4.2 Deployment Scenarios

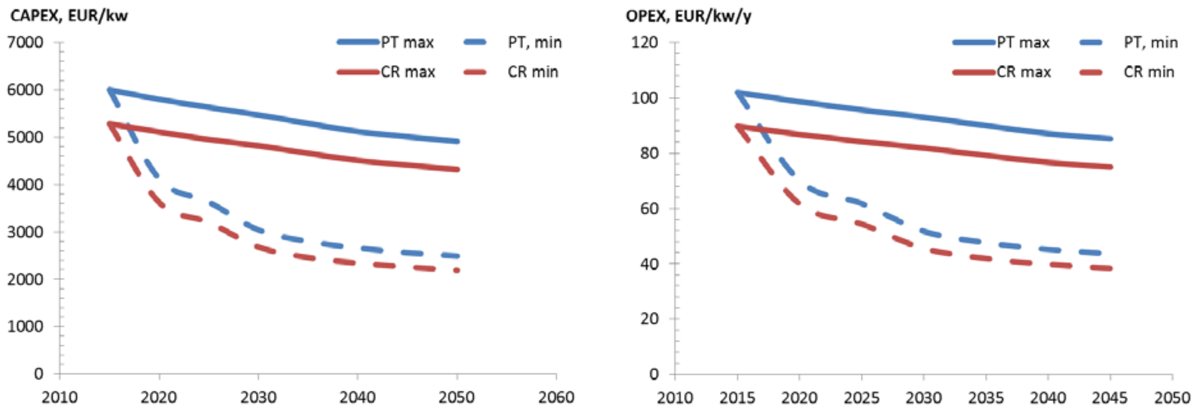
Energy system models help study the possible impact of technology improvements and cost reductions. As mentioned in the introduction, the IEA envisages a modest future role for CSP worldwide, with installed capacity rising to 68 GW by 2040 under the new policies scenario and to 267 GW under the sustainable development scenario [9]. The projected growth is however non-linear, with low growth to 2030 and then accelerating strongly.

In the LCEO, the JRC-EU-TIMES model has been used to look in detail at the possible impact of technology and cost developments in Europe [21]. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. Table 10 shows the main scenarios. Figure 10 shows the CSP-specific inputs for CAPEX and fixed operating and maintenance cost trends – the reference is a 100 MW plant with 12 hours storage.

Table 10 Overview of the JRC-EU-TIMES model scenarios.

GLOBAL SCENARIOS	MODEL SCENARIOS	FEATURES
Baseline	Baseline	- 48 % CO_2 by 2050 (continuation of current trends)
Diversified	Div1	-80% CO2 by 2050
use of all known	Div2_LowLR	Lower cost learning rate for all technologies
options including CCS	Div3_HighLR	higher cost learning rate for all technologies
and new nuclear plants	Div4_DAC	Includes direct air capture of CO2
	Div5_CheapFossil	Oil price declines to $40/barrel
	Div6_NoCC_InPower	No carbon capture on power plants
Pro-Renewables	Res1	-80 % CO_2 by 2050
no new nuclear; no CCS	Res2_LowLR	Lower cost learning rate for all technologies
	Res3_HighLR	Higher cost learning rate for all technologies
	Res4_SET	CAPEX values reach the targets in the SET-Plan
	Res5_DAC	Includes direct air capture of CO2
	Res6_HighForest	Uses full forest potential with forest area equilibrium
	Res7_Near_ZeroCarbon	-95 % CO2 by 2050
	Res8_NoCCU	Further restriction on CO2 use (promotes re-use)

Figure 10 Cost ranges for the nominal 100 MW STE plant (with 8 hours storage) used in the JRC-EU-TIMES model a) CAPEX and b) OPEX. The min and max relate to the highest and lowest cost learning rates observed in the output.

