European Commission

THEMATIC RESEARCH SUMMARY

Concentrating Solar Power

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setis.ec.europa.eu/energy-research

Executive summary

Key messages

- *CSP encompasses a number of different technologies with varying degrees of maturity and with a number of possible applications due to its multi-input/multi-output capability and intrinsic dispatchability through thermal energy storage.*
- *Demonstrating the commercial readiness and competitiveness for CSP, which the Solar Thermal Electricity European Industrial Initiative focuses on, represents the key challenge in meeting EU targets. LCOE currently ranges between 75 and 360 EUR/MWh, being highly dependent on direct normal irradiation and the wise use of thermal energy storage.*
- *RD&D public expenditure for European countries was about 3.6% of the total European public budget for R&D in the RES sectors. Current R&D efforts are mainly focused on: further cost reduction; full exploitation of cost-effective thermal energy storage and hybridisation solutions; and cogeneration.*

This report has been produced by the Energy Research Knowledge Centre (ERKC) funded by the European Commission, to support its Information System of the Strategic Energy Technology Plan (SETIS). The ERKC project aims to collect, organise and disseminate validated, referenced information on energy research programmes and projects and their results from across the EU and beyond.

The Thematic Research Summaries (TRS) are designed to analyse the results of energy research projects identified by the Energy Research Knowledge Centre (ERKC). The rationale behind the TRS is to identify the most novel and innovative contributions to research questions that have been addressed by European and national research projects on a specific theme.

The present Thematic Research Summary (TRS) provides an overview of the developments for concentrating solar power (also known as solar thermal electricity), and is based on research project results. New, ongoing research projects show the current research trends. Important past projects provide an insight into the research background that led to current R&D topics and commercial developments.

Technology status

Concentrating solar power (CSP) systems use the sun's rays – direct normal irradiation (DNI) – as a high-temperature energy source to produce electricity in a thermodynamic cycle, or to produce synthetic fuels (e.g., hydrogen). Reflective surfaces focus the sunlight onto receivers; a heat transfer fluid (HTF) transfers the thermal energy to an energy conversion unit.

CSP technology encompasses a number of different technologies, with varying degrees of maturity. In terms of geometry and the arrangement of the concentrator with respect to the receiver, there are four main system types: parabolic trough collectors, central receivers, linear Fresnel collectors, and parabolic dish collectors. CSP plants can be conceived and designed with sizes ranging from a few kW to hundreds of MW. In addition, CSP technology can be hybridised with fossil fuels or biomass. Energy storage technology enables CSP systems to increase the dispatchability of production, both in terms of shifting supply to the key evening load periods as well as providing the capacity to cope with intermittent load and solar conditions.

As the above shows, CSP should not be approached as a one-dimensional technology (devoted only to large-scale electricity production) but as a complex technology with a number of possible applications, whose main promising features are its multi-input/multi-output capability (hybridisation with fuel and cogeneration of electricity, heating and cooling or water desalination services) and its intrinsic dispatchability through thermal energy storage.

The levelised cost of electricity (LCOE) levels for a CSP plant are highly dependent on both average yearly available direct normal irradiation and the use of thermal energy storage (TES). To date, the LCOE of a CSP plant can range from 75-360 EUR/MWh based on linear parabolic trough (LPT) and solar tower (ST) technologies, with and without storage, in two regional groupings (Spain, the US & Australia – China & India). Estimates about possible cost reductions for an LPT plant with storage indicate a range between 90 and 110 EUR/MWh by 2022. The capital expenditure (CAPEX) at that time is estimated at 2.5-8 million EUR/MW for an LPT plant and 3-6.3 million EUR/MW for an ST plant, with and without storage.

Policy developments
The first part of the paper includes a brief analysis of the scope of the theme, and a policy review summarising the main policy developments at EU level.

Policy developments at EU level have traditionally been related to achieving the share of renewable energy in gross final energy consumption by 2020 as outlined in Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Six EU Member States (Cyprus, France, Greece, Italy, Portugal and Spain) have set CSP targets in their National Renewable Energy Action Plans that should bring total capacity and electricity production to about 7 000 MW and 20 TWh respectively by 2020.

Demonstrating the commercial readiness of CSP represents one of the challenges in meeting the EU targets. The Strategic Energy Technology Plan (SET-Plan) CSP roadmap constitutes the basis for strategic planning and decision making and in defining the related Solar Thermal Electricity European Industrial Initiative (STE-EII). This European Industrial Initiative aims to demonstrate the competitiveness and readiness for mass deployment of CSP plants. The indicative costs of the STE-EII for the period 2010-2020 are estimated at EUR 7 billion, with RD&D activities focusing both on better technical and environmental performance and on cost reduction.

Current data available on RD&D public expenditure on CSP for European countries indicate a total budget of EUR 38.7 million in 2010, representing about 3.6% of the total European public budget for R&D activities in the RES sectors. Spain, Italy, Germany and France accounted for more than 85% of the 2010 total European public budget.

Current and future research areas

The second part of this report includes an analysis of technology costs, a synthesis of the main findings from research projects, their implications for further research, and the interactions with the SET-Plan strategy. The research projects analysed and presented here include both EU (mainly FP7) and nationally-funded projects, with final or partial results available. As much of the research and development (R&D) effort is of direct and immediate interest to industry, the results of the research often remain unpublished or confidential until it is no longer on the frontline of development.

The research projects contribute to the Key Performance Indicators (KPIs). In general, most of the KPIs are covered by one or more projects. Projects are often not directly linked to KPIs but indirectly contribute to them by focusing on cross-cutting KPI aspects such as 'Solar resource measurement and forecasting' and 'Research facilities and basic R&D support'. At the same time, 'Solar chemistry' projects focus on relatively long-term R&D that is considered promising within the scientific community, yet is not included in the more industry-oriented KPIs. Understandably, contributions to those KPIs that can be more directly linked to an R&D activity are greater.

The current R&D effort is mainly focused on further reducing costs, on fully exploiting cost-effective thermal energy storage and hybridisation solutions, and on cogeneration of power and heat. A major effort will continue on increasing temperatures and introducing high-temperature power cycles, for example, supercritical steam and solar-driven gas turbine combined cycles, with gaseous heat transfer media, on further developing thermal storage technologies and on whole system optimisation.

As the renewable input to electrical networks is dramatically increasing, the quantification of the value of CSP dispatchability in the different markets is expected to gain momentum.

At the same time, the share of R&D on solar chemistry, with a long-term industrial outlook, is increasing in terms of the number of projects being implemented, and this trend is likely to continue to expand. Research on solar chemistry and chemical engineering is expected to increase attention on the development of thermo-chemical storage and the production of solar fuels. These two subjects are becoming increasingly important within the context of the long-term potential for the high penetration of renewable energy in the world energy mix.

International developments

The largest share of market potential for CSP products and plants lies outside of Europe. The main comprehensive CSP R&D programmes are in the USA (e.g., the Sunshot Initiative of the Department of Energy) and in China and Australia, but also in Israel and Switzerland. The R&D programmes of these countries involve long-term basic research activities and the R&D challenges are generally similar to those addressed in Europe.

As CSP is developed throughout the world, it must be stressed that spillover effects result in EU and foreign developments jointly improving the technology. The EU benefits as foreign developments help it reach its goals. To maintain a competitive position in the global CSP market, which is mostly outside Europe, European R&D efforts could aim at maintaining Europe's leadership in specific areas within CSP, while linking to the non-EU effort in order to access foreign markets.

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1 Introduction

This publication has been produced as part of the activities of the ERKC (Energy Research Knowledge Centre), funded by the European Commission to support its Information System of the Strategic Energy Technology Plan (SETIS).

The ERKC collects, organises and analyses validated, referenced information on energy research programmes and projects, including results and analyses from across the EU and beyond. Access to energy research knowledge is vastly improved through the ERKC, allowing it to be exploited in a timely manner and used all over the EU, thus also increasing the pace of further innovation. The ERKC therefore has a key role in gathering and analysing data to monitor progress towards the objectives of the European Strategic Energy Technology Plan (SET-Plan). It also brings important added value to the monitoring data by analysing trends in energy research at national and European levels and deriving thematic analyses and policy recommendations from the aggregated project results.

The approach to assess and disseminate energy research results used by the ERKC team includes the following three levels of analysis:

- **Project analysis**, providing information on research background, objectives, results and technical and policy implications on a project-by-project basis;
- **Thematic analysis**, which pools research findings according to a classification scheme structured by priority and research focus. This analysis results in the production of a set of **Thematic Research Summaries (TRS)**;
- **Policy analysis**, which pools research findings on a specific topic, with emphasis on the policy implications of results and pathways to future research. This analysis results in the compilation of **Policy Brochures (PB)**.

The Thematic Research Summaries are designed to provide an overview of innovative research results relevant to the themes which have been identified as of particular interest to policymakers and researchers. The classification structure adopted by the ERKC team comprises 45 themes divided in 9 priority areas. Definitions of each theme can be found on the ERKC portal at:

setis.ec.europa.eu/energy-research.

Table 1: ERKC priority areas and themes

Priority area 1: Low-carbon heat and power supply
Bioenergy / Geothermal / Ocean energy / Photovoltaics / Concentrated solar power / Wind Hydropower / Advanced fossil fuel power generation / Fossil fuel with CCS / Nuclear fission Nuclear fusion / Cogeneration / Heating and cooling from renewable sources
Priority area 2: Alternative fuels and energy sources for transport
Biofuels / Hydrogen and fuel cells / Other alternative transport fuels
Priority area 3: Smart cities and communities
Smart electricity grids / Behavioural aspects - SCC / Small scale electricity storage / Energy savings in buildings / ICT in energy / Smart district heating and cooling grids - demand Energy savings in appliances / Building energy system integration
Priority area 4: Smart grids
Transmission / Distribution / Storage / Smart district heating and cooling grids - supply
Priority area 5: Energy efficiency in industry
Process efficiency / Ancillary equipment
Priority area 6: New knowledge and technologies
Basic research / Materials
Priority area 7: Energy innovation and market uptake
Techno-economic assessment / Life-cycle assessment Cost-benefit analysis (Market-) decision support tools / Security-of-supply studies / Private investment assessment
Priority area 8: Socio-economic analysis
Public acceptability / User participation / Behavioural aspects
Priority area 9: Policy studies
Market uptake support / Modelling and scenarios / Environmental impacts / International cooperation

The purpose of the Thematic Research Summaries is to identify and trace the development of technologies in the context of energy policy and exploitation.

The TRS are intended for policy makers as well as any interested reader from other stakeholders and from the academic and research communities.

The present TRS deals with concentrating solar power/solar thermal electricity. Its aim is to provide the reader with a structured, but not necessarily fully comprehensive review of research activities relating to CSP/STE being carried out in Europe, both at EU level and as part of nationally-funded programmes.

The TRS focuses on those research projects which have sufficient documentation on their results to show technological achievements in the field of CSP. In total, 39 projects are presented.

Specifically, the TRS covers 20 CSP R&D projects that have been recently completed or have not yet been completed but have significant preliminary results available (13 EU projects from FP6/FP7 and 7 national projects). It also includes 13 new projects financed under the last FP7 calls and 6 new nationally-funded projects that make a significant contribution to setting up the path for actual R&D efforts and trends. For completeness, references to significant research projects from previous FPs have been taken into account since they appear to have been particularly fruitful in terms of industrial outcome.

The TRS is organised as follows. **Section 2** includes a brief analysis of the scope of the theme. **Section 3** provides an overview of the relevant policy priorities both at EU and national levels. The sources of this section are European Commission documents, NREAPs (National Renewable Energy Action Plan) and ESTELA (European Solar Thermal Electricity Association) strategic documents. **Section 4** provides an overview on the cost of technology, reports on the results from specific research projects and examines gaps and topics for future research identified in the projects. This section is structured according to sub-themes covering the broad area of CSP research.

The following nine sub-themes have been considered.

Table 2: CSP sub-themes

Sub-theme	Description
1	Parabolic trough technology and components
2	Central receiver technology and components
3	Linear Fresnel technology and components
4	Parabolic dish technology and components
5	Thermal energy storage/heat transfer fluids
6	Plant concepts/prototypes and plant components
7	Research facilities and basic R&D support
8	Solar chemistry
9	Solar resource measurement and forecasting

The research projects identified for each of the nine sub-themes are presented in the table in annex 2 to this report. Links to project websites (if available) are also included in the table. In several cases these websites make project documentation available to the public. This may include the project final reports and selected deliverables, but this is not the general case. It should be stressed that since most of the R&D involved is of significant industrial interest, the technical details of the results are normally kept confidential and are not published until they are no longer on the frontline of development.

Section 5 gives an overview of current trends in CSP R&D and industrial production beyond Europe. **Section 6** provides an updated picture of the latest developments and the future of the technology described in the SET-Plan technology map, based on an analysis of the research results carried out in section 4. **Section 7** gives an overview of public funding for CSP RD&D, based on statistics from the International Energy Agency. Finally, **section 8** provides an overview of the key issues and recommendations that can be drawn from the TRS.

2 Scope of the theme

CSP technology is based on devices that use an optical system to concentrate sunlight – direct normal irradiation (DNI) – and produce high-temperature heat, which is generally transported by a heat transfer fluid (HTF) to an energy conversion unit. The purpose of this unit is to transform the heat into electricity by means of thermodynamic conversion (e.g., a steam turbine) or into a synthetic fuel (e.g., hydrogen or syngas) by means of thermochemical conversion. Up to now, most CSP applications have focused on electricity production with plants in the range of 10 to 200 MW of nominal capacity. This type of plant is becoming commercially available and, therefore, commercially exploited in the Solar Belt area around the tropics, on both sides of the Equator.

Since high-temperature heat can be stored at relatively low cost, a thermal energy storage (TES) system is often added to a plant in order to increase the dispatchability of the electrical output, in other words to increase the degree of independence of the output with respect to solar input. This feature currently gives CSP an increasingly distinct advantage over other renewable technologies – e.g., photovoltaics – and provides opportunities for further development.

Another feature of CSP technology is its ability to cogenerate heat and electricity (in addition to cooling and water desalination), and to be integrated or hybridised with fossil fuel based electricity generation (e.g., natural gas or coal) or other forms of renewable electricity generation (biomass, biogas).

Summing up, CSP comprises a number of technologies and devices at different stages of commercial availability/maturity that can be combined in different ways.

As a consequence, CSP R&D is focused on a number of different areas, including atmospheric physics, optics, materials, chemistry, thermal machinery, process control and manufacturing.

Traditionally, most R&D efforts have focused on concentration devices, but other aspects have been identified as relevant to understand the technological evolution of the theme.

In particular, the sub-themes listed in chapter 1 were selected as being representative of the current stage and the future of CSP thematic research.

The first four sub-themes are:

- Parabolic trough technology and components;
- Central receiver technology and components;
- Linear Fresnel technology and components;
- Parabolic dish technology and components.

These sub-themes (as defined by the SolarPACES website www.solarpaces.org and in chapter 3 of the 2011 Technology Map of the SET-Plan) are devoted to the R&D effort on the solar devices needed to produce medium-high temperature heat for a plant.

The 'Thermal energy storage/heat transfer fluids' sub-theme is devoted to R&D on a basic plant component that has become increasingly important in order to exploit CSP's ability to produce dispatchable output; and is focused on increasing the quality (in terms of temperature range and cost) of the heat transfer fluid.

The 'Plant concepts/prototypes and plant components' sub-theme is devoted to the whole CSP plant; from the development to experimental operation of new plant concepts or new plant prototypes at reduced or full scale.

The 'Research facilities and basic R&D support' sub-theme is becoming increasingly important as the budget required to bring new ideas from the development to the industrial phase increases, therefore the existence of multi-user facilities reduces global expenditure.

The 'Solar chemistry' sub-theme is devoted to the production of synthetic fuels (e.g., hydrogen or syngas) and processing of materials through high-temperature solar heat. This technology is not yet at the stage of industrial exploitation, but is gaining increasing importance since the R&D effort is moving in this direction.

Finally, the 'Solar resource measurement and forecasting' sub-theme has a distinctive scientific background and an increasing commercial importance both for the economic assessment of new plant projects and because radiation forecasts can be used to optimise plant management.

