SOLAR THERMAL ELECTRICITY

STRATEGIC RESEARCH AGENDA 2020-2025

DECEMBER 2012

European Solar Thermal Electricity Association
ESTELA

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Dr. Luis Crepo
President of ESTELA

Mariàngels Pérez Latorre
Secretary - General

PREFACE

Renewable energy is a key component of the future energy supply as acknowledged in the EU 2050 Energy Roadmap. The EU has pursued a sustained support for the introduction of renewable energies in the energy mix because of their importance for reducing the carbon footprint of the economy, for improving the security of the energy supply and for promoting the regional economic and social development. More and better research and development can help overcome two major obstacles to the wider uptake of some promising renewables, which are their higher costs and intermittency.

Concentrating Solar Power (CSP) has the potential to supply substantial quantities of renewable energy in Europe and abroad. Europe's leading position worldwide on many key technological components of CSP and the readiness of the European stakeholders to work together in view of speeding up the commercialisation of this technology led to the launch of the Solar Europe Industrial Initiative under the Strategic Energy Technology Plan.

DG Research and Innovation welcomes this Strategic Research Agenda, which provides a vision for the development of the sector in the years to come and highlights priorities and areas for cooperation. This document will be of use to the sector to contribute to the discussion on the forthcoming Framework Programme for Research and Innovation - Horizon 2020. My wish is for the sector to continue consolidating its position through industrial and research collaborations, notably at European level.

Robert-Jan Smits
Director-General for Research & Innovation
European Commission

GLOSSARY

AENOR	Spanish Association for Normalisation and Certification
AEN/CTN	Spanish Association for Normalisation/Technical Committee for Normalisation
AHS	Auxiliary Heating System
ARENA	Australian Renewable Energy Agency
ASME	American Society of Mechanical Engineers
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CENER	National Renewable Energy Centre of Spain
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas
CLFR	Compact Linear Fresnel Reflector
CNRS	French National Centre for Scientific Research
CR	Central Receiver
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
DKE	German Commission for Electrical, Electronic & Information Technologies
DSG	Direct Steam Generation
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EERA	European Energy Research Alliance
EIB	European Investment Bank
EII	European Industrial Initiative
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPC	Engineering Procurement Construction
ERANET	European Research Area Network
ESFRI	European Strategy Forum on Research Infrastructure
ESTELA	European Solar Thermal Electricity Association
EU-Solaris	European Solar Research Infrastructure for CSP
EU	European Union
FiT	Feed-in-Tariff
FP7	Seventh Framework Programme
GDP	Gross Domestic Product
GUISMO	Guidelines CSP Performance Modelling
GWh	Gigawatt hour
HCE	Heat Collection Element
HDH	Humidification-Dehumidification
HSM	Heat Storage Medium
HTF	Heat Transfer Fluid
HVDC	High Voltage Direct Current
ISCC	Integrated Solar Combined-Cycle
IEC/TC	International Electro-technical Commission/Technical Committee

KPI	Key Performance Indicator
kWp	Kilowatt peak
LCOE	Levelised Cost of Electricity
LF	Linear Fresnel Reflector
LWC	Levelised Water Cost
MBE	Mean Bias Error
MD	Membrane Distillation
MED	Multi-Effect Distillation
MENA	Middle East and North Africa
MoU	Memorandum of Understanding
MSH	Molten Salt Heater
MS	Molten Salt
MSP	Mediterranean Solar Plan
MTBF	Mean Time Between Failure
MWe	Megawatt of electricity
MWth	Megawatt of Thermal Energy
NER300	New Entrant Reserve 300
NREAP	National Renewable Energy Action Plan
NWP	Numerical Weather Prediction
OHL	Over Head Lines
O&M	Operation and Maintenance
OPEX	Operating Expenditure
OPTS	Optimisation of a Thermal Energy Storage System with Integrated Steam Generator
ORC	Organic Rankine Cycle
PCM	Phase Change Material
PD	Parabolic Dish
PPA	Power Purchase Agreement
PT	Parabolic Trough
PV	Photovoltaic
R&D	Research and Development
REFIT	Renewable Energy Feed-In-Tariff
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
RO	Reverse Osmosis
SEGS	Solar Energy Generating Systems
SETIS	Information System for the European Strategic Energy Technology Plan
SET-Plan	Strategic Energy Technology Plan
SEII	Solar European Industrial Initiative
SFERA	Solar Facilities for the European Research Area
SolarPACES	Solar Power And Chemical Energy Systems
STE	Solar Thermal Electricity
TES	Thermal Energy Storage
wt%	Percent in Weight

THE EUROPEAN SOLAR THERMAL ELECTRICITY ASSOCIATION (ESTELA)

ESTELA is an association created by the European industry to support the emerging European solar thermal electricity industry for the generation of green power in Europe and other regions, particularly the Mediterranean and North African region.

ESTELA involves and is open to all main actors in Europe: promoters, developers, manufacturers, utilities, engineering companies and research institutions.

One of the main activities of ESTELA and its members is to collaborate with institutions in the European Union (EU) to develop solar thermal electricity generation and its supporting industry across Europe.

Another core activity in close collaboration with academia is to produce and coordinate studies on scientific, technical, economic, legal or policy issues to further develop solar thermal electricity technologies.

Finally, ESTELA considers of paramount importance to raise awareness by disseminating information about solar thermal electricity and the European Association by organising meetings, workshops, conferences and other events to promote solar thermal electricity.

The emerging industry of solar thermal electricity has strong European roots. It is growing to a great extent due to the technical and economic success of the first projects and to the stable green pricing or support mechanisms to bridge the initial gap in the electricity costs – mechanisms such as feed-in tariffs (FiT). Future growth will depend on a successful costs reduction and a strong effort in R&D to realise the great existing potential for technical improvement. In the long-term, it is envisioned that new markets and market opportunities will appear: a particularly exciting possibility is the generation of solar thermal power in the Mediterranean region and its transmission to other parts of Europe.

ESTELA members will ensure the solar thermal electricity industry contribution to the achievement of renewable energy objectives by 2020, provided that the necessary measures are taken both in the market and in research to support the efforts of the industry.

ESTELA members believe that the EU, in the short and medium-term, should install demand-pull instruments and promote support mechanisms such as feed-in-laws as the most powerful instruments to further solar thermal electricity generation goals. In the long term, the European transmission grid should be opened to bring solar electricity from North Africa and regional agreements should be implemented to secure this reliable power import.

The world's "Sun Belt", that extends from about latitudes 35 North to 35 South and border areas, receives several thousand times the energy needed to meet the world's energy demand. This resource is not being currently exploited. At the same time, dramatic changes are to be implemented in the current energy systems to mitigate their negative impact on the environment and on the world's climate. A large part of the enormous energy resource available in the Sun Belt could be harnessed through solar thermal technologies, conveyed and used in a sustainable way.

The objectives of ESTELA are:

- To promote high and mid temperature solar technologies for the production of thermal electricity to move towards sustainable energy systems;
- To promote thermal electricity in Europe at policy and administrative levels (local, regional, national and European);
- To support EU's action in favour of European industry development and to contribute to reach the Union's energy objectives and its main renewable energy targets;
- To support research and innovation, including vocational training, and favouring equal opportunities for all;
- To promote excellence in the planning, design, construction and operation of thermal electricity plants;
- To promote thermal electricity internationally, mainly in the Mediterranean area and in developing countries;
- To cooperate at the international level to combat climate change;
- To represent the solar thermal electricity sector in Europe and the world.

THE SCIENTIFIC AND TECHNICAL COMMITTEE

Since its creation in 2007, ESTELA has developed its scientific and technical activities in support of research and innovation. It has established guiding priorities for the short and long-term efforts to foster the market penetration of solar thermal power plants and to consolidate the global leadership position of the European industry.

To create an innovation strategy, ESTELA has taken advantage of having among its members the main research institutions active in this field in Europe.

In September 2011, ESTELA stepped up its efforts by creating the Scientific and Technical Committee to help the Association build a Strategic Research Agenda for 2020 and beyond. This is the right moment to strengthen these efforts for two main reasons. First, the economic and financial crisis calls for more innovation and for a mid- and long-term vision. Second, ESTELA's mission is to contribute to the EU's debate on the programmes to support research, demonstration and innovation in the framework of the financial perspectives for the period 2014-2020.

The Scientific and Technical Committee has ten members, eight of them from institutions which are members of ESTELA, and two from universities:

- Dr. Guglielmo Liberati (Coordinator): ESTELA, Italy
- Dr. Manuel Blanco: CENER, Spain
- Prof. Manuel Collares Pereira: Évora University, Portugal
- Dr. Fabrizio Fabrizi: ENEA, Italy
- Dr. Gilles Flamant: CNRS, France
- Prof. Hans Müller-Steinhagen: Dresden University, Germany
- Prof. Robert Pitz-Paal: DLR Solar Research Institute, Germany
- Dr. Werner Platzer: Fraunhofer ISE, Germany
- Dr. Manuel Silva Pérez: Seville University, Spain
- Dr. Eduardo Zarza Moya: Plataforma Solar de Almería, Spain

These members constitute what can justifiably be considered a Team of Excellence, because they represent some of the best scientific knowledge in the sector in Europe and beyond.

The total amount of electricity generated by Solar Thermal Electricity (STE) plants around the world is growing steadily. More than 1 GW have been connected to the grid in Southern Europe in the past few years, and this figure is expected to grow to more than 2 GW by the end of 2012. Operating experience has led to reductions in costs and risk, and plants generating another 1 GW are now under construction in North America, Africa, Asia and Australia. The European industry has a strong presence in many of those projects, and the Renewable Energy Sources (RES) Directive opens the way for even more opportunities in Southern Europe and in the Middle East and North Africa (MENA) region.

Generating the electricity that the world needs without releasing additional gases is now technically possible, and the characteristics of STE plants make them an essential part of an effective renewable portfolio. Dispatchability is a major advantage of these plants, and this characteristic may make it possible for a utility to accommodate an even larger amount of other intermittent technologies.

STE technologies have a huge potential and research and development (R&D) is essential to improve the competiveness of the current designs. An important push must be given to specific technology development activities and to support innovative demonstration plants of commercial size in order to contribute to lower generation costs and to enhance the bankability of the projects.

The regulatory conditions for implementing STE plants, including the RES Directive and the Feed-in-Tariff (FiT) systems in some European countries, particularly Spain, have been the driving force for the deployment of the first generation of STE plants. Due to the expected cost reductions through technological advancement and mass production, the technology will probably no longer depend on such support in a few years, when it will become competitive with electricity generation using fossil fuels.

This Strategic Research Agenda has been elaborated by the European Solar Thermal Electricity Industry Association in order to align R&D efforts with the support of the public administrations, including the European Union.

We have decided to be inclusive and the Strategic Research Agenda covers the four broad categories that up to now have been proposed for the thermal conversion of solar energy by the scientists. To varying degrees, they have been the subject of considerable interest and development and are already making small but meaningful contributions to satisfying electricity needs in many regions of the world. It is possible that advances in other fields (materials and controls, to name two) may create the conditions where other thermal conversion technologies will be conceived. There is no way to know what, if any, approach may someday revolutionise the field, but, the kind of research and development suggested in this report is the best way to foster innovation and open possibilities as the clock ticks for the inhabitants of our planet to find a sustainable path.

We hope this Strategic Research Agenda will contribute to a coherent development of the sector and to a more efficient allocation of R&D resources with the final goal of reaching competitiveness as soon as possible.

EXECUTIVE SUMMARY

The Strategic Research Agenda is the first-of-its-kind for the Solar Thermal Electricity (STE) technology. Drafted by highly qualified expert researchers in Europe composing ESTELA's Scientific and Technical Committee, it sets a solid basis for present and future research until 2025.

Uncertainty deters market penetration for any technology. The diversity of viable technical approaches for solar thermal energy conversion is one of the great advantages of STE, because different options have the potential to address different needs and market niches most effectively. Diversity also poses challenges, because there is some uncertainty associated with each option. Uncertainty derives from many sources, from weather to the changing political and economic environment. Another source arises from technology itself, and from the expectation of future technological advances. Fortunately, support for research and development is an effective tool to lower this uncertainty, and governments and consortia can wield this tool most effectively.

It is the goal of this document to assist decision makers by providing a review of the current economic, financial and technological trends of the STE sector as well as the existing policy and legal framework in different countries within the EU. These are described in chapters 1 to 6. The detailed research topics and related targets for each technology constitute chapter 7. The topics are based on three main objectives defined by the STE industry.

1- General overview	2- Technical aspects	STE-SEII SET-Plan
■ History ■ Industry overview and related economic aspects ■ Policy overview ■ State-of-the-art of STE technologies ■ STE main challenges on innovation	■ Cross-cutting issues ■ Parabolic Trough collectors ■ Central Receiver ■ Linear Fresnel reflectors ■ Parabolic Dishes	Objective 1: Increase efficiency and reduce costs
	■ Hybridisation and integration systems ■ Storage ■ Optimise dispatchability	Objective 2: Improve dispatchability
	■ Environment profile	Objective 3: Improve environmental profile

Economic and political trends

Global warming and economic growth are major current issues worldwide. STE technologies can contribute significantly to mitigate the impact of electricity production on the global temperature increase and to reach a much more balanced situation regarding availability of affordable power in industrialised and developing countries than it is the case today.

A carbon-free generation system can only be achieved with renewable and dispatchable technologies, and STE plants are the alternative with the largest potential amongst all renewable energy systems. At the same time, STE plants add the largest additional local value, even for the first plant in a row. This fact will be a key driver for policy decisions in favour of STE plants in many countries.

That is why STE is an advantageous technology which helps to pave the way out of the economic crisis in the Southern European countries. Because of the leading position of the European industry, this represents a historic opportunity to create partnerships and create business throughout the world, and particularly in the neighbouring MENA region.

By mid-2012, the total electric power generated by STE plants in the world has reached 2 GW; plants generating 3 GW are currently under construction. The majority of these plants are sited in Spain and in the United States. Interest grows in the rest of the world, as new projects are being launched in North Africa, India, China and South Africa. Plants generating 10 GW can be expected to be in place worldwide by 2015.

In Europe, the compulsory targets established on June 30, 2010 through the National Renewable Energy Action Plans (NREAP) for 2020 include the use of solar thermal electricity for the sunniest European countries.

Country	Cyprus	France	Greece	Italy	Portugal	Spain	Total
NREAP targets for 2020	75 MW	540 MW	250 MW	600 MW	500 MW	5,079 MW	7,044 MW

Regarding national subsidies, the situation in Europe is currently uncertain due to the economic crisis, and new measures are being taken at the national level to leverage investment initiatives for renewable projects. At the moment, for solar thermal electricity, the Feed-in-Tariff is around 0.30 c€/kWh, depending on the country and the plant parameters.

The STE industry creates many jobs. In Spain, in particular, the number of jobs related to STE has more than doubled between 2008 and 2010. This suggests a very promising future for jobs creation from the planned STE projects.

The levelised cost of electricity (LCOE) is the main economic parameter to compare different renewable technologies. This figure depends on the ratio between all costs and electricity generation, and it relies on the direct normal irradiation (DNI) for a given area (In Spain, the DNI reaches up to 2,100 kWh/m^2). A lower LCOE is expected in the next few years because of forthcoming technological improvements.

The European research policy context is set by the Common Framework Programme for Research and Innovation for the period 2014-2020, known as 'Horizon 2020'. The Programme places a great emphasis on renewable energies and first-of-a-kind demonstration plants. It also includes the Strategic Energy Technology Plan (SET-Plan) and its industrial initiatives, an instrument especially focused on the development of low carbon technologies. In parallel, the expansion of the grid and the implementation of the inter-continental 'electricity highways' are under way.

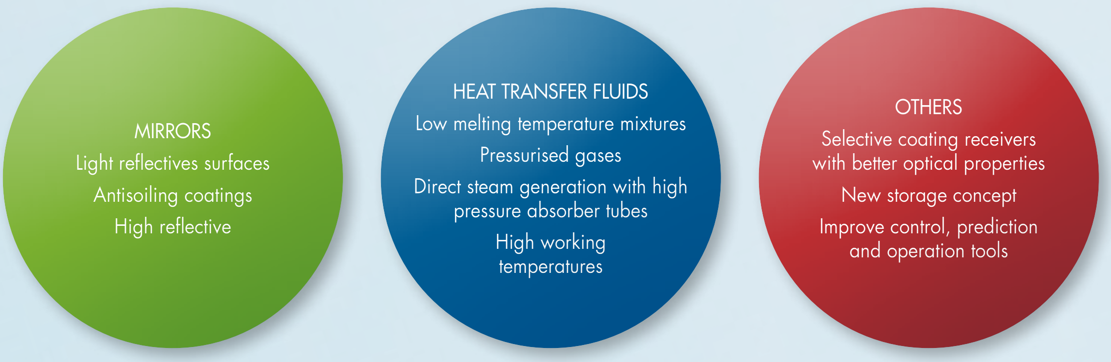
Standardisation:

Standards for STE technology are crucial for accelerating cost reduction. Many efforts have been made towards standardisation, but much improvement is still needed. The EN12975 standard for solar concentrators is now a part of the ISO 9806 standard, currently under revision. Working groups have been created in the last years, particularly in the frame of SolarPACES, and further guidelines are expected to be released in 2012 and 2013.

Standards must evolve towards a common framework and efforts need to be intensified in the following fields: qualification, certification, testing procedures, components and systems durability testing, commissioning procedures, model-based results and solar field modeling.

Objective 1: Increase efficiency and reduce generation, operation and maintenance costs

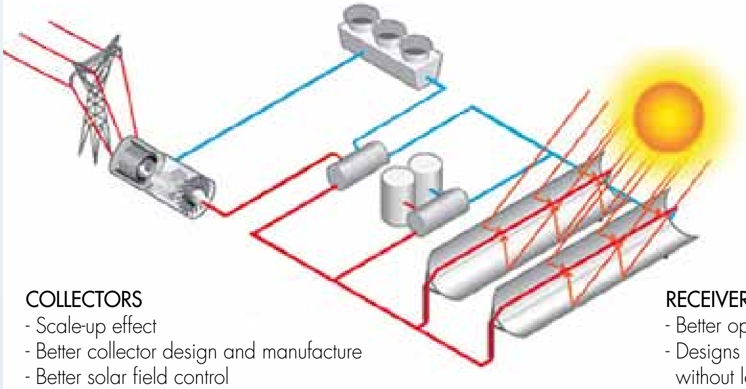
The different targets to reach the first objective ('Improve efficiency and reduce costs') are listed for each technology in the schemes on next page. However, cross-cutting issues exist between the different technologies and need to be taken into consideration. The transversal research topics to be investigated are:



Schemes listing the different investigation topics for each typical technology plant

PARABOLIC TROUGH COLLECTORS

Research topics to be investigated to reach objective 1 for parabolic trough collectors



HEAT TRANSFER FLUID
- Use of compressed gases (CO_2, N_2, air…)
- Direct steam generation
- Molten salt + auxiliary heating

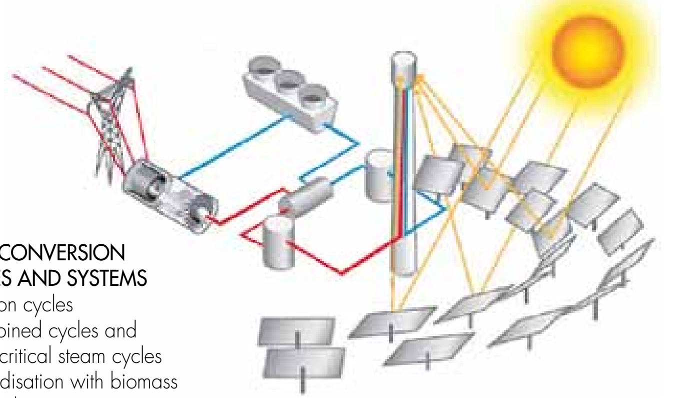
COLLECTORS
- Scale-up effect
- Better collector design and manufacture
- Better solar field control
- Autonomous drive units and local controls (wireless)

RECEIVER TUBES
- Better optimal stability of the selective coatings
- Designs with vacuum, without welds or without lower H_2 permeation
- Cheaper interconnecting elements

CENTRAL RECEIVERS

Research topics to be investigated to reach objective 1 for central receivers

RECEIVER
- Advanced high temperature receiver (direct absorption)
- New engineered materials (ceramic tubes)



HEAT TRANSFER FLUID
- Molten salt for supercritical steam cycles
- Air and CO_2 as primary fluids
- Direct superheated steam
- Particle receiver systems

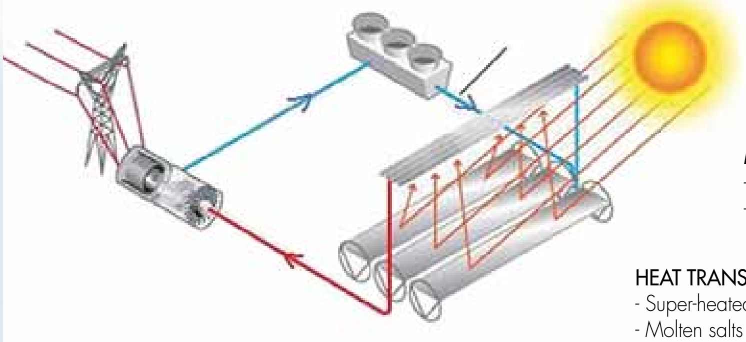
HELIOSTAT FIELD
- Multiple small towers configuration
- Reliable wireless heliostat control systems
- Optimised heliostat field
- Improve drive mechanisms
- Autonomous drive units and local controls (wireless)

NEW CONVERSION CYCLES AND SYSTEMS
- Brayton cycles
- Combined cycles and supercritical steam cycles
- Hybridisation with biomass
- Secondary concentrators

LINEAR FRESNEL REFLECTORS

Research topics to be investigated to reach objective 1 for linear Fresnel reflectors

CONTROL AND DESIGN
- Better tracking options
- Hybridisation of tower and Fresnel technologies



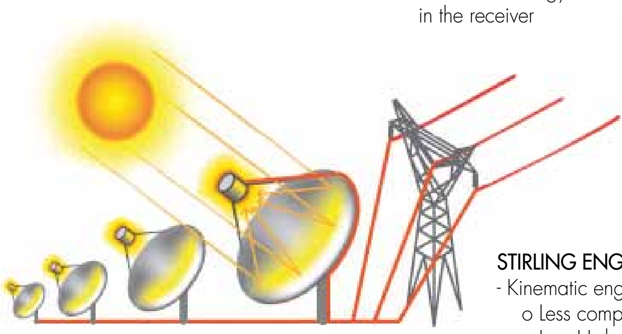
RECEIVERS
- Evacuated tubular receivers
- New generation of non-evacuated tubular receivers

MIRRORS
- Second stage concentration
- Thin films on curved support surfaces

HEAT TRANSFER FLUID
- Super-heated direct steam generation
- Molten salts only
- Pressurised CO_2 or air in non-evacuated receivers

PARABOLIC DISHES

Research topics to be investigated to reach objective 1 for parabolic dishes



Objective 2: Improve dispatchability

Dispatchability is one of the characteristics that makes STE a favored option among other renewable resources, and "Improving dispatchability" is even more is a most objective for STE development. Indeed, systems with the flexibility to feed the grid on demand are the key for solar thermal electricity to reach its potential. Although many plants are already built with a storage system, more efforts need to be done.

Integration systems:

The integration of solar heat in large steam plants can be achieved through the water preheating line or through the boiler steam/water circuit. In the first case, an appropriate boiler design is required to deal with temperature differences. If the integration is done with the boiler, an improvement of its design and control system is needed.

The integration of solar heat with gas turbine or combined cycle plants is also an option. With a gas turbine, the temperature of the air can be increased in high temperature solar collectors, leading to high conversion efficiencies. The ability to handle transient phases requires an improvement of the design of the control system.

The integration of solar heat with biomass, more appropriate for small sized facilities, is a good combination for an all-renewable fuelled plant. Although the combustion of biomass is not easy, it is possible to use organic fluid thermodynamic cycles (ORC), which simplify operation while increasing the overall efficiency.

Storage:

Depending on the HTF (Heat Transfer Fluid), different designs can be set up:

If the HTF is thermal oil, a single storage tank with good temperature stratification instead of a two tank configuration can greatly simplify storage. A single tank can also be optimised by a solid separation between the heat exchanger and the storage material.

If the HTF is molten salts, no exchanger is needed between the solar field and the storage circuit. New salt mixtures with lower freezing point and which avoid corrosion problems are the research and development goals for this topic.

If the HTF is steam, no exchanger is needed before the power block. Solid/liquid phase change materials applied for saturated steam are to be investigated.

If the HTF is gas, very high temperature applications are feasible. The challenges are how to design effective heat transfer systems and to find suitable storage materials.

In general, improved strategies for charging and discharging thermal heat are necessary to maximise storage capacity. Concepts for thermo-chemical energy storage systems are also to be investigated.

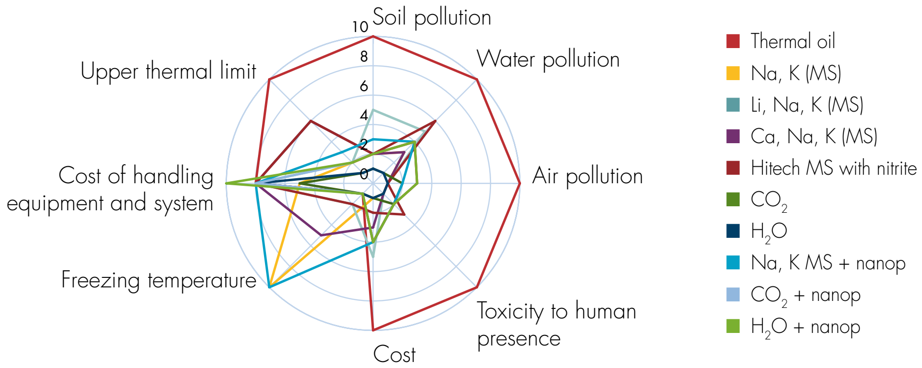
Improve forecasting:

Good forecasts are essential for reliable estimates of the costs of a plant in a given site. Many solutions can be envisioned, such as elaborating a very short term forecast for variable sky conditions, developing an electricity forecasting system software to regulate and manage electricity production, improving ground based DNI measurements, using meteorological satellite results, and improving numerical weather prediction models for DNI forecasting, analysing its inter-annual variability and the time and space correlation between solar and wind energy sources.