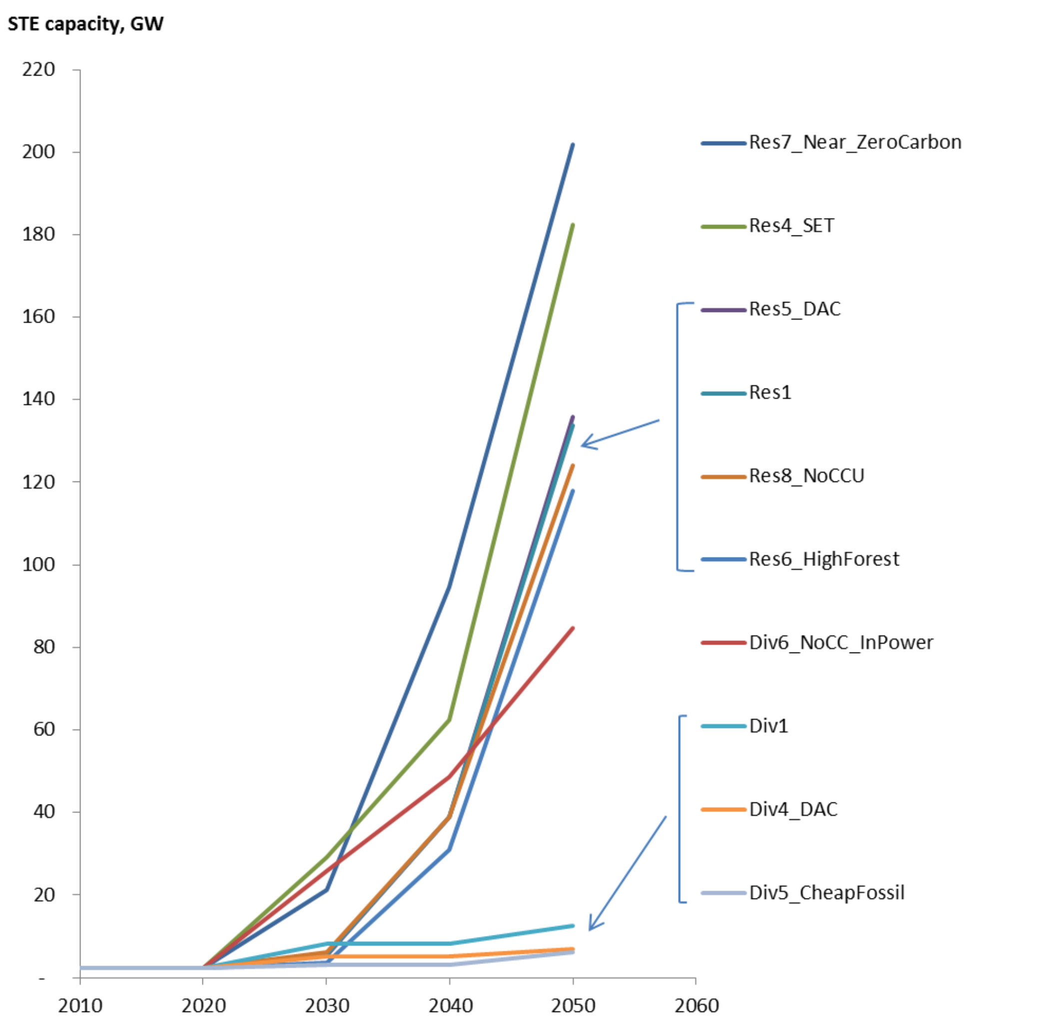


a) CAPEX

b) OPEX

The results for STE deployment are summarised in Figure 11. The baseline scenarios show no STE uptake. For the main diversified scenario (Div1), the capacity reaches 12 GW by 2050 and for the pro-renewables scenario (Res1) this increases by over an order of magnitude to 134 GW. For the SET-Plan scenario, the STE capacity rises further to approximately 180 GW by 2050., and in the near-zero carbon scenario to just over 202 GW.

Figure 11 STE capacities in JRC-EU-TIMES model scenarios.



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5 CONCLUSIONS AND RECOMMENDATIONS

Deployment of STE technology remains at an early stage. Two designs are in full commercial operation (TRL9): parabolic trough systems with thermal oil or molten salts as heat transfer fluid, and central receiver/power tower systems, using steam or molten salt as heat transfer fluid. These plants are only recently being realised at sufficient scale (>100 MW) to be cost competitive, and operational data and experience are needed to encourage significant investments.