3 Policy context

3.1 EU policy framework

CSP represents one of the technologies for achieving Europe's ambitious climate and energy targets by 2020, identified by Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The Directive also requires Member States to produce National Renewable Energy Action Plans (NREAPs) to identify the technological pathways by which these goals can be reached. Six EU Member States (Cyprus, France, Greece, Italy, Portugal and Spain) have set specific CSP installation targets by 2020 in their NREAPs, which should bring the combined European capacity to about 7 000 MW and electricity production to 20 TWh by the end of the current decade[1].

Even if recent political upheaval in North Africa and increasing domestic installation of solar systems in Europe has somewhat lessened the immediate appeal of large energy interchange projects like DESERTEC, CSP remains one of the main technologies that can play a strategic role in the supply of electricity produced from renewable energy sources in neighbouring regions like the Southern Mediterranean, helping to meet both local demand and, with the development of long-distance grid interconnections, a certain amount of EU demand. More interconnections will also enable European countries to export and import renewable electricity, making it possible to ensure reliable energy supplies and to balance power generation. Apart from its potential value for international renewable energy exchange, CSP added value in terms of exporting know-how, plant engineering and high-tech components to Solar Belt markets should also be considered.

The European Commission launched the European Strategic Energy Technology Plan (SET-Plan) to help achieve European objectives and meet challenges related to energy technologies. In the SET-Plan framework, seven roadmaps have been proposed[2] to serve as a basis for strategic planning and decision making and in particular for defining the European Industrial Initiatives (EIIs). The aim of these roadmaps is to raise the maturity of the selected technologies, enabling them to achieve growing market shares by 2050.

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[1] Renewable energy projections as published in the National Renewable Energy Action Plans of the European Member States. ECN, 28 November 2011.

[2] SEC(2009) 1295.

The Solar Thermal Electricity European Industrial Initiative (STE-EII) focuses on CSP technologies. It aims to demonstrate the competitiveness and readiness for mass deployment of advanced CSP plants through the scaling-up of technologies to pre-commercial or commercial level. The STE-EII RD&D activities are focused both on achieving large-scale, sustainable and advanced CSP plants with better technical and environmental performance, and on cost reduction through better system efficiency, storage, hybridisation and reduced water consumption. The development of innovative components and cycles in these areas and their demonstration at industrial level are a priority. The indicative costs of the EII for CSP technologies during the period 2010-2020 are estimated at EUR 7 billion. A detailed cost breakdown is shown in the table below.

Table 3: Indicative costs (2010-2020) for the STE-EII - concentrating solar power

Technology objectives	Costs (million EUR)
1. Increase efficiency & reduce generation costs	4 400
2. Increase dispatchability	1 700
3. Improve the environmental footprint	800
4. Longer-term R&D	100
Total	7 000

The European Energy Research Alliance (EERA[3]) aims to accelerate the development of new energy technologies by implementing Joint Research Programmes in support of the SET-Plan. EERA launched a Joint Programme (JP) on CSP in November 2011. Its main purpose is the integration and scientific coordination of research institutions working on CSP.

More recently, the staff working document[4] to the Communication 'Renewable energy: a major player in the European energy market'[5] has highlighted the importance of CSP, including it in the list of strategic energy technologies which need to be developed for a secure, clean and efficient energy system by 2050 and to maintain European industrial leadership in the field of renewable technologies. In particular, this staff working document emphasises the importance of further research on advanced concepts like molten salts/solar troughs, direct steam/Fresnel collectors and molten salts/solar towers in order to achieve technological innovations.

The 'Roadmap for moving to a competitive low carbon economy in 2050'[6] and the 'Energy Roadmap 2050'[7] of the European Commission

[3] http://www.eera-set.eu
[4] SWD(2012) 164 final.
[5] COM(2012) 271 final.
[6] COM(2011) 112 final.

both emphasise that in the CSP sector much more challenging technological trajectories are required. In particular the Energy Roadmap points out that renewable energy technologies, especially new ones such as CSP, need further development and investments to bring down costs and change them from subsidised to competitive technologies.

Table 4: Relevant policy documents on CSP

Policy documents	
1.	Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions COM(2013) 253 final. Energy Technologies and Innovation.
2.	Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.
3.	Communication from the Commission to the European Parliament, the Council and the European Economic and Social Committee and the Committee of the Regions COM(2007) 723 final. A European Strategic Energy Technology Plan (SET-Plan). 'Towards a low carbon future'.
4.	Communication from the Commission to the European Parliament, the Council and the European Economic and Social Committee and the Committee of the Regions COM(2009) 519 final. Investing in the Development of Low Carbon Technologies (SET-Plan).
5.	Communication from the Commission to the European Parliament, the Council and the European Economic and Social Committee and the Committee of the Regions COM(2011) 112 final. A Roadmap for moving to a competitive low carbon economy in 2050.
6.	Communication from the Commission to the European Parliament, the Council and the European Economic and Social Committee and the Committee of the Regions COM(2011) 885 final. Energy Roadmap 2050.
7.	Communication from the Commission to the European Parliament, the Council and the European Economic and Social Committee and the Committee of the Regions COM(2012) 271 final. Renewable Energy: a major player in the European energy market.

Policy support documents	
1.	Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States. ECN, November 2011.
2.	Plan de Energias Renovables 2011-2020. IDAE, November 2011.
3.	Resolução do Conselho de Ministros N.º 20/2013 (Portuguese government). Diário da República, 1.ª série, N.º 70, 10 April 2013.
4.	Solar Thermal Electricity Strategic Research Agenda 2020-2025. ESTELA, December 2012.
5.	The Essential Role of Solar Thermal Electricity: A Real Opportunity for Europe. ESTELA, October 2012.

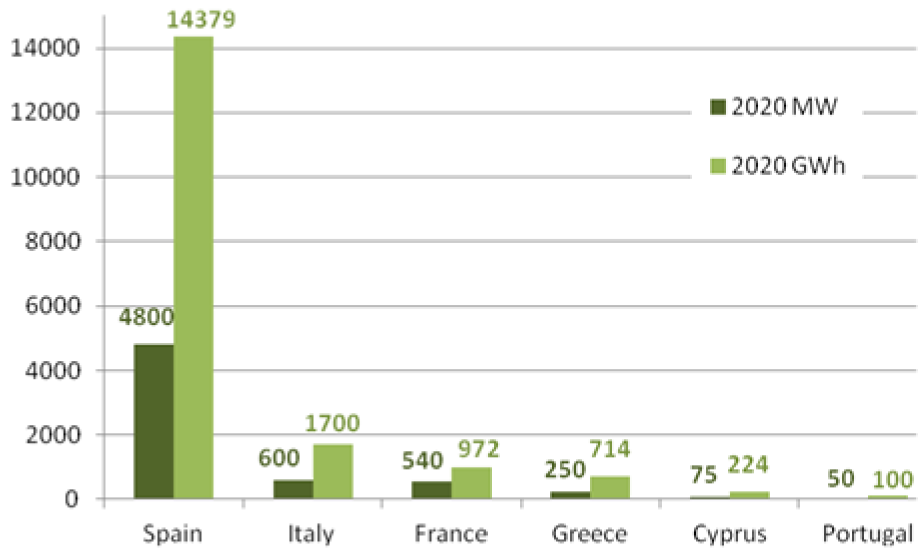
[7] COM(2011) 885 final.

3.2 Member States' activities

Spain is globally the leading country in the CSP sector with an installed capacity of about 2 GW. In its NREAP the country has set the highest CSP capacity target among all Member States. Initially the Spanish government planned to achieve a 5 079 MW capacity target by 2020, but then this figure was revised to 4 800 MW[8] (14.4 TWh of electricity, Figure 1).

In its NREAP, Italy has set the second highest CSP capacity target for 2020, corresponding to 600 MW of capacity and 1.7 TWh of electricity production. France estimates its 2020 CSP capacity at 540 MW with an annual production of 972 GWh. Greece and Cyprus have identified CSP trajectories in their NREAPs estimating a total capacity by 2020 of respectively 250 MW generating 714 GWh, and 75 MW producing 224 GWh. Portugal, a country with high potential for deploying CSP technology, initially set a capacity target in its NREAP of 500 MW by 2020, but then revised this downward to 50 MW[9] as a result of uncertainties surrounding the country's renewable energy policy.

Figure 1: Projected CSP capacity (MW) and electricity generation (GWh) in 2020



Source; ECN, IDAE, Portuguese Government

Regarding national subsidies, feed-in-tariffs are the most widespread form of CSP support in EU countries. To date, the average feed-in-tariff paid for solar thermal electricity in these countries is around 0.20-0.30 EUR/kWh[10], depending on the country and the plant

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[8] Plan de Energias Renovables 2011-2020. IDAE, November 2011.
[9]Resolução do Conselho de Ministros n.º 20/2013 (Portuguese Government). Diário da República, 1.ª série N.º 70, 10 April 2013.
[10] Strategic Research Agenda 2020-2025. ESTELA, December 2012.

parameters, but the situation remains very uncertain due to the economic downturn and a general revision of mechanisms supporting renewable energies.

3.3 CSP outlook

Recently the European Solar Thermal Electricity Association (ESTELA) produced two significant documents about the role and future deployment of CSP plants and technologies in Europe. One is the Association's first position paper, entitled 'The Essential Role of Solar Thermal Electricity: A Real Opportunity for Europe', dated October 2012, which aims to show the significant industrial opportunities for EU countries in the CSP sector in the near future. The second document is the 'Strategic Research Agenda for 2020-2025', dated December 2012. This document sets out the strategic research priorities for Europe in order to identify future challenges for CSP technology. The Strategic Research Agenda estimates a global installed capacity of 10 GW by 2015 and 30 GW by 2020, including 7 GW installed in EU countries in 2020. However, recent economic changes in countries of interest, including EU countries, mean that the 2020 targets are being revised downwards. According to the IEA, CSP reached 2.8 GW of installed operating capacity worldwide at the end of 2012.

4 Research findings

4.1 Introduction

The R&D effort on CSP is currently concentrated on developing devices and plant concepts/prototypes to be manufactured or installed by industrial companies (as soon as the concepts/ prototypes reach commercial maturity). This chapter describes research results obtained from these efforts. The descriptions are based on the final report of projects financed by the European Commission and individual Member States. Relevance to the STE-EII KPIs – listed in annex 3 – is indicated in the project descriptions.

The research summarised in this document is broken down into nine sub-themes, as described in the introduction. The first four sub-themes (concentrating technologies) and the solar chemistry sub-theme are internationally recognised within the CSP community. The other sub-themes have been selected based on observations of CSP research fields.

4.1.1 Short description

The first four sub-themes are devoted to the R&D effort on the solar devices needed to produce medium-high temperature heat for a plant; these solar devices consist of mirrors that collect and concentrate the solar irradiation (i.e. DNI), and receivers that transform the concentrated flux into heat. In some cases, the mirrors and receivers are almost fully integrated, as is the case with dishes. In other cases they are completely separate, as with central receiver/heliostat field systems.

Traditionally (see, e.g., the SolarPACES website www.solarpaces.org or Jäger-Waldau, 2011, for a more detailed technical description), the **four basic technologies** - and consequent sub-themes - related to solar devices are:

- **Linear parabolic trough systems (LPT).** Here, a number of collectors use parabolic mirrors to concentrate the solar flux onto a receiver pipe positioned at a focal point; an HTF circulates inside the receiver and heats up to 300-550 °C due to the concentrated solar flux. The HTF is then used by a thermodynamic conversion unit (power block), normally comprising a steam turbo-generator, to generate electricity. Each collector rotates along one axis in order to track the sun. A number of collectors can be connected into a series to form a solar field. This is the most commercially available technology to date.

- **Central receiver technology and components.** These are more commonly known as solar towers (ST). In this case a number of individual mirrors (heliostats) reflect the DNI onto a solar receiver located on a tower; each heliostat rotates along two axes in order to track the sun. The hot HTF from the receiver is then used by a power block. In some cases the receiver is located at ground level and the concentrated flux is produced by a secondary mirror system – at which the heliostats are aimed - positioned on a tower (beam-down system). Single or multiple towers can be installed at a plant. The tower system makes it possible to reach higher concentration levels and, therefore, higher temperatures. This technology is currently entering the commercial phase.
- **Linear Fresnel technology.** In these systems a number of linear and almost flat mirrors (linear Fresnel reflector collectors - LFRCs) reflect and focus the solar flux onto a receiver pipe, similar to the parabolic trough system. The basic difference is that each collector actually consists of multiple mirrors that rotate independently along one axis in order to track the sun, so the receiver does not move. The power block is similar to that of a parabolic trough. An LFRC permits the maximum exploitation of the available land and promises to be cheap, but it has some efficiency limitations. It is currently entering the commercial phase.
- **Parabolic dish technology.** In these systems a parabolic-shaped mirror (dish), rotating along two axes, tracks the sun in order to concentrate the solar flux onto a receiver positioned at a focal point. A heat engine (e.g., a Stirling engine or a micro-gas turbine driving an electrical generator) transforms the heat into electricity. Due to mechanical limitations, each device is normally rated in the 3-30 kW range of electrical output. Multiple devices can be deployed in order to create large plants. At the moment this technology is still at the pre-industrial R&D stage.

The **thermal energy storage/heat transfer fluids** sub-theme deals both with thermal storage, a basic plant component that is becoming increasingly important from the point of view of exploiting CSP’s ability to produce dispatchable output, and with new developments in HTF, aimed at increasing the temperature range and/or reducing costs.

These two subjects are interconnected since the choice of HTF often influences the choice of storage technology and the medium. A number of HTFs, either liquid, gaseous or solid (microspheres), are being evaluated. There is a variety of solutions available for thermal storage systems, both proven and under development.

The **plant concepts/prototypes** sub-theme is devoted to the whole CSP plant; namely from development to experimental operation of new types of plant concepts or new plant prototypes at reduced or full scale. A CSP plant can be planned and implemented in a number of different ways, influenced by various factors, including: the type of optical technology; HTF choice and temperature level; TES; hybridisation with fossil fuel or biomass fuel; type of power cycle (steam turbine, organic Rankine cycle (ORC), combined cycle with gas turbine); and cogeneration/ trigeneration (electricity/heat/refrigeration). R&D on major plant components that are not part of the solar subsystem has also been included in this sub-theme.

The **research facilities and basic R&D support** sub-theme is becoming increasingly important as the budget required for the development of new ideas up to the industrial phase increases, therefore the existence of multi-user facilities reduces the overall expenditure.

The **solar chemistry** sub-theme is not yet at the industrial exploitation stage, but is gaining in importance as the R&D effort is set to rapidly move in this direction. The aim is to produce synthetic fuels (for example hydrogen) or synthetic materials using CSP.

The last sub-theme is devoted to **solar resource measurement and forecasting**. The type of techniques involved in resource assessment and forecasting are distinctive. The measurement of the solar resource is becoming more and more important since a single large CSP project can cost hundreds of millions of euros or even up to one billion euros, and a margin of error of a single per cent in the solar input evaluation can have a direct influence on the return on investment (ROI). Moreover, the solar input forecast (from a period of 3 days down to minutes) is of commercial interest in order to optimise plant management.

4.1.2 Technology costs

A chapter on the current costs for CSP technology is necessary in order to understand the main drivers of the current R&D efforts.

Generally speaking, the objective of any CSP plant is to produce competitive energy. Restricting ourselves to electric energy production means either minimising the LCOE (levelised cost of electricity, EUR/MWh) or maximising the value of the electricity sold by the CSP plant owner to the customer (e.g., a grid operator).

The actual profitability of a plant depends on the local subsidy schemes such as feed-in-tariffs and its ability to participate in electricity markets such as spot and balancing markets due to the dispatchability of power production.

The LCOE includes fixed costs related to investment, fixed operation and maintenance (O&M) and decommissioning as well as variable costs such as costs for O&M, fuels and consumables. As it is based on the kWh produced, the LCOE is also sensitive to the number of annual full load hours. Annual capital costs depend on the discount rate and the period for amortisation.

Among the above mentioned LCOE components, **investment costs** are the factor most influenced by technology; in turn, these can be related to component costs. Costs, both of the plant and of major components, are dependent on the market, but as a reference - a single CSP plant can cost in the order of EUR 1 billion. The figures illustrated in this TRS are based on recent publicly available studies [*World Energy Perspective – Cost of Energy Technologies*, World Energy Council, 2013. *Concentrating Solar Power – Technology Brief*, IEA-ETSAP/IRENA, 2013][11].