Objective 3: Improve environmental profile

Heat transfer fluids are of concern because of their potential impact on the environment: the pollution from synthetic oil is one of the most worrying. The environmental and economic parameters of different fluids have been studied.

HTF VERSUS TECHNICAL, ENVIRONMENTAL AND ECONOMIC CHARACTERISTICS



Desalination is a very interesting application of solar thermal energy. Despite the drawbacks related to the requirements for siting, desalination presents significant technical and economic advantages. There are several technical solutions, such as multi-effect distillation, reverse osmosis, humidification-dehumidification process and membrane distillation. The desalination system can also be the cooler part of the conventional power block. Thus, the optimisation of the integrated or combined cooling process needs to be considered as a research topic.

Conclusion:

The numerous investigations under way after the creation of research projects consortia at different levels (local, national, international) have opened the way for the STE sector to achieve great technological improvements and lower generation costs. Despite the present circumstances affecting national legislative frameworks and the changing support schemes, many efforts are being made at the European level to stabilise and harmonise the market and to achieve competitiveness.

The set of Key Performance Indicators (KPI) elaborated by ESTELA's Scientific and Technical Committee (ANNEX I) lists the most important parameters to be taken into consideration for the assessment of the technology improvements and determines the progress to be achieved by 2015 and for the time frame between 2020 and 2025. The levelised cost of electricity (LCOE) is the main competitiveness indicator and the estimated impact on this cost from different expected improvements is reported several times in the document, and in particular in the tables within each chapter.

1 HISTORY

Concentrated solar power plants that use direct solar radiation to feed a thermodynamic conversion cycle for the production of electricity were introduced in the early 1980's.

The first demonstration plants used mainly a central receiver configuration (Solar ONE, SSPS-CRS[1], CESA 1 Themis, Eurelios, Nio, Crimea) with a high number of heliostats directing the solar radiation to the top of a tower. At about the same time, SSPS-DCS[2] proved the feasibility of producing electricity with a parabolic trough concept. Issues on the receiver design and the high cost of the heliostats at that time resulted in the choice of parabolic trough systems for the first commercial scale plants in California in 1984. This technology used a novel vacuum type absorber tube that allowed reasonable performance but with a considerably lower concentration ratio than the tower concept.

From 1986 until 1991, nine plants of this type were built very close to one another rapidly reaching almost 400 MWe of installed power. Those SEGS plants, located in California, are still operating and generating revenues, being the basis of the confidence of banks when financing the recent deployment of more than 2 GW in Spain.

For a long period no other solar power plant has been built. This was mainly due to the availability of cheap fossil fuels and the concurrent development of the combined cycle technology, which allowed low investment costs and very high conversion efficiencies.

An increased interest on environmental issues began with the Kyoto protocol which raised again the attention on the production of electricity with no CO_2 emissions. This international commitment triggered a new rise of R&D, both in the PV and the STE sector. A Spanish law, issued in 2004 and improved in 2007, provided a reasonable FiT level which allowed the financing and quick deployment of STE plants and suddenly a high number of projects took off with a pipeline summing up to 2,500 MWe. Thanks to the high confidence for investing justified by its accumulated operating lifetime, the parabolic trough technology was the most suitable option for this set of plants. This led to the development of two "standard" 50 MWe parabolic trough solar plant designs, with and without thermal storage (50 MWe is the maximum plant size allowed by the Spanish law).

However, the central receiver technology also received some attention, achieving higher plant efficiencies at higher temperatures. The first commercial plant of the STS dawn in the world was the PS10 - tower concept with saturated steam - in February 2007. Afterwards, the first commercial molten salt central receiver plant was constructed in Spain in 2011 with 20 MWe nominal power and 15 hours of storage capacity, which allowed the plant to operate 24 hours round the clock during the summer months. Following Spain, other countries set up incentives for STE. In the United States, the first new plant of this period was completed by 2007 (64 MW parabolic trough type in Nevada). The new American large (>100 MW) projects under construction are balanced between central receiver and parabolic trough technologies. The projects 'Ivanpah' and 'Tonopah' are based on the tower concept and use superheated steam or molten salt respectively as primary fluid while 'Solana' and 'Genesis' use the parabolic trough concept. Further initiatives are going on in countries like Morocco, Arab Emirates, India, Australia and South Africa. Plans for deploying STE are also being considered in many other countries in the Sun-Belt.

Meanwhile other promising STE technologies with distinct features, such as linear Fresnel reflectors and parabolic dishes, have been studied and demonstrated by means of several pilot and demonstration plants.

1- Small Solar Power Systems - Central Receiver System
2- Small Solar Power Systems - Distributed Collector System

Four technologies are relevant in the STE sector, and each one of them has reached a different state of development, due mostly to the historical pathway outlined above:

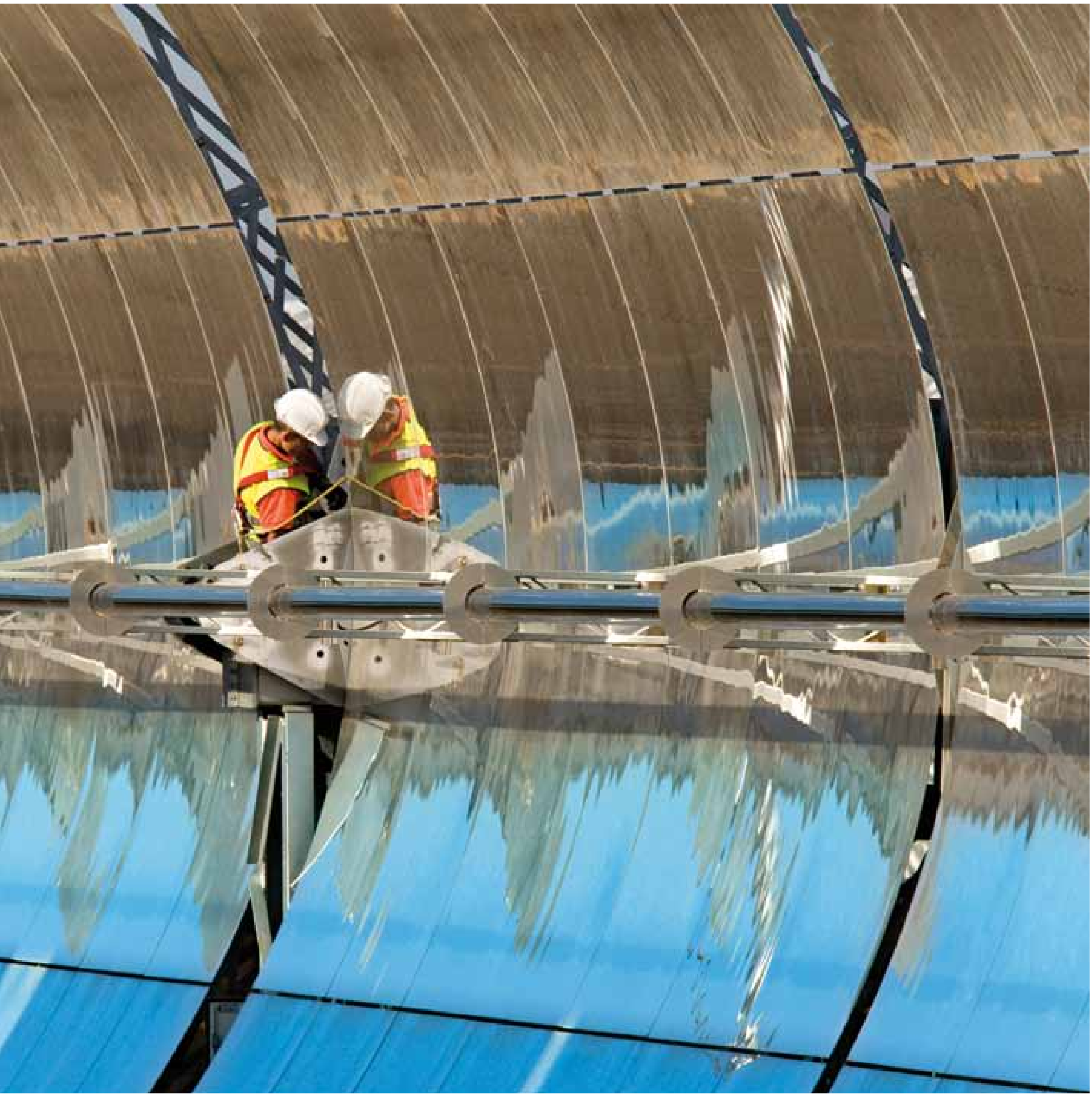
- Parabolic Trough (PT)
- Central Receiver (CR)
- Linear Fresnel reflector (LF)
- Parabolic Dish (PD)

The degree of maturity and development can be expressed in terms of "generations".

STE commercial plants, currently in operation or under advanced construction are "first generation plants".

The "second generation" of STE plants should achieve higher efficiencies with higher fluid temperatures (500°C and above) and incorporate design improvements to improve dispatchability by means of advanced storage and hybridisation techniques.

The "third generation" of plants is expected to be fully competitive by drawing on lessons learned and applying the best design concepts and the use of very high temperatures and higher efficiency conversion cycles.



The time when such a cost parity is reached, that is, the point at which electricity production costs from solar-thermal power plants are equal to the costs for generating power from conventional plants, depends on both the speed of cost reduction and the trend of fossil fuel prices. Different scenarios assume that cost parity for solar-thermal power generation can realistically be reached between 2017 and 2020. However, in some regions of the planet, the peak load supply can already be provided by solar-thermal power plants in a competitive way, as individual contracts are concluded with utilities for regions and times of the day depending on the need.

For the purpose of the Strategic Research Agenda all STE technologies are taken into account as, at this early stage, the four technologies show high potential for cost reduction and efficiency increase.

TABLE 1: Technologies maturity for short, mid and long term period

	Status				
Technology	Generation	Present	Short term [3]	Mid term [4]	Long term [5]
PT	1				
	2				
	3				
CR	1				
	2				
	3				
LF	1				
	2				
	3				
PD	1				
	2				
	3				

Under development   Mature

History

1

3- Until 2015
4- Until 2020
5- Until 2025 and beyond

2 THE BRILLIANT FUTURE OF SOLAR THERMAL ELECTRICITY PLANTS

Global warming and economic growth are the major current issues in the world besides other ones of political nature. Fortunately, STE technologies can contribute significantly to address these two issues, helping to mitigate the impact of electricity generation on greenhouse emissions while providing a pathway for the sustainable and balanced growth of the supply of affordable electricity in both industrialised and developing countries.

A carbon-free generation system can only be achieved with renewable dispatchable technologies, and resource and technology considerations point to STE plants as the alternative with the greatest potential to meet the world's growing energy needs. They are also the alternative with the largest fraction of value provided by local sources, even for the very first plant built. "Local value added" considerations may well be a key factor in policy decisions in many countries.

The three main arguments for a large deployment of STE plants are[6]:

2.1 Dispatchability and other technical features

Solar thermal electricity plants have proven their reliability since the 80s. More recently – since 2008 – STE plants with large thermal storage systems have been in commercial operation, charging and discharging those systems every day.

STE plants can be designed and operated to be fully dispatchable. Because of storage and the possibility of hybridisation, they can effectively follow the demand curve with high capacity factors delivering electricity reliably and according to plan.

Due to the large mechanical inertia of its generation equipment – turbine + alternator – STE plants will help in maintaining the nominal frequency of the grid in case of unexpected incidences. STE plants with storage can participate in ancillary services. For example, if there is a potential for excess generation, the generation equipment may be disconnected and the collected thermal energy stored.

Firmness ***and*** dispatchability are the main advantages over other intermittent forms of renewable energy, such as PV or wind. These technologies require additional investments in conventional power plants to back up generation to follow demand: in addition to the extra investment required and the implications for resource security, they will not provide a CO_2 free generation system.

2.2 Macroeconomic impact on local economies

Decisions concerning the electrical generation mix have a substantial influence on a country's economy. Fossil fuel imports have a negative impact on domestic GDP. As an example, around 80% of the cost of the electricity from a combined cycle plant will go out of a country which does not have natural gas and which imports most part of the plant components.

Among all renewable energies, solar thermal electricity (STE) stands out for its high macroeconomic impact on the economy of a country adding to its GDP through high investments, fiscal contributions, fuel imports reduction and job creation, during both the construction and the operation of the plant.

In terms of the Feed-inTariffs (FiTs) that STE plants still need now, the pool price in the power markets is reduced as less supply is required from the more expensive conventional plants that determine the price for the whole system. Additionally, renewable energies provide stable and known costs that make planning for the future possible: uncertainties regarding the price evolution of fossil fuels hamper investment decisions.

6- ESTELA has published a position paper that presents the main reasons that will boost the deployment of STE plants all around the world's Sun Belt.

Another positive aspect of STE plants is their economic impact in job creation and in the development of local markets during plant construction and afterwards. It is estimated that, if the construction of STE plants is planned at a rhythm of a few hundred MW per year, the attracted investments for the local fabrication of equipment will raise the local content certainly up to a 70% in a few years. In Spain, approximately 400 MW have been installed per year since 2008, and in 2011 a local content of 80% had been reached[7]. The 50 MW plants with thermal storage installed in Spain need 2,250 "one year equivalent jobs" from their design to final construction. Once running, the plants require 50 persons for their operation and maintenance.

Taxes from company profits and from the added in-country value, as well as the personal taxes from workers, will compensate for the support to the deployment of STE plants, and eliminate unemployment subsidies.

In this time of economic crisis, incentives for renewable energies must not be viewed as a load to the electricity system but rather as a catalyst for economic growth, industrial development and job creation; that support also opens the way to sustainability. Support to the deployment of renewable energy generation technologies in the form of adequate and progressively decreasing FiT will mobilise private investments in productive assets.

7- For further information on Spain's STE data and figures, please refer to the Macroeconomic Study of the STE sector in 2010 elaborated by Deloitte: http://www.protermosolar.com/prensa/2011_10_25/Protermo_Solar_21x21_INGLESC.pdf

2.3 Competitiveness

Last but not least, the cost of STE plants will soon decrease significantly: they will become fully competitive with other conventional plants in the near future.

The support that is now required will be less and less necessary and it will be no longer required in a few years.

Since 2007, attractive cost reduction results have been achieved with a learning curve of only 2 GW of installed capacity. As reference, we may note that the current cost of PV profited from a learning curve of 70 GW; for Wind, from the experience of around 250 GW.

The cost of the electricity produced by STE has come down from 28 c€/kWh for the projects approved in Spain in 2009 to 14 c€/kWh for the latest project awarded in Morocco in 2012.

New plant concepts, larger sizes, improved component performance and scale factors will significantly contribute to lower the costs. Therefore, it is reasonable to say that if by 2020 the 30 GW threshold is achieved, STE power plants could be feeding dispatchable and predictable electricity to the grid at 10 - 12 c€/kWh, depending on the available irradiation. In other words, this technology will become totally competitive with conventional power generation in the near future.

Against the prospects of rising and unpredictable prices for fossil fuels and with the awareness of the weaknesses of non-dispatchable renewable technologies, the predictable and decreasing costs of STE will open the way to a safe transition towards a sustainable model of electricity generation.

Europe has enough renewable energy resources to become energy independent and to drastically cut its greenhouse gas emissions in the near future. A European energy system mainly based in Solar and Wind with a certain contribution of Hydro and Biomass along with the Supergrid is both feasible and desirable.

In the near future, dispatchability, job creation, the need to limit greenhouse emissions and the potential for cost reduction will ensure that STE will account for an important share of the electricity generation worldwide. This is why STE represents such a great opportunity to help pave the way out of the economic crisis in the Southern European countries. This is a historic opportunity to strengthen the European business presence in the whole world; given the present leading position of the European industry, it is also an unprecedented opportunity to collaborate with partners in the neighboring MENA region for the benefit of all.

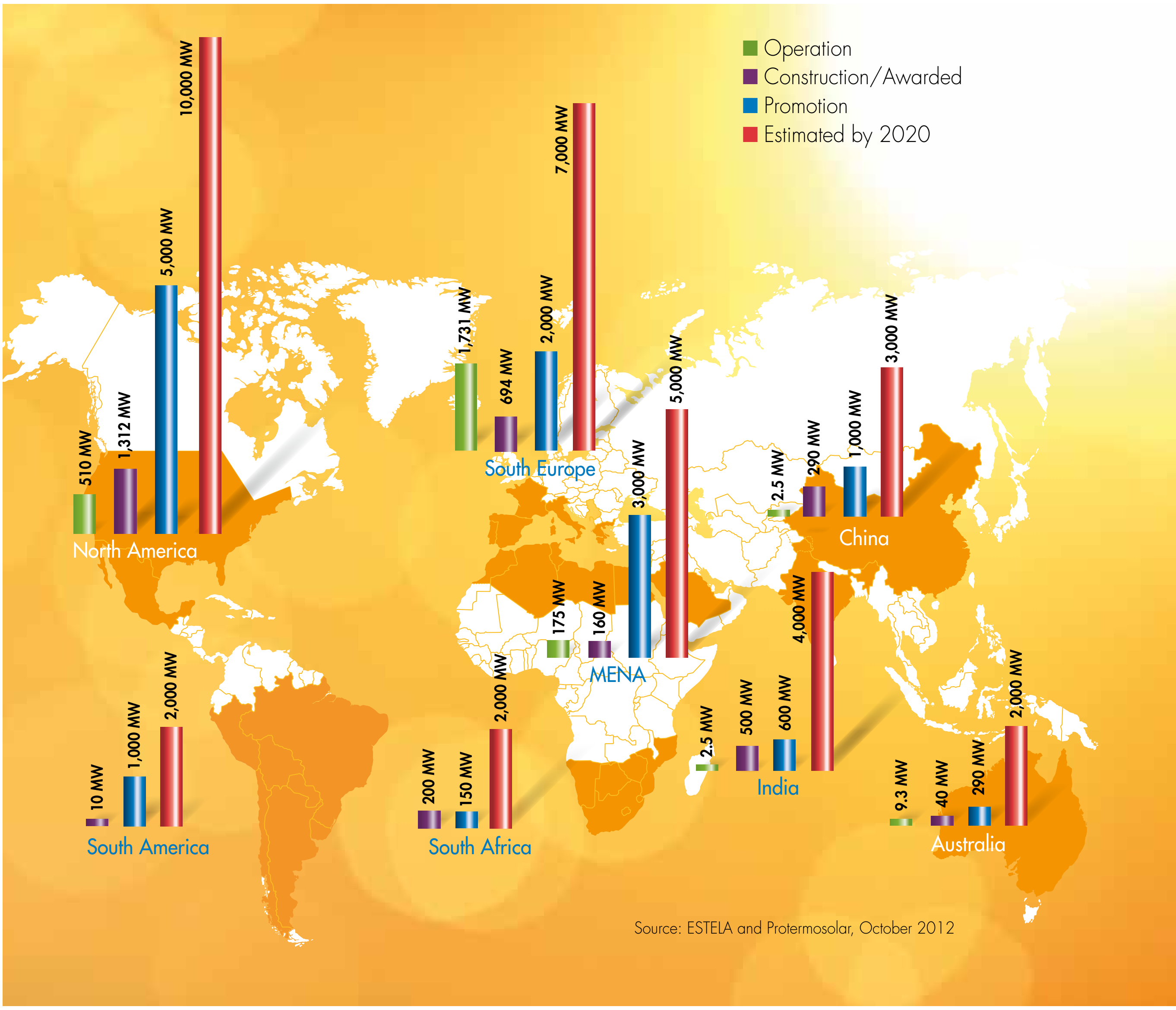
3 INDUSTRY OVERVIEW AND RELATED ECONOMIC ASPECTS

European industry and technological centres cover the whole value chain of STE plants. Advanced research is performed in highly qualified laboratories and research institutions. European promoters are developing projects all around the world. European manufacturing companies provide solar specific components, power blocks and all the necessary balance of plant equipment. Private European financing institutions and funds, along with the European Investment Bank, have supported the fast STE plant deployment in Spain. Technical and legal consultants, O&M service providers and European electrical utilities complete the rest of added value in this sector.

From the basis of the total output from plants which are already in operation, significant increases can be expected in major regions and countries in the next few years. Cumulatively, it is expected that STE plants will be generating approximately 10 GW of electricity by 2015. For 2020, this can be complemented with information on the capacity from new plants which are either part of present official plans or whose implementation can be derived from reasonable expectations based on current development (Figure 1). More information on national and regional markets is outlined below.

FIGURE 1: STE estimate installed capacity [8]

(Planned STE plants refer to either official plans or reasonable expectations according to current development)



8- Source: Protermosolar

3.1 National and regional markets

Power plants
Research facilities

Interactive World Map of STE plants and research facilities on ESTELA's home page: www.estelasolar.eu

Spain

The Special Regime for electricity generation from renewable sources was established in Spain in 1998. Nevertheless, STE plants needed to wait until 2004 with the royal decree law R.D.L 436 to have the appropriate FiT to allow the promotion of projects. The FiT was substantially improved in 2007. With the R.D.L 661 which really boosted the promotion of new plants, the banks found more favourable conditions to finance the projects.

The first STE commercial plant in the world – after the long period since the last one was commissioned in 1991 in California – was the PS10 in Seville. This 11 MW plant used a tower concept with saturated steam and small pressurised steam buffer storage.

Since then, the total commissioned power reached 61 MW in 2008 (including the first European PT power plant, Andasol 1), 331 MW in 2009, 532 MW in 2010, 999 MW in 2011and 1,925 MW in 2012.

According to the royal decree law R.D.L 6/2009, 60 plants – including the plants already in operation – were registered under the current FiT framework. All these plants, totalling 2,475 MW must be commissioned before the end of 2013 in order to receive the former FiT. The current tariff for these projects (for 2012), which varies with the annual consumer price ratio, is 29.89 c€/kWh.

As a result of the easier financing conditions, which tended to reward mature technologies and plants of a certain scale, 94% of the power is generated in plants based on PT, while the other three STE technologies share only a minor part.

In addition to all registered plants, site and project development was carried out for more than 10,000 MW, in sites where land suitability, access to the grid, environmental conditions, water availability, etc. are suitable to develop STE plants.

The Renewable Energy National Action Plan (RENAP), submitted by the Spanish Government to the EU Commission in 2010, foresaw a total installed capacity of 5,079 MW by 2020. In the new Renewable Energy Plan, this figure was reduced to 4,800 MW.

In addition, another 50 MW molten salt tower plant, to be placed on line after 2013, has been included under the STE Innovative Project programme. Another 50 MW hybrid tower plant, based on a hybrid tower concept, has been awarded for funding under the NER 300 scheme.

Early in 2012, the Spanish Government issued a law (R.D.L 1/2012) stopping the approval of a new set of projects until a complete review of the situation regarding installed power on the Spanish electrical system is done, and a new path to reach the 2020 targets is defined.

Italy

According to the RENAP established in March 2011, STE plants are expected to reach 600 MW by 2020, generating some 1,700 GWh, or 0.5% of the electricity consumption.

A new Decree for the renewable energy mix has been released in July 2012 by the Minister of Economic Development in coordination with the Minister of Environment. The FiT will be in force starting from January 2013.

The Decree regulates a new incentive scheme for large scale STE plants according to the FiT schedule given below:

System in which the solar fraction is higher than 85 %	0.32 €/kWh - Energy Sale
System in which the solar fraction is between 50 % and 85 %	0.30 €/kWh - Energy Sale
System in which the solar fraction is below 50 %	0.27 €/kWh - Energy Sale

It is possible to hold the FiT with additional public financial contribution. In order to benefit from the incentive, two conditions must be met: a non-polluting heat transfer system must be used (unless the system is sited in industrial areas) and installations must show the minimum accumulation capacity established by the Decree.

Incentives are available for up to a maximum of 2.5 million m^2 of mirror surface and a grace period of 36 months is granted after that maximum of total installed mirror surface is reached, to allow connecting STE plant to the grid accessing to the FiT (this grace period is still under discussion).

For small scale STE plants, the new decree regulates the following updated incentive scheme:

System in which the solar fraction is higher than 85 %	0.36 €/kWh - Energy Sale
System in which the solar fraction is between 50 % and 85 %	0.32 €/kWh - Energy Sale
System in which the solar fraction is below 50 %	0.30 €/kWh - Energy Sale

These incentives apply to STE plants with less than 2,500 m^2 of installed solar collectors.

For all type of STE plants (both large and small scale), the incentives, calculated at the rates given above, are in addition to the revenues from the sale of electricity generated and fed into the national grid. The FiT will be reduced by 5% for the power plants connected to the grid in 2016 and by 10% for those connected in 2017. The incentives will be paid for 25 years.

The first STE plant using molten salt as HTF is already in operation in Italy. It is a 5 MW plant. It features thermal storage and is based on a combined cycle. A potential market of hundreds of MWs is expected in Italy by 2017.

France

According to the French NREAP approved in June 2010, STE plants are estimated to reach 540 MW of capacity by 2020, generating some 972 GWh per year), or 0.2% of the electricity consumption in France.

A 12 MW plant, Alba Nova1, was approved by the French government in July 2012. The plant will be built in Corsica and will combine linear Fresnel reflectors, direct steam generation and thermal storage. The 'Caisse des Dépôts et Consignations', the French sovereign wealth fund, is financially supporting the project. Another 9 MW Fresnel concept in the Pyrenees region has been approved as well.

The FiTs are in general fairly satisfactory for the different renewable technologies, except for STE, because of the low DNI levels in the country.

Portugal

Portugal has a very high potential for the implementation of solar energy technologies, given the high solar availability in the country (one of the highest in Europe) and their very good public acceptance.

Since 2000, the Portuguese government kept regulated tariffs for end consumers below the real cost of the generated electricity. A 'tariff debt' was then accumulated and financed annually with a guarantee by the government. However, the share of that tariff debt attributable to renewable energy (mainly for wind energy) has been shown[9] to be small (less than 15%). Following major updates in FiT schemes, the Iberian Electricity Market MIBEL entered in operation in 2007. Tenders for solar technology plants began in 2009, even though some consortia attempted at applying for STE licenses as early as 2007.

The 2008 crisis led to a rise of interest rates, aggravating the burden that the accumulated tariff debt represented to the national economy. After peaking in 2009, the overall tariff debt became progressively smaller starting in 2010. The fall of the government in May 2011 was followed by the financial bailout of the country. An MoU was agreed with the EU, and this also required a review of support schemes for RES.