STE technology has significant scope for improvement in all areas: the solar field, the power block, higher efficiency cycle and thermal storage. However, with very modest global market growth, it remains a challenge to develop volume production processes to drive down costs, as has happened for other renewables. This is all the more critical as the deployment of a new generation of large battery storage units with capacity of hundreds of MWh is already underway in Australia and the US.

European organisations continue to play a leading role in research and technology development, but now face a challenge from China. EU researchers are top publishers of scientific papers and for high value (internationally recognised) patents. EU projects such as SFERA-I and -II, and most recently the EU-SOLARIS Research Infrastructure initiative have helped develop effective long-term collaborations. This may become even more important in future, together with efforts to focus support to the sector in Europe and the export of European technology.

To date Horizon 2020 has provided significant support to CSP/STE research, with 49 projects and 161 million funding, approximately 30% of all "solar" grants. The 25 completed projects have in general been successful in meeting their objectives, although typically the ambitious target TRL is not be fully meet. Over 2017-2019 several major projects started work on concepts going beyond current design in terms of maximum temperature and efficiency, developing solar receiver, heat transfer and storage technologies. A strategy may be needed for prioritising funding for the subsequent development to TRL8 to 9.

Regarding first-of-a-kind plants, the SET-Plan implementation plan for CSP stressed the need for several of these, but none have been realised to date. Of the two remaining NER300 projects, one will use Chinese technology. Plans to use the new Innovation Funds or Recovery funds for CSP projects can make use of the market analyses performed on H220 projects considering economies of scale, smaller modular plants to address specific market needs, and hybridisation.

Standardisation is also relevant at the level of critical components and for installation qualification; here project results and targeted pre-normative R&D can support current efforts at international level.

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List of abbreviations

CPC	common patent
CSP	Concentrated/ing Solar [thermal] Power
CR(S)	central receiver (system), aka solar tower system
EPC	engineering, procurement and construction
ETS	Emission Trading System
FiT	feed-in tariff
FOAK	First–of-a-Kind
GW	Giga Watt
HTF	heat transfer fluid
IA	Innovation Action
IEA	International Energy Agency
ISCC	integrated solar combined cycle
IP	Implementation Plan
LCoE	levelised cost of electricity
MENA	Middle East and North Africa
MSCA	Marie Skłodowska-Curie Action
PPA	power purchase agreement
PV	photovoltaic
RES	Renewable Energy Source
RIA	Research and Innovation Action
SET	Strategic Energy Technology
STE	solar thermal electricity
TES	thermal energy storage
TRL	Technology Readiness Level

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ANNEX 1 – LISTING OF HORIZON 2020 CSP PROJECTS

NB this listing is in order of project start date

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
645725	FRIENDS2	Framework of Innovation for Engineering of New Durable Solar Surfaces	MSCA -RISE	346,500	01-01-2015	31-12-2018	European network for the transfer of knowledge in the field of surface engineering into innovative solutions for concentrating solar power (CSP) applications with Abengoa, University of Cranfield, Helmholtz-Zentrum Dresden - Rossendorf e.V., and Metal Estalki (SME).	N/A	N/A
664000	TRANSREGEN	Portable thermal fluid regeneration system for Solar Thermal Plants	SME-1	50,000	01-03-2015	31-08-2015	- New high efficiency oil regeneration system for HTF synthetic oil that implements a compact & transportable design. - Design & validate TRANSREGEN technology in a relevant environment - Demonstration in solar thermal plants in real operating conditions.	SME	N/A
657690	ORC-PLUS	Organic Rankine Cycle - Prototype Link to Unit Storage	IA	6,249,316	01-05-2015	30-04-2019	Improve an existing CSP plant (ORC system , 1 MWe, linear Fresnel collectors, HTF is mineral oil) - Increase thermal storage to 20 MWht, i.e. approx. 4 hours production - Assessment of two kinds of TES system(TRL6) - Demonstration of pilot power plant in relevant environment (TRL7)	5	6
640905	CAPTure	Competitive SolAr Power Towers – CAPTure	RIA	6,104,033	01-05-2015	30-04-2020	- demonstrate a novel concept using multiple towers. - Demonstrate a novel receiver operating at 1200°C with a thermal efficiency of 80%, - develop a complete solar-receiver-Brayton-cycle unit and test it in a controlled and relevant environment. - develop a low cost mirror field using small area heliostats and innovative control systems. - calculate the optimal parameters for a plant that would use the novel distributed power plan concept.	3	*5*