It should be taken into consideration that an established market exists only for parabolic troughs and partially for solar towers (ST).

LCOE is highly dependent on the average yearly available direct normal irradiation (DNI), in fact the higher the electricity production, the lower the LCOE. DNI levels can vary from 1 900-2 200 kWh/m^{2}y at the best sites in Southern Europe to up to 3 500 kWh/m^{2}y in some desert spots, like Chile's Atacama. Values in the range of 2 400-2 500 kWh/m^{2}y are common at most of the best DNI sites, where a CSP plant could be located.

Another important aspect to take into account is the effect of thermal energy storage (TES). Storage influences not only the value of the electricity produced (increasing its dispatchability) but also the LCOE itself; in fact, the introduction of TES makes it possible to increase the capacity factor (ratio between **expected production** and **theoretical production** that could be achieved if the plant were to operate at its rated power on a year-round basis). The so-called "equivalent hours of production" per year also increase (up to 6 000 hours/year with 15 hours of TES capacity). As a result, a decrease in the LCOE can be achieved while increasing the **overall CAPEX**. However there is no general consensus on whether, and at what level, LCOE is reduced by adding TES.

Taking this into account, the actual figures for LCOE can range from 75 to 360 EUR/MWh for LPTs and STs, with and without TES, in the two market groups (Spain, US, Australia - China & India) identified in the World Energy Council (WEC) document. The same study quotes a possible reduction for LPTs with storage to 90-110 EUR/MWh by 2022, from the current level of 220 EUR/MWh, quoting a study from 2012.

In turn, the IEA-ETSAP/IRENA study quotes a potential reduction in LCOE to 110-175 EUR/MWh by 2015, from the current levels of 145 EUR/MWh for LPT plants with six hours of storage and high DNI, to 240 EUR/MWh for LPTs without storage and low DNI. According to the same source, the LCOE for ST ranges from 125-175 EUR/MWh (with 12-15 hours of storage) to 160-200 EUR/MWh (with 6-7 hours of storage).

[11] Cost figures are reported in euros using the average exchange value between 2008-2012 of 1.3736 US$/EUR.

On the other hand, a recent power purchase agreement (PPA) for a 110 MW ST in the US (SolarReserve's Crescent Dunes project) was officially signed at 98 EUR/MWh.

Finally, it should be noted that the US SunShot R&D programme targets an LCOE level of 45 EUR/MWh by 2020; this target is considered quite optimistic.

The spread in total investment costs also varies for different sources. Again, it must be stressed that a relatively established market exists only for LPTs and STs, while Fresnel collectors are considered cheaper (but less efficient) than LPTs, and solar dishes are at the prototype stage, so no data are currently available.

The WEC quotes the following data, in millions of EUR per MW of rated capacity, from existing installations:

Table 5: Total investment cost of CSP by region and technology

Market location	Type of technology	CAPEX (M€/MW)
Spain, US & Australia	LPT without TES	2.5 – 5.6
	LPT with TES	4.4 – 8.0
	ST without TES	3.0 – 4.5
	ST with TES	4.4 – 6.3
China & India	LPT without TES	2.2 – 3.3

Source: World Energy Council – from Bloomberg data

It's worth noting that even if Spain, the US and Australia are considered a unique market grouping in the report, CAPEX in the US market is generally lower than in the European market.

The IEA-ETSAP/IRENA study in its LCOE analysis assumes the following CAPEX data for LPTs and STs:

Table 6: Specific investment cost of CSP by technology

	CAPEX – 2011 (M€/MW)	CAPEX – 2015 (M€/MW)
LPT without TES	3.3	2.8-3.0
LPT with 6 h TES	5.2-7.1	4.6-6.0
ST with 6-7.5 h TES	4.6-5.4	4.1-4.6
ST with 12-15 h TES	6.6-7.6	6.0-6.6

Source: IEA-ETSAP/IRENA 2013

CSP is a capital intensive technology with specific investments significantly higher than those for onshore wind. Nevertheless, depending on local conditions, the LCOE of CSP and onshore wind power are in the same range (SBC 2013).

R&D can contribute at different levels to improve all the factors involved in CSP competitiveness.

Local **solar resource knowledge** can be improved through a targeted R&D effort, by both introducing new methods and measurement devices and performing local studies; this in turn could increase the value of electricity (e.g., using weather forecasts to increase the value of production) and reduce O&M costs by optimising maintenance schedules.

Reducing upfront **investment costs** is where R&D can contribute most, in a number of different ways ranging from components to plant design. It must be stressed that the effect of the R&D effort on components and new plant concepts on the commercial outcome (real market price of CSP) is generally deferred for a considerable period of time.

O&M costs can be reduced by specific R&D actions, mainly focused on increasing both component and plant reliability and reducing the cost for component repair or replacement.

Finally, **financial conditions** may be positively influenced by actions aimed at the dissemination of knowledge and better performance modelling; this should increase investor confidence in the specific market.

4.1.3 List of projects sorted by sub-theme

Information on the findings of CSP research is based on the projects listed below. Funding programme information for each of these projects is presented in annex 2.

Table 7: List of projects by sub-theme

Sub-theme 1: Parabolic trough technology and components		
Project acronym	Project title	Budget (million EUR) total/funded[12]
TUBOSOL	Tubo Assorbitore di Energia Solare (Solar Energy Absorber Pipe)	12.45 total 3.9 govt. funds
HITECO	New Solar Collector Concept for High Temperature Operation in CSP Applications	5.75 total 3.44 EC contrib.
GEDIVA	Estudios Termo-Hidráulicos de Sistemas con Captadores Solares Cilindroparabólicos para la Generación Directa de Vapor (Thermo-hydraulic Analysis of Parabolic Trough Receivers for Direct Steam	0.27 total 0.1 govt. funds

[12] Budget cost in million euros reports the total project cost (if available) and the funded amount (by EU or national Governments).

	Generation)	
DUKE	Durchlaufkonzept-Entwicklung und Erprobung (Once-through Concept Development and Testing)	3.9 total 2.5 BMU fund
Ultimate Trough	Ultimate Trough	Total N.A. 1.9 BMU fund

Sub-theme 2: Central receiver technology and components		
Project acronym	Project title	Budget (million EUR)
SOLUGAS	Solar Up-Scale Gas Turbine System	11.62 total 6.0 EU funding
HYGATE	Hybrid High Solar Share Gas Turbine Systems	Total: N.A. 1.3 BMU fund

Sub-theme 3: Linear Fresnel technology and components		
Project acronym	Project title	Budget (million EUR)
AUGUSTIN FRESNEL 1	AUGUSTIN FRESNEL 1	N.A.
LFR500	Linear Fresnel Reflectors 500	5.9 total 2.9 govt. funds
eCARE	eCARE	10.1 total 4.4 govt. funds

Sub-theme 4: Dish technology and components		
Project acronym	Project title	Budget (million EUR)
OMSOP	Optimised Micro-Turbine Solar Power System	5.84 total 4.42 EU contrib.

Sub-theme 5: Thermal energy storage/heat transfer fluids		
Project acronym	Project title	Budget (million EUR)
OPTS	Optimisation of a Thermal Energy Storage System with Integrated Steam Generator	13.7 total 8.6 EU contrib.
CSP2	Concentrated Solar Power in Particles	3.14 total 2.26 EU contrib.
RESTRUCTU RE	Redox Materials-Based Structured Reactors/Heat Exchangers for Thermochemical Heat Storage Systems	3.07 total

	in Concentrated Solar Power Plants	
TCSPOWER	Thermochemical Energy Storage for Concentrated Solar Power Plants	4.25 total 2.85 EU contrib.
STARS	Stockage Thermique Appliqué à l'Extension de Production d'Energie Solaire Thermodynamique (Thermal Storage applied to the Extension of Solar Thermodynamic Energy Production)	16.3 total 6.7 govt. funds
STORRE	High Temperature Thermal Energy Storage by Reversible Thermochemical Reaction	3.08 total 2.23 EU contrib.

Sub-theme 6: Plant concepts/prototypes		
Project acronym	Project title	Budget (million EUR)
ARCHETYPE SW550	Demonstration of Innovating Parabolic Solar Trough Using an Alternative Heat Transfer Fluid Producing Electricity and Fresh Water: ARCHIMEDE Hot Energy Typology Enhanced Water Solar 550	24.4 total[13] 14.4 EU contrib.
MATS	Multipurpose Applications by Thermodynamic Solar	20.45 total 11.45 EU contrib.
DiGeSPo	Distributed CHP Generation from Small Size Concentrated Solar Power	4.54 total 3.28 EU contrib.
E2PHEST2US	Enhanced Energy Production of Heat and Electricity by a Combined Solar Thermionic-Thermoelectric Unit System	2.69 total 1.98 EU contrib.
HYSOL	Innovative Configuration for a Fully Renewable CSP Plant	9.25 total 6.16 EU contrib.
STS-MED	Small Scale Thermal Solar District Units for Mediterranean Communities	4.95 total 4.45 EU contrib.
SOLMASS CSP	Solmass CSP Power Project 4 MW	60 total
MICROSOL	Microcentrale solaire pour l'Electrification rurale (Solar Micro-plant for rural Electrification)	10.9 total 5.1 govt. funds
MACCSOL	The Development and Verification of a Novel Modular Air-Cooled Condenser for Enhanced Concentrated Solar Power Generation	5.67 total 4.09 EU contrib.

[13] The budget covers only the "R&D" amount of the prototype investment cost.

Sub-theme 7: Research facilities and basic R&D support		
Project acronym	Project title	Budget (million EUR)
SFERA	Solar Facilities for the European Research Area	9.04 total 7.4 EU contrib.
Solare Termodinamico	Progetto B.1.3, Energia Elettrica da Fonte Solare, Linea Progettuale 2: Solare Termodinamico (Solar Thermodynamic Electricity; Project B.1.3, Electric Energy from Solar Sources, Project Line 2: Solar Thermodynamic Electricity)	0.6 govt. funds
EU-SOLARIS	The European Solar Research Infrastructure for Concentrated Solar Power	5.9 total 4.45 EU contrib.

Sub-theme 8: Solar chemistry		
Project acronym	Project title	Budget (million EUR)
HYDROSOL-3D	Scaling up a Solar Monolithic Reactor for Thermochemical H2 Production: A 3rd Generation Design Study	1.73 total 0.98 EU contrib.
SOLHYCARB	Hydrogen from Solar Thermal Energy: High Temperature Solar Chemical Reactor for Co-Production of Hydrogen and Carbon Black from Natural Gas Cracking	3.25 total 2.0 EU contrib.
TEPSI	Innovative Technologies and Processes for Hydrogen Production Systems	5.8 total 4.0 govt. funds
CONSOLI+DA	Consortium of Solar Research and Development	N. A.
HycycleS	Materials and Components for Hydrogen Production by Sulphur-Based Thermochemical Cycles	5.12 total 3.75 EU contrib.
CoMETHy	Compact Multifuel-Energy to Hydrogen Converter	4.93 total 2.48 EU contrib.
ENEXAL	Novel Technologies for Energy and Exergy Efficiency in Primary Aluminium Production Industry	8.47 total 4.95 EU contrib.
SOL2HY2	Solar to Hydrogen Hybrid Cycles	3.7 total 1.99 EU contrib.

Sub-theme 9: Solar resource measurement and forecasting		
Project Acronym	Project title	Budget (million EUR)
MESoR	Management and Exploitation of Solar Resource Knowledge	1.03 total 0.9 EU contrib.
MACC-II	Monitoring Atmospheric Composition and Climate	27.73 total [14] 19.0 EU contrib.

4.2 Description of sub-themes

This section summarises the main findings from research projects, their implications for further research, and the Key Performance Indicators (KPIs) they address. The aim of the KPIs is to monitor the impact of technological innovation on the targets of the European Industrial Initiatives.

4.2.1 Sub-theme 1: Parabolic trough technology and components

General trends in research and historical background

Parabolic trough systems were the first to be commercialised in the so-called SEGS (solar electric generation system) plants installed in the late 1980s (totalling 354 MW, divided into 9 plants located in the Mojave Desert USA).

The most specific European R&D effort on collector structures was made by the EUROTROUGH project and its extension (EUROTROUGH II). This project, financed by the EU (Joule-III Programme), dates from 1998 to 2002.

Work on collector structures was soon taken over at national level and closely tied to industrial activities (e.g., the SOLTERM project in Italy), or was taken over directly by industrial enterprises on a proprietary basis; the same process is also taking place for receiver pipes. The projects initially focused on long-term work, from 1996 until 2005, on the direct steam generation (DSG) concept (DISS, DISS-2 and INDITEP), where the HTF is pressurised water that vaporises in the receiver line to produce saturated or superheated steam, typically at 100 bar with temperatures ranging from 400 to 500 °C.

The DSG concept for parabolic troughs has led to a commercial project using saturated steam (330 °C at 30 bar) in the 5 MW Kanchanaburi KTSE 9100 pilot plant in Thailand (developed by Germany's Solarlite); eventually it also resulted in commercial utilisation with linear Fresnel systems. The direct use of molten salt

[14] The MACC-II budget covers a number of activities; only a limited part is related to CSP.

mixtures in parabolic trough receivers, at temperatures up to 550 °C, was developed instead in the SOLTERM project, leading to the ARCHIMEDE solar plant demonstrator (see 4.2.6).

Research objectives and R&D challenges

This sub-theme concerns both the parabolic collector (mirrors and collector structures) and the receiver pipe. Activities on the parabolic collector mostly focus on new types of structures able to lead to a reduction in costs (e.g., material inventory and/or assembling effort, structure weight loss/optimisation) and to an increase in the overall optical performance; as mentioned earlier, activities on collector structure and mirror manufacturing have mostly been taken over by industrial operators.

Work on the receiver pipe is mainly focused on new HTFs – different to the traditional synthetic oil – that are able to increase the output temperature and avoid the drawbacks of oil (toxicity and flammability). Basically, the effort is focused on increasing the HTF temperature, with the possibility of using DSG and eventually molten salts instead of synthetic oil. The latter is limited to 400 °C, which leads to steam at 380 °C. DSG from water makes it possible to achieve 500 °C while maintaining an acceptable level of pressure, but the bi-phase mixture during vaporisation provides a challenge in terms of controllability in transient conditions. Indeed the direct production of high temperature superheated steam in parabolic trough systems is still an engineering challenge.

Molten salts can typically reach 550 °C, but they freeze at temperatures in the order of 100-240 °C (depending on the mixture), which creates an additional challenge. In both cases, thermal losses in the higher temperature range require the adoption of improved selective coatings on the receiver pipe. The development of effective and durable selective coatings able to withstand temperatures up to 600 °C with low thermal loss levels is still an R&D challenge, as is the glass/metal seal for high-temperature receivers.

Research projects and results

On the direct steam generation (DSG) side, the **DUKE** project funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) aims at testing DSG with parabolic troughs in a "once-through" configuration. Once-through means that – like in fossil-fired once-through steam generators – the water evaporation and steam superheating are performed "in series" without the interposition of a pressurised water-steam separator. This in turn reduces investment costs, but is challenging from the point of view of process control, due to the presence of a bi-phase mixture in a large and variable proportion of the receiver line. To this end the DISS plant at the Plataforma Solar de Almeria (PSA) has been completely rebuilt, adding three new collectors that extend the length of the line to a total of 1 000 metres. Outlet temperatures of 500 °C and a pressure of 110 bar are targeted by DUKE, directly addressing KPI 1.2 and 2.1, even if data on the expected cost reduction are not publicly available.

Also on the DSG side, the Spanish **GEDIVA** project aims to study the thermo-hydraulic behaviour of the solar field, using steam as the HTF. The project aims to produce a set of performance recommendations (in terms of conversion efficiency and parasitic losses) depending on the configurations of the solar field and output steam quality.

Work on high-temperature molten salt receivers is still ongoing as part of the **TUBOSOL** project, which is building on the receiver developments initiated in SOLTERM. The TUBOSOL project aims at fully industrialising this type of receiver solution. Indeed, TUBOSOL contributed to establishing the industrial manufacturing process for molten salt receivers, particularly focusing on the use of selective coatings, the glass/metal seal, anti-reflective glass coating, control of vacuum leakage and product quality control. An increase in HTF temperature from 400 to 550 °C is targeted by TUBOSOL. TUBOSOL addresses KPIs 1.2 and 2.1.