In 2010 the Government issued licenses to 10 STE demonstration projects (two projects of 4 MWe each for PT, CR and LF technologies and four projects of up to 1.5 MWe for PD technologies). In 2012, because of the uncertainties surrounding the energy policy for renewable energies, and in particular for STE, none of these projects had been started. In fact, some of the licenses were lost, after a deadline was established by DGGE[11] for confirmation of the intention to proceed. In May 2012, the government announced regulatory changes in the rules affecting the RES, taking advantage of the uncertainties in legislation to change the FiT conditions.

In any case the Portuguese target established by the NREAP for STE for 2020 has been lowered from 500 MW to 50 MW[12].

The FiT assignment of new grid connection licenses for RES has been suspended until 2014/2015. In the meantime, the government still supports the development of ongoing, licensed and already assigned projects for RES. Most of these projects are wind projects.

Greece

According to the Greek NREAP approved in June 2010, STE plants are expected to reach 250 MW by 2020, generating some 714 GWh, or 1% of the renewable electricity consumption.

Greece provides a FiT of 26.5 c€/kWh, which rises to 28.5 c€/kWh if at least 2 hours storage is incorporated. This FiT is payable for 20 years.

The NREAP will be the basis for a Ministerial Decree that will allocate 2020 installed capacity targets to the different RES sectors. A change in the support mechanism is not foreseen: it is expected that it will remain a fixed FiT.

The law on the "Acceleration of RES Development" streamlines administrative procedures and addressees local barriers to RES deployment. Furthermore, the new government has merged several administrations into the MEECC (Ministry of Environment Energy and Climate Change) that now functions as a one-stop-shop for RES licensing. With the Physical Planning law (2008), the MEECC gives priority to RES projects over other land uses and determines restricted as well as priority areas for development.

One large scale dish Stirling power plant (75.3 MW) and a 50 MW-central receiver power plant with superheated steam have been awarded in Greece within the first call of the NER 300 scheme.

9- Source: APREN (Portuguese Renewable Energy Association). Study from Roland Berger, 2011
10- Source: ERSE (Portuguese Regulatory Entity of Energetic Services)
11- Source: DGEG (Portuguese General Direction of Energy and Geology)
12- Source: DGEG (Portuguese General Direction of Energy and Geology)

Cyprus

According to the Cyprus NREAP, approved in June 2010, STE plants are expected to reach 75 MW by 2020, generating some 224 GWh, or 3% of the electricity consumption in the country.

There is an indication that future amendments to the renewable energy law (the law affecting the FiT) may re-establish investment security for the major part of the renewable energy industry.

Cyprus has been awarded by the first call of the NER 300 with a large scale dish Stirling power plant (50.76 MW).

SEAPEK (Cyprus Association of Renewable Energy Enterprises) believes that Cyprus can achieve much more than the binding target of 13% of generated energy from renewable sources by 2020, as foreseen in the RES Directive. However, this would require some governmental, financial and administrative effort.

North Africa

The launch of initiatives such as the MSP (Mediterranean Solar Plan), which was strongly supported by ESTELA, has already placed STE on top of utilities', governments' and decision makers' agendas.

The MSP aims at increasing the use of solar energy and other renewable energy sources for power generation. The key element of the proposal is setting up a common legal, regulatory and investment framework to develop 20 GW of new renewable generation capacity in the countries around the Mediterranean Sea by 2020. To this end, the MSP will build on the enormous potential for renewable electricity generation available in these countries, mostly through the development of STE but also through other available and mature technologies such as PV and wind energy.

The MSP needs to overcome the important transmission issue as well as administrative and legal barriers. The figure of a solvent off-taker as recommended by ESTELA could be an essential piece to launch this ambitious plan. As of today, there are three integrated solar combined-cycle (ISCC) plants in Morocco, Algeria and Egypt with an equivalent electric power of about 25 MW each. The solar contribution to these plants represents considerable gas savings.

In Morocco the tender process for the first STE plant in the region, a 150 MW PT type with storage, under a pure PPA commercial scheme has been completed in October 2012 and the contract has been awarded.

Independently of the national plans incorporated in the MSP, STE deployment has been announced in most of the northern African countries. These plans range from some hundreds to 2,000 MW per country.

Middle East

The first plant in Abu Dhabi of about 100 MW, Shams 1, is nearly completed and it is expected to be followed by Shams 2 and 3. Other Arab Emirates and Saudi Arabia have also included STE in their respective plans, for a total power of 900 MW by 2013 and a final amount of 25 GW in the future.

Israel has its first plants under construction and plans to have 1,000 MW of installed capacity in the short term. Other countries in the region (Jordan, Iran, Syria, etc.) are also considering the construction of STE plants.

United States of America

There are already over 500 MW of installed STE capacity, including the 354 MW SEGS plants which have been in continuous operation for 25 years. The largest ISCC in the world with 75 MW has been recently completed.

There are huge projects under construction. Four projects with a total power of 500 MW are tower plants using either superheated steam or molten salt as the receiver fluid. Three large PT type projects will add another 810 MW.

These projects are based on signed PPAs with the utilities and they take advantage of tax credits and warranteed loans.

New support mechanisms need to be established in the near future to realise the large current pipeline of projects.

South Africa

The REFIT program (under FiT schemes) foresees 1,200 MW for STE in 2030. Nevertheless, the program will be reviewed periodically and the share among different technologies can be interchanged according to technology developments and policy considerations.

The first three projects have been recently awarded: these are a 100 MW PT, a 50 MW PT and a 50 MW CR plant with superheated steam. In addition, the public utility is preparing feasibility studies to launch a tender process for a total of 150 MW in the short term.

Australia

A long term goal of 25% of solar power has been set for 2050.

The Clean Energy Initiative within the Solar Flagships Programme has been launched with solar projects totalling 1,000 MW. The first call for 400 MW (PV and CSP) is closed. The new agency ARENA has made clear that solar thermal electricity development is very much in its thinking, and has structured its initial strategic priorities in a way that should be favorable for STE projects. A recent study estimates at least 2000 MW STE plants by 2020.

India

There is a tremendous need for additional electricity generation in this country. An ambitious solar agenda is being planned, aimed at generating 20 GW from both STE and PV plants by 2022.

Awards for the first 500 MW of STE plants have been given to local promoters under a combined bidding/FiT scheme, and most of them have already started construction.

China

At the moment, there are 250 MW STE plants about to start construction. There is a pipeline of projects under development which exceeds 4,000 MW although the support conditions are still not clearly defined. International success references might accelerate these plans.

Latin America

There is only one project under construction: an ISCC 15 MW equivalent in Mexico.

Several projects are being promoted in Chile under direct PPA schemes with mining companies.

No support schemes are being considered until now by the governments but there are specific places where STE is very close to competitiveness. Macroeconomic impacts and energy dependency may contribute to the establishment of support mechanisms for STE plants.

3.2 Employment

The growth of the STE industry in Spain has had a major impact in terms of the number of jobs it has created in recent years. Many of these jobs are during construction; the rest are from operation and maintenance activities. They all have a multiplicative effect on the rest of the economy. The number of equivalent jobs generated during 2008-2010 has been quantified in terms of equivalent jobs per year. The information for the estimates have been drawn from the following sources:

- For specific plant construction, assembly and commissioning activities, inquiries were made of the construction companies and verified with plant records. Coefficients of employment per unit of added value specific to each industry were used to quantify employment generated in those industries and in the rest of the economy.
- For plant operation and maintenance activities, the companies were asked not only for information on the work force directly employed by them but also by the subcontractors in charge of operation and maintenance. The impact on other economic industries (power supply, water, gas, insurance, etc.) was added to this, based on generally accepted employment multipliers. According to the information collected, the STE industry employed a total of 23,844 people in 2010: 23,398 people during construction and 446 people during operation.

FIGURE 2: Total number of jobs created by the STE industry (2008-2010) in Spain [13]

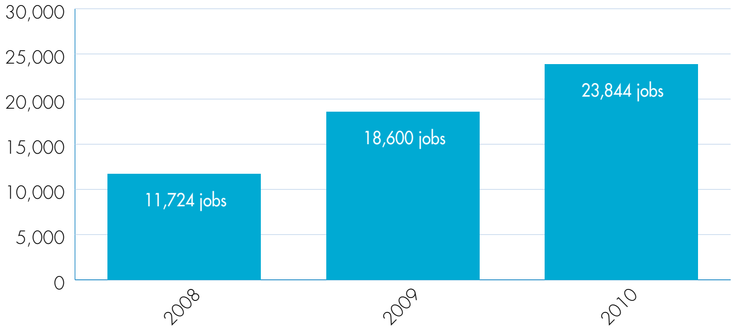


TABLE 2: Breakdown by industry activity of jobs created by the STE industry (2008-2010) in Spain [14]

Jobs	2008	2009	2010
Construction	11,713	18,492	23,398
- Plan contracting construction and assembly	4,399	6,447	8,049
- Components and equipment	4,515	7,442	9,542
- Jobs in the rest of the economy	2,799	4,603	5,807
Power production - O&M	13	123	446
- Plant operation and maintenance	11	108	344
- Jobs in the rest of the economy	2	15	102
TOTAL JOBS	11,724	18,600	23,844

13- Sources: Deloitte/Protermosolar. Macroeconomic impact of the Solar Thermal Electricity Industry in Spain, October 2011
14- Sources: Deloitte/Protermosolar. Macroeconomic impact of the Solar Thermal Electricity Industry in Spain, October 2011

3.3 Economics

Given the development for STE technologies described in this Strategic Research Agenda, and considering specifically predicted changes in cost and scale that have an impact on plants' CAPEX and efficiency, it is possible to estimate their relative impact on the LCOE for STE projects in the following years (Figure 3).

FIGURE 3: Expected LCOE reductions from 2012 to 2025[15]

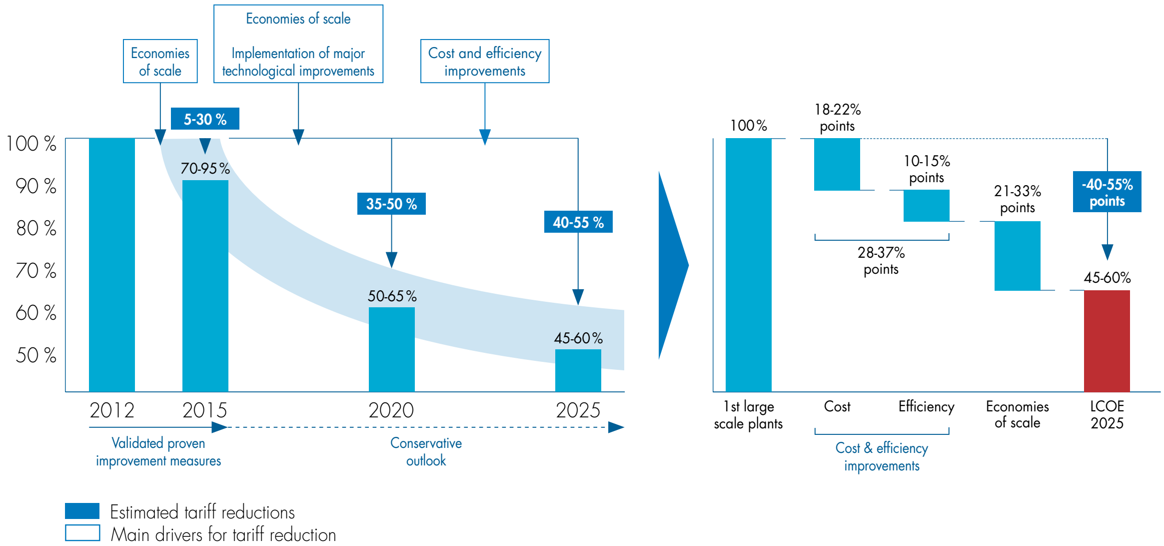
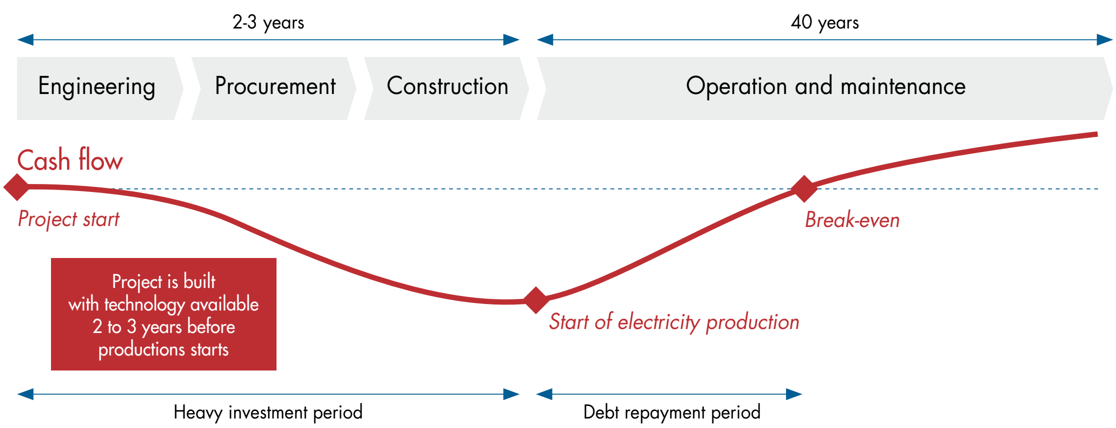


FIGURE 4: STE project lifetime[16]



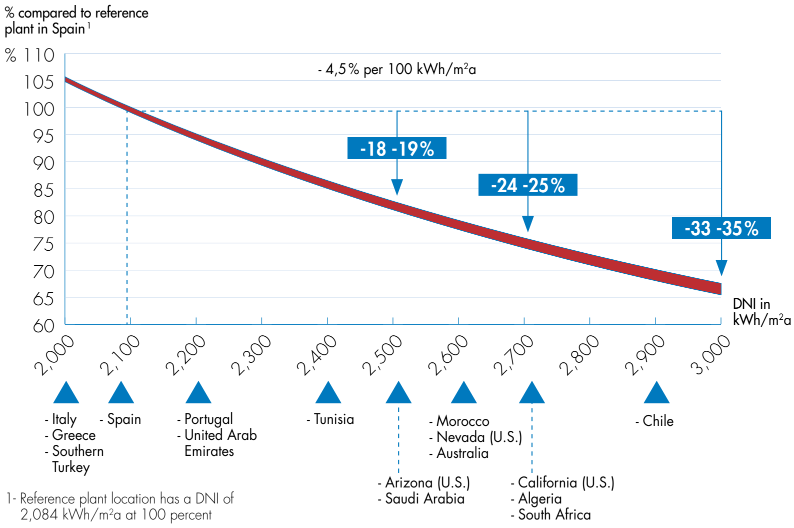
From 2013 onwards, significant cost reductions can be expected for STE plants, driven by the deployment of technological improvements and by the economies of scale related to the increase of the plant size. By 2015, a reduction ranging from 5 to 30% can be expected, depending on STE technology and the dispatchability of the plant.

Between 2015 and 2020, with the implementation of the remaining technical improvements already in the pipeline and with further plant size increases, tariffs for STE can be reduced by up to 50%. With the expected cost development and further breakthrough innovation and scale gain by 2025, tariffs are expected to be less than 50% compared with current ones. Such cost development would enable STE technologies to become self-sustained without the need for support schemes for newly installed plants.

15- Source: A.T.Kearney/ESTELA. Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production, June 2010
16- Source: A.T.Kearney/ESTELA. Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production, June 2010

Another factor that can further drive down the required tariff for STE projects is the solar irradiation level of the deployment location. The larger the available solar resource is, the higher the annual output will be, and the lower the required tariff for the same plant's CAPEX. Figure 3 shows how the DNI level of a specific location can influence the minimum required tariff.

FIGURE 5: Impact of direct normal insolation (DNI) on levelised cost of electricity[17]



On average, tariffs can decrease up to 4.5% per each additional 100 kWh/m²a of DNI. This means that for high DNI locations such as the MENA region or California (US) a STE project requires less 25% of minimum tariff to break even when compared with the same project in Spain. (For these estimates, only the variation of DNI was considered. Country specific risk, financing and labour costs variations also play a significant part in defining the minimum required tariff.)

These facts demonstrate that STE technology has the potential to improve its competitiveness in the near future and that the industry is committed to materialise this with the development of technological improvements, construction of larger plants and with the STE deployment in high DNI regions such MENA. All of these initiatives contribute to the achievement of the industry vision laid out earlier.

Also, according to the defined technological and cost roadmap[18], STE technology can achieve its positioning within the energy sources portfolio mix which shall be discussed next. There is a wide range of STE concepts from pure peak power to base-load including designs with a very narrow dispatch profile with large storage and turbines to provide electricity when the price is highest. In addition, significant economies can be achieved through hybridisation of power plants or a combination of solar fields with existing or new plants. ISCC plants, or schemes to boost the performance of coal-fired thermal power plants can be effective options.

3.4 Standardisation

Standards are very important in any technology field, but especially in young technologies like STE. In fact, the implementation of standards is crucial for the commercial success of the technology. A quick deployment of new markets requires customers' confidence in the performance and durability of the products. Standards play also an important role in accelerating cost reduction, since they allow for a better transparency of product quality and for the comparability of different products. This leads to more competition based on knowledge about quality and cost.

17- Source: A.T.Kearney/ESTELA. Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production, June 2010

18- Source: A.T.Kearney/ESTELA. Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production, June 2010

Although standards used in other sectors could be partially used for STE technologies, the uniqueness of these technologies demand specific standards that have not been developed yet. Development of these specific standards is the "leitmotif" of the standardisation work initiated during the last years, on both national and international levels. While present solar collector standards, such as EN12975, might set a background for solar concentrator testing methodologies and simulation models, their early development was for stationary collectors, mostly factory-made. They really fall short when dealing with more complex (and/or accuracy demanding) optical effects present in STE technologies. The importance of establishing a common framework for the testing and characterisation of solar concentrators has been already recognised in the latest revisions of EN12975, and it is also the driver for the new ISO 9806, which is presently undergoing the inquiry stage.

Existing standards related to solar collectors are mainly intended for factory-made collectors which are small (up to a few m^2 in size), and that are either flat or have relatively low concentrations. On the other hand, STE technologies require large size concentrators, on-site field assembled, with high concentrations, and with a variety of 2D or 3D geometries, thus creating a new set of problems and demands. STE technologies therefore demand specific standards that are not yet available.

Several working groups have been set up to develop specific standards for STE technologies, and a few new standards are already in an advanced stage of development. The members of SolarPACES established working groups in 2008 with the charge to develop standards for PT components, and a first draft guideline for mirror reflectance measurement was published in May 2011. Another draft guideline for mirror module shape measurement is expected to be released in 2012, followed by a guideline for PT receiver performance measurements in 2013.

Other working groups for standards development have been set up within the framework of different standards organizations:

- IEC/TC 117 "Solar Thermal Electric plants" (three working groups established in 2012). Mirror committees in several countries will be established;
- AENOR (Spain) sub-committee AEN/CTN 206/SC "Solar thermal power systems", launched in 2010 for standards on systems, storage and key components;
- ASME PTC 52 Performance Test Code for Concentrating Solar Power Plants (four working groups established in 2011 for PT, LF, power tower, storage);
- DKE (Germany): funding of development of guidelines for standards for reflectors.

Therefore, the first steps to develop the required standards for STE technologies have been already taken, but this effort has to be supported and further promoted because very limited funding is still available for standardisation activities. This must be considered a high-priority topic because the availability of proper standards will significantly enhance the commercial development of STE technologies. Standardisation activities should cover several fields, which are summarised in the following paragraphs.

a) Qualification/certification and testing procedures: Adequate procedures applicable to different technologies are required. They must specify manufacturer-independent standards defining the procedures to test and qualify not only components (e.g. reflectors, receiver tubes, solar tracking systems, etc.), but also complete solar concentrating systems (e.g. heliostats, PT collectors, linear Fresnel modules, etc.) and complete systems (e.g., solar field, thermal storage system, etc.) These are required to make a fair and neutral comparison of technical features possible. These standards must cover not only the procedures to measure thermal, optical and geometrical parameters, but also a clear definition of those parameters in order to avoid possible misunderstandings concerning their meaning (e.g., clear definitions of absorptivity, specular reflectance, hemispherical reflectance, etc.). These standards should define the requirements to be fulfilled by adequate testing infrastructures and they also must settle a number of current open questions, such as:

- The definition and importance of "near normal incidence" conditions throughout the testing period. These are difficult to match when testing primaries (the primary set of mirrors responsible in the first stage of radiation concentration) of linear concentrator systems such as LF or even field-installed PTs;
- The validity of a biaxial approach to reproduce the true incidence angle modifier as the simple product of the longitudinal and the transversal incidence angle modifiers;
- The importance of circumsolar radiation conditions in the experimental results obtained throughout the testing period.

Another important item within the scope of these standards is the definition of methodologies and equipment for optical characterisation of solar concentrators, namely in the detection and quantification of manufacturing errors, reflector surface deviations or concentrator misalignments, etc.

Concerning certification, product certification schemes must be defined also, because this is a well-proven strategy to raise consumer awareness and build market trust. This will enable the generation of independent product assessment results and guarantee product reliability within a well-defined product operation framework. As in the case of the development of low temperature solar collectors, the increase of available technologies and products reaching the market will benefit from the development of a certification scheme, relying not only on standardised testing results, but also on the certification of the manufacturing processes used in the fabrication of a given product. Producing clear, reliable and comparable results, such certification scheme is likely to contribute decisively to the creation of more favorable bankability conditions, reducing the importance of those based in operation time records which are not available for some very promising technologies.

b) Components/system durability testing: System lifetime is, of course, a fundamental parameter when assessing the overall energy production and profitability attainable with a given STE system. Standards must consider the ageing process starting after manufacturing by component assessment, and performance degradation of the overall system from one year to the next. From this type of information derived from acceptable standards, it is possible to extrapolate the estimates of system lifetime. Therefore, specific testing of the standard properties of materials and/or components used in the manufacturing of solar concentrators must be defined, enabling an inference/estimate of system lifetime. A special attention should be devoted to the development of reflector and absorber durability testing procedures, including accelerated aging procedures for the analysis of the decay of optical properties, the impact of sand in reflectivity decay (this is very important for arid zones), the effect of prolonged exposures at high temperature (especially important for CR systems), etc. Results obtained using these standards will promote market confidence, enhancing STE technologies bankability.

c) Commissioning procedures: The lack of standards defining the procedure for the commissioning of systems (e.g., solar field, thermal storage system, etc.) and complete STE plants has become evident during the start-up process of the STE plants put into operation during the last years. This lack of standards has led the EPC companies to define their own procedures, which are usually different from the procedures defined by other companies. This situation is a significant barrier to the efforts to raise awareness and significant barrier to STE plants bankability. Development of this type of standards in Europe is already underway within the framework of the Spanish AEN/CTN 206 standardisation groups, without any public financial support. Due to the current situation of the STE market, this standardisation activity should be included in the list of high-priority topics to be supported.

d) Model-based results: Due to the difficulties to fulfill some test conditions experimentally (e.g., normal incidence angle onto linear Fresnel concentrators) model-based results might be used instead (e.g., results obtained with ray tracing models). The use of model-based results in the process of testing, qualification and/or certification should be regulated by proper standards to assure compatibility of results obtained by different entities.

e) Solar field modeling: the establishment of a common framework for solar field and STE plants modeling is very important to avoid the differences found at present when comparing the results delivered by the available simulation models. These differences are sometimes very large and they do not help to enhance the bankability of STE technologies. Different levels of quality must be defined to classify the simulation models according to the way they consider all relevant parameters and operating conditions affecting the solar field and/or STE plant yield. This classification of simulation models would avoid comparison of results delivered by models of very different quality.

Due to the complexity of a STE plant, the number of parameters (receiver thermal losses, mirror reflectivity, piping thermal inertia, etc.) and operating conditions (ambient temperature, effect of wind speed and direction on the optical and thermal efficiency of solar concentrators, atmosphere transmissivity, etc.) affecting its yearly yield is high. They can be simulated with different accuracy levels, leading to the possibility of having simulation models of very different quality. The development of a common framework for solar field and STE modeling is, thus, of paramount importance for obtaining reliable and comparable solar field yield results which are suitable for both plant design and project finance. This standardisation activity was launched in 2010 and it is currently underway within the SolarPACES project GUISMO.

4 POLICY OVERVIEW

4.1 Contribution to EU's renewable energy policy

Dramatic changes must be made to the present energy systems to mitigate the negative impact of greenhouse emissions on climate. Europe has so far adopted binding targets for renewable energy consumption and created a carbon emission market, the Emission Trading Scheme. It has also taken several other measures to foster and promote sustainable development.

STE is crucial in Europe's energy future. It is the main renewable energy generation technology that does not require additional back up from conventional power plants to meet demand. It has the unique characteristic of being predictable and totally dispatchable: it can contribute to meeting demand at all times, day and night. It also contributes to the stability to the transmission grid. Barring unforeseeable and unlikely breakthroughs in technologies which by their own nature do not share these characteristics, STE presents important advantages in comparison with other renewable sources.

Six countries have reflected STE in their National Renewable Action Plans (NREAPs): Cyprus, France, Greece, Italy, Portugal and Spain. In total, these plans would have added a total of 7 GW to the generating capacity by 2020. However, changes in the financial circumstances in the Continent are forcing a revision of this prediction, lowering the target to 2 GW. These plans are to be implemented by Member States on the basis of the Renewable Energy Directive of 2009, which set the regulatory framework to achieve the Union's binding target of 20% of final energy supply from renewable energies by 2020.

Overall, STE contributes enormously to meeting carbon emission targets while alleviating the price pressure on finite fossil fuels and ensuring the security of the electricity supply. The contribution to security and reliability has the potential to be especially significant for mid loads which are met currently only by conventional energy sources. Finally, as STE relies on an unlimited 'fuel' supply which, unlike gas and oil, is independent of market fluctuations, it ensures the predictability of the cost of electricity and enables better long-term political decision-making regarding the energy supply.

4.2 Energy transmission infrastructure

The energy infrastructure needs are drawing focussed attention from European policymakers, because only an updated energy transmission system will make the free circulation of electricity possible. Presently, the European Commission is working on a new regulatory framework for infrastructure. In the long-term, the 'Electricity Highway' system shall make it possible to deliver throughout the continent the increasing share of electricity generated by renewable and distributed plants.