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
654984	PreFlexMS	Predictable Flexible Molten Salts Solar Power Plant	IA	14,362,194	01-06-2015	31-05-2018	1) design and operation of molten salt once-through steam generator with innovative integration of existing technologies 2)integrated weather forecasting and dispatch optimization; 3) pilot plant will be realized to demonstrate integrated operation of 1) and 2) .	6	7
684780	helioSTEAM	A novel concentrated solar steam system for industrial applications with a high degree of pre-manufacturing at extremely low prices.	SME-1	50,000	01-07-2015	31-12-2015	market feasibility study for Fresnex Gmb's solar mirror system	N/A	N/A
667942	CySTEM	Cyprus Solar Thermal Energy Chair for the Eastern Mediterranean	CSA	2,500,000	01-07-2015	30-06-2020	Establish a cluster of outstanding researchers in Cyprus with focus on the Eastern Mediterranean and Middle East. Address CSP technologies for electricity production, desalination, air conditioning and heating.	N/A	N/A
697271	TENCENT	The next generation of Hybrid Concentrating Solar Power Plants	SME-1	50,000	01-08-2015	31-10-2015	Commercial development of Brenmiller Energy 's50kW CSP pilot plant.	N/A	N/A

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
697197	HELIOtube	Inflatable solar collectors for a low cost CSP Plant with irreducibly small carbon footprint	SME-2	1,843,052	01-11-2015	31-10-2017	HELIOtube (is an inflatable cylindrical concentrator made of plastic films. It can concentrate light by a factor of 100 and heats the thermal receiver fluid to a temperature of 400 to 600° C, enough to provide steam to turbines for electricity generation. Tech objectives: 1. Engineering optimisation of the scaled-up collector (9m diameter, 7.5m mirror width, 220m long) and supporting structures. 2. Pilot production line for (partly automated roll-to-roll process); large scale products manufactured. 3. Field demonstration of a system with multiple HELIOtubes (a loop)	6	7
654479	WASCOP	Water Saving for Solar Concentrated Power	RIA	5,941,608	01-01-2016	31-12-2019	Overall aim: reduction in water consumption of up to 70% - 90% and improve the water management; demonstrate technologies in the lab and then validate at four testing sites after lab demonstration. Specific technology targets: - Hybridized cooler TRL 3 to TRL 5 - Adiabatic cooler TRL 3 to TRL 5 - Anti-soiling coatings TRL 3 to TRL 5 - Dust barriers TRL 3 to TRL 5 - Soiling detectors TRL 3 to TRL 6 - Ultrasonic cleaner TRL 3 to TRL 5 - Gravity lip system ?	3	5-6
654443	MinWaterCSP	MinWaterCSP - Minimized water consumption in CSP plants	RIA	5,861,372	01-01-2016	31-12-2018	Combination of i) hybrid dry/wet cooling systems ii) wire structure heat transfer surfaces iii) axial flow fans iv) mirror cleaning techniques and v) optimized water management. -Reduce water evaporation losses by 75 to 95% compared to wet cooling systems. - Increase the net efficiency of the steam Rankine cycle by 2%, or alternatively reduce the capital cost of a dry-cooling system by 25%, while maintaining cycle efficiency. - Reduce PTC mirror cleaning water consumption by 25%, develop a cleaning robot for linear Fresnel collectors and reduce number of cleaning cycles by monitoring of the reflectance of the mirrors.	2-4	4-5