Another recent project in this field is the **HITECO** project, which is still ongoing and also aims to produce an innovative receiver pipe able to operate with molten salts at temperatures up to 600 °C. HITECO directly addresses KPI 1.2.

Finally, the **Ultimate Trough** project, financed by the BMU, aimed at prototyping – up to serial production – a new increased-size parabolic trough collector. The target is to reduce the cost of large solar fields (500 000 to 2 500 000 m^2, so typically for plants of 50 to 250 MW) by 20% to 25% from current levels.

The Ultimate Trough module has an aperture width of 7.51 metres (25-30% larger than the current standard of 5.77-6 metres) and a length of 24 metres (twice the current standard of 12 metres). The typical collector is therefore 7.51 metres wide and 247 metres long, with an aperture area of 1 716 m^2. The solar field cost reduction derives from a more than 50% reduction in the number of collector drives, sensors and control elements. In addition, the number of parts needing to be fitted, tested, assembled, aligned and commissioned decreases significantly.

A prototype with two collectors was assembled in summer 2011 in Cologne (Germany), then in a demonstration power loop in the USA, where commissioning and testing are due to be completed in 2013. It is worth noting the fact that the Ultimate Trough concept is explicitly intended for the direct use of molten salts, even if the project itself is not testing this type of operation, which will be the subject of a follow-up project. Ultimate Trough addresses KPIs 1.2 and 2.1.

4.2.2 Sub-theme 2: Central receiver technology and components

General trends in research and historical background

Early work on central receiver (power tower) systems dates back to the 1960s-1970s (e.g., the Francia experiments in Italy) and the 1980s (e.g., ENEL's Eurelios project in Italy, and Themis in France), but it is only now that this technology is starting to be increasingly manufactured and deployed on a commercial basis.

Key current breakthroughs include progress in high temperature receiver design and the recent availability of much more powerful and cheap calculation capability for plant management and image treatment, together with wireless technology and remote imagery capability. These improvements have been crucial in order to control and continuously trim the thousands of independent heliostats that are present in a typical power tower plant, in a cost-effective manner.

While R&D on heliostats and on solar field control is normally conducted on an industrial (proprietary) basis, activity on solar receivers and hybrid-plant concepts still requires public funding.

In the first decade of the 21st century, an explicit R&D effort aimed at investigating volumetric air receiver technology and, moreover, utilising it for the development of solar hybrid power systems with direct solar heating of pressurised air in the gas turbine. In combination with highly efficient combined-cycle systems or recuperated gas turbines, the predicted levelised electricity cost (LEC) of 0.069 EUR/kWh at 50% solar share, and specific investment cost of 1 410 EUR/kW were expected to result in future commercial applications. The solar hybrid concept also has the advantage of providing a plant that produces reliable and fully dispatchable power, even if it is not fully renewable.

Three projects were promoted under the European FP5 and FP6 R&D programmes: SOLAIR, SOLGATE, and SOLHYCO.

- SOLAIR is aimed at investigating metallic volumetric air receiver technology for plants up to 10 MW, with a conservative design approach in order to minimise technical and financial risks; such a project was implemented just before the development of the 10 MW PS10 project (see 4.2.6), even if the approach chosen for PS10 was different, as direct steam generation was eventually used.
- SOLGATE, led to the development of a high-temperature air receiver able to drive a 240 kW gas turbine in hybrid mode (solar and/or fuel).
- SOLHYCO, funded under FP6, focused on the development of a prototype solar hybrid microturbine conversion system for cogeneration, to be coupled with a monolayer tube receiver.

Research objectives and R&D challenges

One of the most challenging objectives for hybrid solar/gas cogeneration is still operating the receiver at temperatures close to 1 000 °C, in order to transfer the heat to the pressurised air entering the combustion chamber of a gas turbine by means of a piping system that will be subject to severe thermal stress.

Other challenges are related to the modifications needed for the gas turbine itself and its control procedure, in order to successfully operate in hybrid mode.

For non-hybrid solar plants, the development of central receivers to directly produce supercritical steam at temperatures up to 650 °C has continued mostly on an industrial basis, with most work underway in the US, Israel and Australia, either with direct steam production at 600 °C or with novel molten salt mixtures able to operate at temperatures up to 700 °C. In Europe the current effort is more focused on:

- Continuing work on pressurised air receivers to be used in hybrid solar-driven gas turbine systems;
- The implementation of complete plant concepts/prototypes, either operating with air or with molten salt receivers, as described in sub-theme 6 (see 4.2.6);
- Very high-temperature receivers for solar chemistry, as described in sub-theme 8 (see 4.2.8).

Research projects and results

The most recent results have been obtained by the **SOLUGAS** project, a hybrid solar-driven gas turbine demonstration system on a MW scale, with a foreseen market in North Africa or other high DNI desert areas. The plant builds on previous experience gained in the SOLGATE and SOLHYCO projects, with the objective of reaching an output air temperature from the receiver of up to 800 °C. A complete plant with heliostat field, tubular receiver and combined cycle was commissioned in May 2012, and experimental operation of the plant is still ongoing in Seville (Spain). In the future, the integration of a volumetric receiver could lead to the target temperature of 1 000 °C being reached.

Another project, **HYGATE**, funded by the BMU, aims to adapt a gas turbine for use in solar towers. The objective is to analyse the key aspects of a solar-hybrid gas turbine plant that can operate either in solar-only, fuel-only or mixed solar-fuel mode.

A demonstration plant will be built in a follow-up project. Development will be based on the assumption of a maximum process temperature of 950 °C by direct solar radiation. The main technological challenge lies in connecting and operating the solar receiver with the parallel combustion chamber, both supporting a target linear operation from 0 to 100% of capacity. The incorporation of a high-temperature heat store will also be examined.

4.2.3 Sub-theme 3: Linear Fresnel technology and components

General trends in research and historical background

Linear Fresnel systems are based on collectors where a number of linear, almost flat mirrors that rotate independently along one axis, focus solar radiation onto a linear receiver.

Use of linear Fresnel technology means that the maximum use can be received from the available space; the technology is also simple and cheap. On the other hand, optical losses mean a partial reduction in the overall cost-effectiveness of the concept. Linear Fresnel technology is currently considered to be at the early commercial stage.

The linear Fresnel concept was not particularly a subject of investigation by the CSP R&D community; as a consequence most of the development was, and still is, performed directly by industrial companies, albeit with some government support. Among them, the FRESQUALI project aimed at developing measurement techniques for use in Fresnel-collector industrial production and on-site qualification.

Research objectives and R&D challenges

The main research objectives have so far been the development of Fresnel technology and Fresnel plant prototypes, in very close collaboration with industrial stakeholders or, more often, in a proprietary industrial framework. The main R&D challenges involve cheap industrial production of mirrors, automatic cleaning machines and high-temperature (up to 500 °C) direct steam production.

The use of molten salt in the receivers is provided for, with problems similar to the parabolic trough approach, but with some additional advantages since Fresnel receiver lines do no need rotating joints (a weakness in terms of reliability).

Research projects and results

Three projects have recently been implemented and promoted by the French government, all of them involving direct steam generation.

- **AUGUSTIN FRESNEL 1** aimed at developing and installing a Fresnel pilot plant of 1 MW. This project, in turn, laid down the basis for the construction of a 12 MW plant in Corsica, called Alba Nova 1. This project addresses KPIs 2.1 and 2.2, even if no cost targets are declared.
- **LFR500** has the objective of developing Fresnel prototype technology for direct steam generation at temperatures higher than 500 °C. This project addresses KPI 1.2.
- **eCARE** is a pre-industrial Fresnel demonstration plant, to be built in Morocco, coupled with a method for solar resource prediction. The project involves the development of 2 hours of thermal

energy storage using a steam drum and a power block based on a 1 MW organic Rankine cycle (ORC), operating at 280 °C at 70 bar. This system will use dry cooling. eCARE addresses KPIs 3.1, 3.6 and 4.1.

The last two projects are quite recent and the results are not yet available.

4.2.4 Sub-theme 4: Dish technology and components

General trends in research and historical background

Since the parabolic mirror in dish systems is controlled along two axes and focuses the radiation onto a focal point, maximum optical efficiency can be reached; high concentration ratios are also possible, leading to high-temperature/high-efficiency systems in principle.

On the other hand, a drawback of the dish system is that it needs individual, relatively small-sized conversion systems (from thermal to electrical, or from thermal to chemical), which are not readily industrially available at a reasonable cost, or often require expensive maintenance. As a result, dish systems are still at the R&D/demonstration stage.

In the first decade of the 21st century, the EURODISH project led to the development of a dish/Stirling prototype with a capacity of 5 to 25 kW (typically 8.4 kW). The prototype has been replicated in several units and tested by some research institutions. The main weaknesses of this system were the cost of the Stirling engine, and the reliability and maintenance requirements of the system.

A second project, ENVIRODISH, focused on conducting further field measurements on the EURODISH prototype.

Research objectives and R&D challenges

The main research objectives up to now have been the development of dish prototypes operating with Stirling engines; very recently the use of micro-gas turbines has also been proposed.

Both solutions are intended to drive an electric generator either for isolated or grid-connected power supply. The main R&D challenge is to produce a high-temperature power conversion system to be located at the focal point, which must be both cheap and reliable.

Research projects and results

A very recent project – **OMSOP**, co-financed under FP7 – provides for the development and demonstration of technical solutions for using a state-of-the-art concentrator dish coupled with a micro-gas turbine to produce electricity.

The planned system will be modular and capable of producing electricity in the range of 3-10 kW. The results are not yet available since the project only started in 2013. OMSOP addresses KPIs 1.1 and 1.2.

4.2.5 Sub-theme 5: Thermal energy storage/heat transfer fluids

General trends in research and historical background

TES is an important feature of CSP plants that can give a distinctive advantage in terms of dispatchability of electricity over other renewable energy sources. Therefore R&D on TES is now one of the main issues in CSP technology. The leading technology in TES is currently the two-tank molten salt direct storage system, first adopted in the SOLAR TWO tower prototype, introduced in 1994, and later in the SOLAR TRES/GEMASOLAR tower and in the ARCHIMEDE parabolic trough plant. Indirect molten salt technology was also used in the ANDASOL parabolic trough project, leading to the construction of a number of commercial plants in Spain. In the ANDASOL case the storage is indirect since the HTF in the collectors (synthetic oil) interacts with the molten salt storage by means of a heat exchanger. This type of indirect storage is therefore limited in temperature by the temperature limit of the oil.

Other storage concepts adopted a number of alternatives comprising lower-cost options for direct steam, like the DISTOR project, or latent heat pace change materials (PCM). These storage concepts are still being studied. Since the storage system interacts with the primary HTF operating in the solar part of the plant, R&D on TES is therefore often linked to R&D on new HTFs.

Research objectives and R&D challenges

The objectives of TES R&D are linked to the type of HTF used by the plant (oil, water/steam, molten salt) and the aim is, generally speaking, to achieve the most cost-effective solution in terms of cost per kWh of stored energy. New arrangements, like thermocline or stratifying concepts, are also being studied. In turn, this objective involves increasing the operating temperature of the TES and/or decreasing the TES cost in terms of the specific cost of the equipment and of the storage medium per unit of stored energy. The range of possible solutions is large and growing; thermochemical reactions were also recently added to possible ways of storing energy in TES. Thermochemical heat storage offers high storage densities, loss-free and long-term storage and the possibility of use in a wide temperature range (up to 1 000 °C).

In conclusion, R&D challenges in TES and HTF include: increasing temperature limits, both the higher and lower limits, since most HTFs (e.g., molten salt mixtures) have a high melting point; maximising heat transfer properties; enhancing compatibility with containing materials (e.g., tank walls); exploiting new material properties (e.g., phase change behaviour of mixtures, nanoparticles); increasing the life of materials subject to cyclic thermal loads (e.g., concretes); introducing new forms of storage (e.g., thermochemical reactions); reducing the overall costs of TES capital expenditure of commercial systems in the range of 25-40 EUR/kWh.

Research projects and results

A number of projects have been launched recently, but none of them has been completed to date.

- The **OPTS** project, where the stratifying properties of molten salt will be exploited in order to allow the use of a single-tank instead of a two-tank arrangement, with an associated reduction in costs; an additional feature of OPTS is the integration of steam generation within the tank, with a further associated reduction in equipment and maintenance costs. OPTS addresses KPIs 3.3 and 3.5.
- **CSP2** is a project that will develop a new HTF, using a dense gas-particle suspension in a tubular bundle type receiver for central receiver (tower) CSP systems. This new type of HTF is expected to behave like a liquid, extending the operating temperature range from 100 to 1 000 °C. It is assumed that it will also be possible to use this new HTF as a heat storage medium. The technology will be tested in a 150 kW thermal pilot loop, with an assessment for the scaling-up the concept to the industrial range (10-50 MW). CSP2 addresses KPIs 1.2 and 3.5.
- **STARS** aims at developing a storage solution for linear Fresnel plants with DSG, addressing KPI 3.1.
- **RESTRUCTURE**, **TCSPOWER** and **STORRE** explore thermo-chemical reactions in order to store heat, in other words, the use of the heat effects of reversible chemical reactions to store solar heat.
- **RESTRUCTURE** involves central receiver (tower) plants and proposes gas-solid reactions, namely the use of a pair of redox reactions involving multivalent solid oxides. The idea is to employ porous monolithic structures made entirely or partially from redox oxide materials, combining ceramic volumetric receiver and structured solar reactor technologies in order to develop an integrated receiver/reactor/heat exchanger configuration with enhanced heat storage characteristics. This is achieved through a series of innovations involving new reactor/heat exchanger designs, enhanced incorporation of redox materials in the reactor structure, improved redox material compositions and the utilisation of industrial waste as raw materials to synthesise the oxide redox system.
- The aim of **TCSPOWER** is to evaluate the potential of thermo-chemical energy storage to be used with CSP plants and to develop and test an experimental 10kW TCS reactor with a storage capacity of about 100 kWh. The reactor is intended for integration with a direct steam parabolic trough, a molten salt tower CSP plant or a central volumetric receiver. The specific targets of TCSPOWER are: to characterise the reactions; to develop calcium hydroxide and manganese oxide materials with the proper characteristics; to develop, validate and construct an

experimental 10 kW/100 kWh reactor; and to evaluate the integration of the concept into commercial plants.

- The goal of **STORRE** is to develop a new heat storage solution, ranging from mid-term (24 hours to a few days) to long-term (several months); both high storage density (300-500 kWh/m³) and relatively high temperatures (300-550 °C) are targeted. The solution will be based on the dehydration of calcium hydroxide - $Ca(OH)_2$. The concept is to be developed to pre-industrial level. STORRE addresses KPIs 3.1 and 3.5.

All these projects are relatively recent and ongoing, so the interim results are not yet publicly available.

4.2.6 Sub-theme 6: Plant concepts/prototypes

General trends in research and historical background

CSP plants can be assembled in a number of ways. However, a plant concept or prototype should have all the components needed to produce electricity and/or process heat from the solar input, and therefore not be limited to the solar component or TES, in such a way as to be industrially replicable. Major components of the power block subsystem have also been added to the sub-theme.

As CSP plants can normally be quite large and expensive, public R&D funding typically covers only a small amount of the expenditure, namely the innovative part of the project. In the first decade of the 21st century, one of the most significant projects leading to a full plant prototype has been the ANDASOL project, where for the first time a large parabolic trough solar field with oil as the HTF was equipped with an indirect molten salt TES. A number of Andasol-type units, each of 50 MW, were then deployed on a commercial basis.

Other significant projects include the PS10, a 10 MW central receiver plant, operating with saturated steam at 250 °C, and SOLAR TRES, a molten salt 15 MW central receiver plant prototype with a large storage capacity (15 hours of nominal capacity); the SOLAR TRES project was finally commissioned in late 2011 with the commercial name Gemasolar and an effective capacity of 20 MW.

Also worthy of mention is the ARCHIMEDE project, commissioned in 2010, which exploited know-how developed under the Italian SOLTERM project to produce the prototype of a molten salt parabolic trough solar field with TES, with nominal output of 12 MW thermal of 530 °C saturated steam (5 MW electric equivalent), supplied to a large combined cycle gas-fired power station.