The new Infrastructure regulation proposal from the European Commission sets down the rules for the identification and timely development of projects of common interest. These are understood to make up the energy transmission infrastructure that is essential to ensure security of supply to the European Union and the effective function of the internal market. Along with the 'Connecting Europe Facility', this new regulatory framework is embodied in the next Multiannual Financial Framework 2014-2020, which identifies 12 key energy transmission corridors and sets out provisions on new ways for the financing of the projects. One of these corridors is the North-South Corridor in Western Europe, which will help to eliminate energy bottlenecks between the Iberian Peninsula and the rest of Europe. The North-South Corridor will also make it possible to import renewable energy from North Africa: the largest potential for STE lies in what is known as the Mediterranean Solar Ring, which comprises not only the Southern European countries but also the Middle East and North Africa Region.

The transition towards a 100% decarbonised energy market in the EU requires the development of a larger transmission capacity between remote generation and existing load centres. This new trans-European 'Electricity Highways' shall not be an extension of existing interconnectors between states but a new network of high voltage direct current (HVDC) transmission lines. 'Electricity Highways' will be the most economic and efficient way to connect Europe and its neighbouring countries, facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity to create a well-functioning internal electricity market.

In this context, the European Network of Transmission System Operators of electricity (ENTSOe), in coordination with the European Commission, has elaborated the "Study Roadmap towards a Modular Development Plan on pan-European Electricity Highways System" (MoDPEHS) to establish guidelines for the strategic planning to reach a 2050 pan-European electricity system.

4.3 European context and frameworks 2014-2020

The Framework Programme for Research and Innovation Horizon 2020[19]

Horizon 2020 is the European Framework Programme for Research and Innovation for the period 2014-2020. It streamlines and identifies the directions for future research and covers a broad range of sectors. The Programme is formulated along three sections: 'Excellence Science', 'Industrial Leadership' and 'Societal Challenges'. The funding dedicated to Horizon 2020 (about 80 b€) is part of the Multi-annual Financial Framework (MFF) for the period 2014-2020.

Following the Seventh Framework Programme for Research and Innovation (FP7), Horizon 2020 gets rid of administrative barriers and seamlessly integrates research and innovation activities by allowing more flexibility and innovative initiatives than in the previous Framework Programme FP7.

In the context of the knowledge triangle of research, education and innovation, the Knowledge and Innovation Communities (KIC), under the European Institute of Innovation and Technology (EIT), will help address the objectives of Horizon 2020, including the societal challenges, by integrating research, education and innovation.

Horizon 2020 and the STE:

The emphasis given to Renewable Energy and Energy Efficiency in Horizon 2020 is significant: It is expected to account for almost two thirds of the total commitments, and this is proportional to the environmental challenges that must be addressed in the near future. The framework includes the SET-Plan, which is expected to facilitate greatly the development of first-of-its-kind projects and to bring research to market in the renewable energy field.

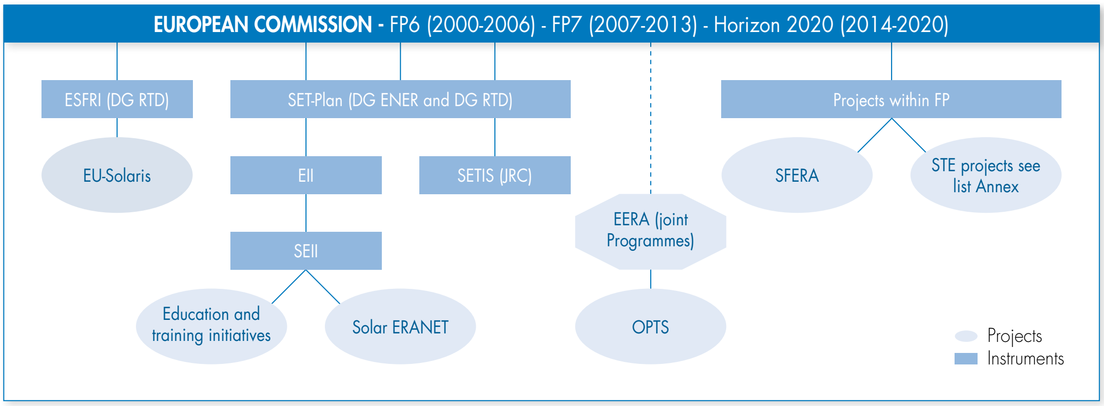
With a strong focus on technological demonstration projects, **this framework is of great importance for the STE sector** and a main driver to reach the objectives described in the STE Solar Industrial Initiative: to reduce cost, increase efficiency and improve dispatchability and environment profile.

19- COM(2011) 809: Proposal for a regulation of the European Parliament and of the Council establishing Horizon 2020
The Framework Programme for Research and Innovation (2014-2020)

4.4 Research overview: participation of the STE sector in the EU instruments

The solar thermal industry depends fully on the strong support from both the public and private sectors to reach quickly the integration level of the other renewable sources already in the market. In the past, Member States have awarded significant incentives and European entities have funded important projects. Past and present projects financed by the European Commission are listed in ANNEX II: Past and present EU-funded projects.

FIGURE 6: Overview of the European schemes for STE funding



To achieve the targets leading to a decarbonised environment in the coming decades, the European Commission has implemented a set of tools targeted to research institutions and industry. Those tools are elaborated to enhance knowledge exchange and cooperation among all the players in the renewable energy field. Monitoring, coordination and support for the implementation of energy research projects constitute further added value from those instruments.

The STE technology benefits from the following instruments:

EERA:

The European Energy Research Alliance (EERA) is one of the initiatives of the SET-Plan (Strategic Energy Technology Plan). It is an instrument of the European Commission aimed at accelerating the development and deployment of cost-effective low carbon technologies for the achievement of Europe's 2020 targets and vision on greenhouse gas emissions, renewable energy and energy efficiency.

The associated Joint Programme on Concentrated Solar Power is coordinated by CIEMAT: it aims to integrate and coordinate scientific collaboration among the leading European STE research institutions to contribute to the achievement of the 'Solar Thermal Electricity - European Industrial Initiative' (STE-EII). Eleven partners are involved. Within this scheme, the OPTS (Optimisation of a Thermal Energy Storage System with Integrated Steam Generator') programme has been launched in early 2012: this is coordinated by ENEA.

SETIS:

The Strategic Energy Plan Information System (SETIS), elaborated by the European Commission and led by the Joint Research Centre, provides a complete set of information related to the implementation of the SET-Plan in general and to the STE technology in particular. Key Performance Indicators (KPI) have been defined and approved by the SETIS team in order to define with precision the targets to be reached and the improvements to be made in the coming decades. A technology map and a material roadmap elaborated by a set of STE experts were released at the end of 2011.

ESFRI:

The European Strategy Forum on Research Infrastructure (ESFRI) was launched in April 2002 to coordinate the work on new research infrastructure to address industry needs and to ensure a better exploitation of existing facilities. The Forum brings together representatives from EU Members and associated States to work on regulatory issues of research infrastructures led by a common advancing strategy.

A pan-European solar thermal electricity research infrastructure "EU-Solaris", promoted and coordinated by CTAER (Centro Tecnológico Andaluz de Energías Renovables) and supported by ESTELA, has been included in the ESFRI Roadmap by the European Commission and it will be financially supported by the FP7 for its preparatory phase. This project aims to establish an effective network among the most relevant STE research centres in Europe and associated countries. It will provide an effective interface between the technology centres and the industry. This STE coordinated and distributed research infrastructure will also play an important role in reaching the goals of the European Strategic Energy Technology Plan (SET-Plan).

ERANET:

The European Research Area Net (ERANET) fits in the FP7 and is intended to support Member States' joint actions in the form of public-private partnerships.

The specific programme 'Solar ERANET' is dedicated to solar energy and will last 4 years, starting in the beginning of 2013. The STE technology benefits from this programme through the implementation of concrete research actions selected by priority order. 2 M€ are provided for coordination actions to mitigate costs and efforts.

SFERA:

The 'Solar Facilities for the European Research Area' (SFERA) is a project of the European Commission within the frame of the FP7. It aims to boost scientific collaboration among the leading European research institutions in solar concentrating systems, financing networking activities through yearly rounds.

Education and training initiative:

At the beginning of 2012, the European Commission launched an exercise to define the European Energy Education and Training Initiative, building on the technology and research initiatives of the SET-Plan to ensure a coordinated approach to assess the current and future situation regarding energy skills in Europe and to engage in actions aimed at building up and attracting energy expertise.

The scope of this initiative is to establish a strategic document addressing the whole innovation chain, from basic research through applied research and development, to first-of-its-kind demonstration.

5 STATE-OF-THE-ART OF STE TECHNOLOGIES

Parabolic trough collectors

The parabolic trough (PT) is currently the most widely used technology around the world, particularly in Spain and in the United States where plants in operation generate over 1,000 MW and 500 MW, respectively.

PT technology consists of installing rows or loops of parabolic trough-shaped mirrors that collect the solar radiation and concentrate it onto a receiver tube where a fluid is heated up to about 400°C. This fluid is later used to either generate steam to drive a turbine connected to a generator or to heat a storage system consisting of two tanks of molten salt.

The collector rows are usually oriented north-south to maximise the amount of energy collected during the year. A tracking system moves the collectors from east to west during the day, following the sun to ensure the proper angle of incidence of the direct solar irradiation on the mirrors.

The heat transfer fluid (HTF) used in these plants is a synthetic diathermic oil. Although the specific formulation of the HTF has varied slightly during the years, the HTF sets limits in the upper temperature and consequently in the conversion efficiency of the whole system. Some concerns have been expressed about the environmental compatibility of the HTF. Fluids allowing higher temperatures and having a lesser environmental impact are being tested.

These plants can be designed to allow rather simple hybridisation with other technologies, so they can be used with a traditional fossil or biomass fuel to generate electricity during the night or on cloudy days, boosting solar operation. The advantages of hybridisation are that it makes it possible to maximise the use of the turbine generator and that it allows the design of more robust dispatchable systems. This, in turn, makes it possible to take advantage of economies of scale in many subsystems of the project during both operation and construction: power lines are an obvious example.

Current power plants in Spain are limited to 50 MW per plant by the Special Regime. About 60% of the plants which have been registered for the FiT include a molten salt two-tank system providing 7.5 hours of storage. In the United States, power plants are being built with much larger turbines (>100 MW), taking advantage of the fact that, in this technology, while energy collection performance is practically unaffected by size, costs of generation are lowered considerably.

In terms of the maturity of the technology, PT can be considered "mature", since a number of manufacturers are available for erecting entire plants or subsystems. There is good experience in engineering procurement and construction (EPC) and 20-year operating experience allows for good confidence on the operation. Therefore, these can be considered low-risk projects. All the existing commercial PT plants can be placed in the "first generation" category as defined in Chapter 1.

A new "second generation" of PT plants will aim to reach a higher HTF temperature, allowing the full integration of the solar field and the storage system. This "second generation" should provide significant improvements in the average conversion efficiency and further reduction of costs. Although a demonstration plant has already been built, adequate operating experience is still needed and components with enhanced performance and durability are being studied and developed.

Central receivers

Solar towers with central receiver (CR) concentrate solar radiation by means of a field of heliostats, each consisting of a reflecting surface mounted on a pedestal which can track the sun on two axes. The heliostats reflect the solar radiation onto a receiver located at the top of a tower. A HTF, which in current power plants is either steam or molten salt, is heated in the receiver and used to generate electricity in a conventional steam turbine.

The efficiency of these plants is usually better than PT plants, because fluid temperatures are higher – around 550°C. This leads to better thermodynamic performance and it also facilitates storage: smaller volumes are possible because of the higher temperature difference between the cold and the hot tanks. At present, there are only three commercial size power plants of this type in Spain; in the United States, several larger projects are currently under construction.

Although commercial experience with CR plants is limited, it is estimated that the cost (LCOE) of the electricity from such plants could be lower than that generated in PT plants, even though land use is slightly less efficient. The requirements for "flat land" are less demanding than for PT. Growing confidence for this type of plant is expected as more of them go into operation. These plants could have a rated power of over 100 MWe although their efficiency decreases slightly with the size.

The first two commercial CR plants using saturated steam below 300°C can be considered as "first generation" technology, whereas later systems are already in the "second generation" category. This is especially true when the HTF is a molten salt or when the plant includes an "integrated storage system". CR plants are still on their way towards maturity. Much of the development work outlined later will be focused on the optimisation of components, systems and operating strategies, based on the findings from the operation of these plants.

In a future generation of CR plants, the full capacity of the high concentration allowed by CR will be exploited to reach temperatures which are high enough to drive the advanced power cycles, such as combined cycles and supercritical steam/gas turbines, which are associated with much higher conversion efficiency.

Linear Fresnel reflectors

This technology is also based on solar collector rows or loops. However, in this case, the parabolic shape is achieved by almost flat linear facets. The radiation is reflected and concentrated onto fixed linear receivers mounted over the mirrors, combined or not with secondary concentrators. One of the advantages of this technology ("linear Fresnel reflectors", or LF) is its simplicity and the possibility to use low cost components. Direct saturated steam systems with fixed absorber tubes have been operated without problems. This technology eliminates the need for HTF and heat exchangers. Increasing the efficiency depends on superheating the steam; however, this is still a challenge. Overcoming this challenge has still to be demonstrated.

This technology is currently less deployed than the other two (PT and CR) already described. Concentration and temperature of the fluid in the solar field – to date mostly saturated steam – are lower than in the other two technologies. Because steam is the working fluid, it is more difficult to incorporate storage systems. However, other fluids and/or solutions can be considered to allow for storage.

After a first pilot scale application in Australia, a few new pilot plants have been tested in Spain and in the United States, and a first commercial 30 MWe LF plant is already in operation in Spain. France has already implemented a LF pilot plant and is currently building two new commercial plants with this technology, of 9 and 12 MW respectively.

Compared to other technologies, the investment costs per square meter of collector field using LF technology tend to be lower because of the simpler solar field construction, and the use of direct steam generation promises relatively high conversion efficiency and a simpler thermal cycle design. Many improvements in the absorber tubes and the geometry are under development. Some of those ongoing improvement efforts relate to the shape and the disposition of mirrors to accommodate some of the peculiarities of this technology and to achieve a performance which is closer to that of other technologies, in particular PT.

The LF technology is also quite useful for direct thermal applications, such as cooling or generating process steam.

The future deployment of the LF technology will depend on whether investment and generation costs can be lowered enough to compensate for the slightly lower performance and fulfil its promise of being competitive.

Due to the small number of demonstration installations, we cannot refer to a mature "first generation" plant, but it is expected that this will change very soon. The gain in operating experience with present and future installations will define this basic level. Future improvements matched with important cost reductions which are possible because of the simplified design can render this technology very competitive, especially when combined with other energy systems.

Parabolic dishes

Infinia – Yuma PowerDish II

Power plants using parabolic dishes (PD) with Stirling engines consist of two basic components, a concentrator or solar dish and a power generator. Each complete unit produces electricity by itself. The power of the current devices varies from 3 kW to 25 kW per unit.

The paraboloidal concentrators collect the solar radiation directly and reflect it onto a receiver located over the dish close to the focal point. The structure rotates, tracking the sun and thus concentrating the rays onto the focus where the receiver – connected to the engine – is located. The most common thermo-mechanical converter used is a Stirling engine connected to an alternator. The Stirling engine uses a heated gas, usually helium or hydrogen, to generate mechanical energy in its shaft. The efficiency of these plants is much higher than those of the other three technologies already described.

This design eliminates the need for water, because cooling of the engine is achieved by means of a radiator similar to those used in some cars. This is an advantage compared to the usual designs employed by other technologies – although some of them could also utilise dry cooling systems. On the other hand, as the PD's are single units, Thermal Energy Storage (TES) and hybridisation solutions are not easy to implement and this constitutes a major bottleneck to the large scale development of this technology. Dispatchability and stability are other important issues, as the PD systems have no thermal inertia. However, this technology can be displayed modularly and PD's are easier to site on uneven land than other collecting systems. Therefore, PDs could be a solution for distributed generation.

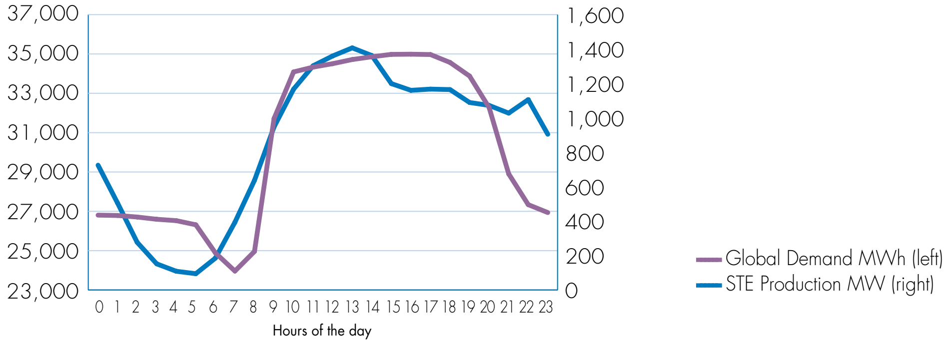
Storage

One of the main challenges for renewable energy technologies is finding solutions to problems derived from the varying or intermittent nature of many renewable resources. Among these resources, solar energy has some major advantages, not only because it is much more abundant than any other source but also because the hours of solar radiation are more predictable. However, the key advantages for the thermal option are that thermal energy storage (TES) is efficient and relatively cheap and that there are already many available commercial solutions. In addition, because STE plants are eminently suitable for hybridisation, a plant which takes advantage of the solar radiation when it is available can deliver energy upon request and can follow the demand curve even when neither sun nor stored energy is available.

The energy collected can be stored for later use during the night or on cloudy days by increasing the internal energy of a substance. Storage makes it possible to separate energy collection from electricity generation, and therefore the storage system for the STE plant can have a high capacity factor.

In many regions, daily peak demand coincides with the hours of highest solar radiation availability. Depending on the season, for a few hours after sundown there is a second peak demand. In Spain, in particular, plants with storage usually have up to 7.5 additional hours of capacity; this allows the operation of the solar thermal plants to be extended and makes them more competitive.

FIGURE 7: Electricity demand and STE production on 11th July 2012 and in the full month of July 2012[20]



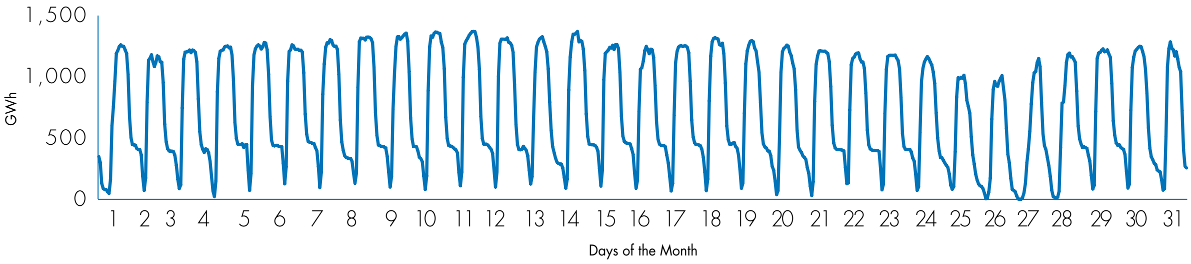


Figure 7 shows the curve of electricity demand in Spain (scale on the left) and the aggregated production of all the STE plants (scale on the right) on 11th July 2012 and in the full month of July. There is a good match between the curves.

Practically all solar thermal plants have either storage systems or allow hybridisation with other technologies. This helps to regulate production and guarantee that power is available, especially during peak demand hours.

Hybridisation

For STE plants, hybridisation is the combination of the use of solar energy with heat coming from other sources such as biomass or conventional fossil fuels. The advantages of hybridisation are:

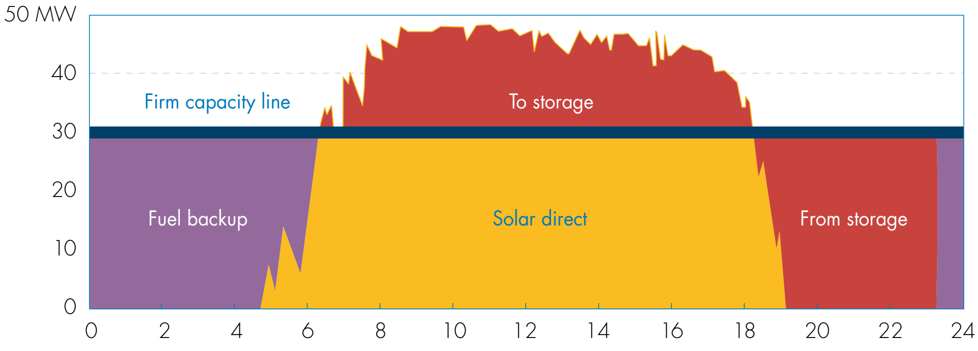
- Making it possible to convert the collected solar power with higher efficiency;
- Ensuring dispatchability to cover peak demand and deliver energy on demand;
- Overcoming the variability of the solar radiation;
- Reducing start-up time; and
- Minimising the generation cost (LCOE).

Steam produced with solar energy can be used to boost the capacity of a conventional fossil-fuel power plant, saving fuel, reducing CO_2 emissions and achieving higher solar energy conversion efficiencies.

All STE plants (PTs, CR and LF), with or without storage, can be equipped with fuel-powered backup systems that help to prepare the working fluid for start-up, regulate production and guarantee capacity (Figure 8). The fuel burners (which can use fossil fuel, biomass, biogas or, possibly, solar fuels) can provide energy to the HTF or the storage medium or directly to the power block. In areas where DNI is less than ideal, fuel-powered backup makes it possible to almost completely guarantee the production capacity of the plant at a lower cost than if the plant depended only on the solar field and thermal storage. Providing 100% firm capacity with only thermal storage would require significantly more investment in a larger solar field and storage capacity, which would produce relatively little energy over the year.

20- Source: ESTELA Position Paper 'The Essential Role of Solar Thermal Electricity: A real opportunity for Europe' October 2012.

FIGURE 8: Combination of storage and hybridisation in a solar plant



Source: Geyer, 2007, SolarPACES Annual Report

Fuel burners also boost the conversion efficiency of solar heat to electricity by raising the working temperature level; in some plants, they may be used continuously in hybrid mode. STE can also be used in hybrid mode by adding a small solar field to fossil fuel plants such as coal plants or combined-cycle natural gas plants in so-called integrated solar combined-cycle plants (ISCC) There are operating examples in several northern African countries with solar fields of 25 MWe equivalent and, in the United States, there are examples with a larger solar field (75 MWe.) A positive aspect of solar fuel savers is their relatively low cost: with the steam cycle and turbine already in place, only components specific to STE require additional investment.

Other applications (desalination, process heat, solar fuels)

The thermal energy generated in solar thermal power plants can also be used for industrial purposes other than the production of electricity and thus enhance the applicability of the plants. One conceivable option would be the combination of electricity production with the **desalination of seawater**. Particularly in arid coastal areas, it would be an interesting perspective not only to generate electricity but to make drinking water that is often scarce in these areas available as well.

Furthermore, the plants can also provide **steam, heat or cooling for industrial purposes**. One example is the use of concentrating solar thermal systems for the generation of steam to enhance oil recovery, as proved in a commissioned feasibility study for a plant in the sultanate of Oman. Here, hot steam is injected into the mostly exploited deposits under high pressure in order to mine the remaining resources. Previously, fossil fuels were mainly used for the generation of steam. However, if the steam is provided using solar thermal methods, emissions that are harmful to the climate could be reduced significantly.

Regarding production of **fuels from concentrated solar power** there are basically two routes. The first one is the electrochemical route which uses the solar electricity generated by STE plants to power an electrolytic process. Another approach is the thermochemical route which uses solar heat at high temperatures followed by an endothermic thermochemical process. Solar fuels could be the means to store solar energy to enhance the performance of a solar thermal plant and they could also be the means to transport the collected (and transformed) solar energy to sites that may be far from the collector fields.

6 STE MAIN CHALLENGES ON INNOVATION

6.1 The STE European Industrial Initiative

The Strategic Energy Technology Plan (SET-Plan) is the major instrument elaborated by the European Commission to strengthen and give coherence to the overall European effort to accelerate innovation in cutting edge European low carbon technologies. In doing so, the SET-Plan will facilitate the achievement of the 2020 targets and the 2050 vision of the Energy Policy for Europe. In its Communication entitled 'A European Strategic Technology Plan'[21], the European Commission proposes to launch the European Industrial Initiatives (EII) to accelerate the development and deployment of cost-effective Low Carbon Technologies. EIIs have launched in six sectors: Solar, Wind, Bioenergy, Grid, Carbon Capture and Sequestration (CCS) and Nuclear. The "Solar Europe Initiative" encompasses large-scale demonstration projects for both PV and STE.

In July 2009, ESTELA released its "European Solar Thermo-Electric Industry Initiative" (STEII) contributing to the SET-Plan of the European Commission. A final version includes the Key Performance Indicators (KPIs), developed by ESTELA in collaboration with the SETIS team.

The proposed STEII has been developed for the purpose of achieving two main goals for the EU:

- To contribute to achieve the EU targets for 2020 and beyond by implementing large-scale demonstration projects to be carried out by industry and aimed at increasing the competiveness of the solar thermal electricity sector.
- To enhance market penetration and to consolidate the European industry global leadership throughout medium-term research activities aimed at reducing generation and operation costs in solar thermal electricity generation plants.

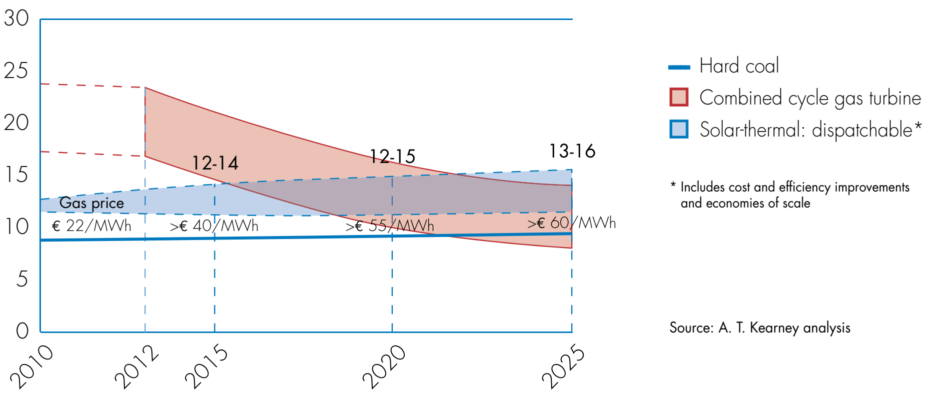
In particular, the STE industry in its STE-EII (European Industrial Initiative)[22] has identified three technology objectives to be considered for funding:

- Increase efficiency and reduce costs
- Improve dispatchability
- Reduce environmental impact

Increase efficiency and reduce costs

This objective is of utmost importance for the development of STE technologies and to further their market penetration. Many improvements need to be achieved through technological advancements on components and cycle efficiency, creating a new generation of efficient solar thermal power plants. This aspect cannot be dissociated from a substantial reduction of investment and O&M costs, an optimisation of the information and communication technologies, a better use of the installations (better use of land, larger plants) and more adequate terms of credit (lower interest rates, less technical risks).