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
654663	SOLPART	High Temperature Solar-Heated Reactors for Industrial Production of Reactive Particulates	RIA	4,366,563	01-01-2016	31-12-2019	Decarbonise cement production with reduction of CO2 by approx. 40% - design and manufacture two lab-scale solar reactors for particle treatment - pilot scale, a high temperature (950°C) 24h/day solar process -supply the thermal energy requirement for CaCO3 calcination, with a 30 kWth solar reactor producing 30 kg/h CaO and a 16h hot CaO storage.		4
692259	NESTER	Networking for Excellence in Solar Thermal Energy Research	CSA	1,060,798	01-01-2016	31-12-2018	Upgrading the scientific and innovation performance of the Cyprus Institute in the field of solar-thermal energy by embedding the Institute's activities in a network of excellence of leading institutions (CIEMAT, ENEA, PROMES/CNRS and RWTH – Aachen).	N/A	N/A
711041	DIMONTEMP	Distributed Monitoring of HTF Temperature at Solar Thermal Power Plants	SME-1	50,000	01-02-2016	31-07-2016	Development of a system for distributed monitoring of HTF temperature at PTC plants using fibre-optics Reduce HTF O&M cost by 38% and enable an 8% increase of production	N/A	N/A
718197	HELITE	High precision and performance heliostat for variable geometry fields of Thermosolar Plants	SME-1	50,000	01-03-2016	31-08-2016	Product that allows variable geometry designs of solar field, allowing them to increase the energy efficiency and the overall performance from the field, improving the relation benefit/cost of current systems. TEWER aims to use this need to sell their pioneer solution.	N/A	N/A
686008	RAISELIFE	Raising the Lifetime of Functional Materials for Concentrated Solar Power Technology	IA	9,291,723	01-04-2016	31-03-2020	Aims to achieve: • 2 different protective coatings for primary 4 mm silvered-glass mirrors • 2 different anti-soiling coatings for silvered-glass mirrors • Primary silvered ultra-thin glass mirror • Secondary silvered high-temperature mirror on stainless steel substrate, for operation up to 350°C • 4 different High Solar Absorptance (HSA) coatings applied on metallic absorber tubes for ST (PVD, ceramic paint with and without aluminide coating and a multi metallic diffusion coating) for steam and molten salts • Absorption and transmittance coating for non-evacuated line focus collectors	4-6	4-7

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
656753	GLASUNTES	Innovative high temperature thermal energy storage concept for CSP plants exceeding 50% efficiency	MSCA	259,558	01/05/2016	30/04/2019	1. An innovative CSP concept with (i) the receiver co-located with the TES vessel, (ii) solar radiation directly absorbed by the liquid storage medium, and (iii) the thermal energy withdrawn by bubbling gas through the TES to be used for a Brayton cycle. 2. Use of common glass-forming compounds as novel TES materials. 3. Integration between receiver–TES and power conversion units.	3	3/4
735379	LIGHTHOUSE	LIGHTHOUSE: concentrated thermal solar power directly connected to the heating and cooling systems of buildings at the local level.	SME-1	50,000	01-08-2016	31-01-2017	Business and market feasibility plan for BCND's Lighthouse Concentrated Solar Collectors with solar tracking	N/A	N/A
723596	Innova MicroSolar	Innovative Micro Solar Heat and Power System for Domestic and Small Business Residential Buildings	RIA	3,999,384	01-09-2016	31-08-2020	- develop a 2-kWel/18-kWth solar heat and power system for application for buildings using solar thermal energy at temperature levels of 250-280 oC. -validate in lab and perform field tests on a demonstration site.	4	(6)
727362	GRIDSOL	Smart Renewable Hubs for Flexible Generation: Solar Grid Stability	RIA	3,421,448	01-10-2016	30-11-2019	- Smart Renewable Hub concept, where a core of synchronous generators (CSP and biogas combined cycle HYSOL) is integrated with PV -research an advanced control (DOME = dynamic output manager for energy) to ensure operation efficiency and grid stability with higher RES penetration - research a multi-tower concept for CSP cost reduction and efficiency improvement,		6 5 4