Research objectives and R&D challenges

Research into CSP plant prototypes normally focuses on developing and prototyping a fully-commercial or pre-commercial scale plant that is expected to be both cost-effective and highly reliable during operation. The challenges are therefore mostly linked to the ability to design, manufacture and demonstrate solutions ready to be employed by industrial operators and of immediate interest to investors in the highly competitive power market.

As already mentioned, since the total CAPEX on a CSP plant can easily exceed EUR 300 million, R&D objectives, and consequently the relevant R&D funding effort, normally focus only on a specific part of the innovation, for example, off-standard design and design optimisation.

Most of the plants being currently proposed integrate the production of electricity and heat to be used for water desalination and/or cooling, and integrate the solar input with fuel, normally natural gas or biomass.

In other words, the current R&D trend is to implement multi-input, multi-output plants, rather than stand-alone electricity production from solar input, as in a traditional CSP plant.

Recently, new plant concepts are also being proposed with a longer R&D timeframe and/or a limited plant scale, therefore R&D funding can cover a significant fraction of the more limited project budget. Based on this approach, micro CSP plants are also being proposed with sizes in the order of a few kW instead of the traditional MW or multi-MW scale, targeting the residential and industrial market.

The challenges here are more technology-specific and less linked to the immediate market-oriented approach.

Research projects and results

Quite recently a number of projects related to this sub-theme have been launched, either with European or national funding. Since none of them is likely to be completed at the time of publishing this summary, their results are not yet available.

Medium-large projects

- The objective of **ARCHETYPE SW550** is to develop, construct and operate an industrial-sized CSP plant based on parabolic trough technology with molten salt as the HTF and storage medium, as in the ARCHIMEDE project. The plant will involve the integrated production of electricity and fresh water, with hybridisation with biomass. The size will be in the order of 20-30 MW. The prototype includes an R&D/innovation effort, partially funded by the EU under FP7. The project addresses KPIs 1.2, 3.2 and 3.5.
- **MATS** is aimed at the development and installation of a MW-sized hybrid multi-source (natural gas or biomass and solar) multi-output (electric power, heating/cooling, desalinated water) concept, the core technology of which is the application of a stratifying molten salt single-tank TES with integrated steam generator unit, able to reach 550 °C. This TES solution is similar but smaller than that under development in OPTS. The MATS components will be first tested in Italy, then a full plant comprising 18 parabolic trough collectors with a molten salt HTF,

each 100 metres long, will be deployed in the final plant prototype in Egypt. Achievements up to now include the design of the major components and the beginning of installation of the collector prototype. MATS addresses KPIs 3.2, 3.3 and 3.5.

- **HYSOL** is a very recent project, aiming at prototyping to pre-industrial scale a new hybrid CSP system concept, including a new configuration in a conventional CSP system with heat storage. The concept includes the development and manufacture of an aeroderivative gas turbine (AGT) exhaust gas simulator and a heat recovery system (HRS) that will utilise the exhaust heat of the AGT to charge a molten salt storage system. The AGT fuel will be biomass-derived fuel (biogas and syngas). The AGT simulator and HRS will constitute a hybrid demonstrator that will be then integrated into an innovative CSP facility inside, or attached to, an existing full-scale CSP plant. The project addresses KPI 3.2.
- **SOLMASS CSP** is also a recent project aimed at developing a central receiver (tower) CSP plant of 4 MW. The plant will comprise a thermal energy storage system and will be hybridised with natural gas (biogas). This project also addresses KPI 3.2.

Micro CSP and CSP diffusion projects

- **DIGeSPo** is developing a modular 1-3 kW, 3-9 kW thermal micro-combined heat and power (m-CHP) system based on CSP and equipped with a Stirling engine. The concept aims to provide electrical power and heating/cooling services for homes and commercial, industrial and public buildings. The technological targets have been identified as the development of low-cost cermet materials for medium-temperature (300–350 °C) applications; a parabolic trough solar collector for this temperature range; and a Stirling engine operating at 300 °C. The project is still ongoing and a demonstration system has been commissioned in Malta.
- **STS-MED** will deploy four demonstration plants based on concentrating solar power serving the energy demands of 20 000 end users in 20 Mediterranean local communities, providing a total of 400 kW. Project implementation will be supported by economic and policy studies, including recommendations on regulatory issues, fiscal incentives and public innovative procurement. The project is also intended to create new business opportunities, notably by supporting the involvement of SMEs in local solar energy supply chains generated by the construction of the four pilot plants. STS-MED is therefore more focused on the diffusion of CSP technology for public buildings than on technology R&D.
- The objective of **MICROSOL** is the application of small CSP systems in rural areas, with solutions able to supply constant power, heat and desalinated water to a village of 500 inhabitants. Two prototypes will be manufactured and tested in France and later two additional ones will be installed in Africa. The technology development programme comprises evacuated receivers, parabolic trough collectors, TES, a Stirling engine and

an ORC (organic Rankine cycle) turbine. The project addresses KPIs 3.2 and 3.6.

Non-conventional CSP

- **E2PHEST2US** adopts a non-conventional approach to CSP, investigating the combined production of heat and electrical power based on thermionic and thermoelectric direct conversion devices. The target temperature for the thermionic-thermoelectric conversion module is 800-1 000 °C. The main development expected from the project is a new conversion module. A small scale solar test platform based on the concept has been installed and tested, using a parabolic dish with concentration ratio in the range of 400-1 000 suns. The project addresses KPI 1.2.

Industrial R&D on major plant components

- **MACCSOL** is focused on industrial R&D applied to a major component of the power block of a CSP plant, namely the dry-cooling unit for steam condensation in the thermodynamic cycle. As for any Rankine cycle, the steam from the turbine must be condensed. Traditionally, in fossil-fuelled plants, water cooling is used to condense this steam. However, in desert areas, where solar power is most abundant and CSP plants are likely to be deployed, water scarcity prevents water-cooled condensers from being used. Dry cooling is therefore necessary. The development of a dry-cooling unit is therefore important to promote the use of CSP. Despite their widespread use in conventional power plants, dry-cooling technologies such as air-cooled condensers (ACC) give rise to high thermodynamic losses. The aim of MACCSOL is to develop a more efficient technology; the proposed solution is a modular air-cooled condenser (MACC).

  The objectives of the project are to:

  - Eliminate the use of water in cooling CSP plant condensers;
  - Minimise costs and power consumed by air cooling, and maximise the power output of CSP plants with dry-cooled condensers;
  - Minimise the lifetime cost of dry cooling a CSP plant;
  - Remove a significant barrier to the deployment of CSP plants in desert areas, thereby helping the EU to achieve its 2020 renewable energy targets.

  Although not finished yet, MACCSOL has achieved a number of interim results:

  - Experiments on the first MACC prototype and lab tests have indicated that air-side and condensate-side characteristics in the first MACC prototype are in line with the theoretical models;
  - Using the MACC optimisation methods, a finned tube system has been identified which, subject to manufacturability, could give rise to increases in revenue of the order of EUR 5 million

over the lifetime of a 50 MW plant when compared to current state-of-the-art air-cooled condensers;
- LCA (Life Cycle Assessment) shows that the main impact on the environment of a MACC is during the operation phase;
- MACC theoretical performance models have quantified the effects that controlling the fan speed has on the power plant output.

MACCSOL addresses KPI 4.1.

4.2.7 Sub-theme 7: Research facilities and basic R&D support

General trends in research and historical background

Apart from funding specific R&D projects, public support for CSP R&D is provided through the launch of research facilities and the implementation of national programmes to support industrial R&D.

The main research facility for CSP R&D in Europe is the Plataforma Solar de Almeria (PSA), which has been operating in Spain since 1977, with a number of installations and experiments on different technologies, from direct steam generation in parabolic troughs to central receivers.

Other European countries started working in this area even earlier; among them, the French Odeillo research area of PROMES-CNRS, with its solar furnace (with a first installation dating back to 1946 and the present one launched in 1970) and the THEMIS central receiver prototype, initiated in 1979 and renovated recently (2004).

In Switzerland the Solar Technology Laboratory of the Paul Scherrer Institute (PSI), with its solar furnace installations, was set up in 1997. In Italy, the ENEA Casaccia molten salt CSP test centre near Rome was started up in 2001, almost 20 years after a small central receiver experiment was installed at the same site (1980-84) but quickly dismantled.

All these installations had, and still have, the objective of allowing basic research and technology development in the CSP sector as well as performing tests and experiments with the assistance of specialised staff. The cost of establishing and maintaining an efficient complex of ad hoc laboratory equipment is quite high and can be borne only at national or European level. Since, apart from the PSA, most of the laboratories specialised in a particular technology (e.g., very high temperatures - in Odeillo and PSI; or molten salts, in ENEA) the current trend is also to coordinate efforts among European researchers and permit the exchange of researchers so as to get the most benefit from investments in existing hardware.

On the other hand, as CSP technology becomes commercially attractive, the most mature industrial developments tend to be carried out either by research institutes licencing out technology or working under a (non-disclosure) agreement with an industrial party; on a proprietary basis at existing commercial plant sites; or by suppliers of specialised industrial R&D services, who can provide better protection for proprietary know-how.

Regarding national support programmes, all major European countries interested in CSP have, in the past, implemented programmes that have aroused industrial interest in the subject, for example, the Italian SOLTERM project, which operated from 2001 to 2006 and developed the line of molten salt in the troughs now utilised in the ARCHIMEDE plant.

Research objectives and R&D challenges

National or international cooperation and the availability of high-level research facilities remains essential for the most long-term R&D activities; these include the availability of solar furnaces able to test materials, receiver concepts, and reactors for thermochemical processes at temperatures in the order of 1 500 °C or more (up to 3 000 °C).

The challenges in this area are mostly linked to the ability to provide in good time the equipment that will be needed by future research.

Recent projects and results

Two projects related to R&D infrastructure and one programme to support industrial research have been initiated recently.

The **SFERA** project, which is due to terminate at the end of 2013, aims to boost scientific collaboration among the leading European research institutions in solar concentrating systems, offering European research and industry access to the best research and test infrastructures and creating a virtual European laboratory. The project created a consortium and incorporates several activities.

- **Transnational access**. Researchers have access to five state-of-the-art high-flux solar research facilities, unique in Europe and in the world: the PSA in Almeria, the PROMES solar furnace in Odeillo, the PCS molten salt test facility at ENEA, the solar furnaces of PSI in Switzerland, and the Weizmann Institute of Science (WIS) in Israel.
- **Networking**. These activities included the organisation of training courses and schools to create a common training framework, providing regularised, unified training of young researchers to familiarise them with concentrating solar facilities and give them the skills to operate them. Communication activities were stimulated to strengthen relationships within the consortium.
- **Joint research activities**. These activities aim to improve the quality and service of existing infrastructure, extend their service lifespan and jointly achieve a common level of high scientific quality.

The results achieved can be summarised in approximately 25 projects/year performed from 2010 to 2013.

EU-SOLARIS is a recent initiative to foster, contribute to, and promote the scientific and technological development of solar thermo-electric technologies in Europe. The initiative is also integrated in the framework of the European Strategy Forum on Research Infrastructures (ESFRI) of the European Commission (EC). The aim of EU-SOLARIS is to contribute to improving the state of the art of these technologies, so as to preserve and reinforce European leadership in this field. Through this project, new concentrating solar energy technologies will be developed and coordinated by the main European centres in the sector, to respond to future technological needs.

Nine countries are participating in EU-SOLARIS, namely Germany, Cyprus, Spain, France, Greece, Italy, Portugal, Turkey and Israel. The first phase of EU-SOLARIS will establish the project's infrastructure in the form of a legal entity called EUSOLARIS – which will rely on a sustainable financial mechanism over time – along with a structured organisation that brings together the R&D resources and infrastructure of its members, and a shared management that acts as single point of access to European solar thermal research for the rest of the world. The future infrastructure will operate for 20 years, with a budget of about EUR 80 million to build new facilities, and an additional EUR 3 million/year to cover operating costs.

Solare Termodinamico (solar thermal electricity) is an Italian programme, established in 2012, supporting the industrial R&D effort on CSP. It is funded by the Italian Ministry of Economic Development. Its objective is to achieve the development of new plant configurations using parabolic trough solar collectors and incorporating TES; multi-generative integrated systems for small- and medium-sized CSP plants; new cermet-based coatings for solar receivers; and replacing graded technology with interferential optical filtering.

4.2.8 Sub-theme 8: Solar chemistry

General trends in research and historical background

Within CSP technology, thermochemical production of solar fuels - solar chemistry - is still quite far from commercial exploitation, even if an industrial initiative has been launched recently. The aim of R&D activities on solar chemistry is to develop and optimise solar-driven thermochemical processes and demonstrate their technical and economic feasibility on an industrial scale. Among the objectives, three should be highlighted:

- **Production of energy carriers**, in other words synthetic **solar fuels;** the objective is the conversion of solar energy into chemical fuels that can be stored long-term and transported over long distances. A special focus is made on solar thermal production of hydrogen and syngas (essentially a mixture of carbon monoxide (CO) and hydrogen (H_2) with the presence of variable quantities of methane (CH_4) and carbon dioxide (CO_2)).

- **Processing of chemical commodities**, in other words the use of solar energy to process energy-intensive, high-temperature materials.
- **Detoxification and recycling of waste materials**, in other words the use of solar energy to detoxify and recycle hazardous waste and secondary raw materials.

Among the three objectives, the production of solar fuels is probably the most interesting in terms of practical output, even if a solar furnace can reach, at its focal point, temperatures up to 3 000 °C in a few seconds and, apart from being a very useful tool to study material properties at high temperatures, it is useful also for processing materials that require high temperatures under controlled and very clean conditions.

The direct production of synthetic fuels generally requires at least 550 °C, but often much higher temperatures, in the range of 1 000-1 500 °C, so it is usually powered by high-concentration solar devices. Solar furnaces are typically used in the R&D phase, while central receiver plants are generally envisaged for future industrial production of solar fuels or solar chemicals.

Some previous important research projects can be cited: the SOLZINC project, which investigated the storage of solar energy by producing metallic zinc from zinc oxide (ZnO) and carbon (C), requiring 1 200 °C; INNOHIP-CA investigated the existing knowledge in Europe on high-temperature processes and other innovative ideas for large-scale hydrogen production; the HyDROSOL project investigated the production of hydrogen by two-step water splitting, beginning with water and a metal oxide; and finally the SOLREF project investigated solar steam reforming of methane rich gas for syngas production, based on the previous SOLASYS project.

Research objectives and R&D challenges

Since, as already mentioned, solar chemistry is still a long way from commercial use, R&D objectives are focused on the development of the thermochemical conversion process at the theoretical and laboratory levels, and of a reactor prototype to be eventually tested using an existing solar furnace or available research facility. Recently full-concept plants, including the solar part, have been proposed, although no industrial-sized prototype has been built yet.

R&D challenges are mostly involved in developing the proper thermochemical reactions, and the practical arrangement of the reactor, thereby resolving a number of problems connected with very high temperatures, high solar flux, chemical compatibility, and so on.

Indeed, reaching a very high temperature in a solar receiver is particularly challenging not only due to the resistance of the materials but also because the thermal efficiency of the receiver (which feeds the thermochemical reactor) is severely affected by increasing losses due to thermal radiation and convection. Recently, relatively low-temperature processes (e.g., in the range of high temperature parabolic troughs) have been proposed, using catalytic materials in order to accelerate the commercial exploitation of solar chemistry.

Research projects and results

Most projects are focused on the production of solar fuels by water splitting or steam reforming of methane. One project, however, is focused on high-temperature aluminium production.

Regarding solar fuels, **SOLHYCARB**, completed in 2010, addressed the solar thermal decomposition of natural gas or methane for the clean coproduction of hydrogen (H_2) and carbon black, an alternative process to steam reforming of methane. Indeed, this solar process reduces the carbon dioxide emissions per kilogramme of hydrogen produced compared to conventional processes. The project aimed at designing, constructing and testing prototype reactors in the 10-50 kW thermal scale, operating at temperatures between 1 400 and 1 800 °C, as well as optimising the design of a 10 MW thermal commercial scale solar reactor to be mounted on a solar tower.