FIGURE 9: LCOE comparison of solar thermal energy versus conventional sources[23]



21- COM (2007) 723: Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions – A European Strategic Energy Technology Plan (SET-Plan)
22- Source: ESTELA. 'Solar Power from Europe's Sunbelt', A European Solar Thermo-Electric Industry Initiative Contributing to the European Commission 'Strategic Energy Technology Plan', June 2009
23- Source: A.T.Kearney/ESTELA. Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production, June 2010

Studies performed to analyse how the solar field size influences the specific investment cost in €/m^2 have shown that the current cap of 50 MWe imposed in Spain for STE plants is a rather artificial limit and it is by no means a technical limit. As PT technology is very sensible to the effect of scaling-up, the design of bigger solar fields could lead to a significant cost reduction.

The maximum power output of a single plant is theoretically not limited by any physical constraint. In practice, the pressure drop of the HTF does imply that there is an optimum scale and this effectively limits the size of the solar field. However, STE plants of more than one hundred MW with a single power unit are being designed.

Improve dispatchability

Dispatchability is a strong advantage over other renewable sources. It allows flexibility, financial savings, and competition with fossil fuels. The improvement of the thermal energy storage systems (through improvements in filler materials, transfer fluids, phase-change systems, "ultra" capacitors) and the hybridisation with other power plants will lead to an increase in the hours of production and have a direct impact on the overall plant performance and economics.

The dispatchability of STE plants can be further increased, when thinking in terms of system collections rather than individual plants, by connecting the plants in an inter-continental grid, increasing the flexibility and availability of the power supply on demand.

Reduce environmental impact

Examples of measures to reduce environmental impact are the development of new cooling systems with lower water needs (steam cycles) and the deployment of enhanced dry cooling systems. A better use of land and materials and the desalination and purification of water will also contribute to fulfill this objective.

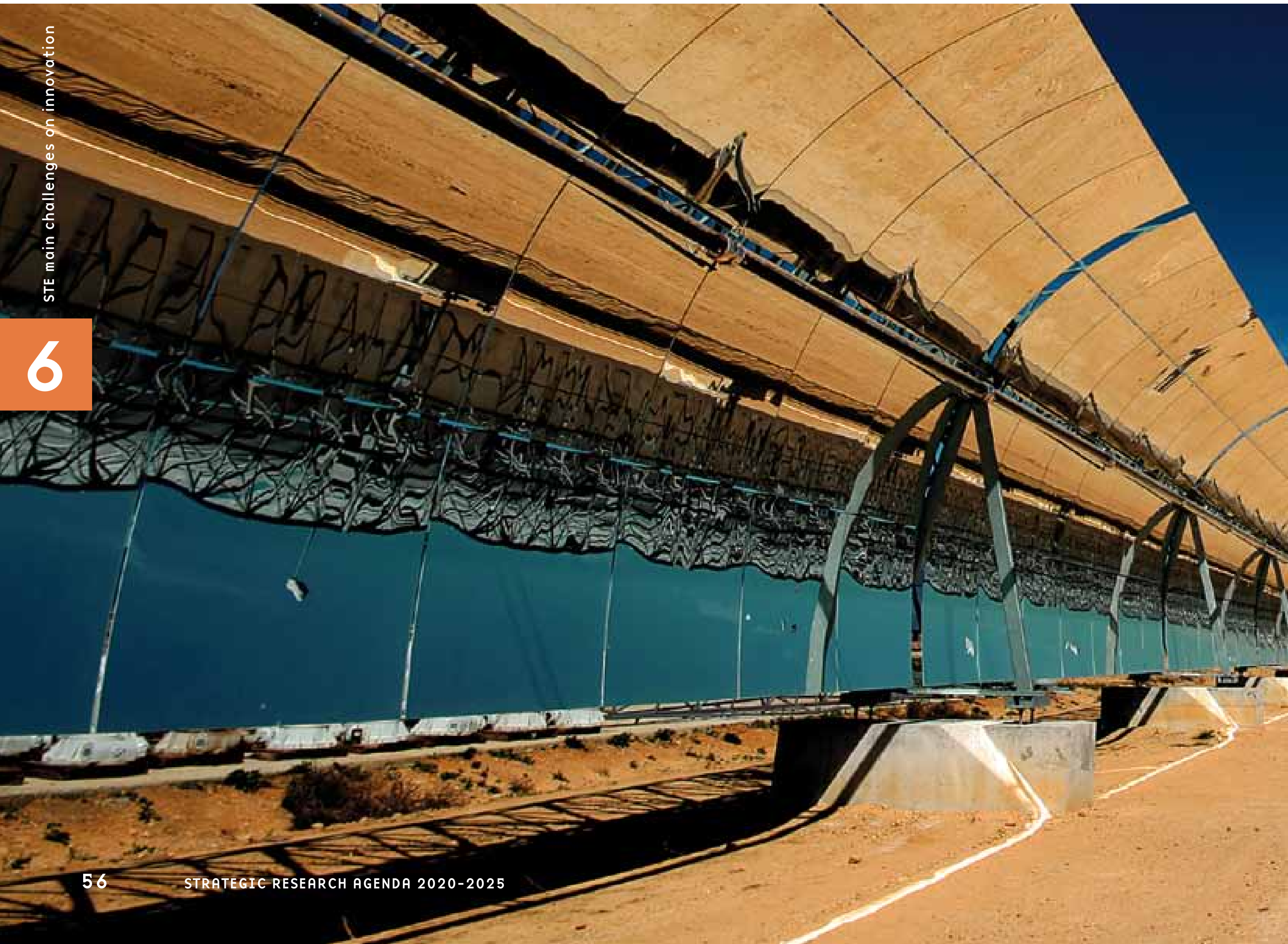
6.2 Upcoming challenges

The first objective described in the previous chapter is crucial to all electricity generating renewable energy systems if they are to be competitive with conventional power plants, even if funding is reduced or phased out in the future. The second objective is related to the "quality" of the electricity supply, i.e. to provide grid stability and availability on demand. These are two of the major advantages of STE plants thanks to their thermal inertia, storability and their ability to operate in hybrid mode. The third objective is largely imposed by the STE industry on itself, because the industry and its market acceptance are driven by the goal to achieve sustainability, and to eliminate or reduce the cost of externalities is key to achieving sustainability.

The measures taken to meet these objectives affect components, systems and configurations. Table 3 illustrates where measures are being taken to achieve the objective to reduce costs. A detailed description including KPIs is given in ANNEX I: Key Performance Indicators.

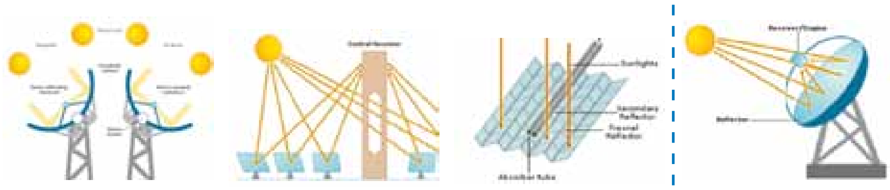
TABLE 3: Solar power cost reduction factors

Components	Systems	Configurations
Solar receivers: linear and central	Receptor systems: hot air to gas turbine	Hybridisation
Mirrors	HTF systems: direct steam generation	Dual electricity water-plants
New HTFs	Storage Systems	
Storage media	Cooling systems: hybrid cooling systems	
Supporting structures		
Trackers		
Auxiliary systems: pumps, valves		



The different STE technologies presented in chapter 5 represent different stages of maturity, since PTs and CRs as well as LFs in an early stage already exist as commercially operating power plants. Barring some unforeseen breakthrough, therefore, the challenges for these technologies can be addressed through incremental innovation, although the "increments" may be quite important. The situation is different for parabolic dishes, however, since so far these have only been tested as demonstration plants. For PD, therefore, the first challenge is to prove that plants based on this technology can also be operated commercially.

FIGURE 10: From innovation to commercial operation



	PT	CR	LF	PD
Commercially proven for utility scale power	✔	✔	✔	
Description	The reflector concentrates the sunlight to a receiver tube, through which the HTF is circulated.	Heliostats follow the sun to reflect the sunlight to the top of a tower where the HTF is heated.	Rows of mirrors concentrate the sunrays onto a receiver tube where the HTF is pumped.	A group of mirrors with a parabolic shape reflect the sun to an engine located in the focus point
Track record	✔ 30 years	✔ 5 years	✔ Demonstration	✔ Demonstration
Application	✔ Utility scale power	✔ Utility scale power	✔ Heat applications	✔ Distributed power
Next challenges	Incremental innovation and possible breakthroughs			Commercial operation

Incremental changes (such as new collector designs in an existing collector field or innovative mirror cleaning mechanisms) can help improve the performance of an STE plant and meet the objectives already described. However, very often, this kind of short term demonstration is not possible in commercial power plants, since some innovative components and systems cannot easily be incorporated into an existing power plant. To give just one example, it would be almost impossible to test a direct steam generation system in a plant which uses an oil heat transfer fluid system. Therefore, besides short term demonstration of innovative components and systems, a key need in terms of R&D funding to achieve commercially viable STE plants is the financing of first-of-its-kind commercial power plants with innovative technologies. These power plants are typically larger than "pure" R&D demonstration plants and, thus, require significantly more investments, but they are too small to operate as efficiently as commercial power plants (cf. diagram below).

FIGURE 11: Financing first commercial plants for breakthrough technologies

	Demo Plant	First Commercial	Commercial Plant
Size	1-5 MW	5-20 MW	> 20 MW
Cost	5,25 M€	25-100 M€	> 100 M€
Financing Instrument	Balance Sheet R&D Funding		Project Financing Feed-in-Tariffs/PPAs

- Essential to achieve bankability, especially for breakthrough technologies
- Risk too high for individual CSP players
- Suboptimal scale to operate efficiently
- R&D funding and FiT exclude each other

As a consequence, financial instruments are needed to help roll out both incremental and breakthrough innovation. In addition, risk sharing mechanisms for first-of-its-kind and commercial power plants are required.

To clarify the priorities for R&D efforts in STE plants, it is useful to divide the objectives for innovation into short- mid- and long-term. The individual targets to address each objective are described in detail in the following chapters.

7 STRATEGIC RESEARCH AGENDA

In this time of growing concern for future investment, the Strategic Research Agenda appears like a necessary and inevitable step for setting up the baselines for the short to long term research for STE technology. Its target is to identify clearly the bottlenecks, milestones and challenges of this emerging technology through the accomplishment of the three objectives outlined above: to increase efficiency and reduce costs, to improve dispatchability and to improve the environmental profile.

STE research priority topics are defined in the following chapters, ordered by objective and technology, with dedicated chapters for cross-cutting issues. They include storage, hybridisation and environmental profile. A table at the end of each chapter brings to light the objectives to be achieved in the short (2015), mid (2020) or long term (2025 and beyond). The table also shows the associated targets.

These technical topics must be addressed with due consideration to the standardisation aspects that have been described in chapter 3.4. An efficient and concrete reduction of costs is not possible without the establishment of clear international standards.

7.1 Objective 1: Increase efficiency and reduce generation, operation and maintenance costs

Reduction of cost is the key point for the future large scale deployment of STE plants. It can be achieved by increasing the efficiency of the systems, reducing the costs of the equipment and lowering O&M costs. Certainly their combination will provide a further reduction on the costs of the generated electricity.

Larger size of plants along with scale factors in component manufacturing and the lessons learned in assembly of components and construction of plants will certainly contribute to achieve the cost reduction objective.

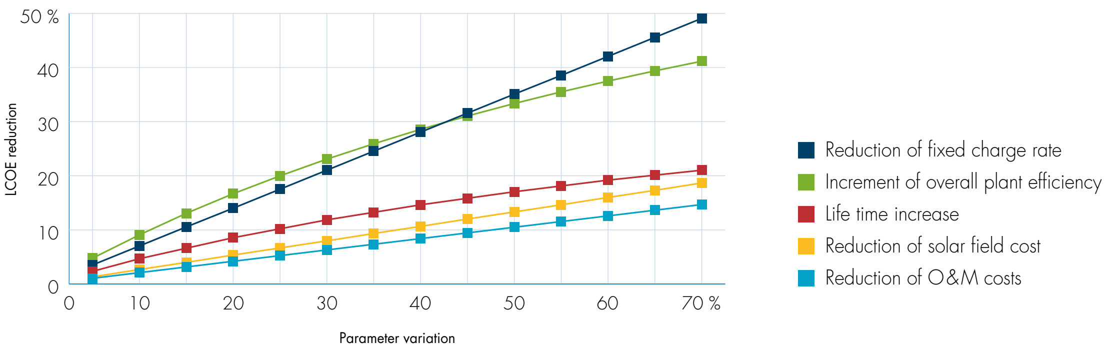
In our previous approach on the SEII, increasing efficiency and reducing costs were considered independently. However, they are so interconnected that we have preferred to present them jointly in this Strategic Research Agenda.

The STE industry is committed to push technological improvement initiatives along these lines in close collaboration with the technological research centres.

By 2015, when most of the planned improvements are to be implemented in new plants, energy production boosts greater than 10% and cost decreases up to 20% are expected to be achieved. Furthermore, economies of scale resulting from the increase of the plant size will also contribute to reduce the CAPEX per produced unit of energy up to 30%. STE deployment in locations with high solar radiation will further contribute to achieving cost competitiveness by reducing LCOE by up to 25%.

All these factors can lead to electricity cost savings of up to 30% by 2015 and up to 50% by 2025, thus reaching competitive levels with conventional sources (e.g. coal/gas with LCOE <10 c€/kWh).

FIGURE 12: Sensitivity analysis of several parameters on the LCOE of a 50 MWe PT plant with 7.5 hours of thermal storage (Reference case: plant located in Southern Spain, 2011)



Strategic Research Agenda

7

Figure 12 shows the impact of changes in several characteristics on the LCOE. The items represented in the graph and their reference values are:

- Plant life time (reference value: 20 years)
- Solar field specific costs (reference value: 225 €/m²)
- Plant operation and maintenance costs, excluding the power block (reference value: 40 €/MWh)
- Fixed Charge Rate (reference value: 0.0682)
- Overall plant yearly efficiency (reference value: 15.2%)

Although values represented in Figure 12 are for a 50 MWe PT plant with 7.5 hours of thermal storage system with molten salt, sensitivities shown in this graph are very similar to the values for a 50 MWe plant without storage.

The two parameters showing a greater influence on the LCOE are the fixed charge rate (financial costs) and the overall plant efficiency. The impact of a reduction of the O&M costs (€/MWh_e) and of the specific solar field costs (€/m^2) have a smaller influence.

The life time of the plant has an intermediate impact, and an increase from 20 to 30 years would reduce the LCOE by about 17%. This number shows the great importance of improvements on the durability of components to extend lifetime.

Today, a quick evolution through the learning curve can be observed in the STE technology. Most of the new plants which have been recently connected to the grid were constructed in Spain requiring FiTs which were settled in 2009 at a level of around 27 c€/kWh. Ongoing projects which have been awarded on competitive bases in India or Morocco or which resulted on bilateral PPA negotiations between utilities and promoters in the United States show promising results, in accordance with the A.T. Kearney/ESTELA cost reduction forecast.

The development of the topics included in this Strategic Research Agenda of the STE industry will certainly contribute to reaching these goals.

7.1.1 Cross-cutting Issues

7.1.1.1 Mirrors

Since mirrors are key elements in any STE plant, improvements reducing the manufacture or maintenance costs associated with mirrors will be important to achieve the pursued LCOE reduction.

The state-of-the-art for the reflective surface of solar reflectors is represented by either facets of thick (4-5 mm) glass mirrors with structural functions or thin (0.8-1.1 mm) glass mirrors attached to a structural surface (fibre glass, composite, metallic…) that provides shape and stiffness. While the first solution is currently used in all four technologies considered in this document (PT collectors, heliostats, LF and PD), thin glass mirrors have been used mainly in PD. The use of other reflective surfaces, such as silver polymer films, is possible but it will require proven durability.

Light reflective surfaces

The use of lightweight reflective surfaces will result in cheaper mirrors. However, alternative solutions to thick glass mirrors must be at least comparable in terms of durability and reflectance.

Glass reflector with anti-soiling coating

Mirror washing is one of the most frequent maintenance activities at the solar field of solar thermal power plants. Any improvement that reduces the number of washings would also reduce not only the maintenance costs but also the plant water consumption, which is a critical factor for the commercial deployment of STE plants in desert areas.

Mirror samples exposed to outdoor conditions to evaluate anti-soiling coatings (CIEMAT-PSA, Plataforma Solar de Almería)

Mirror glass with higher solar transmissivity

The solar transmissivity of the glass currently used for solar reflectors can be improved. Improvement of transmissivity will improve the mirror reflectivity and lower optical losses for the four STE technologies; in addition, for PT and linear Fresnel systems, it will also improve the overall efficiency of the receiver tubes by improving the solar transmittance of their glass cover.

7.1.1.2 Receivers

The receiver is the key component of a STE plant, because it is in the receiver that the concentrated solar radiation is converted into thermal energy. The receiver efficiency is key for the overall STE plant performance. Therefore, any improvement that increases the efficiency of the receiver will have a significant impact on the final LCOE, provided that the additional costs associated with such improvement are affordable.

Selective coatings with better optical properties

The solar-to-thermal conversion efficiency depends greatly on the optical properties of the receiver selective coating. The optical properties of selective coatings currently available for evacuated tubes (used in PT and in LF collectors) are excellent, but their emittance and absorptance properties could still be improved. However, for non-evacuated tubes, there are no commercially available coatings for operating temperatures above 400°C. This limitation is particularly severe for linear Fresnel technologies. Also, for tower applications, selective coatings which are stable at atmospheric conditions at temperatures higher than 600°C are not available yet.

7.1.1.3 Heat transfer fluids

The thermal oil used nowadays as working fluid in most PT collectors limits the maximum working temperature (398°C). It also poses some environmental hazards due to possible leaks and fires. These factors increase the operation and maintenance costs and they limit the maximum power block efficiency.

Synthetic oil with new chemical formulation

The performance of existing solar plants using oil as heat transfer fluid can be enhanced if a new chemical formulation is developed that reduces the chemical degradation with time. New fluids with lower viscosity at low temperature can be studied, avoiding the need to preheat the fluid and to maintain it above a minimum temperature. The addition of PCM, nanoparticles (nanocrystals) or fullerenes are some of the possible solutions. Binary systems such as ionic liquid-carbon nanotubes can also be considered.

Low melting-temperature salt mixtures

Molten salt, most commonly, a Na/K 60/40 wt%[24] nitrates mixture used as a thermal storage medium in STE plants, would be an alternative to thermal oil as the salt remains stable at temperatures higher than 400°C. One drawback, however, is the melting temperature of the salt mixture normally used in the TES, which lies between 220 and 240°C. This means that the temperature in the solar field must always be kept above this range to prevent the salt from solidifying in the absorber tubes, or that some alternative solution must be found.

Therefore, the development of novel molten salt mixtures with a lower melting temperature (i.e. <100°C) and which are thermally stable up to 450°C (such as. Na/K/Ca nitrates mixture) or higher (such as Na/K/Li nitrates mixture), and which have an acceptable cost would be a significant improvement for PT and compact linear Fresnel systems. Such mixtures would allow more efficient thermal storage systems based on a two-tank molten salt direct system, because the current oil/molten salt heat exchangers would no longer be needed. However if the cost of the novel mixture is high, it would be necessary to maintain the intermediate heat exchanger (indirect system) using the mixture only in the solar field – exactly as with the oil.

For CR plants, the reduction of the melting temperature must be accomplished without reducing the thermal stability at 600°C or more. This means that a melting temperature lower than 100°C must be complemented with a good thermal stability up to at least 600°C. Otherwise the lower overnight thermal losses due to lower salt temperatures would not compensate for the lower plant efficiency during sunlight hours and the net impact on the yearly plant efficiency would be negative. Therefore, different targets must be defined depending on the STE technology being considered.

Pressurised gas

The use of pressurised gas (air, CO_2, etc.) for both PT and CR plants should be further investigated. In spite of their poorer heat transfer properties pressurised gases have no temperature limits and no important constraints regarding the receiver tube materials. Although pressure losses are higher with pressurised gas than with liquids, this problem can be significantly overcome with an optimised design of the piping. Furthermore using pressurised air as the working fluid for CR plants would make the solar combined cycle concept possible with some support of gas firing before the air enters the gas turbine, and this has the potential to result in a considerable increase in the conversion efficiency from solar energy into electricity.

Direct steam generation

The use of water/steam as working fluid in PT, CR or compact linear Fresnel STE plants has been widely studied during the last two decades. Its advantages and disadvantages have been evaluated and compared to other options for commercial STE plants (molten salt or air in CR, thermal oil in PT or in linear Fresnel systems). For PT plants, in particular, cost assessments performed recently have shown that a 6-7% LCOE reduction can be achieved by direct steam generation (DSG) in comparison with options based on heating up thermal oil in plants without thermal storage.

Peculiarities due to the existence of a two-phase flow in the receiver tubes introduce some technical uncertainties, related to controls in particular, that must be fully clarified. Although the technical feasibility of DSG in PT, CR and linear Fresnel plants has been already proven, there are many aspects for optimisation that must be fully investigated to assess the commercial potential of DSG.

24- Na/K 60/40 wt %: Percentage in weight of 1st component/2nd component of the mixture

Development of high pressure/temperature absorber tubes for direct steam generation

DSG technology allows avoiding the use of an intermediate HTF between the solar field and the conversion cycle, with a potentially beneficial effect on plant costs. High efficiency steam cycles are characterised by high steam temperature and pressure. They can be used primarily in linear type concentrators (PT and linear Fresnel), although there may also be some potential for CR applications. DSG technology uses the water/steam fluid directly in the absorber tubes. In order to have a good conversion efficiency, steam cycle conditions are required with pressures higher than 100 bar at 500°C or more. Absorber tubes are to be built accordingly and special coatings could be required.

7.1.1.4 Storage

The potential to store thermal energy to follow the demand is one of the most important advantage of STE compared to PV. Enhancing this feature at the lowest possible cost is essential to increase the share of STE in the future.

Advanced high temperature thermal storage systems

The two-tank molten salt concept is proven and reliable. However, due to salt stability, the maximum operating temperature is limited to around 550°C. Therefore, new materials and concepts need to be developed to provide efficient and economic storage system when working at 600°C or beyond.

7.1.1.5 Control and operation tools

User-friendly equipment and procedures for on-site checking of optical and geometrical quality of solar concentrators constitute an important tool. Very efficient quality control procedures are implemented during the assembly of the solar collectors at the construction site, but there is a lack of equipment and procedures allowing an easy and quick evaluation of their optical and geometrical quality after their installation in the solar field.

Laboratory at Fraunhofer ISE for testing the dynamical operation of high temperature storage systems and small steam heat engines for combined heat and power. The steam output of a solar field using concentrating collectors is simulated in real time by a gas heater with evaporator

The cross-cutting issues that have been identified above are summarised in the following Table. By the specific parameters, it identifies targets and action items where applicable.

TABLE I: RESEARCH PRIORITIES FOR CROSS-CUTTING ISSUES

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Mirrors	Light reflective surfaces	• Identify and develop light-weight and durable reflective surfaces with high reflectance	**Parameter:** Durability Demonstrate the durability of aluminum, thin glass mirrors and polymer films	X		
	Glass reflectors with anti-soiling coating	• Reduce maintenance cost and plant water consumption => enhance commercial deployment of STE plants in desert areas with high solar radiation levels	**Parameter:** Water requirement for mirror washing [$m^3/m^2/y$] **Target:** < 0.015 (water consumption = - 50% in southern Spain) LCOE = - 0.1%		X	
	Mirror glass with higher solar transmissivity	• Increase the reflectance of glass solar reflectors and the efficiency of the receiver tubes	**Parameter:** Glass solar transmittance (ρ) **Target:** ρ = 0.93 for glass thickness = 3.5mm LCOE = - 1% for CR LCOE = - 2% PT & LF	X		
Receivers	Selective coatings with better optical properties	• Increase solar-to-thermal efficiency - of the receiver tubes used in PT and CLFR systems - of the tubular receivers in CR systems	**Parameter 1:** Solar emittance (ε) **Parameter 2:** Solar absorbance (α) PT and LF: **Target 1:** ε < 0.1 (450°C) **Target 2:** $\alpha \geq$ 0.96 (vacuum conditions) LCOE = -1.5% CR: **Target 1:** ε < 0.25 (600°C) **Target 2:** $\alpha \geq$ 0.94 (stable atmospheric conditions) LCOE= - 2%		X	
Heat transfer fluids	Synthetic oil with new chemical formulation	• Lower the value of viscosity at low temperature • Add PCM • Consider binary systems	**Parameter:** O&M solar field cost **Target:** 5 to 10% reduction		X	X
	Low melting-temperature salt mixtures	• Reduce the thermal losses overnight and the risk for crystallisation in the piping of STE plants using molten salt => reduce maintenance costs	**Parameter 1:** Melting temperature (T) and thermal stability limit of the novel salt mixture **Parameter 2:** Overall efficiency η **Parameter 3:** Cost (C)			
			Target 1: T ≤ 100°C (good thermal stability up to 450°C) **Target 2:** η = + 4% (15.2% > 15.8%) **Target 3:** C < 40% of the cost of oil LCOE = - 4%		X	
			Target 1: T ≤ 100°C (good thermal stability T > = 600°C) **Target 2:** η = + 6% (15.2% > 16.1%) **Target 3:** C < 120% of the cost of the Na/K 60/40 wt% nitrates mixture LCOE = - 5.5%			X
			Action: Implementation of a small plant (< 5 MWe) to investigate O&M related issues using new working fluid under real solar working conditions			
	Pressurised gas	• Increase solar-to-electric efficiency	**Parameter:** overall conversion efficiency			
	Development of high pressure absorber tubes for DSG	• Develop novel design absorber tubes, with suitable metals and thickness to withstand pressure and temperature limits	**Parameter:** Working pressure (p) and temperature (T) of the absorber tubes Target 1: p = 125 bar at T = 575°C for PT and LF Target 2: p = 150 bar at T = 700°C for CR	X		
Storage	Advanced high temperature thermal storage systems	• Develop new systems based on new materials or new concepts in order to obtain technical and economically feasible solutions at temperatures above 600°C	**Parameter:** Storage working temperature (T)			
			Target 1: T = 600°C Storage concepts for air receivers with T = 800°C by 2015	X		
			Target 2: Storage concepts for air receivers with T > 1,000°C by 2020		X	
Control and operation tool		• Develop faster & cheaper tools & procedures => maximise solar radiation => improve efficiency and LCOE	**Parameter:** Cost and time required to assess the optical quality of a life-size solar concentrator **Target:** < 2 kW, < 6 h, total uncertainty < 1.5% (11.2 x 5.7 m PT module, a 120 m^2 heliostat, or any concentrator with an aperture area ≥ 30 m^2) **Action:** Implementation and evaluation of a prototype for the intended on-site evaluation equipment		X	

7.1.2 Parabolic Trough Collectors

Parabolic trough (PT) is by far the solar thermal electricity (STE) technology with the widest commercial implementation today, with a high number of commercial plants in operation. However, the potential for technical and economic improvements is still high and a significant cost reduction of the electricity generated by this type of STE plants is possible.