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
727762	NEXT-CSP	High Temperature concentrated solar thermal power plan with particle receiver and direct thermal storage	RIA	4,947,420	01-10-2016	31-12-2020	-Demonstrate at industrial pilot scale the validity of the particle-in-tube concept atop the Themis facility solar tower. - Construct and test a 4-MWth tubular solar receiver able to heat particles up to 800°C, a two-tank particle heat storage and a particle-to-pressurized air heat exchanger coupled to a 1.2 MWel gas turbine. - Design a commercial scale power plant (150 MWel)	4	(5)
705944	THERMOSTAL L	High Performance Seasonal Solar Energy Latent Heat Thermal Storage Using Low Grade, Low Melting Temperature Metallic Alloys	MSCA -IF-EF-ST	195,455	01-11-2016	31-10-2018	- Select a range of low melting temperature metallic alloys (ELMTAs) for application in LHTESS - Use differential scanning calorimetry to measure their thermal properties. - Conduct thermal cycling tests, numerical investigations of heat transfer and flow in the LHTESS with ELMTAs		2
730609	MSLOOP 2.0	Molten Salt Loop 2.0: key element for the new solar thermal energy plants.	IA	2,243,085	01-11-2016	31-07-2019	Develop a cost effective solar field for CSP PTPs using optimized ternary molten salts as HTF with an innovative hybridization system (HYSOL). - WP2 - Loop Prototype Advanced Development: check ternary molten salts with additives: minimize degradation up to 565 ºC and reduce freezing point below 140 ºC: dynamic loop testing, checking all the properties for 1000 h - WP3 System Manufacturing And Testing: detailed engineering of the loop prototype's main components obtained in WP2; test and validate systems. - WP4 Validation At Pilot Plant Scale	6	6/7
727540	PEGASUS	Renewable Power Generation by Solar Particle Receiver Driven Sulphur Storage Cycle	RIA	4,695,365	01-11-2016	31-10-2020	• Synthesize catalytically active propants that can demonstrate in combination: conversion of SO_3 to SO_2 and O_2 close to respective thermodynamic value, low catalytic deactivation in long-term exposure to reaction conditions, high solar absorptivity and low losses due to abrasion. • Synthesize large-scale quantities (>3 tons) and demonstrate a prototype 500 kWth centrifugal particle solar receiver (to temperatures >900 °C). • Design a particle storage system T>900 °C for at least 6 hours. • Design and operate a lab prototype sulphuric acid decomposition cascade. • Develop and realize a lab-scale (10 kW) sulphur burner with15 bar outlet	2 to 5	(5)

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
							pressure for GT applications.		
727402	MOSAIC	MOdular high concentration SolAr Configuration	RIA	5,077,734	01-12-2016	30-11-2020	- Innovative CSP modular configuration based on a fixed hemispheric semi-Fresnel solar field and a high temperature mobile receiver to decrease costs & increases cycle efficiencies. - Design, manufacture and test molten salt receiver for the application. - LCOE reduction of up to 20 %, pursuing a LCOE below 0.11€/kW	3/4	5
720749	IN-POWER	Advanced Materials technologies to QUADRUPLE the Concentrated Solar Thermal current POWER GENERATION	IA	4,998,928	01-01-2017	31-12-2020	- Develop high efficiency solar harvesting architectures based on holistic materials and innovative manufacturing process - Innovation focus on advanced materials such as High Reflectance Tailored Shape light Free glass mirror, High working temperature absorber in Vacuum Free receiver, optimized Reduced Mass support structure allow upgrading current solar field. - Reduce environmental impact by reducing by 3 standard thermal storage systems;4x reduction the required land - Validation in Lineal Fresnel Collector and Parabolic through collector pilot plants	4	(6/7)
721045	NEXTOWER	Advanced materials solutions for next generation high efficiency concentrated solar power (CSP) tower systems	IA	4,981,304	01-01-2017	31-12-2020	Materials for next gen CSP air-based tower systems: 1– Durable ceramic solar receivers, working under thermal cycling at a maximum materials temperature of at least 800°C and for 20 years. Options for exploitation with molten salt HTF or innovative liquid lead HTF/TES system. 2–Demonstrate the durability of FeCrAl alloys at 700-900°C, thus paving the way to use of liquid lead as innovative heat transfer fluid. 3 – New SOLEAD demo tower CSP with lead loop. Field testing for 12 months with lead at average 700°C 4–Develop harmonized protocols for the solar receiver and for the high temperature FeCrAl steels.	4 to 5	(6 to 7)