Some of the experimental results showed methane conversion rates of from 72% to 100% and hydrogen yields of from 57% to 88%, depending on the temperature and residence time.

The solar-to-chemical energy conversion efficiency of the commercial-size reactor has been estimated at 42%, with a solar-to-thermal energy conversion efficiency of 75% at 1 600 °C.

The third phase of the previous HYDROSOL project, **HYDROSOL-3D**, has been recently completed. This project led to the design study of a solar monolithic reactor for thermochemical hydrogen production. The approach, similar to the previous one, consists of using a two-step water-splitting thermochemical process operating at moderate temperatures (less than 1 200 °C). The design to be developed is focused on a future 1 MW solar demonstration plant, comprising the design and development of the solar receiver/reactor; the validation of the operational reliability of the plant design and control system through laboratory and pilot plant testing; and the design of the solar field control system.

Reported achievements include fine-tuning the composition of the redox materials, the reduction of reactor re-radiation losses by using a secondary concentrator attached to the front of the receiver, and the introduction of a spherical absorber made from a set of individual monoliths.

A 100 kW pilot reactor has been tested at the PSA SSPS tower in Almeria.

The **TEPSI** project in Italy involved ENEA and five Italian universities and aimed to build lab-scale plants for the production of about 10 normal litres of hydrogen per hour, using both sulphur-iodine (SI) and manganese-ferrite (MF) thermochemical cycles. Some of the reactions involved, particularly the hydrogen-iodide (HI) section within the SI cycle, require moderate temperatures that can be produced by, for example, molten salt parabolic troughs, while the other reactions require much higher temperatures that must be achieved by solar towers.

TEPSI achievements on the SI cycle include the development of a new procedure for phase separation and purification, and the quantification of the effect of impurities due to incomplete species separation. The different sections of the SI cycles have been connected in a closed-loop pilot plant operating at atmospheric pressure. Preliminary energy efficiency calculations indicate a potential hydrogen cost of 8.5 EUR/kg.

On the MF cycle it was demonstrated that the $NaMn_{1/3}Fe_{2/3}O_2/MnFe_2O_4/Na_2CO_3/CO_2$ system is cyclically able to produce hydrogen and release oxygen at 750 °C. The study continued for two further years, leading to the design, construction and validation of an inconel alloy receiver/reactor.

CONSOLI+DA in Spain was an initiative involving an industrial consortium of 20 private Spanish companies, led by Abengoa, and 18 solar R&D institutions, with the goal of enhancing various high-concentration solar thermal technologies. In the solar hydrogen field, two-step water-splitting ferrite cycles were considered attractive. A number of ferrite cycles have been evaluated in laboratory tests. Cobalt iron oxide ($CoFe_2O_4$) appeared to be the most promising material for hydrogen production (42.7 Ncm^3/g after two thermochemical cycles).

HycycleS further evaluated the sulphur-iodine (SI) and hybrid sulphur (HyS) cycles with the aim of achieving solar driven thermochemical production of hydrogen. The main challenges here are the high temperature and the corrosive environment. The project aimed at developing and improving materials and key components for sulphuric acid (H_2SO_4) decomposition. The sulphur trioxide (SO_3) decomposer, operating at 850 °C, was one of the main focuses of HycycleS. Results include the testing and simulation of a prototype receiver/reactor for sulphuric acid decomposition into sulphur dioxide (SO_2) and oxygen at the DLR solar furnace in Cologne. Reactor efficiencies higher than 40% were observed. A prototype compact heat exchanger was designed as a sulphur trioxide decomposer, and built and tested by coupling it to a heat loop.

CoMETHy is a recent project that is still underway, and aims to intensify hydrogen production processes, develop an innovative compact and modular steam reformer to convert reformable fuels (natural gas, biogas, bioethanol, etc.) into pure hydrogen, and be adaptable to several heat sources (solar, biomass, fossil, etc.), depending on the locally available energy mix. The objective is to achieve decentralised hydrogen production. The project will use biomass and parabolic trough technology to store heat in a molten salt-based TES. A flow of molten salt will then supply the process heat to a new type of catalysed steam reformer. The first feature of the proposed technology is therefore the reduction of the steam reformer temperature from the typical 850-950 °C to 500 °C. Another feature is the use of a selective membrane to separate hydrogen from the gas mixture.

In order to achieve these goals, CoMETHy faces the following R&D challenges:

- Development of a suitable catalyst for relatively low-temperature (500 °C) steam reforming, with enhanced heat transfer properties;
- Identification and development of suitable selective membranes for this application;
- Integration of the catalyst and membrane into a reactor heated by molten salts;
- Modelling, optimisation and advanced control analysis of the integrated reformer system;
- Identification of the best strategies to couple the system with a CSP plant.

SOL2HY2 is a very recent project, aiming to develop and demonstrate a 500 kW solar-driven thermochemical water-splitting hybrid sulphur cycle (Hys); the first reaction (powered by low-temperature solar-driven electrolysis) will transform water and sulphur dioxide (SO_2) into hydrogen (H_2) and sulphuric acid (H_2SO_4); the second reaction (powered by high-temperature solar heat, at 800-1 000 °C) will transform the sulphuric acid into water, sulphur dioxide and oxygen. The total process therefore involves splitting the water into hydrogen and oxygen, with sulphuric acid and sulphur dioxide being the intermediate reactants. The main challenges in HyS still concern the materials (electrolyser, concentrator, acid decomposer/cracker and plant components) and the optimisation of the entire process flow-sheet, tailored to specific solar inputs and plant site locations.

Involved in the solar production/processing of materials, **ENEXAL** is a recent and still ongoing project, that aims to demonstrate and validate, on an industrial scale, the production of primary aluminium by high-temperature alumina reduction, based on a carbothermic reduction process. Primary aluminium production is the largest worldwide industrial consumer of energy and one of the most carbon dioxide intensive industries.

Two different technologies are being investigated in ENEXAL: high-temperature carbothermic reduction in an electric furnace and moderate (1 000-1 700 °C) carbothermic reduction in a novel solar furnace. The utilisation of bauxite residue (red mud), produced in the Bayer process using an environmentally-friendly technology is also an aim of the project. Preliminary results include exploratory experimental runs using a solar reactor at temperatures in the range of 1 000-1 700 °C and total pressures of 3.5-12 mbar, with the reactants aluminium oxide (Al_2O_3) and bio-charcoal being directly exposed to simulated high-flux solar irradiation.

4.2.9 Sub-theme 9: Solar resource measurement and forecasting

General trends in research and historical background

Solar radiation measurement is a traditional sector of meteorological sciences, with a number of institutions and universities involved.

As solar energy has become an increasingly important component of the energy sector, the measurement and forecasting of solar radiation has also become increasingly important for the solar business.

An important difference between solar resource assessment and solar forecasting is that the resource assessment focuses on the statistical behaviour of radiation in order to predict the energy yield of a plant, which is useful for energy planners and solar project developers; whereas forecasting focuses on short-term pattern predictions of radiation values that will affect the plant operation and its value for the grid operator.

At the moment, 'Solar Resource Knowledge Management' is an IEA task under the Solar Heating and Cooling (SHC) Programme Implementing Agreement. The IEA SolarPACES Implementing Agreement on CSP systems has recently initiated collaboration under its 'Task V: Solar Resource Assessment and Forecasting'. Collaborations are also maintained with the IEA Implementing Agreement PVPS (Photovoltaic Power Systems). The scope of this work addresses all solar resource topics, including satellite-derived solar resource products, ground-based solar measurements as well as solar forecasting and data dissemination methodologies. The task also covers solar thermal heating and cooling, photovoltaics and concentrating solar applications. However, the most important parameter for CSP is the DNI that can be concentrated. DNI measurement requires special equipment that is not generally available in general purpose meteorological stations.

Research objectives and R&D challenges

The main goals of R&D activity in this field are:

- Standardisation and benchmarking of solar radiation data sets for better comparability and acceptance of data products;
- Improved data availability and accessibility in formats that address user needs;
- Development of methods that improve the quality and the spatiotemporal coverage of solar resource products, including forecasts.

Solar radiation forecasting (with time horizons ranging from a few days down to minutes) is becoming increasingly important for plant management (optimal scheduling of maintenance and production; storage management optimisation; HTF flow control) and grid management, assuming an increasingly large penetration of solar powered plants in the electric grid, at both the distribution and transmission level. Indeed, good solar forecasting can improve a plant's dispatchability and, as a result, its grid management value.

Since the economic value of solar resource assessment and forecasting is increasing, R&D activities are being increasingly carried out by providers of specialised solar engineering services.

R&D challenges include new satellite-based methods, validation/ benchmarking of DNI data, and solar radiation forecasting methodologies with special emphasis on DNI. Ground-level DNI data can be estimated from satellite information and data on atmospheric composition.

Research projects and results

The EU-funded **MESoR** project had the goal of setting up a user-oriented solar resource data portal. MESoR developed the common access to this portal. A prototype has been set up, and can be accessed online. By using the Google Earth interface, users can click on a specific location of interest and a file containing the various data sources available for that location appears.

MACC-II is a collaborative project (2011-2014) funded under FP7. It is coordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF) and operated by a 36-member consortium. It provides data records on atmospheric composition for recent years, and data for monitoring present conditions and forecasts on the distribution of key constituents for a few days ahead.

MACC-II combines state-of-the-art atmospheric modelling with Earth observation data to provide information services covering European air quality, global atmospheric composition, climate forcing, the ozone layer, UV and solar energy, and emissions and surface fluxes.

MACC-II activities cover a number of related meteorological subjects; only a small part of the effort is related to CSP.

4.3 Implications for future research

Industrial companies are currently commercialising either parabolic trough or Fresnel collectors, therefore most of the R&D in this field is performed within an industrial and proprietary framework. Molten salts are starting to be used as a HTF in parabolic trough systems; their use could be extended to Fresnel collector fields, making it possible to increase the output temperature to 550 °C and allowing the inclusion of relatively cost-effective TES, as an alternative to the

DSG options currently used. A thorough analysis should be carried out of the piping layout and the additional heat supply devices needed in this case.

In tower systems, while R&D activity in heliostat manufacture and control is currently being taken over directly by industrial companies that commercialise these components, using proprietary solutions, it is still a challenge to increase the temperatures of central receivers to 700 °C for the adoption of supercritical steam cycles - with enhanced HTFs – or up to 1 000 °C for the adoption of solar-driven gas turbine combined cycles (with a gaseous HTF). In the latter case, the connection between the receiver and the gas turbine also poses a challenge.

For dish systems the main challenge continues to be the development of cost-effective and reliable solutions for the thermal engine.

TES and HTFs will continue to face a number of challenges, since many possible solutions are emerging. Materials and chemical engineering will play an increasing role as new PCMs, molten salt mixtures, high-temperature liquids, and thermochemical storage options are being introduced.

New plant concepts will incorporate multi-input/multi-output features, in other words hybridisation with fuels and cogeneration of power and heat. Optimising increasingly complex plants will increase the importance of simulation in the design and commissioning phase. A lot of proprietary solutions exist, but a standardisation effort should be made in order to guarantee investors.

The role of advanced/optimal control should also increase as plant complexity increases.

The main solar chemistry challenges are largely unchanged, as no commercial solution has been found or implemented to date. Two trends are emerging: a continuing increase in temperature – with significant challenges in terms of materials and thermal losses in the receiver/reactor – and the use of catalysed reactions at moderate temperatures.

Finally, resource assessment and DNI forecast will become ever more important as electric grids become more populated by RES plants. An R&D effort in these fields and in grid management optimisation will generally bring about an increase in the share of RES in electricity production, which will benefit CSP, thanks to its intrinsic advantages in terms of hybridisation potential and cost-effective storage.

5 International developments

The main international forum on CSP R&D is SolarPACES (www.solarpaces.org), in which 18 countries (plus the European Commission) participate. India is often hosted, while Qatar, Cyprus and Chile recently expressed their interest in joining the organisation. The forum organises two meetings per year with a view to exchanging information. Of these 18 countries, only five are part of the European Union. However, the international trends and R&D challenges faced in major countries outside Europe are generally similar to those addressed in Europe, as outlined in this document. Moreover, it should be stressed that the lion's share of the potential market for the application of CSP products and plants lies outside Europe.

More specifically, depending on the specific situation, three categories can be defined in relation to potential for domestic application of CSP technology and local industrial interest in the technology:

A. Countries with both high domestic potential for the application of CSP and high industrial potential;
B. Countries with a high technological/industrial interest in CSP;
C. Countries with high domestic potential for the application of CSP.

Countries in group A (e.g., USA, China, Australia, Israel) are promoting both the market (in different forms, depending on the specific political approach) and basic and industrial R&D on CSP.

Countries in group B (e.g., Japan, South Korea, Switzerland) are promoting basic and/or industrial R&D on CSP with the aim of achieving a leading position in some of the technological aspects involved, with a view to exporting to foreign markets.

Countries in group C (e.g., India, South Africa, UAE, Morocco) generally have a potentially large market but do not lead in technological R&D. Their R&D effort is generally limited to the internalisation of leading international R&D efforts (e.g., significantly reducing costs by setting up local manufacture in India) or focuses on specific issues.

The main comprehensive CSP R&D programmes are in the USA, China and Australia. The US effort is part of the Sunshot Initiative of the US Department of Energy (DOE)[15]. Sunshot aims at increasing the attractiveness of solar power in the competitive energy market by dramatically reducing costs, both of photovoltaic and CSP technology, through competitive awards to industry, national laboratories, and universities. In the CSP sector the target is to reach a levelised cost of electricity of 0.06 US$/kWh by 2020[16]. The main effort is on components (e.g., collectors), thermal storage and system analysis. Higher temperatures, above 650 °C, and new storage media are being investigated. On the market side, the largest single CSP plants in the world are currently under construction in the USA: the 392 MW Ivanpah solar tower and the 280 MW Solana parabolic trough with storage.

China's significant effort on CSP began in the first decade of the 21st century, initially reproducing European and US technology. Recently, in its 12th Five-Year Plan for National Economic and Social Development, China increased its goal for solar installed capacity from 21 GW to 50 GW. On the CSP side four projects with an aggregate capacity of roughly 250 MW are under development: a first 1 MW solar tower was inaugurated in August 2012, while the first phase of a 50 MW solar tower plant was commissioned in November 2012.

Australia has recently launched its own AUS$87.3 million[17] R&D programme on CSP, the Australian Solar Thermal Research Initiative (ASTRI), coordinated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and partnered by Australian and international universities and by two leading US institutes active in CSP (Sandia and NREL).

Also worthy of mention is the effort in Israel, Switzerland and Australia on long-term R&D activities on the production of solar fuels by high-temperature CSP-driven thermochemical conversion of water or carbonaceous materials.

All these foreign developments have clear implications for EU goals since the CSP business is fully internationalised and the CSP market is mostly outside Europe.

To maintain a position in the global CSP market, European R&D efforts should aim at maintaining Europe's leadership in specific areas within CSP, while linking to the non-EU effort in order to access foreign markets (e.g., funding of multinational efforts on expensive R&D developments, while also drastically reducing the cost of mature CSP technology).

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[15] www1.eere.energy.gov/solar/sunshot
[16] Corresponds to EUR 0.0443 at November 2013 exchange rates.
[17] Corresponds EUR 58.73 to million at November 2013 exchange rates.

6 Technology mapping

6.1 Synthesis of the research findings

CSP research activities are mainly focused on reducing costs. The LCOE levels for a CSP plant are highly dependent on both average yearly available solar irradiation and the use of energy storage. To date, the LCOE of a CSP plant can range from 75 to 360 EUR/MWh for linear parabolic trough and solar tower technologies, with and without storage, in two main market groupings (Spain, US & Australia – China & India). Estimates about possible cost reductions for an LPT plant with storage indicate a range between 90-110 EUR/MWh by 2022. The CAPEX at that time is estimated at 2.5-8 million EUR/MW for an LPT plant and 3-6.3 million EUR/MW for an ST plant, with and without storage.