A significant R&D effort is still needed to increase efficiency and reduce operation and maintenance costs. Together with better durability and reliability, this effort should lead to a very important cost reduction of the electricity produced by this type of STE plants.

Research priorities described below focus on efficiency and durability improvements and on the reduction of operation and maintenance costs for PTs. Assuming a baseline LCOE of 0.21 €/kWh in 2011 for a 50 MWe STE PT plant without thermal storage, and 0.19 €/kWh for a plant with 7.5 hours of thermal storage, successful development and implementation of these improvements would lead to achieving the LCOE-related KPI estimated by ESTELA for 2013 (15% LCOE reduction) and 2020 (45% LCOE reduction).

7.1.2.1 Receivers

Receiver tubes are the key component of solar fields with PT collectors, because the overall solar field efficiency very much depends on their performance. Improvements related to receiver tubes may increase the overall plant efficiency if higher working temperatures are achieved; and may also reduce the O&M cost associated to the replacement of the tubes themselves, if a higher durability is achieved.

Evacuated receiver tubes suitable for higher temperatures

Evacuated receiver tubes using current design (i.e., metallic bellows, glass/metal welds and getters) and suitable for higher temperatures (550°C at the steel pipe, at least) need the development of new selective coatings with better thermal stability than the current choices. Achieving an improvement of the reliability and durability of the glass to metal welds at higher temperatures without increasing the cost is also an important goal within this research priority.

Innovative receiver tube designs

This R&D item includes not only innovative receiver designs with vacuum and without glass-to-metal welds (the welds are the most critical part in current commercial receiver tubes) but also standard designs with improvements to reduce H_2-permeation through the steel pipe.

7.1.2.2 Heat transfer fluids

Thermal oil is the HTF (heat transfer fluid) used at present in PT STE plants. Thermal oil has two major disadvantages:

- Low thermal limit of 398°C, because the oil suffers a high degradation rate if this temperature limit is exceeded. It imposes a temperature limit to the superheated steam produced for the power block and limits its efficiency;
- High O&M costs due to the need for safety equipment (because of fire hazards) and of a purification plant (the so-called ullage system).

These two disadvantages of thermal oil make the consideration of different HTFs advisable in order to reduce O&M costs while increasing the power block efficiency.

Pressurised gas

Pressurised gas (e.g. CO_2, N_2, air, etc.), is usually suitable for temperatures of at least 500°C, which can lead to higher efficiencies than the current thermal oil used in parabolic trough plants. Although pressure losses are higher with pressurised gas than with liquids (due to higher speeds in the gas), this problem can be significantly overcome with an optimised design of the piping.

The direct steam generation once-through option

In a DSG (direct steam generation) solar field operated in once-through mode, the preheating, evaporation and steam super-heating sections of each row in the solar field are directly connected: the end of each preceding section is directly connected to the beginning of the next section without any device in between.

Since the once-through operation mode does not need water/steam separators or water recirculation system in the solar field, the investment cost for a DSG solar field to operate in once-through mode is lower than if operating in injection or recirculation modes.

On the other hand, with the once-through mode, technical requirements to ensure a stable steam temperature and pressure at the solar field outlet introduce some uncertainties on technical and commercial feasibility. Experimental R&D is needed to assess and address these uncertainties.

Direct steam generation: assessment of saturated steam vs. superheated steam

A DSG system can produce saturated or superheated steam, and both options have advantages and disadvantages. An in-depth study of both options under real solar conditions is important.

The PSA HTF test facility, which is used for evaluation of new components and parabolic trough designs (CIEMAT-PSA, Plataforma Solar de Almería)

Molten salt

The use of molten salt as HTF would have clear advantages when compared to the thermal oil currently used in PT STE plants. From an environmental point of view, sodium and potassium nitrates have been used in agriculture as fertilizers for a long time, and the maximum working temperature with an affordable corrosion rate in metallic components is higher than 525°C.

At present, there are only demonstration or experimental facilities that use the same salt mixture (Na/K binary nitrates mixture) as heat storage medium or as HTF. The mixture makes it possible to reach up to 550°C in the solar field in a direct system – molten salt directly heated in the receiver tubes of the PT collectors, without using any other HTF between the solar field and the molten salt system. During operation, the fluid circulation (night and day) avoids any kind of problems. However, during maintenance operations (while charging and discharging the loops, or when cooling or warming of the loops by an auxiliary heating system) the lower the freezing temperature the lower are the risks of occurrence of solidified salt plugs inside the piping during cold periods.

7.1.2.3 System components with enhanced properties

The operational experience gained by current STE plants with PT collectors shows that some improvements concerning system components are not only possible but also advisable because of their potential to reduce O&M costs. Several research priorities are recommended here:

Interconnecting elements for receiver tube

Interconnecting the elements may lower the costs associated with the ball-joints and flexible hoses now used to connect the receiver tubes of adjacent PT collectors, as well as the inlet and outlet of every row with the header piping.

FIGURE 13: Different interconnecting elements used nowadays

Ball-joint connection

Flex-hose connection

Autonomous drive units and local controls

The hydraulic drive and local control units being used now in PT plants require a power supply from central switch-board cabinets located close to the plant central control room. Thousands of meters of electrical wires are run all over the solar field to supply electricity to each drive unit and local control. Thousands of meters of communication wires are also used to send and receive commands to and from the local controls to the main control room. Uninterrupted power supply is also required to assure safety conditions in case of a failure in the conventional power supply. Development of autonomous drive units and wireless control systems powered by small PV cells and batteries, similar to the already developed and patented for the "Autonomous Heliostat Concept", could lower the investment cost without penalising the reliability and durability of the system.

7.1.2.4 System size, component manufacturing and other improvements

The scale-up effect is very important in the technology of PT collectors, because the infrastructure needed for the on-site assembly of components can be optimised. Since there are many elements composing a PT collector, the optimisation (e.g. automation) of the manufacturing process can also play a significant role in the final investment cost, and therefore on the LCOE of a commercial STE plant.

Improved collector designs

New PT collector designs could lead to a significant reduction in the plant investment costs. This cost reduction can be achieved in different ways, such as increasing the collector size and optimising the manufacture and assembly processes to reduce manpower requirements.

7.1.2.5 Control and operation strategy

The amount of thermal energy delivered by the solar field can be increased with optimised control systems and a strategy that would maximise the amount of solar radiation captured by the solar collectors during the sunlight hours. The operational experience gained by STE plants already in operation has shown that the solar field output can be significantly increased during days with soft cloud transients if proper control and operation strategies are implemented.

Solar field control

In existing plants, the solar field outlet temperature is usually controlled by partially defocusing solar collectors to change the amount of solar energy collected and transmitted to the working fluid. Since this partial defocusing reduces the solar field active collecting area, new control approaches based on the solar field mass flow instead of the solar field collecting area would increase the amount of solar energy collected at the solar field increase the overall plant efficiency. Development of new advanced control and operation strategies should therefore be based on the maximisation of the amount of solar radiation collected during both clear days and days with cloud transients.

Early detection of HTF leakage

Leakages are a concern in PT plants using thermal oil as the working fluid. The early detection of these leakages is the key to avoid spills and to prevent possible fires. Oil spills also cause soil contamination: savings in operating costs and an important reduction of environmental hazards can be targeted with dedicated instruments and methods to alert about a leakage.

Auxiliary heating system for molten salt plants

The use of molten salt as working fluid in PT solar fields requires the installation of an Auxiliary Heating System (AHS) for the receiver tubes, piping and other components throughout the molten-salt circuit. Although the AHS should operate only for short periods during the year to meet the maintenance needs of the solar plant or in the case of accidents that require the AHS support, the current investment costs of this AHS are high, and so is the associated electricity consumption. These costs should be compensated by the lower costs of the molten salt, i.e., lower purchasing cost and lower degradation rate (longer lifetime), in comparison to oil.

TABLE II: RESEARCH PRIORITIES FOR PARABOLIC TROUGH COLLECTORS

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Receivers	Evacuated receiver tubes suitable for higher temperatures	• Increase solar-to-electric plant efficiency	**Parameter:** Maximum metal temperature (T) with specific operating life warranty			
			Target 1: T = 575°C in 2013 LCOE: - 5%	X		
			Target 2: T = 600°C in 2020 LCOE: - 6%		X	
			Action: Qualification of prototypes at existing solar test facilities	X		
	Innovative receiver tube designs	• Reduce O&M costs and increase receiver tubes life time	**Parameter:** Commercial evacuated receivers with lower O&M costs			
			Target 1: Evacuated receiver tubes without glass/metal welds, life time 25 y	X		
			Target 2: Commercial evacuated receivers with glass/metal welds and a H_2 permeation 50% lower than in 2011 LCOE: a reduction of 1% in the yearly reposition rate of receiver tubes would reduce LCOE by about 1%. (from 200 to 198 €/MWh)		X	
Heat transfer fluids	Compressed gasses	• Increase overall plant efficiency	**Parameter:** Maximum working fluid operating temperature **Target:** T ≥ 500°C	X	X	
		• Decrease thermal storage system size • Reduce oil environmental impact	**Action:** achieve for small STE plants (< 15 MWe) the same LCOE as that of bigger plants with Rankine cycle			X
	The DSG once-through option	• Reduce LCOE (Feasibility to be assessed under real solar conditions)	**Parameter:** LCOE [€/kWh] **Target:** LCOE: - 9% (if solar field connected to a PCM storage system of 50 €/kWh_{th})			X
	DSG: assessment of saturated steam versus super-heated steam	• Increase working temperature and reduce investment cost due to a simplification of the plant configuration • => LCOE reduction	**Parameter:** LCOE [€/kWh] **Target:** LCOE: - 6% (w/o TES) - 9% (w TES 50 €/kWh_{th}) **Action:** implementation of a small plant (between 3 and 5 MWe) able to operate with the two solar field options	X		
	Molten salt	• Increase working temperature for a higher power block efficiency • Reduce molten salt quantities => reduce storage cost • Reduce fire hazard • Reduce the freezing temperature	**Parameter:** $\eta_{sol\text{-}elec}$ /y & LCOE [€/kWh] **Target:** $\eta_{sol\text{-}elec}$ /y : + 5% (15.2% to 16%) LCOE: - 5%		X	
System components with enhanced properties	Interconnecting elements for receiver tube	• Reduce investment costs and O&M costs => reduce costs of electricity	**Parameter:** Investment costs (purchasing and installation) of the new interconnecting elements and guaranteed life time **Target:** 2,500 € per complete interconnection between adjacent collectors LCOE : - 1% (25% costs reduction)	X		
	Autonomous drive units and local controls	• Reduce investment and O&M costs	**Parameter:** Total cost (purchasing + installation) of the drive and local control units **Target:** 4,000 € LCOE: - 1%	X		
System size, component manufacturing and other improvements	Improved collector designs	• Develop new collector designs with lower costs and manpower requirements	**Parameter:** Solar field investment cost [€/m^2] **Target:** - 25% compared to 2011 LCOE: - 6%		X	
Control and operation strategy	Solar field control	• More efficient control and operation strategies => increase solar to electric efficiency	**Parameter:** yearly average $\eta_{sol\text{-}th}$ **Target:** $\eta_{sol\text{-}th}$: + 5% (considering a baseline solar field efficiency of 46% for PT plants in 2010) LCOE: - 9% **Action:** Implementation in a commercial PT plant by replacing the old control system based on collectors defocusing	X		
	Early detection of HTF leakage		**Target:** Availability of an innovative early leakage detection system		X	
	Auxiliary heating system for molten salt plants	• Develop more cost-effective auxiliary heating systems for molten salt plants	**Parameter:** AHS specific investment cost (C_i) in €/m^2 and yearly electric energy consumption cost (C_{ec}) in €/m^2 of solar field for a lifetime of the solar plant assumed to be 25 years, compared with the cost (C_{oil}) of a single charge of oil in the solar field for the number of substitutions foreseen in the life of the solar plant, assumed to be 4 **Target:** $C_i + C_{ec}*25 < C_{oil}*4$ LCOE: - 1%		X	

7.1.3 Central Receivers

The central receiver (CR) or solar tower technology has a great potential. Because of the high concentration ratios that can be achieved in CR systems, these can operate at high temperatures. The high operating temperatures make it possible to achieve higher solar-to-electricity conversion efficiencies than those possible with other technologies.

To transform the CR promise into reality, a significant R&D effort is still needed. This effort should be targeted to improve efficiencies, increase durability and reliability and reduce investment and O&M costs. The research priorities described below are intended to achieve substantial progress in each of the technology targets summed up in the table at the end of the chapter.

7.1.3.1 Heliostat field

General issues regarding mirrors have been already described in point 7.1.1.

As a general comment, it may be stated that mechanical requirements are much higher in parabolic curved mirrors where tempered techniques are applied. In the case of heliostat fields, float glass, a cheaper solution, is preferred.

However, reflectivity improvements are essential, and reflectivity may be improved by reducing the thickness of the front layer of the mirrors. In comparison with conventional flat mirror manufacturing techniques, cost and performance considerations may justify new manufacturing techniques to reduce the thickness.

Optimisation of the heliostat field layouts

Yearly average optical performances of heliostat fields in current large commercial CR plants are of the order of 55% to 60%. In those plants, the solar collection and concentrating systems are composed of one heliostat field and a single tower. There are other options that should be explored, such as the use of multiple smaller towers delivering the HTF to a central power block with storage.

Wireless heliostat control systems

In order to track the sun properly and to have an autonomous heliostat field, a two-way communication system between the central computer, the group control boxes and the individual heliostat control boxes must be continuously in operation. Some developments are under way to assess the feasibility of wireless connections between the heliostat individual control boxes, the group controllers and the central computer for this kind of autonomous power supply and a safe and effective control of the field.

The aim is to develop secure and reliable wireless heliostat control systems with a low overall cost.

Optimisation of heliostat technology

State-of-the-art in heliostat technology is represented by the so-called T-type heliostat configurations. The potential of different drive technologies as well as other orientations of the rotation axes that allow for improved performance and/or denser heliostat positioning should be explored.

7.1.3.2 Receiver

The receiver is the heart of CR plants and its design is strictly dependent on the chosen working fluid. Efficiency and durability are the essential concerns of each approach.

Advanced high temperature receivers

The CR technology can achieve high concentration ratios onto the receiver, usually one order of magnitude higher than PT collectors. The higher temperatures in the working fluid make higher conversion efficiencies and better overall performance possible. Handling high radiation fluxes at high temperatures is a very challenging issue, however, and further development is needed in new receiver concepts and materials. Among those new concepts, direct absorption receivers offer the potential to address the material challenges while making high efficiencies achievable.

New engineered materials for high temperature solar receivers

Research and development to improve the optical and mechanical performance and durability of materials is needed. Recent developments on designs show improved performance on metallic tube receivers through improvements in the optical and mechanical features of the coatings and of the Inconel based alloys.

Reaching outlet temperatures of 1,000°C or more can only be achieved by using ceramic materials either in studded tube designs or pressurised volumetric receivers. Headers and joining parts of the ceramic tubes are important challenges that need to be addressed.

7.1.3.3 Heat transfer fluids

Working fluids suitable for higher temperatures and radiation fluxes are to be selected.

Molten salt, others

New molten salt, liquid metals, air or CO_2 as well steam at higher temperatures and pressures have to be investigated.

Molten salt appears to be the short-term next step with working temperatures up to 620°C; these will make supercritical steam cycles possible. Ternary fluids rather than the current binary mixtures could provide a higher temperature range and lower costs.

Air and CO_2 allow for working temperatures above 1,000°C and they can be the primary fluids for solar combined cycles.

Direct superheated steam at supercritical conditions can be also considered for future power plants. The current tube panel must be correspondently adapted to overcome important mechanical and thermal issues.

Another promising option is particle receiver systems. These systems offer the potential for efficient operation at even higher temperatures. In this option, the heated particles also serve as the storage material.

7.1.3.4 New conversion cycles and systems

Current receiver operating conditions only allow for conventional Rankine cycles. Reaching more than 600°C in a supercritical steam turbines at a working pressure of 25 MPa could provide a significant increase in the conversion efficiency and, therefore, on the plant performance and cost.

Using air as primary coolant fluid in the receiver makes it possible to conceive a solar combined cycle and to increase considerably the conversion efficiency from thermal energy to electricity. Nevertheless, a combustion chamber between the air receiver and the turbine has to be designed in order to reach and maintain stable the optimal inlet conditions into the gas turbine.

In addition, new possibilities may appear in terms of hybridisation with biomass. With gasified biomass, for example, one can conceive a renewable combined cycle where biomass is used for the Brayton cycle (open cycle based on air or gas turbines reaching very high temperatures) while solar energy is used for the Rankine one (a closed cycle based on water/steam turbines, operating at lower temperatures than the Brayton cycle). Gasified biomass could also be used in a solar combined cycle with air receivers instead of natural gas, recovering the high temperatures from the Brayton cycle and enhancing the overall efficiency.

Advanced power cycles and thermal storage system integration schemes

Advanced power cycles and thermal storage integration schemes, such as combined cycles or supercritical steam cycles, offer great potential for performance improvements, and they must be explored.

Advanced hybridisation schemes with other renewable energy sources

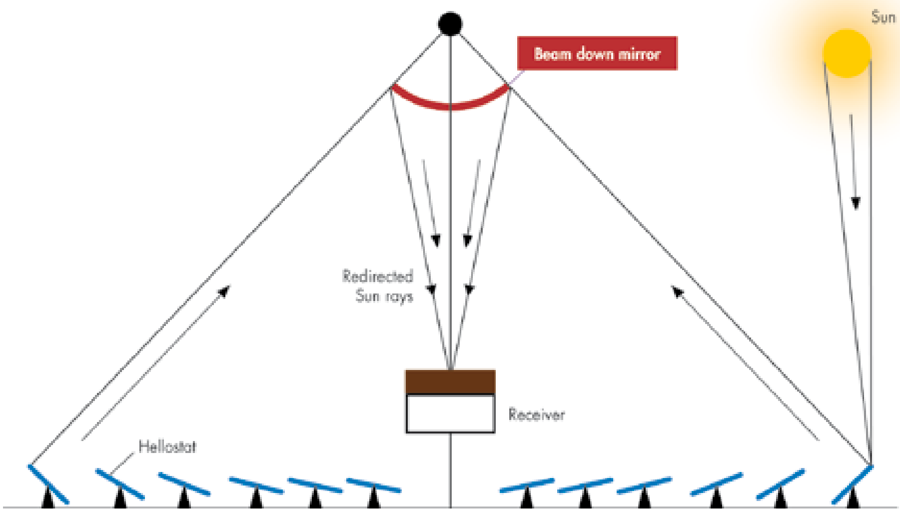
Advanced hybridisation schemes with other renewable energy sources such as integrated solar-biomass plants should to be explored.

Biomass boilers or HTF heaters can be easily integrated into the STE designs. Biomass can then function either as a backup of the solar energy when heating the HTF in different operational modes or as an alternative to the solar radiation producing or supplementing the suitable steam conditions for the turbine. Although this technology can be considered state-of-the-art, there is no STE plant using it yet. Therefore, applied research is also needed to optimise the integrated operation.

Secondary concentrators

Second stage concentrators for heliostat fields are meant to produce higher solar energy flux levels in comparison to those achieved at conventional solar furnaces. Higher concentration factors will permit higher operating temperatures; leading to higher thermodynamic conversion efficiencies or creating better conditions for other applications of concentrated solar energy (applications such as solar fuels production, thermo-chemistry at high temperatures, etc.).

FIGURE 14: Typical secondary concentrator redirecting the impinging sun rays from the heliostat field to a receiver placed at ground level



Second stage concentration can be achieved at the top of the tower, but can also be combined with other optical solutions such as the beam-down reflectors that redirect the impinging rays from the heliostat field onto a receiver placed at ground level.

For large heliostat fields, effective optical solutions are likely to require the use of a combination of second stage concentrators (multiple second stage configurations) facing different portions of the field.

For large flux levels, cooling of the secondary and/or tertiary mirrors is still an issue which requires further attention, in particular if the energy absorbed by the mirrors produces temperatures that may lead to their quick degradation or destruction.

Solar furnaces or cavities at ground level combined with beam-down solutions, are also different in their geometry and configuration from conventional furnaces at tower level, and, therefore, will constitute an important R&D topic by themselves.

The new Variable Geometry Central Receiver Test Facility at the CTAER premises in Tabernas, Almería. In the first phase, recently commissioned, the facility onsists of a field of 13 heliostats mounted on mobile supports and a tower with a rotating platform on top, equipped to host different types of receivers. The facility has been commissioned in October 2012

TABLE III: RESEARCH PRIORITIES FOR CENTRAL RECEIVERS

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Heliostat Field	Optimisation of the heliostat field layouts	• Explore advanced optical designs (bio-inspired, multi cavities or poli-towers)	**Parameter:** η_{Solth} **Target:** η_{SolTh} = 5%		X	
	Wireless heliostat control systems	• Development of a low overall cost, secure and reliable wireless heliostat control system • Wide use of wireless system before 2020	**Parameter:** €/m^2 **Target:** - 5%		X	
	Optimisation of heliostat technology	• Development of advanced structure and drive mechanisms	**Parameter:** €/m^2 **Target:** - 15%	X		
Receiver	Advanced high temperature receiver	• Improve the performance and durability of conventional pressurised tube receivers working with different fluids • Explore advanced CR designs (high efficiency and high temperature heat pipe, particles, and compressed gas receivers) • Explore solar receiver designs based on the use of new materials and of meta-materials with improved thermal and optical properties	**Parameter:** Outlet receiver temperature (T) in air pressurised modules **Target:** T = 1,000°C (For tubes < 8 m and volumetric modules < 50 m^2)		X	
	New engineered materials for high temperature solar receiver	• Increase tube coating absorptivity • Reduce time degradation effect • Increase mechanical characteristics and panel array designs to withstand higher fluxes at higher temperatures	**Parameter:** Max pressure radiation flux (p) **Target:** p = 1.5 MW/m^2	X		
Heat Transfer Fluids	Molten salt, others	• Increase of receiver outlet temperature with safe and stable conditions => increase plant performance	**Parameter:** Extended use of new fluids **Target:** Molten salt use with working temperature up to 620°C **Action:** Direct superheated steam at supercritical conditions in future power plants	X		
New conversion cycles and systems	Advanced power cycles and thermal storage system integration schemes	• Take advantage of the high temperatures that can be reached with tower systems by implementing the most appropriate cycles depending on the HTF used in the receiver	**Parameter:** η_{SolTh} Conversion efficiency with solar combined cycle **Target:** η_{SolTh} = + 25%			X
	Advanced hybridisation schemes with other renewable energy sources	• Use biomass in order to: - Increase dispatchability and firmness of STE plants - Reduce LCOE	**Parameter:** Plant robustness and reliability **Action:** Implement hybrid solar/biomass plants in a wide range of coverage	X		
			2013: Simple integration concept	X		
			2015: Hybrid plants using gasified biomass classical Rankine cycles		X	
			2020: Combined cycles using biomass for the air and solar energy for the steam LCOE = - 10%			X
	Secondary concentrators		**Parameter:** Breakthrough applications 2020: Implement larger installations (higher than 10 MW$_{th}$) for specific applications different than electricity generation		X	

7.1.4 Linear Fresnel Reflectors

It is important to place a strong emphasis on early development, demonstration and up-scaling projects designed to create the right opportunities for the Fresnel technology to follow its learning curve and reach a status of maturity where it can exhibit and prove its competitiveness. Reference demonstrations projects are major requirements for the bankability of a technology.

The state-of-the-art linear Fresnel technology on the market is a single or multiple tube receiver with a directly attributed mirror field (primary concentrators), where saturated steam is generated directly in the single or multiple-tube receiver at about 270°C. Other HTF such as thermal oils are also used. In some designs with single tube receivers there is a second stage concentrator, concentrating radiation from the primary concentrators onto the receiver. These different configurations still exhibit a low solar to electricity conversion efficiency (in the order of 8 to 9%) because of the low operation temperature and the simple turbine designs. It is important to modify the collectors to produce (directly or indirectly through another HTF) superheated direct steam at 450°C and about 120 bar. Then, with more sophisticated thermodynamic cycles using turbines for superheated steam, a very important and promising alternative for low-cost electricity production at higher efficiencies can be deployed.

In order to make the linear Fresnel technology bankable, it is necessary to:

- Demonstrate and validate new concepts and components, including control and operation strategies;
- Achieve linear Fresnel reflector systems with adapted storage concepts, including optimised charging and discharging operation and pressure-steam management;
- Ensure the stability of operation under fluctuating conditions;
- Design predictive control strategies for maximised useful solar gains, profit and minimised stress on plant components.

Efficiency improvement and cost reduction can come through a number of different developments at the level of the optical properties of materials, new materials and manufacture solutions, etc.

7.1.4.1 Mirrors

An important research target is the increase in optical efficiency for both design (at midday) and off-design conditions. The optical performance depends on the optical configuration. In the case of Fresnel optics there are designs that consider just a primary set of mirrors and there are others where both primary and second stage concentration are present. Optimised performance will result from changes in the size, shape and placement of the mirrors, and from the optical properties of all the materials used.