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
731287	INSHIP	Integrating National Research Agendas on Solar Heat for Industrial Processes	RIA	2,498,661	01-01-2017	31-12-2020	progressing Solar Heat to Industrial Processes (SHIP) beyond the state-of-the-art through: • an easier integration of low and medium temperature technologies suiting the operation, durability and reliability requirements of industrial end users; • expanding the range of SHIP applications to the energy intensive sector with suitable process embedded solar concentrating technologies; • increasing the synergies within industrial parks,		
706788	NPMSSES	Nanoparticle Enhanced Molten Salts for Solar Energy Storage	MSCA -IF-EF-ST	195,455	01-03-2017	28-02-2019	Study on use of high conductive nanoparticles (NP) to improve the stability and thermo-physical properties of conventional PCMs for solar energy storage, termed as NPMSSES. Molten salts will be used as the matrix, and NPs (i.e., nickel, graphite platelet nanofibers and graphene) or expanded graphite (EG).	N/A	N/A
774866	HP-MOSES	Solar assisted high temperature heat pumps for molten salt energy storage applications.	SME-1	50,000	01-05-2017	31-10-2017	Technical and economic feasibility analysis of a large-scale (50-1000MW) molten salt energy storage system based on solar assisted high temperature heat pumps	N/A	N/A
744914	Solar-Store	Solar Powered Thermochemical Heat Storage System	MSCA -IF-EF-ST	195,455	01-07-2017	30-06-2019	proposed solar powered thermochemical heat storage (Solar-Store) system will integrate solar collector, evaporative humidifier and heat pipe technology with a novel THS reactor design for seasonal storage of solar energy	N/A	N/A
764626	MUSTEC	Market uptake of Solar Thermal Electricity through Cooperation	CSA	2,396,526	01-10-2017	30-09-2020	Analyse European energy market design and policies regarding the value of CSP and related economic and environmental benefits.	N/A	N/A

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
746167	SESPer	Solar Energy Storage PERovskites	MSCA	195,455	13/11/2017	12/11/2020	Study perovskites with earth abundant compositions (Ca-, Fe-, Mn- or Co-based)as storage media for thermo-chemical storage. Specific objectives include: 1. Synthesis by redox-precipitation method. 2. Tuning the thermochemical properties by doping. 3. Enhance the HT properties shaping it in a porous form to get high storage density. 4. Preliminary design of a cascaded TCS system.	N/A	N/A
727348	SOCRATCES	SOlar Calcium-looping integRAtion for Thermo-ChemicalEnergy Storage	RIA	4,994,153	01/01/2018	31/12/2020	Integration of a CSP with a lime calcination process for thermochemical energy storage and power generation by means of a closed CO2 loop. Build a small scale prototype demonstrator and plan for pilot plant Claimed features - Reduced cost for energy storage system below 15€/kWh(th) - Temperatures above 850 ºC for high efficiency power cycle - Solar receivers temperatures below 700ºC for reducing costs - Circulating fluidized bed reactor technology	4	(5)
808944	TurboSol	TurboSol: Turbo-Solar Thermal Power for Industrial Drying Processes	SME-1	50,000	01-03-2018	30-06-2018	Business development for TurboSol, an innovative solution to provide heat for industrial processes using solar thermal power in a system in which solar collectors and a turbocharger integrate to provide hot air at 300ºC without the use of any additional energy sources	N/A	N/A
764048	POLYPHEM	Small-Scale Solar Thermal Combined Cycle	RIA	4,975,961	01-04-2018	31-03-2022	- Develop a solar-driven micro gas-turbine as top cycle and an Organic Rankine Cycle as bottom cycle, with no water requirement for cooling. -meet variable demand of energy with a high average conversion efficiency of 18% and a low environmental profile with an investment cost target below 5 €/W - Build a 60 kW prototype plant with a 2 MWh thermal storage unit and will validate in a relevant environment	4	(5)