Parabolic trough and Fresnel concentrators are already commercially exploited. Still, cheaper manufacturing methods for collector structures and mirrors could lead to more cost-effective plants. The industrial R&D effort is still ongoing on linear receivers in order to increase the output temperature to 550-600 °C using molten salts or gas as the HTF, or adopting direct steam generation. Developments in this field are connected with the type of TES to be used. In central receiver technology, the industrial R&D effort is ongoing on a proprietary basis on heliostat manufacture and heliostat aim control and monitoring, while this technology still requires basic R&D in order to increase temperatures to 650-700 °C for supercritical cycles, 1 000 °C for solar-driven gas turbine combined cycles or production of medium-temperature solar fuels, and up to 1 800 °C for very high-temperature solar chemistry.

In dish technology, the main focus is on the industrial development of cost-effective and reliable solutions for the thermal engine, namely Stirling engines or micro-gas turbines.

R&D on thermal energy storage/HTF is increasing in importance, with a lot of possible solutions for potential development. Two molten salt storage tanks coupled with an oil HTF from parabolic troughs or directly fed by the receiver HTF in central receiver plants is still the most commercial solution, but new molten salt mixtures with an improved temperature range are also the subject of basic and industrial R&D. Alternatives to two molten salt storage tanks include: concrete or other low-cost bulk storage of sensible heat; single-tank arrangements based on thermocline, stratification properties or separation devices; and PCM-based storage. Thermochemical reactions have also recently been the subject of basic and industrial R&D for improved TES systems.

As CSP plants can be assembled in many different ways, R&D on new plant concepts or prototypes covers a wide range of possibilities. For large plants the R&D effort involves only a small part of the expenditure, namely the innovative aspects of the design. New plant concepts generally include hybridisation features with conventional or biological fuels; cogeneration of electricity, heating/cooling and/or water desalination; and the inclusion of some form of TES.

The availability of R&D infrastructure will remain crucial in order to develop the most long-term aspects of CSP R&D, namely the development of high-temperature receivers, up to 2 000 °C for solar chemistry applications.

Solar chemistry is becoming increasingly important, mainly for the production of solar fuels but also for processing high-temperature materials, due to the high penetration of renewable energy in the world energy mix. Basic R&D in this area is still needed in order to reach a commercial level for this type of application. A number of possible reactions are being proposed, with those based on sulphur being closest to industrial use, particularly sulphur-iodine and hybrid sulphur, which require a temperature level lower than 1 000 °C. Even relatively low-temperature (500 °C) steam reforming of natural gas, assisted by catalysis, is being studied.

Finally, solar resource assessment based on satellite data and solar radiation forecasting is becoming increasingly important due to its economic value both for plant developers and investors and for optimal management of plants and grids.

6.2 R&D challenges for future research

The diversity and complexity of the technology is such that it would be impractical to list all the specific challenges here. In general the main R&D objectives are:

- Reducing component and overall plant costs;
- Increasing operating temperatures;
- Increasing overall plant performance, reliability and service life;
- Fully exploiting hybridisation and cogeneration potential;
- Increasing the dispatchability of plant production;
- Commercialising solar chemistry (e.g., solar fuels).

In order to meet these objectives new solutions are being proposed and studied, such as:

- Introducing new types of HTFs;
- Introducing new types of TES;
- Developing higher-temperature receivers;
- Introducing new plant concepts;
- Introducing new types of chemical reaction both for thermochemical TES and for solar chemistry.

In turn, these objectives are having direct consequences in terms of a number of related scientific and engineering challenges, namely: manufacturing methods (e.g., for cheap mass production of mirrors); components and plant design optimisation; thermodynamic optimisation (e.g., high-temperature supercritical steam or solar-driven combined cycles); plant process control; synthesis and characterisation of new materials (e.g., new molten salt mixtures or PCMs); material performances and durability; and material corrosion properties (e.g., the ability to manage high-temperature sulphuric acid).

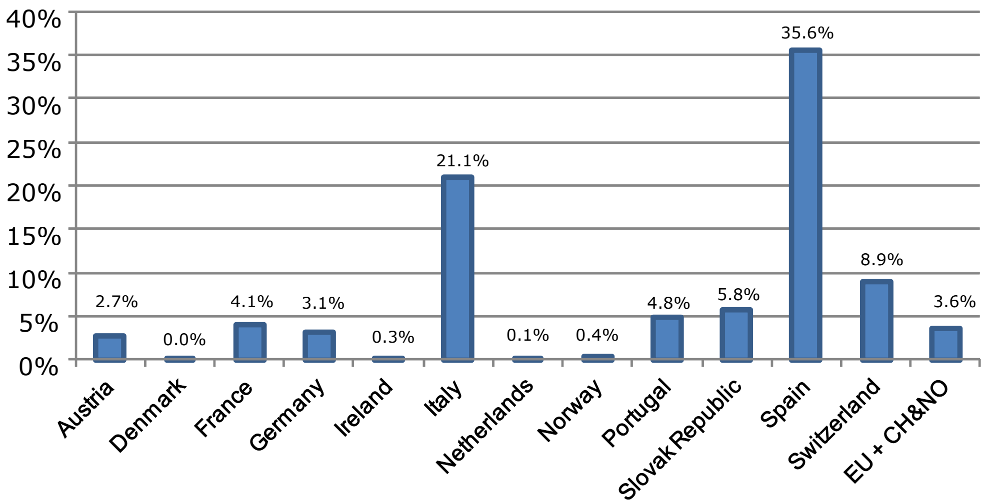
Some of these challenges are common to other sectors of energy and plant engineering, namely conventional thermal power plants, chemical processing plants, and thermal solar energy. This provides an opportunity to exploit synergies.

Other challenges that are currently not sufficiently covered by R&D efforts will continually emerge as solar energy in general increases its role in the energy mix, mostly in grid-connected applications. These challenges will be related to the management and correct valuation of the increased total power of solar generation assets in relation to the average load of the electrical network. However, these challenges will provide an opportunity to enhance the role and the value of CSP and of DNI forecasting in the most ambitious RES scenarios required by European carbon emissions reduction targets.

7 Capacities mapping

Data available from the International Energy Agency RD&D Statistics Database indicate that the overall public R&D expenditure on CSP in 2010 amounted to EUR 38.7 million, representing about 3.6% of the total European public budget for R&D activities in the RES sectors (Figure 1).

Figure 2: Member States' RD&D expenditure on CSP as a share of total RD&D expenditure for RES in 2010 (% - 2011 prices and exchange rates)



Source: IEA RD&D Statistics Database

The European Commission has estimated the financing needs for CSP research for the period 2010-2020 at EUR 7 billion[18], with RD&D activities focusing both on better technical and environmental performance and on cost reduction.

Over the past few years Italy and Spain have been the main European countries supporting R&D spending, both in relative and absolute terms. This lines up with the observation that the Mediterranean countries have the most favourable locations and the highest potential for CSP plants.

The Spanish public budget has remained quite steady, increasing from about EUR 9 million at the beginning of the last decade to a little more than EUR 10 million in 2010 and 2011, peaking at roughly EUR 16 million in 2009 (Figure 2). The CSP expenditure in 2010

[18] SWD(2013) 157 final

accounted for more than 35% of total national R&D funding for RES. The estimate for 2011 is more than 38%.

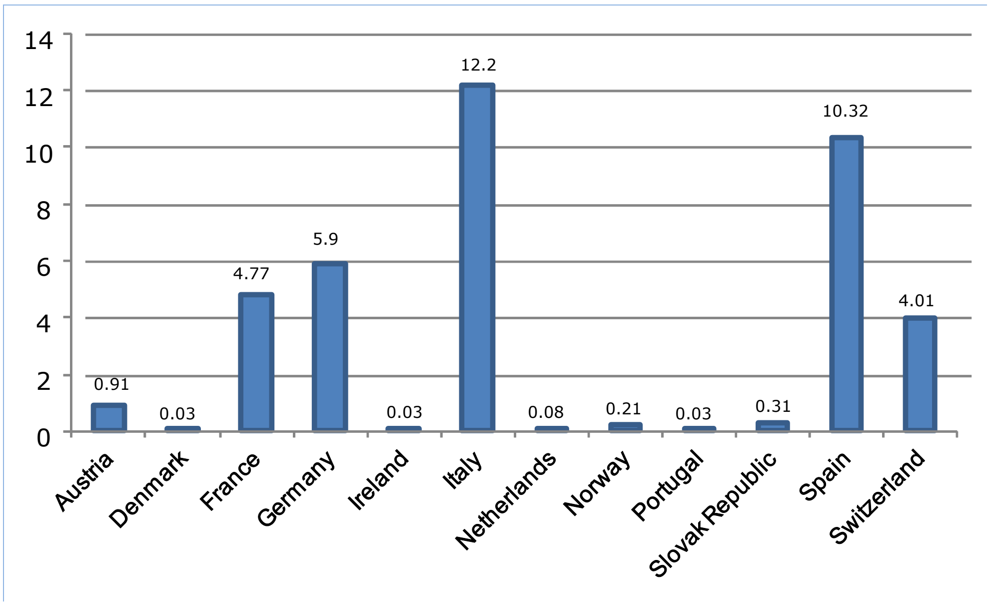
In Italy the CSP sector has received roughly between 21% and 22% of the total national RES R&D budget in the last two years, corresponding to a total expenditure of around EUR 12 million in 2010 and EUR 15 million in 2011. This country has shown a fluctuating trend, increasing from approximately EUR 20 million in 2001, driven by the ARCHIMEDE project, to a peak of EUR 39 million in 2003, but falling to less than half this amount at the beginning of the current decade.

In absolute terms, Germany is the third main contributor to research activities in the CSP sector in Europe. Its public budget amounted to EUR 5.9 million in 2010 and to EUR 8 million in 2011, representing more than 3% of the total national expenditure on renewable energy technologies.

France also has a strong position in this sector with almost EUR 5 million in 2010 (no data available for 2011), accounting for a little more than 4% of total RES R&D expenditure.

Excluding Switzerland, four EU countries (Spain, Italy, Germany and France) accounted for more than 85% of the total European public budget for R&D activities in the CSP sector in 2010.

Figure 3: Member States' total RD&D expenditure on CSP in 2010 (million EUR - 2011 prices and exchange rates)



Source: IEA RD&D Statistics Database

8 Conclusions and recommendations

Key messages

- *Most of the examined projects aim to increase the temperature of the heat collecting fluid and the performance of storage and hybridisation. Other strategic targets are to decrease the size of storage and reduce the cost of installed products.*
- *Although CSP technology is currently approached as a complex technology, dedicated to large-scale electricity production only, this may change in future, as the technology is also suitable for cogeneration of electricity and heat.*
- *Further research efforts should focus on: simulating complex plant behaviour; setting component standards for industrial design; quantifying CSP dispatchability in various markets; introducing high-temperature power cycles; chemistry and chemical engineering for thermochemical storage and production of solar fuels.*

The projects' contribution to the European KPIs (see annex 3) can be summarised as follows, considering that some of the KPIs (namely the number of "down-time" hours per year (3.1) and partially the increased number of operating hours (3.6)) are more linked to the commercial implementation/exploitation of results than to specific R&D actions.

Regarding the KPIs, the projects SOLUGAS, HYGATE and OMSOP explicitly address KPI 1.1 (Increased CSP solar to electricity conversion efficiency) since the solar-driven gas turbine system (either driven by a central receiver or a dish system) is one of the most promising ways to increase the efficiency of solar to electricity conversion, especially if combined with a steam bottoming cycle, by increasing HTF temperature.

KPI 1.2 (Increase heat collecting fluid steam temperature) is addressed by a number of projects, namely DUKE, TUBOSOL, HITECO, Ultimate Trough, SOLUGAS, HYGATE, LFR500, OMSOP, ARCHETYPESW550, CSP2 and E2PHEST2US. The full range of concentration technologies (LPT, ST, Fresnel and Dishes) are involved in this effort.

KPIs under category 2 (Reduce CSP costs) are directly addressed by the projects DUKE, TUBOSOL, Ultimate Trough, and AUGUSTIN FRESNEL 1 (KPI 2.1: Reduce cost of installed products), while KPI

2.2 (Life-time levelised electricity cost) is addressed by SOLUGAS, HYGATE and AUGUSTIN FRESNEL 1.

KPIs under category 3 (Increase dispatchability) are addressed by all the projects involving the use of storage and/or hybridisation. In particular, KPI 3.1 (Number of "down-time" hours per year) is addressed by eCARE, STARS and STORRE. Increased performance of storage and hybridisation (KPI 3.2) is addressed by SOLUGAS, HYGATE, ARCHETYPESW550, MATS, HYSOL, SOLMASS CSP and MICROSOL. Investment cost of storage of stored energy (KPI 3.3) is addressed by MATS and OPTS. Decrease size of storage (KPI 3.5) is addressed by OPTS, CSP2, STORRE, ARCHETYPESW550 and MATS. The increased number of operating hours (KPI 3.6) is addressed by eCARE and MICROSOL. No activities were found on research in increasing the efficiency of storage and dispatch flexibility and in decreasing the cost of electricity produced (outside the activities within the other cost related KPIs).

Finally, reducing water consumption with only minor moss of performance (KPI 4.1) is addressed by eCARE and MACCSOL.

Projects in sub-themes 7 (research facilities) and 9 (solar resource) are not directly related to European KPIs, but indirectly contribute to all of them. Sub-theme 8 (solar fuels and solar chemistry) is not yet considered in KPIs since it is not classified in the short/medium-term industrial horizon.

Table 8 overleaf relates the projects with the KPIs which they address.

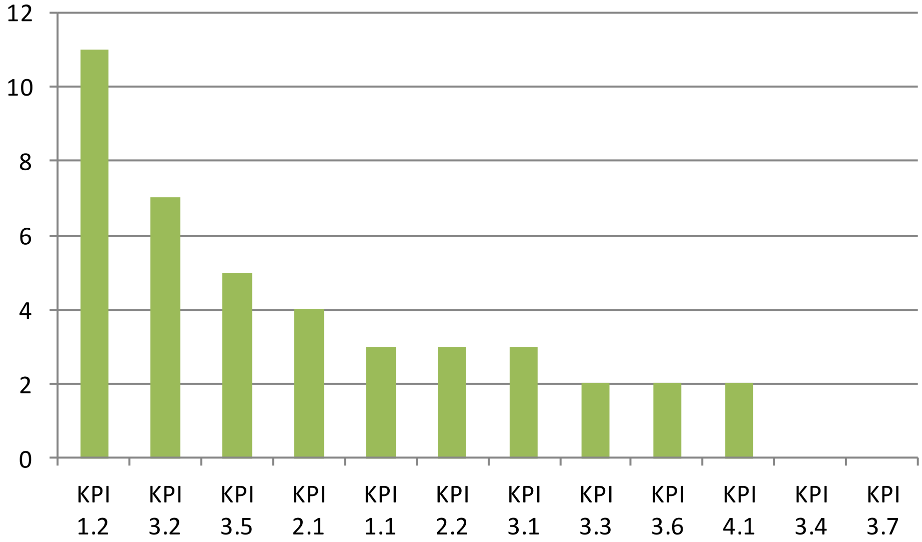
Table 8: List of CSP projects addressing KPIs[19]

	KPI 1 Increase CSP efficiency		KPI 2 Reduce CSP costs		KPI 3 Increased dispatchability							KPI4 Environmental profile
Project	1.1 Conversion efficiency	1.2 Fluid steam temperature	2.1 Installed products	2.2 LCOE	3.1 Down-time h/y	3.2 Performance of storage and hybridisation	3.3 Cost of storage	3.4 Efficiency of storage	3.5 Decrease size of storage	3.6 Number of operating hours	3.7 Decrease the cost of produced energy	4.1 Reduction of water consumption
TUBOSOL		**x**	**x**									
HITECO		**x**										
DUKE		**x**	**x**									
Ultimate Trough		**x**	**x**									
SOLUGAS	**x**	**x**		**x**		**x**						
HYGATE	**x**	**x**		**x**		**x**						
AUGUSTIN FRESNEL 1			**x**	**x**								
LFR500		**x**										
eCARE					**x**					**x**		**x**
OMSOP	**x**	**x**										
OPTS							**x**		**x**			
CSP2		**x**							**x**			

[19] See annex 3 for full KPI titles.