Second stage concentration and optical performance optimisation

Increasing concentration leads to higher temperatures and higher efficiencies. However, this should not be achieved by sacrificing the desirable high optical efficiency of the whole system. This implies that new designs require the joint optimisation of primary and secondary concentration stages that take into account the conservation of radiant power per area and solid angle (i.e. "etendue" conservation) at all stages of optical collection and transmission.

Solutions will be different for evacuated and non-evacuated tubular receivers, requiring specific designs and resulting in different final solutions.

Second stage concentrators can be designed for evacuated and for non-evacuated tubular receivers, and the design should minimise optical gap losses.

Primary mirrors performance and manufacture

Mirror performance is crucial and linear Fresnel mirrors are currently fabricated from flat (thin) glass mirrors, forced to be slightly curved to accommodate the proper primary performance requirements. Alternatively, thin films can be glued or applied over already slightly curved supporting surfaces. These techniques are not yet massively developed and there are many possible practical ways still to be explored. Shape accuracy is the key for mirrors with large distance to the focal line. Properties such as stiffness, torsion resistance and optical properties of the reflecting surfaces are very relevant to the optical performance.

7.1.4.2 Receivers

Receivers are an integral part of a receiver cavity. The performance of the linear Fresnel concentrator is very dependent on the thermal behaviour of the cavity, with or without second stage concentration. Receivers with the proper emissivity and absorptivity are required for operation at 500°C. The type of receiver, evacuated or non-evacuated, is determinant of the kind of R&D needed.

Evacuated tubular receivers

The best evacuated tubes for linear Fresnel technologies are not necessarily the same as the ones standardised for PT collectors. An important design issue is the cost-effective choice of the primary mirror width, the number of mirrors, the secondary concentrator design and the tube diameter. A cost-optimised configuration will probably need different tube diameters. Second stage concentration is also particularly sensitive because of the radiation loss in the gap between the tubes. The size advantage of LF collectors – i.e. the fact that very large primary mirrors can be considered – is lost when using evacuated tubes which were originally designed for smaller PT aperture widths.

Non-evacuated tubular receivers and receiver cavities

Non evacuated receiver cavities are presently being used in linear Fresnel technologies. However, going from 270°C, which is the current day practice, to more than 450°C or even 550°C requires a new generation of materials and materials combinations for the cavity tubes and coatings which will have to be studied, developed and demonstrated.

7.1.4.3 Heat transfer fluids

The research in HTF should address the issues arising from raising the temperature from 270°C, where wet steam can be produced, to about 500°C, for high-pressure superheated steam or about 560°C, for molten salt. Using steam, the thermodynamic efficiency of the power block can be vastly enhanced from around 25% to close to 40%.

Superheated direct steam production

The use of environmentally friendly water/steam as the working fluid is standard in linear Fresnel solar fields. However, superheating and control strategies have to be investigated more thoroughly.

Peculiarities due to the existence of a two-phase flow in the receiver tubes of the solar field evaporating section introduces some technical uncertainties that must be fully clarified. Although the technical feasibility of DSG (direct steam generation) in linear Fresnel collectors has already been proven, there are many aspects for optimisation that must be fully investigated to assess the commercial potential of DSG.

Molten salt

The use of molten salt as the working fluid in the solar field could replace the current oil/molten salt heat exchangers, reducing costs and increasing efficiency. If a lower melting point is complemented with good thermal stability at temperatures above 450°C, the improvement would be even more important because it would allow both higher power block efficiencies and a smaller size of the thermal storage system.

Pressurised CO_2 or air in non-evacuated receivers

The use of compressed air as HTF is an entirely new possibility and must be studied and demonstrated for the kind of extended tubular receivers which are applied in PT and linear Fresnel technologies.

7.1.4.4 Control and operation strategy

A general aim should be to minimise energy and hydraulic pressure loss in parallel loops and to increase the overall plant efficiency.

Particular focus should be laid on the tracking system.

Tracking options

LF and compact linear Fresnel reflectors (a multiple receiver configuration) with second stage concentration and new solutions that conserve the "etendue", can benefit from more sophisticated aiming strategies. A strategy may be based on tracking long rows individually; alternatively, it may be based on moving complete groups with one motor. In addition, the communication between the tracking motors and the control centre can be achieved in different ways.

7.1.4.5 Field design and configuration

Hybridisation of collector fields with different performance parameters

Tower and LF can be combined in order to boost operation temperatures. One possibility is to use LF for the phase change part of the heating cycle and the tower for superheating, with the goals of reducing cost and land use. Another possibility is the combination of a cheaper saturated steam linear Fresnel configuration with superheating linear Fresnel collectors.

TABLE IV: RESEARCH PRIORITIES FOR LINEAR FRESNEL REFLECTORS

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Mirrors	Second stage concentration and optical performance optimisation	• Increase concentration by use of second stage optics • Optimise simultaneously primary and secondary mirrors • Design of low-weight, modular and heat resistant cavity concepts	**Parameter:** Improve maintenance requirements and reliability **Target:** Lifetime = 20 years	X	X	
	Primary mirror performance and manufacture	• New materials and support constructions for primary mirrors • Increase optical efficiency (mirror width, accurate shape and high rigidity parameters) • Lower weight and reduce component costs	**Parameter:** €/m² **Target 1:** - 5%	X		
			Target 2: -10%		X	
Receivers	Evacuated tubular receivers	• New materials and coatings for non-evacuated and evacuated receivers (for T~500°C) • New production techniques and configurations (relation between the inner and the outer tube diameter)	**Parameter:** Temperature (T) **Target:** T = 500°C		X	
	Non-evacuated tubular receivers and receiver cavities	• Multiple tubular receivers arranged in different geometries and adapted to the second stage concentrators	**Parameter:** €/m **Target 1:** - 5%	X		
		• New materials and new selective coatings for high temperatures • Gas filled cavities and other convection suppression/reduction techniques • Insulation materials, connectors, bearings, cover, better adapted to the high operating temperatures • New materials for second stage mirrors capable of withstanding high temperatures resulting from energy absorption • Covers with low emissivity/anti-reflective coatings	**Target 2:** - 10%		X	
Heat transfer fluids	Superheated direct steam production	• Raise operating temperature for increased thermodynamic cycle efficiency conversion => LCOE reduction	**Parameter:** LCOE [€/kWh] **Target:** LCOE : - 10%	X		
	Molten salt	• New molten salt: - Freeze prevention /risk reduction - Other materials or system concepts - Cheap salt compositions • Raise operating temperature for increased thermodynamic cycle efficiency conversion • Reduce the cost and increase the efficiency of the thermal storage system • Reduce size of the thermal storage system • Proof concept in non-evacuated tubular receiver configurations • Proof concept in evacuated tubular receiver configurations • Proof freezing prevention measures	**Parameter:** verification of feasibility **Action:** Two levels of investigation: 1. experimental in a small solar test facility to prove the technical feasibility 2. O&M related issues using the new working fluid in a small plant (i.e. < 5 MWe) under real solar working conditions		X	
	Pressurised CO_2 or air in non-evacuated receivers	• Optimise the whole collector field for possible new concentration factor and receiver configuration • New heat extraction loop (pressure and temperature optimisation in view of better overall energy performance)	**Parameter:** Temperature (T) **Target:** ≥ 550°C		X	X
Control and operation strategy	Tracking options	• Most effective aiming strategies • Reduce costs with parasitic losses • Control communication strategies • Reduction of maintenance	**Parameter:** LCOE **Target:** LCOE: - 3%	X		
Field design and configuration	Hybridisation of collector fields with different performance parameters	• Check the cost reduction potential using different materials in temperature-specific collector field segments	**Parameter:** cost/m² **Target:** - 5%		X	

7.1.5 Parabolic Dishes

The most attractive features of the parabolic dish technology are:

- High efficiency in the conversion of solar radiation to electricity, derived from the ability to operate at high temperatures thanks to the high concentration ratios achievable ;
- Modularity and negligible requirement of water for engine cooling, when the power conversion system is based on Stirling engines or gas turbines.

The development of this technology has been very closely connected to Stirling engines. In fact, the highest record in the conversion of solar radiation to electricity has been achieved with a combination of a parabolic dish (PD) concentrator and a Stirling engine, a configuration commonly known as dish-Stirling system.

Dish-Stirling systems have attracted much attention due to their high efficiency, modularity, negligible water consumption and potential for mass-production of their major components. Playing against these positive features, there is the issue of dispatchability. The dispatchability of dish-Stirling systems is compromised by the fact that there is no proven thermal energy storage system which can be efficiently coupled to dish-Stirling systems: none of the most developed systems has been hybridised in an efficient way so far. In this context, dish-Stirling systems have to compete directly with PV in terms of investment and electricity generating costs, while their O&M is significantly more complex. Therefore, the future viability of this technology relies on the improvement of dispatchability by adding storage or hybridisation capabilities and/or significant cost reductions, reaching levels at least comparable to those of PV generation.

It does not seem realistic to expect great improvements in the peak efficiency of dish-Stirling systems in the near future. The development of the dish-Stirling technology during the last years has been mainly oriented towards the reduction of costs for both PD concentrator and Stirling engine and the improvement of the system reliability and availability. However, there is no large commercial plant in operation at this moment and there are serious concerns about the future of the most significant projects in Spain and the United States.

The efforts to reduce the costs of the different system components – mainly the parabolic concentrator and the Stirling engine – have been focused on the potential for mass production of these elements. In both cases, synergies with the car manufacturing industries have been identified and explored to different levels. Despite the fact that there has been significant progress, this has been insufficient to bring this technology to the market so far.

Another potential path of development of the PD technology is the combination of the PD concentrator with other power conversion systems, such as gas turbines [25,26,27] or steam engines [28].

According to the SETIS KPI document defined in 2010, the baseline yearly solar-to-electric efficiency for dish-Stirling systems is 17%. This figure reflects the relatively high downtime (unavailability) of these systems due to preventive or corrective maintenance. Therefore, the R&D efforts should be directed to the improvement of the availability of the system more than to the increase in efficiency itself. However, for mass-production components, there are some challenges related to the system efficiency.

The current total capital investment for a large dish-Stirling solar plant is likely in the range of 4 €/W.

7.1.5.1 Stirling engine

Although there has been some experience with gas turbines or steam engines in combination with PD concentrators, the Stirling engine is by far the most commonly used thermal engine with this type of concentrators. The characteristics of the Stirling engine make it extremely attractive for solar electricity generation. Some of these characteristics are the dependence on an external heat supply, high efficiency, silent performance and relatively well-known mechanics.

Two types of Stirling engines are being considered for STE: kinematic engines and free-piston engines. In the kinematic engines, the pistons are connected by a crank mechanism, whereas in the free-piston engines there is no mechanical linkage between the moving components and the displacer oscillates by resonance.

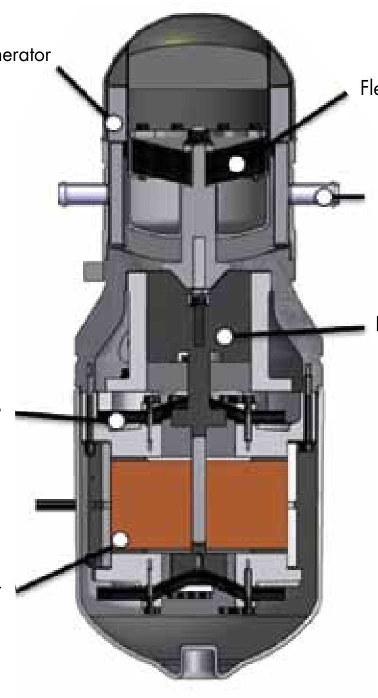
25- Source: Buck, R.; Heller, P.; Koch, H. Receiver development for a Dish-Brayton system. Proceedings of the ASME 1996 International Solar Energy Conference, 1996; p 91-96, 1996

26- Source: Bammert, K.; Seifert, P. Design and part-load behavior of a receiver for a solar-heated gas turbine with a parabolic dish collector. American Society of Mechanical Engineers (Paper), 1984

27- Source: www.swsolartech.com/pages/SolarTurbineEngine

28- Source: www.greencarcongress.com/2009/05/cyclone-renovalia-20090507.html

FIGURE 15: Free-piston Stirling generator[29]



Kinematic engines require complete isolation between the working gas (usually hydrogen, helium) and the lubricant of the drive mechanism. Due to the high operating pressure of Stirling engines, the seals have to be replaced regularly. Finally, engines operating with hydrogen are subject to leaks that make it necessary to recharge the hydrogen deposits after a certain number of operation hours, depending on the engine. As a result, maintenance requirements of kinematic Stirling engines are relatively high and expensive, and the operational availability of these engines is relatively low.

Free piston engines (Figure 15) used in solar applications have only two moving parts in a single cylinder and generate electricity by means of a linear generator. They are conceptually simpler and eliminate most of the problems associated to kinematic engines, including leaks of working fluid and replacement of rings and seals. They also exhibit excellent part-load performance and easy start-up. However, the complex control and the design of the linear generator need to be improved to achieve the expected performance.

Increase availability (increase MTBF: Mean Time between Failures)

A reduction of component failures and maintenance requirements for kinematic Stirling engines is essential for this technology. The use of new materials for rings and seals and the redesign of the engines to this purpose seem to be the best alternatives.

Reduce needs for H_2 refilling in kinematic engines

Hydrogen has a better thermodynamic performance as working fluid of the Stirling engine in comparison to helium. However, kinematic Stirling engines using hydrogen have suffered leakage problems to different degrees, making it necessary to refill the hydrogen reservoirs periodically in order to make sure that the required high operating pressures can be achieved. This requires the installation of refilling stations in most units as a short to medium term solution.

29- Source: Infinia

Optimise manufacturing

Stirling engines, especially the kinematic ones, have many similarities with the internal combustion engines used in transportation. Significant cost reduction can be achieved by redesigning the Stirling units to take advantage of mass production and the quality control and assurance techniques developed in the car manufacturing industry.

7.1.5.2 Gas turbines

The combination of gas turbines and PD concentrators is not new, but it became more attractive with the development of small and efficient gas turbines and the need to provide dispatchable power. In this respect, the integration of the gas turbine facilitates the hybridisation with natural gas or biogas or the combination of the dish-turbine system with compressed air energy storage (CAES) system.

7.1.5.3 Receivers

The low thermal inertia of the receivers of solar Stirling engines results in high ramp rates of the power output, especially during cloud passages. This low inertia makes it more difficult to control the system. This challenge can be addressed by replacing the currently used tubular receivers by reflux receivers of either the pool boiler or heat pipe types.

Increase thermal inertia (improve part-load operation)

Existing dish-Stirling engines exhibit a very fast reaction to solar radiation changes, due again to the very low thermal inertia of the receiver. This is a disadvantage from the point of view of integration in power grids.

7.1.5.4 Dispatchability

Dispatchability, based either on energy storage or hybridisation with other energy sources is a key factor for the success of the dish-Stirling technology. However, developing energy storage and hybridisation systems for PD is still at a very early stage and only a few pilot experiments[30] have been conducted so far.

Developing storage concept

Due to the geometrical and structural constraints of dish-Stirling systems, only small thermal energy storage can be integrated into present designs. Alternatives for larger energy storage systems are being explored. According to the AT Kearney report for ESTELA[31], "there are currently two alternatives being pursued to develop storage solutions for the dish-Stirling technology: these are the electro-mechanical and the thermal storage. Based on the stage of development of these alternatives, large commercial deployment of storage for the dish-Stirling technology can be expected between 2013 and 2016". At least one American company is considering the use of Compressed Air Energy Storage (CAES) as an alternative.

Infinia - SuperQuark

Developing hybrid receiver/heater units

Dispatchability can be achieved by integrating an alternative or secondary energy source such as natural gas or biomass. Ideally, this integration should be achieved in the receiver, to avoid duplicity of elements. Hybridisation would also ease the use of PD in stand-alone applications such as power generation for remote areas.

30- Source: Ramos, H.; Ordóñez, I.; Silva, M. An overview of hybrid receivers for solar applications. In: Proceedings Of SolarPACES 2010. The CSP Conference: Electricity, Fuels and Clean Water from Concentrated Solar Energy (Cd-Rom). Perpignan, France. 2010

31- Source: A.T.Kearney/ESTELA. Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production, June 2010

7.1.5.5 System components with enhanced material properties

The PD concentrator needs to be efficient (that is, it must have a high intercept factor and have the flux distribution matched to the receiver design) and economic, both from the points of view of manufacture and installation. Economy of scale can be achieved by exploring and exploiting the synergies with the car manufacturing industry, as some manufacturers have recently done both in the United States and in Europe. Efficiency relies on mirror reflectance, stiffness of the structure and tracking accuracy. The use of new reflective surfaces and new materials for the structure – including structural support for the reflective surface if necessary – may help to achieve these objectives.

Structure and tracking system

The PD concentrator is basically a paraboloidal reflective surface mounted on a structure that includes a two-axis tracking system. The reflective surface can be constructed in different ways and with different materials. As for the structure and tracking system, there are two basic mounting types: pedestal and carrousel. The present costs of the concentrator, including tracking, installation and adjustment, are above 2.5 €/W. The intercept factor varies widely between different designs, with values ranging between 85% and 95%. Concentrator cost should be reduced by at least 50% to make this technology competitive with PV.

7.1.5.6 Controls and operation issues

The operation of large PD farms requires power electronics and operating strategies to ease grid integration. The challenges are similar to those of wind farms, although they are less demanding and have particular characteristics. In the case of free-piston engines, the control of the linear generator is a major issue.

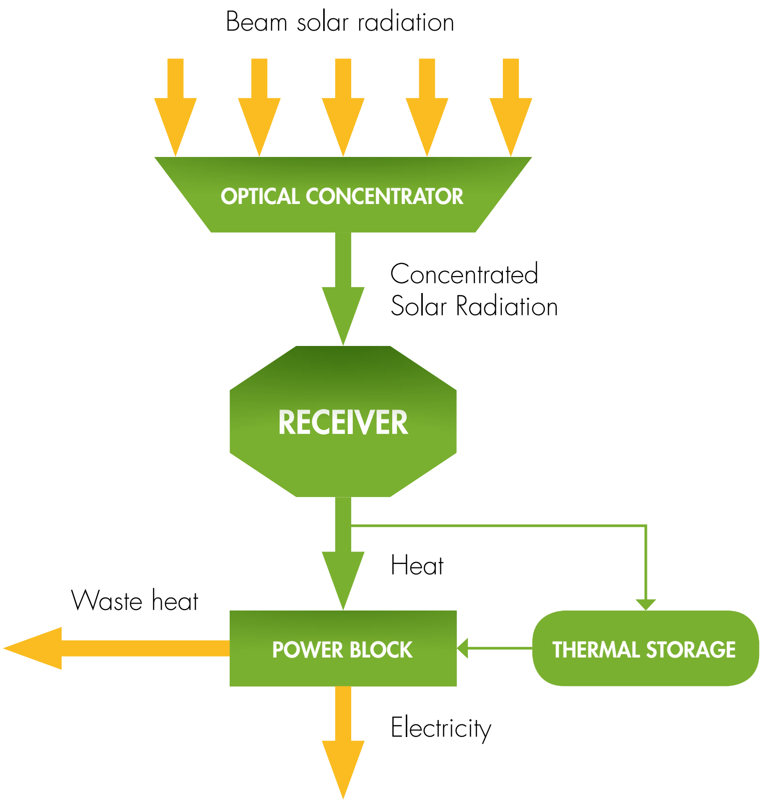
TABLE V: RESEARCH PRIORITIES FOR PARABOLIC DISHES

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Stirling engine	Increase availability (increase MTBF, reduce scheduled maintenance)	• Increase MTBF of essential engine components	**Parameter:** Kinematic engine operating hours [h] **Target:** 4,000 h	X		
	Reduce needs for H_2 refilling (kinematic engines)	• Reduce or eliminate hydrogen leakages by using the appropriate materials and components (valves, seals)	**Parameter:** Gas reposition rate **Target:** 0 or negligible	X		
	Optimise manufacturing	• Achieve a significant cost reduction via efficient mass production (know-how from car manufacturing industry)	**Parameter:** Stirling engine cost **Target:** 50% cost reduction		X	
Gas Turbines		• Ease hybridisation and energy storage	**Parameter:** Year of first commercial units **Target:** 2013 - 2014	X	X	
Receivers	Increase thermal inertia	• Increase operational stability and controllability by improving the thermal inertia of the receiver	Improve part-load operation	X	X	
Dispatch-ability	Developing storage concept	• Development of economic and efficient energy storage systems	At present, there is no thermal storage system commercially available for parabolic dishes		X	X
	Developing hybrid receiver/heater units	• Develop hybrid receivers able to operate both from the concentrated solar radiation and an alternative energy source (natural gas, biogas)	**Parameter:** Year of first operational prototype **Target:** 2015		X	X
System compo-nents with enhanced material properties	Structure and tracking system	• Develop lighter and more efficient structures • Optimise manufacturing by exploiting synergies with the car manufacturing industry • Ease on-field installation • Develop on-factory adjustment procedures that reduce or eliminate the need for on-field adjustment • Reduce the cost of tracking systems	**Parameter:** Concentrator cost **Target:** 30% cost reduction	X		
Controls and operating issues		• Develop the power electronics and controls required to ease the integration of a large number of units; • Develop efficient power electronics for free-piston engines	**Parameter:** Efficiency of power electronics for free-piston engine system **Target:** + 2%	X	X	

7.2 Objective 2: Improve dispatchability

A STE plant comprises four main sub-systems (Figure 16): concentrating system, heat transfer system, storage and/or supplementary firing (labelled 'thermal storage' in Figure 16) and power block. They are linked together by radiation transfer or fluid transport. The heat transfer system absorbs the concentrated solar energy and transfers the energy to the power block and/or into a hot storage tank.

FIGURE 16: Main components and sub-systems of a STE plant including storage



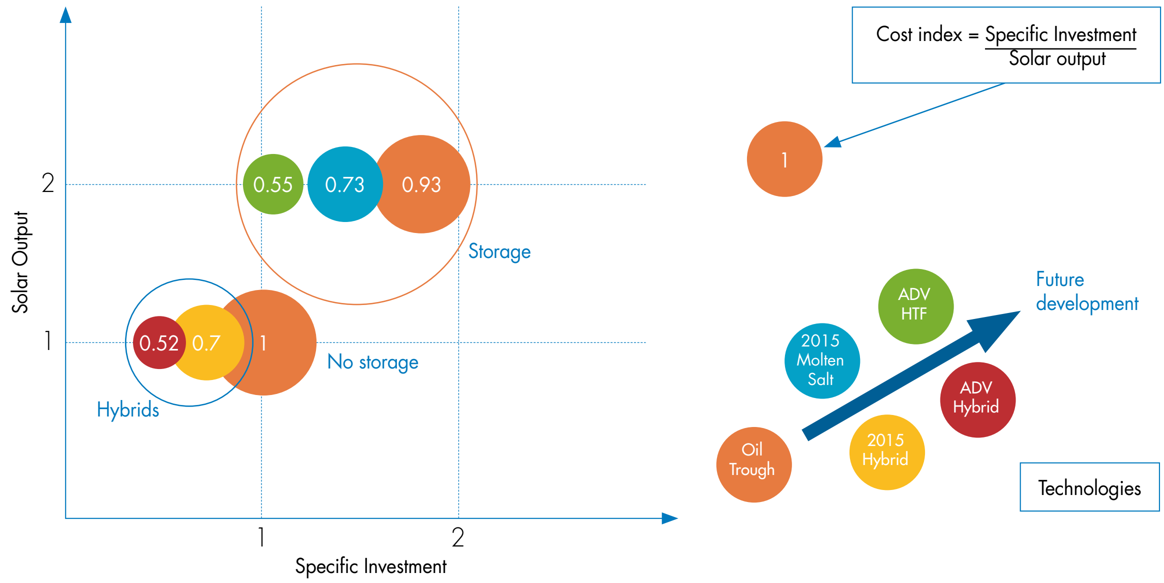
To illustrate the key drivers for the cost reduction for STE technology, a simplified cost model of a STE power plant can be used, evaluating the specific investment and annual energy output. The reference plant is supposed to be the present technology PT 50 MW plant without storage. The ratio of total investment to the annual output, which represents an important part of LCOE and can be named "cost index", is used as a simple figure of merit. Plants with storage are supposed to provide a substantial increase in energy output in comparison to a similar plant without storage. The solar field size is increased accordingly and additional storage losses are offset by adding suitable costs to over-size the solar field and HTF systems.

Estimates for the following plants have been made (Figure 17):

- Oil Through without storage
- Oil Trough with storage
- 2015 Salt HTF at 550°C
- 2015 Hybrid[32]
- Advanced HTF[33]
- Advanced Hybrid[34]

32- Hybrid system: Injection of heat from other sources (such as biomass, etc.) to the thermodynamic conversion cycle or to the HTF.
33- Advanced HTF system: Use of high temperature HTF, increasing overall efficiency.
34- Advanced hybrid system: Combination of a hybrid system with a high temperature HTF with increased performances due to technical improvements.

FIGURE 17: Comparison of today's state-of-the-art PT power plants with and without storage and targets for solar-only and hybrid concepts in 2015



An important lesson to be drawn from the illustrated results is the role that thermal energy storage plays on the expected electricity cost in the case of state-of-the-art PT technology using thermal oil and two-tank molten salt thermal energy storage. Systems with storage and oversized solar fields produce twice the energy of the reference plant, but do not require twice the investments because other parts of the plant, e.g. the power block, do not need to be scaled. Electricity from a system with storage is therefore less expensive than electricity from one without storage.

Concepts with storage are therefore particularly competitive for markets which assign extra value to **solar-only dispatchability**. There are key drivers that can further help to reduce the electricity costs while providing dispatchable electricity.

If the HTF is used also as storage medium and elevated temperatures are reached (which is not the case for state-of-the-art configurations), the specific cost of the storage can be significantly reduced because:

- only one fluid circuit is needed, instead of separate circuits for HTF and storage ;
- heat exchangers are not required ;
- more energy can be stored in the same volume because of the higher temperature achievable with the molten salt.

Furthermore, as the higher molten salt temperature also leads to higher power block efficiency, less solar collector field (and HTF circuit) is needed per kWe and the specific cost of these components could also be reduced. Both effects lead to a significantly improved output-to-investment ratio and a lower cost index, 0.73.

Further improvements can be achieved if advanced HTFs can be developed that allow for a wider temperature range. Higher subsystem efficiencies and advanced designs with lower manufacturing costs will greatly contribute to the cost reduction. The expected achievable cost index is 0.55.