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
792276	SHIP2FAIR	Solar Heat for Industrial Process towards Food and Agro Industries Commitment in Renewables	IA	7,996,793	01-04-2018	31-03-2022	- set of tools for the development of industrial solar heat projects during its whole life-cycle - demonstrate at 4 demo-sites for the agro-food sector - achieve up to a 40% of solar fraction		
792103	SOLWARIS	Solving Water Issues for CSP Plants	IA	10,812,50 4	01-05-2018	30-04-2022	- Reduce the water used by CSP plants by 35% for wet cooled & by 90% for dry cooled with innovations on solar field cleaning, power-block cooling, water recycling system, and plant operation strategy. - Implement at La Africana PT plant in Spain and Ashalim CR plant in Israel aiming - save > 0.5 M€/year on OPEX for a 50 MW CSP plant.	5	*(7)*
792073	HyCool	Industrial Cooling through Hybrid system based on Solar Heat	IA	5,818,972	01-05-2018	30-04-2021	Couple Fresnel CSP Solar thermal collectors (FCSP) with Hybrid Heat Pumps ("two-in one" combination of adsorption and compressor based heat pumps) for a wider output temperature range for SHC for industrial environments	4 to 5	7
794562	Small-scale CSP	Numerical and experimental analysis of a novel thermal energy storage for a small-scale concentrated solar power plant	MSCA -IF-EF-ST	212,195	01-06-2018	31-05-2020	- design a novel thermal storage for Fresnel reflector integrated foil based CSP plants, based on a packed bed storage system with heat storage charging and discharging using evaporation/condensation of one or more heat transfer fluids - target cost around 4 €/kWh, less than half that using molten salt (~ 11 €/kWh)	N/A	N/A
789051	OCONTSOLAR	Optimal Control of Thermal Solar Energy Systems	ERC-ADG	2,500,000	01-09-2018	31-08-2023	Develop 1) control methods for sensors mounted on drones and unmanned ground vehicles, 2)spatially distributed solar irradiance estimation methods using a variable fleet of sensors mounted on drones and UGVs., 3) new model predictive control algorithms	3	5

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
823802	SFERA-III	Solar Facilities for the European Research Area - Third Phase	RIA	9,102,631	01-01-2019	31-12-2022	N/A	N/A	N/A
855159	SWCSP - Solar Water	Creating sustainable fresh water from desalinating seawater using Concentrating Solar Power (CSP)	SME-1	50,000	01-02-2019	31-05-2019	Business plan and feasibility study to develop Solar Water Plc's "dome" desalination concept. The glass/steel dome (20 m to 120 m diameter) is surrounded by a heliostat field.	N/A	N/A
814985	SCARABEUS	Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plants	RIA	4,950,266	01-04-2019	31-03-2023	- develop an innovative power cycle based on CO2 blends - test CO2 blend in a loop at 300 kWth scale with typical CSP fluids for 300 hours; measure stability for 2000 hours and material compatibility in dedicated experiments - reduction of CSP CAPEX and OPEX by about 32% and 40% respectively, with final LCoE below 96 €/MWh (30% less than actual value) through	4	(5)
838514	HORIZON-STE	Implementation of the Initiative for Global Leadership in Solar Thermal Electricity	CSA	999,656	01-04-2019	31-03-2022	N/A	N/A	N/A
866633	TANKRETE	A breakthrough concrete mega tank for thermal fluids storage over 500ºC in thermal solar energy generation	SME-1	50,000	01-05-2019	31-10-2019	Feasibility study for an innovative tank for storing thermal solar energy that is 20 % cheaper than current tanks on the market and longer lasting.	N/A	N/A

Id	Acronym	Title	Type	EC Grant	Start Date	End Date	Technical Objectives	TRL start	TRL end
857768	HIFLEX	High storage density solar power plant for FLEXible energy systems	IA	13,557,625	01-09-2019	31-08-2023	Design, build and operate a prototype system including: - 20 MWhth particle storage system with 2.5x higher storage density; - 6000 m^2 heliostat field, providing up to 2 MW/m^2 in the receiver aperture; - 800 kWth particle to steam generator at 620°C; - 100 kWel electric and 800 kWth fuel-base particle heaters; - 800 kWth steam to pressurized water heater (135°C); - Testing over 1000 hour on real industrial environment	5	(7)
831756	THERMES	A new generation high temperature phase change micro-emulsion for latent thermal energy storage in dual loop solar field	MSCA-IF-EF-ST	224,934	17-09-2019	16-09-2021	Study of high energy density, enhanced heat transfer performance through the addition of nanoparticles, and cost-effectiveness due to the use of commercial grade paraffin as the latent heat storage medium.	2	2
880218	AUTO-RST	Flexible automated manufacturing of RST Facets: High Performance Solar Reflectors for CSP industry	SME-2	1,577,233	01-10-2019	30-09-2021	TEWER's patented RST solar reflector is a unique sandwich-type, high performance facet. Phase 2 objective is the large-scale production with facets having an area of up to7 m^2.	6 to 7	(9)

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