	KPI 1 Increase CSP efficiency		KPI 2 Reduce CSP costs		KPI 3 Increased dispatchability							KPI4 Environmental profile
Project	1.1 Conversion efficiency	1.2 Fluid steam temperature	2.1 Installed products	2.2 LCOE	3.1 Down-time h/y	3.2 Performance of storage and hybridisation	3.3 Cost of storage	3.4 Efficiency of storage	3.5 Decrease size of storage	3.6 Number of operating hours	3.7 Decrease the cost of produced energy	4.1 Reduction of water consumption
RESTRUCTURE												
TCSPOWER												
STARS					x							
STORRE					x				x			
ARCHETYPE		x				x			x			
MATS						x	x		x			
DigeSPo												
E2PHEST2US		x										
HY-SOL						x						
SOLMASS CSP						x						
MICROSOL						x				x		
MACCSOL												x

Figure 4: Number of CSP projects per KPI



In conclusion, CSP technology encompasses a number of different technologies, each working towards the objective of exploiting the solar resource through concentration, in order to produce electricity, process heating and cooling, water desalination, solar fuels or high-temperature material processing.

New concepts such as hybridisation with fossil fuels or biomass and increasing dispatchability through cost-effective thermal storage can improve the state of the art in CSP. CSP plants can be conceived and designed with sizes ranging from a few kW to hundreds of MW.

As a consequence, the approach to CSP R&D is necessarily faced with a number of possibilities and a number of basic technology sectors to exploit and enhance, ranging from optics to material properties, thermodynamics and chemistry.

CSP technologies also have different degrees of maturity, depending on the market segment and geographic position. The more the technology becomes commercially attractive, the more the R&D effort is being taken over by industrial companies, with associated restrictions on the ownership of know-how.

A first recommendation is therefore to think of CSP not as a one-dimensional technology (devoted only to large-scale electricity production) but as a complex technology with a number of possible applications.

The most promising CSP features to exploit are:

- The decreasing cost of electricity produced;
- Its intrinsic dispatchability through thermal energy storage;
- Its hybridisation potential, in other words, the possibility of a multi-input approach (fuels and solar);

- Its cogenerative potential, in other words, the possibility of a multi-output approach (e.g., cogeneration of electricity and heat).

From an industrial design point of view, the importance of the ability to simulate complex plant behaviour will increase, together with the setting of standards for components. Some R&D work in these areas is still required.

An effort to quantify CSP dispatchability in various markets and situations, either as a stand-alone technology or hybridised with fuels, will also be beneficial as electric grids become increasingly populated by intermittent renewable energy plants.

Research efforts are expected to continue on increasing temperatures and introducing high-temperature power cycles, for example, supercritical steam and solar-driven gas turbine combined cycles, with gaseous HTFs.

Research on various thermal storage technologies has shown great potential and a number of new options are being introduced in this field.

Finally, chemistry and chemical engineering will increase their role both for the development of thermochemical storage and for the production of solar fuels. These two subjects will become very important within the context of high-level penetration of renewable energy in the world energy mix.

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Annexes

Annex 1: Acronyms and abbreviations used in the TRS

General

ASTRI	Australian Solar Thermal Research Initiative
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
CORDIS	Community Research and Development Information Service
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Agency)
DOE	Department of Energy (USA)
ECMWF	European Centre for Medium-Range Weather Forecasts
EERA	European Energy Research Alliance
EII	European Industrial Initiative
ERKC	Energy Research Knowledge Centre
ESFRI	European Strategy Forum on Research Infrastructures
ESTELA	European Solar Thermal Electricity Association
EU	European Union
FP4/5/6/7	Fourth/Fifth/Sixth/Seventh Framework Programme for Research and Development
IEA	International Energy Agency
JP	Joint Programme
KPI	Key Performance Indicator
NREAP	National Renewable Energy Action Plan
NREL	National Renewable Energy Laboratory (USA)
PSI	Paul Scherrer Institute
PB	Policy Brochure
R&D	Research and Development
RD&D	Research, Development and Demonstration
SEII	Solar European Industrial Initiative
SETIS	Strategic Energy Technologies Information System
SET-Plan	European Strategic Energy Technology Plan
STE-EII	Solar Thermal Electricity European Industrial Initiative
SWD	Staff Working Document
TRS	Thematic Research Summary

Technical and related to the theme

ACC	Air cooled condensers
AGT	Aeroderivative gas turbine
ANI	Aperture normal irradiation
CAPEX	Capital expenditure
CSP	Concentrating solar power (mostly used in the US)
DNI	Direct normal irradiation
DSG	Direct steam generation
GW	Gigawatt
GWh	Gigawatt-hour
HI	Hydrogen-iodide
HRS	Heat recovery system
HTF	Heat transfer fluid
HyS	Hybrid sulphur
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCOE	Levelised cost of electricity
LFRC	Linear Fresnel reflector collectors
LPT	Linear parabolic trough
MACC	Modular air-cooled condenser
MF	Manganese-ferrite
MW	Megawatt
MWh	Megawatt-hour
M-CHP	Micro-combined heat and power
OPEX	Operation & management expenditure
ORC	Organic Rankine cycle
O&M	Operation and maintenance
PCM	Phase change material
PPA	Power purchase agreement
PSA	Plataforma Solar de Almeria
PV	Photovoltaic
PVPS	Photovoltaic power systems
RES	Renewable energy sources
ROI	Return on investment
SHC	Solar heating and cooling
SEGS	Solar electric generating system
SI	Sulphur-iodine
SolarPACES	Solar power and chemical energy systems Implementing Agreement of IEA
ST	Solar tower
STE	Solar thermal electricity: synonym of CSP, mostly used in Spain
TW	Terawatt
TWh	Terawatt-hour
TCS	Thermochemical storage
TES	Thermal energy storage
WIS	Weizmann Institute of Science

Annex 2: Complete list of projects relevant to the theme

Sub-theme 1: Parabolic trough technology and components				
Project acronym	Project title	Programme	Project website	Dates
TUBOSOL	Tubo Assorbitore di Energia Solare (Solar Energy Absorber Pipe)	Italian Government Programme Industria 2015	www.portici.enea.it/index.asp?p=57&t=TUBOSOL	July 2009 – July 2013
HITECO	New Solar Collector Concept for High Temperature Operation in CSP Applications	FP7- 2010/2013 agreement no. 256830	www.hitecoproject.com	Nov 2010 – Nov 2013
GEDIVA	Estudios Termo-Hidráulicos de Sistemas con Captadores Solares Cilindroparabólicos para la Generación Directa de Vapor (Thermo-hydraulic Analysis of Parabolic Trough Receivers for Direct Steam Generation)	Spanish Ministry of Economy and Competitiveness, Ref. ENE2011-24777	www.psa.es/webesp/areas/ussc/grupomedia/gediva.php	Jan 2012 – Dec 2014
DUKE	Durchlaufkonzept-Entwicklung und Erprobung (Once-through Concept Development and Testing)	BMU	www.dlr.de/sf/desktopdefault.aspx/tabid-8592/12159_read-36870/	2012 – Apr 2014

Ultimate Trough	Ultimate Trough	BMU	www.flabeg.com/uploads/media/FLABEG_Solar_Ultimate_Trough_24.pdf	Jan 2010 – Dec 2013

Sub-theme 2: Central receiver technology and components				
Project acronym	Project title	Programme	Project website	Dates
SOLUGAS	Solar Up-scale Gas Turbine System	FP7-ENERGY-2007-2.5-04 prog. ref. 219110	www.solugas.com	Nov 2008 – April 2013
HYGATE	Hybrid High Solar Share Gas Turbine Systems	BMU	phpframe.wcms-file3.tu-dresden.de/generalize/?g_nid=0103&node=203&e_id=13145&t_id=107	2011-2014

Sub-theme 3: Linear Fresnel technology and components				
Project acronym	Project title	Programme	Project website	Dates
AUGUSTIN FRESNEL 1	AUGUSTIN FRESNEL 1	French Government/EU	www.solareuromed.com/en/technology/augustin-fresnel	Aug 2011 - Jan 2012
LFR500	Linear Fresnel Reflectors 500	French Government (Ademe-programme Investissements d'Avenir)	www.solareuromed.com/sites/default/files/120420_CP-LFR500.pdf www2.ademe.fr/servlet/doc?id=82739&view=standard	June 2012 – June 2014
eCARE	eCARE	French Government (Ademe-programme Investissements d'Avenir)	www2.ademe.fr/servlet/doc?id=82730&view=standard	May 2011 – July 2015

Sub-theme 4: Dish technology and components				
Project acronym	Project title	Programme	Project website	Dates
OMSOP	Optimised Microturbine Solar Power System	FP7-ENERGY prog. ref. 308952	www.omsop.serverdata.net/Pages/Home.aspx	Feb 2013 – Jan 2017

Sub-theme 5: Thermal energy storage/Heat transfer fluids				
Project acronym	Project title	Programme	Project website	Dates
OPTS	Optimisation of a Thermal Energy Storage System with Integrated Steam Generator	FP7-ENERGY.2011.2.5-1 prog. 282138	www.opts.enea.it	Dec 2011– Nov 2014
CSP2	Concentrated Solar Power in Particles	FP7-ENERGY.2011.2.5-2 prog. 282932	www.csp2-project.eu	Dec 2011 – Nov 2015
RESTRUC TURE	Redox Materials-Based Structured Reactors/Heat Exchangers for Thermochemical Heat Storage Systems in Concentrated Solar Power Plants	FP7-ENERGY-2011.2.5.1 prog. 283015	www.restructure-project.org	Nov 2011 – Oct 2015
TCSPOWE R	Thermochemical Energy Storage for Concentrated Solar Power Plants	FP7-ENERGY prog. 282889	www.tcs-power.eu	Nov 2011 – April 2015
STARS	STARS	French Government (Ademe Programme des Investissements d'Avenir)	www2.ademe.fr/servlet/doc?id=82736&view=standard	May 2012 - 2016

STORRE	High-Temperature Thermal Energy Storage by Reversible Thermochemical Reaction	FP7-ENERGY prog. n. 282677	www.apt.cperi.certh.gr/index.php?option=com_content&view=article&id=94%3Astorre&catid=10&Itemid=13&lang=en	Sept 2012 – Aug 2015

Sub-theme 6: Plant concepts/prototypes				
Project acronym	Project title	Programme	Project website	Dates
ARCHETYPE SW550	Demonstration of Innovating Parabolic Solar Trough Using an Alternative Heat Transfer Fluid Producing Electricity and Fresh Water: ARCHIMEDE Hot Energy Typology Enhanced Water Solar 550	FP7-ENERGY-2010.2.9-1 prog. ref. 268181	na	Jan 2012 – Dec 2016
MATS	Multipurpose Applications by Thermodynamic Solar	FP7-ENERGY	192.107.92.31/mats/	July 2011 – Jan 2015
DiGeSPo	Distributed CHP Generation from Small Size Concentrated Solar Power	FP7 – Energy – 2009-1 prog. ref. 241267	www.digespo.eu	Jan 2010 – Oct 2013
E2PHEST2US	Enhanced Energy Production of Heat and Electricity by a Combined Solar Thermionic-Thermoelectric Unit System	FP7-ENERGY prog. ref. 241270	www.ephestus.eu	Jan 2010 – Dec 2012
HYSOL	Innovative Configuration for a Fully-Renewable CSP Plant	FP7-ENERGY-2012.2.5.2 grant. 308912	na	May 2013 – May 2016

STS-MED	Small-Scale Thermal Solar District Units for Mediterranean Communities	EU funded Priority 2 – Topic 2.3 Solar Energy Ref. I-A/2.3/174	www.stsmed.eu	2012 – 2014
SOLMASS CSP	Solmass CSP Power Project 4 MW	European Industrial Initiative	na	2013 – 2015
MICROSO L	Microcentrale solaire pour l'Electrification rurale (Solar Micro-plant for rural Electrification)	French Government (Ademe-programme Investissements d'Avenir)	www2.ademe.fr/servlet/doc?id=82737&view=standard	Nov 2011 – May 2014
MACCSOL	The Development and Verification of a Novel Modular Air-Cooled Condenser for Enhanced Concentrated Solar Power Generation	FP7-ENERGY-2010-1	www.drycooledcsp.eu/	Sept 2010 – Feb 2015

Sub-theme 7: Research facilities and basic R&D support				
Project acronym	Project title	Programme	Project website	Dates
SFERA	Solar Facilities for the European Research Area	FP7 – NFRASTRUCTURES Prog. 228296	sfera.sollab.eu/	July 2009 – June 2013

Solare Termodin amico	Progetto B.1.3, Energia Elettrica da Fonte Solare, Linea Progettuale 2: Solare Termodinamico (Solar Thermodynamic Electricity; Project B.1.3, Electric Energy from Solar Sources, Project Line 2: Solar Thermodynamic Electricity)	Accordo di Programma Ministero dello Sviluppo Economico – ENEA sulla Ricerca di Sistema Elettrico, Piano annuale 2012	na	2012 – 2014
EU-SOLARIS	The European Solar Research Infrastructure for Concentrated Solar Power	FP7-INFRASTRUCTURES-2012-1 prog. 312833	www.eusolaris.eu/	Sept 2012 – Sept 2016

Sub-theme 8: Solar chemistry				
Project acronym	Project title	Programme	Project website	Dates
HYDROSOL-3D	Scaling up a Solar Monolithic Reactor for Thermochemical H2 Production: a 3rd Generation Design Study	Hydrogen and Fuel Cell Joint Undertaking	www.hydrosol3d.org/	Jan 2010 – Dec 2012
SOLHYCARB	Hydrogen from Solar Thermal Energy: High Temperature Solar Chemical Reactor for Co-Production of Hydrogen and Carbon Black from Natural Gas Cracking	FP6-SES-CT-2005-019770	www.promes.cnrs.fr/index.php?page=solhycarb	March 2006 – Feb 2010

Sub-theme 8: Solar chemistry				
Project acronym	Project title	Programme	Project website	Dates
TEPSI	Innovative Technologies and Process for Hydrogen Production Systems	Italian Government (FISR programme)	na	Feb 2006 – Feb 2010
CONSOLI +DA	Consortium of Solar Research and Development	CENIT programme of Spanish Ministry of Science and Innovation	www.solarpaces.org/Tasks/Task6/consolida.htm	July 2009 – Dec 2011
HycycleS	Materials and Components for Hydrogen Production by Sulphur-Based Thermochemical Cycles	FP7	www.dlr.de/sf/desktopdefault.aspx/tabid-7237	Jan 2008 – March 2011
CoMETHy	Compact Multi-Fuel Energy to Hydrogen Converter	FP7-JTI (FCH JU, contract number 279075)	www.comethy.enea.it	2011 – 2014
ENEXAL	Novel Technologies for Energy and Exergy Efficiency in Primary Aluminium Production Industry	FP7-ENERGY-2009-2 grant ENER/FP7EN/249710/ENEXAL	www.labmet.ntua.gr/ENEXAL/	June 2010 – May2014
SOL2HY2	Solar to Hydrogen Hybrid Cycles	FP7 -FCH-JU-2012-1 prog. 325320	https://sol2hy2.eucoord.com/	June 2013 – May 2016

Sub-theme 9: Solar resource measurement and forecasting				
Project acronym	Project title	Programme	Project website	Dates
MESoR	Management and Exploitation of Solar Resource Knowledge	FP6 - contract 038665	www.mesor.org	June 2007– May 2009
MACC-II	Monitoring Atmospheric Composition & Climate	FP7	www.gmes-atmosphere.eu	2011 – 2014

Annex 3: List of ERKC KPIs for CSP

The following list of KPIs for CSP technology is utilised in the ERKC portal and has been agreed with the European Commission (EC-JRC-IET and EC DGs RTD and ENER). Note: a progressive number has been added here to easily identify KPIs.

1 Increase CSP efficiency
   1.1 Increased CSP solar to electricity conversion efficiency
   1.2 Increase heat collecting fluid steam temperature
2 Reduce CSP costs
   2.1 Reduce cost of installed products
   2.2 Life-time levelised electricity cost
3 Increased dispatchability:
   3.1 Number of “down-time” hours per year
   3.2 Increased performance of storage and hybridisation
   3.3 Investment cost of storage of stored energy
   3.4 Increase efficiency of storage as well as time dependency
   3.5 Decrease size of storage
   3.6 Increase number of operating hours, based on maximum storage capacity
   3.7 Decrease the cost of produced energy
4 Environmental profile
   4.1 Reduction of water consumption with only minor loss of performance

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