It is very reasonable to consider that some markets, and in particular those where the demand is growing continuously, will target not only for dispatchable energy but also for **firm capacity**.

The hybridisation of STE power plants with fossil or biofuel is an attractive option for these markets. Hybrid plant concepts have some benefits that could help to reduce the overall system costs of the solar electricity that differs in part from those concepts that employ storage:

- Lower specific power plant costs due to more conventional plant design ;
- Lower specific field costs due to higher plant efficiency when operated at higher temperature ;
- Lower HTF system cost due to simpler and less expensive (HTF such as steam or gas).

Due to these factors, hybrid plant systems in 2015 could have a cost index as low as 0.7. Further improvements are expected, for example, through the change to advanced power cycles using gas turbine technology. Higher subsystem efficiency and advanced designs with lower manufacturing costs will contribute to an additional cost reduction with an expected cost index reaching 0.52, i.e. about one half of the present day reference plant.

7.2.1 Hybridisation and integration systems

7.2.1.1 Integration with large steam plants

Hybridisation can be performed by injecting solar heat at different temperature levels in the water preheating line or in the boiler water/steam circuits. Although integration with the boiler is more difficult because of the heavy interaction with the delicate equilibrium of heat transfer parameters inside the boiler, it should be preferred, as a higher conversion efficiency can be obtained through integration. However, even a lower-temperature application in the preheating line, which generally requires a lower cost solar collecting field such as one of LF, could result in a simpler and cheaper design of the cycle modifications and possibly a lower LCOE.

There are several design concepts for hybridising a solar power plant with fossil fuels (gas or coal) or biomass (solid or gasified).

The optimal design and the economic convenience of the application must be evaluated on the basis of global plant cost.

Independently of the design approach and solution adopted, an important aspect to be developed and studied in depth is the modification of the power plant control systems to accommodate the issues deriving from the variability of the solar source. For each application, the optimal operation of the hybridisation is the key for achieving the best cost effectiveness of the plant.

Large steam cycle plants are commonly used for base load operation or heavy intermediate load.

Positive effects on dispatching are expected from these systems because they make it possible to save fuel in the early morning hours, and this fuel can then be freely used in the evening peak hours to produce cheap energy at high market prices.

HTF/steam cycle heat exchangers

The different temperatures and pressure levels of the steam cycle boiler require a cleverly designed set of heat exchangers between the HTF (heat transfer fluid) and the water (or steam) of the thermal cycle, because the heat exchange must be balanced between different sections of the boiler to optimise temperature differences and heat transfer. The resulting solar heat-to-electricity conversion efficiency strongly depends on the design choices.

Boiler design

The coupling of solar heat exchangers to the steam cycle boiler can be built in different ways, providing various flow solutions (e.g. series or parallel), valve positioning, pump modifications and other options. The design and dimensioning depend on the specific steam cycle configuration chosen. The possible variations in short-term periods of solar collection can be handled by the control system only within the limitations arising from the practical boiler design and setup.

However, an optimised coupling between the HTF and the thermal cycle is required, and this is to be achieved through specific designs and experimental and demonstration installations that lead to full size applications.

Boiler control system

The combined operation of the solar steam generator and the steam cycle boiler requires a careful modification of the current boiler control system designs to enable them to maintain the stability of the power plant operation with varying solar radiation in the course of the day and year.

Therefore, modifications to the boiler control system must be made in order to handle the variations.

7.2.1.2 Integration with gas turbine and combined cycle plants

The most convenient way to improve stability is to interact with the steam bottoming cycle. In this case all the considerations made for the hybridisation with steam plants are applicable.

Higher temperature solar collectors, either PT or CR, can be effectively used to preheat air in the gas turbine at the compressor output, before the injection of the fuel. This will raise the temperature of the air, lowering the amount of fuel needed for the same output power. The result is a very high efficiency of the conversion of solar energy into electricity.

This application requires the development of compact, high temperature-to-air heat exchangers that are to be closely coupled to the gas turbine body or a pressurised air receiver technology. An adaptation of the gas turbine combustion systems due to the increased inlet temperature is necessary.

An intermediate and necessary step in research and development is the hybridisation with the gas turbine alone, intended to develop and optimise the heat exchanger and to test the operation of this critical component at a low power level. The result is a solar gas turbine hybrid plant with a solar heat–to-electricity conversion efficiency in the range of 35-39%. The final step will lead to a full combined cycle solar hybrid with solar heat-to-electricity conversion efficiency of above 50%.

A clever re-design of the control system is necessary to handle solar transients and to balance the operation of the gas turbine and the steam turbine under every possible working conditions of solar availability and load demand.

Design of HTF/steam cycle heat exchangers

The heat recovery steam generator of a combined cycle is a type of boiler which differs from what is normally used in steam only power plants. Depending on the design, two or three different water/steam circuits at different pressure levels are used. Consequently, the coupling with a solar heat generator must be optimised in order to get the maximum efficiency of solar heat-to-electricity conversion.

Materials for high temperature heat exchangers (such as ceramic or metal)

Integration of heat into the gas turbine section of a combined cycle requires exchanging heat at high temperature. Typically, the temperature of the output air from the compressor is around 350°C, while the turbine input temperature ranges from 1,100°C to 1,400°C. Compact heat exchangers require special materials and special compact design to allow for high efficiency and low thermal and fluid dynamic losses.

Overall system design optimisation

To achieve efficient coupling between the solar field and the combined cycle requires an effort to optimise the design, properly placing the heat exchangers and the various system components (pumps, valves etc.). Combined cycles with a heat recovery steam generator are often designed using two or three different pressure levels, and many features are studied and optimised to maximise the overall combined cycle efficiency. The addition of external heat has to be designed in such a way that it does not produce negative effects. Sizing of combined cycle components is also affected and different designs (1-on-1 or 1-on-2) can be effectively used to achieve the best solar hybrid system performance. The goal, of course, is to maximise the solar heat-to-electricity conversion efficiency.

7.2.1.3 Integration with biomass plants

The integration of solar energy with a biomass fuelled plant allows the building of an all-renewable resource which can operate all year long, taking advantage of the benefits deriving from the two different sources.

Forests and energy crops must be brought to the biomass plant from an extensive area of land, and this makes the fuelling and sitting of a very large size power plant difficult. The size is therefore normally limited to the range of a few MWe or even less. The conversion efficiency of such cycles is not very high because of the small size of the plant and the higher relative importance of cycle losses.

Combustion may be not easy because of the composition of the available biomass, and specially designed fire beds and boilers are needed which may have a lower boiler efficiency and a lower output steam temperature. Alternatively, biomass gasifiers can produce hot gas to be used in the boilers with reduced fouling problems.

Bio-gas or bio-oil obtained from appropriate processing plants (fomenters, digesters, pyrolysers, etc.) can also be used as fuels.

Some recent applications use organic fluid thermodynamic cycles (ORC), heated by burning the biomass, for energy conversion with low temperature working fluids (about 300°C).

The heat from different sources can also be integrated into TES (thermal energy storage) and this may have a beneficial effect on dispatchability.

Related research priorities are:

Integration of low cost solar fields with biomass steam boiler or ORC

The small size of available biomass plants and the relatively low temperatures of the conversion cycles make them well suited to host a low-cost solar hybridisation by means of low cost solar field, such as one using LF. The use of ORC, which is already applied in biomass fuelled applications as well as in solar plants, will simplify the operation while increasing the efficiency.

The research and development goal here is to design small size solar/biomass hybrid configurations to obtain an all-renewable power plant.

Molten salt PD development

The PD presently used in dish-Stirling systems can be effectively used to heat molten salt HTF to high temperatures, and these systems can be coupled with a biomass plant by means of heat exchangers.

7.2.1.4 Hybridisation for the direct systems using the same molten salt mixture as HTF and HSM (heat storage medium)

In the STE direct systems, where the same molten salts mixture is used as HTF and HSM, another option already explored (i.e. demonstrative FP7 projects MATS, OPTS and HYSOL) is to hybridise the system using a gas-fired molten salt heater placed in parallel with the solar field. The gas-fired heater enters in operation if the solar energy input decreases below a certain value. When it does, the molten salt circulating in the solar field is switched to the molten salt heater loop where it is heated to the operating temperature and flows into the TES (and/or the Steam Generator). This supplies all the back-up thermal energy necessary for a continuous operation.

In this way, the operation of the TES and the power block never suffers from variations of solar radiation and the dispatchability can be greatly improved. This option lowers the LCOE largely because the investment cost on the power block is shared over a large number of operation hours.

On an annual basis, the percentage of hybridisation of the dispatched electric energy depends on the size of TES and of the solar field relative to the rated power of the plant. Each component is selected by comparing yearly their impact on the LCOE from the different solar components, which depend on the investment costs and the solar radiation on the site. For the back-up component, the impact on the LCOE depends on the expenses for the integrative gaseous fuel.

The related research priorities are:

Gas-fired molten salt heater for the system back-up

The molten salt heater has to be designed carefully by suitable thermo-fluid dynamic and thermo-mechanical codes in order to use at best the characteristics of the molten salt, up to 550 °C, and to avoid hot spots in the tube bundle that could cause the decomposition of molten salt with development of gas. The combustion chamber shall be separated from the tube bundle, which will be flooded by exhaust gases at controlled temperature, without direct exposition to the flame. The discharge of flue gas at the outlet of a gas-turbine shall be also considered.

The sensible heat of the flue gases can be used for heating the molten salt down to the minimum temperature of operation of the solar field (e.g. 290 °C), and more or less down to 120 °C, for producing auxiliary steam for the power block or other heating services. Among the possible gaseous fuel, gasified biomass should be considered as main option.

Demonstrations at relevant scale close to commercial one are necessary.

TABLE VI: RESEARCH PRIORITIES FOR HYBRIDISATION AND INTEGRATION SYSTEMS

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Hybridisation with large steam plants	HTF/Steam cycle heat exchangers	• Increase solar heat-to-electricity conversion efficiency	**Parameter:** $\eta_{th\text{-}elec}$ (including heat exchangers)			
			Target 1: $\eta_{th\text{-}elec}$ > 40%		X	
			Target 2: $\eta_{th\text{-}elec}$ > 45%			X
	Boiler design	• New boiler design best suited to the coupling with external heat	**Parameter:** $\eta_{th\text{-}elec}$ (including heat exchangers)			
			Target 1: $\eta_{th\text{-}elec}$ > 40%		X	
			Target 2: $\eta_{th\text{-}elec}$ > 45%			X
			Action: Specific designs and experimental/ demo installation leading to full size applications			
	Boiler control system	• Obtain a set of control system algorithms and procedures to be inserted in the boiler control system to maintain the boiler fully operational with the highest performance and stability	**Parameter:** Availability of a validated set of control algorithms implemented into a hybrid plant boiler control system		X	X
Integration with gas turbine and combined cycle plants	Design of HTF/steam cycle heat exchangers		**Parameter:** $\eta_{th\text{-}elec}$ (including heat exchangers) **Target:** $\eta_{th\text{-}elec}$ > 40%	X		
	Materials for high temperature heat exchangers (such as ceramic, metal)	• Select and develop materials and designs suitable for high performance for gas turbine heat exchangers that can be applied in high temperature solar hybrid combined cycle	**Parameter:** $\eta_{th\text{-}elec}$ (including heat exchangers) **Target:** $\eta_{th\text{-}elec}$ > 45%	X		
	Overall system design optimisation	• Obtain a set of schematic system layouts related to hybrid solar plants to increase plant dispatchability and lower the LCOE	**Parameter:** $\eta_{th\text{-}elec}$ (including heat exchangers) **Target:** $\eta_{th\text{-}elec}$ > 55%			X
			Action 1: Construction of significant size demo plants 30 to 50 MWe (solar equivalent) with steam bottoming hybridisation	X		
			Action 2: 1 to 5 MWe (solar equivalent) with simple gas turbine hybridisation		X	
			Action 3: 30 to 50 MWe (solar equivalent) complete combined cycle hybridisation (gas turbine and in steam cycle)			X
Integration with biomass plants	Integration of low cost solar fields with biomass steam boiler or ORC	• Design of small size solar/biomass hybrid plants to obtain an all-renewable power plant	**Target:** Availability of one or more reference design for this type of plant **Action:** Construction of small size demo	X		
	Molten salt parabolic dishes development	• Design and test very small size solar/biomass hybrid plants	**Target:** Availability of one or more reference design for this type of plant **Action:** Construction of small size demo		X	
Hybridisation for the direct systems using the same molten salt mixture as HTF and HSM	Gas fired molten salt heater for the system back-up	• New MS heater design suited to couple with a back-up energy source supplied as gaseous fuel	**Parameter:** number of hours of operation in a year: N **Target 1:** N > 5,500 h/y	X		
			Target 2: N > 7,000 h/y		X	
	Overall system design Optimisation	• Design of the system aimed to control easily and to manage at the best the plant for the integration of the two energy with great benefit on the LCOE	**Target:** LCOE < 20% than only solar		X	

Overall system design optimisation

The design of the overall system should optimise the energetic contribution of the solar radiation and the back-up fuel. The solar field and the TES shall be sized according to the rated power and the solar radiation at the site. The MSH (molten salt heater) shall be sized so that it can provide the power necessary to integrate the system in the absence of solar radiation.

The MSH loop is placed in parallel with the solar field upstream of the TES so that it can compensate for any kind of fluctuations and avoid any influence on the operation of the power block. This facilitates easy control and makes it possible to manage the plant effectively. The integration of the two energy sources makes it possible to extend the hours of plant operation greatly, with great benefit on the LCOE.

Demonstrations at a scale large enough to approximate actual commercial plants are necessary.

7.2.2 Storage

Thermal energy storage (TES) systems are an integral part of a STE power plant. Due to the variety of STE concepts reflected by different HTF and operating temperatures, there is no single storage concept which could be applied to all STE plants.

The cost and performance of storage depends not only on the storage design, but is also affected by the integration of the storage system into the overall STE system. The value added by storage depends on the investments in the storage and its integration into a STE power plant but it also depends critically on the conditions from the grid, i.e. on how much the grid values dispatchability.

Today's reference for storage is an indirect two tank molten salt storage integrated into a PT power plant using thermal oil as HTF. The research targets are to reduce the investment costs of storage (See ANNEX I: Key Performance Indicators, 2010: 35,000 €/MWh_{th}; 2020 15,000 €/MWh_{th}), and to increase the efficiency of storage (ANNEX I: Key Performance Indicators: 2010: 94%; 2020: 96%). As today, it is not clear which of the different STE technologies (characterised by the different HTF) will finally be found to be the most effective, and it is necessary to follow up on several concepts in parallel.

The figures given above refer to the conventional PT design where the temperature difference between the cold and hot tanks is 100°C. CRs where the temperature difference is around 300°C could have lower values.

7.2.2.1 Storage design

To lower the storage cost and increase storage efficiency, the following priorities have been identified for the different systems:

Storage system for thermal oil as HTF

PT systems using thermal oil as HTF still constitute the majority of all installed STE systems. Two-tank molten salt storage systems coupled through a heat exchanger with the HTF circuit are state-of-the-art technology. In order to reduce the storage costs, two approaches are discussed below. The first idea is to limit the storage container to a single tank and the other is to use a low-cost solid material as an alternative storage medium.

- Single tank solutions
A single tank solution requires an optimised thermal storage design in order not to penalise the storage efficiency by mixing hot and cold storage fluid. For this purpose an excellent temperature stratification or separation between the hot and cold sections in the tank needs to be achieved.

- Solid media storage solutions
A thermal storage design that allows a separation of the heat exchanger material (which relates to power) and the storage material (which relates to capacity) must be developed to take advantage of low material costs.

Storage system for molten salt as HTF

Significant cost reduction can be achieved if molten salt is not only used as storage medium but also as HTF, because this avoids the use of two independent HTF circuits and of the heat exchanger system. If the temperature of the salt mixture can be further increased, higher cycle efficiencies are expected. Lower costs for the HTF system are achievable by choosing an HTF with a lower freezing point. Three different approaches are discussed below.

- New salt mixtures

As storage materials, new salt mixtures with lower freezing point and higher temperature stability are targeted. Screening of salt mixtures and evaluation of the physical and chemical properties of the most promising mixtures is required. In addition, longer term stability and corrosion tests need to be done.

- Storage container materials, inner liners, gas blankets

New salt mixtures operated at higher temperatures may result in corrosion problems. New materials, inner liners and gas blankets can potentially lower the overall material cost.

- Single tank solutions

A single tank solution requires an optimised thermal storage design in order not to penalise the storage efficiency by mixing hot and cold storage fluid. For this purpose, options that lead to an excellent temperature stratification or separation between the hot and cold sections in the tank need to be developed. The integration of the steam generator into the tank is possible, thus enhancing the capability of stratification and furthering the reduction of costs.

Storage system for steam as HTF

Steam as HTF is attractive as it can be directly used in the power block. However, steam storage concepts must take into account that water undergoes a phase change (at constant temperature) during evaporation. In this context, phase change materials (PCM), typically based on salt mixtures, can be used as storage media because they undergo a phase change in the required temperature range. The water may be preheated until it reaches the evaporation point and the resulting steam may be superheated with the heat from sensible heat storage which may be solid or liquid.

There are research activities in applications using saturated and superheated steam. Concepts based on solid/liquid PCM to heat saturated steam would make it possible to use steam as a single HTF in the STE system. This could provide certain advantages to PT and linear Fresnel systems.

Storage system for gas as HTF

Gases used as HTF have no practical limit for upper and lower temperature operation and are therefore considered of interest for very high temperature applications. Due to the low density and heat capacity of the gas, however, storage systems are based on solid or liquid storage media. A design for an effective heat transfer and the identification of suitable high temperature storage materials are major challenges.

- Heat transfer optimisation in storage concepts

The heat transfer in storage concepts based on gas to solid or gas to liquid has to be optimised.

- Low cost materials / particles as storages media

Low cost materials/particles as storage media suitable for packed bed or fluidised bed configurations have to be investigated.

7.2.2.2 Storage optimisation

Optimised charging and discharging strategies

Optimised charging and discharging strategies to maximise the storage capacity of existing storage designs should be based on a detailed dynamic modelling of existing storage configurations in order to optimise the future designs taking into account the complete system of the plant.

These strategies should be based on a detailed dynamic modelling of existing storage configurations.

Optimised multi-storage concepts

A combination of multiple storage tanks of different types and capacities may be used to achieve cost-effective optimisation, not only when using direct steam as HTF but also for other systems. Multiple storage can also be combined to achieve a better match of storage capacity to the operating temperature range.

7.2.2.3 New storage concepts

The advantage of storing solar energy in chemical form is that the storage time can be extended without further losses. The higher energy density achievable in chemicals, in comparison with storage in the form of sensible heat allows moving the stored energy to other locations. This offers a variety of benefits that clearly goes beyond the TES technology. However the development of the technology is still in an early phase and fundamental problems need to be resolved.

Thermo-chemical energy storage systems

Reversible chemical reactions based on non-toxic low-cost materials can be driven by high temperature STE. In systems based on such chemical storage, the heat is released when the reverse reaction takes place.

It is necessary to evaluate concepts that use chemical reactions as heat storage systems in engineering studies and to characterise the thermo-physical, kinetics, and stability of those materials in laboratory scale research that is already under way.

7.2.2.4 Storage as energy integrator

In order to identify the most reasonable markets for STE systems with storage, it is important to identify and quantify the value of energy, capacity and grid services in future energy scenarios.

Comprehensive electric grid models

There is a need to develop and update comprehensive electric grid models that allow estimates of the value of STE systems with storage for different scenarios of Europe's energy system until 2050. They are needed to predict the value of dispatchable electricity in a future energy system and to identify suitable markets for STE technology.

TABLE VII: RESEARCH PRIORITIES FOR STORAGE

		Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Storage design	Storage system for thermal oil as HTF	Single tank solutions	• Reduce the costs of storage and increase the storage efficiency and dispatchability	**Parameter:** Specific costs **Target:** 25€/kWh_{th}		X	
		Solid media storage solutions	• Reduce the costs of storage and increase the storage efficiency and dispatchability	**Parameter:** Specific costs **Target:** 25€/kWh_{th}		X	
	Storage system for molten salt as HTF	New salt mixtures	• Reduce the costs of storage and increase the dispatchability • Working at higher temperatures to increase the cycle efficiency of the plant • Increase solar to thermal efficiency using salt with lower freezing temperature due to lower overnight heat losses.	**Parameter:** Specific costs **Target:** 20€/kWh_{th}	X		
				Parameter: η_{thelec} **Target:** η_{thelec} = 42%	X		
				Parameter: η_{thelec} **Target:** η_{thelec} = +1%		X	
		Storage container materials / inner liners / gas blankets	• Reduce the costs of storage and increase the dispatchability	**Parameter:** Specific costs [€/kWh_{th}] **Target:** - 10% compared to high temperature alloy design		X	
		Single tank solutions	• Reduce the costs of storage and increase the storage efficiency and dispatchability	**Parameter:** Specific costs **Target:** 20€/kWh_{th}		X	
			• Decrease the thermal losses by integration of the steam generator into the tank	**Parameter:** η_{thelec} **Target:** η_{thelec} = +1%		X	
	Storage system for steam as HTF		• Minimise energy losses in heat transfer and reduce the cost of storage	**Parameter:** Specific costs **Target:** 25€/kWh_{th} (sensible heat systems) **Target:** 50€/kWh_{th} (latent heat, PCM) **Parameter:** $\eta_{Storage}$ **Target:** $\eta_{Storage}$ = 95%			X
	Storage system for gas as HTF	Heat transfer optimisation in storage concepts	• Increase the energy efficiency	**Parameter:** $\eta_{Storage}$ **Target:** $\eta_{Storage}$=95%	X		
		Low cost materials / particles as storages media	• Reduce the cost of storage and minimise energy losses	**Parameter:** storage and energy loss **Target 1:** 20€/kWh_{th} **Target 2:** 95%			X
Storage optimisation	Optimised charging and discharging strategies		• Maximise storage capacity of existing storage designs thus reducing specific storage cost (€/kWh)	**Parameter:** Specific costs [€/kWh_{th}] **Target:** - 10% compared to non optimised strategy	X		
	Optimised multi-storage concepts		• Minimise storage cost by effective combination of several individual storages depending on temperature level and capacity	**Parameter:** Specific costs [€/kWh_{th}] **Target:** - 10% compared to non-optimised combination for DSG	X		
New storage concepts	Thermo-chemical energy storage systems		• Increase the round trip storage efficiency (heat-to-heat)	**Parameter:** $\eta_{Storage}$ [%] **Target:** 90€/kWh_{th}			X
Storage as energy integrator	Comprehensive electric grid models		• Predict the value of dispatchable electricity in a future energy system	(No technical KPI of STE applicable here)			X

7.2.3 Forecasting tools

7.2.3.1 Operation strategy

Studies on the use of solar irradiance for very short term forecast

A major concern in the management of solar thermal power plant is the potential instabilities due to steep changes in the solar radiation along solar field area associated with the presence of scattered clouds and/or transients originated by cloud movements. This kind of sky conditions requires special plant operation strategies to accommodate the local solar radiation spatial variability and to reduce the thermal stress into the solar field.

An accurate very short-term forecast can increase plant profits by dispatching energy into the time periods of greatest value.

Electricity production forecasting system

A precise electricity forecast reduces the amount of backup power needed in network management.

Systems with storage facility can be operated more efficiently if the solar forecast is known, avoiding inefficiencies (for example, by first feeding the storage and running the power system at full load out of the storage).

The goal is to develop prototype software that integrates all forecasting, modelling and output generation for concentrating solar technologies.

7.2.3.2 Solar resource assessment

Before a STE project is undertaken, it is critically important to have the best possible information regarding the quality and reliability of the energy source. That is, project developers need to have reliable data on the solar resource available at specific locations, including historic trends with seasonal, daily, hourly, and (preferably) sub-hourly variability, in order to predict the daily and annual electricity output.

Improving DNI measurement ground base data network

Because site selection is always based on historic solar data and weather pattern changes from year-to-year, a maximum number of years of data are better for determining a representative annual data set.

Therefore, the radiation database based on a network of ground solar radiation sensors with extended geographical coverage of Southern Europe and other Mediterranean and North African regions has to be improved.

Deriving the global and beam irradiance components from meteorological satellite images

Models converting satellite images into the different radiation components are becoming increasingly accurate and they allow the access to a good number of statistics and physical models. More accuracy in the data could be obtained by comparing and validating the different models. This could be done by deriving the global and beam irradiance components from meteorological satellite images for different latitudes and altitudes in Europe, to obtaining reliable and accurate knowledge of the aerosol optical depth and of the beam irradiance for specific areas.

Both statistics and physics models are to be developed further.

DNI forecasting system

Solar power forecasting is the primary requirement for efficient integration of STE into power systems and for the reduction of grid integration costs. The electricity production forecast is driven mainly by the direct normal irradiance (DNI) forecast.

Two approaches must be followed to obtain reliable DNI data: the first one based on satellite images, which provides valuable forecasts for a time horizon of up to 6 hours and the second one based on numerical weather prediction models which provide valuable forecast for a time horizon of up to 72 hours.

This includes the analysis of the dependence on the forecasts reliability on the time horizon, season of the year and sky conditions.

Improved Numerical Weather Prediction (NWP) models for DNI forecasting

DNI forecasts are the primary requirement for efficient integration of STE plants into power systems. Numerical Weather Prediction (NWP) models are the only tools that provide DNI forecast with up to 72 hour time horizon.

Therefore, increasing the reliability of the DNI forecasts based on NWP models has a direct impact on the reduction of grid integration costs.

Analysis of the inter-annual variability of the DNI

Accurate resource evaluation is a key issue in the first stages of any renewable energy project. Particularly, as the life span of solar power plants is about 20 years, the economic feasibility study of such projects must take the inter-annual variability of the resource into account.

Therefore, analysis of the causes of the interannual/decadal variability of the DNI in regions of interest is crucial for a better predictability of the expected performance.

Analysis of the space-time correlation between solar energy (DNI) and wind energy resources

A major challenge for the future regarding renewable energy will be the integration of major wind and solar yields into the existing energy supply infrastructure, considering the fluctuation of these resources and their sensitivity to weather patterns.

One of the most promising ways to reduce the power fluctuation from solar and wind energy is to take advantage of the spatial variability of these resources. Since the spatial correlation of wind and (to a lesser extent) solar energy resources diminishes with distance, interconnection of wind and solar power in a region will reduce fluctuations in total production. This balancing effect becomes significant, provided that weather conditions across the interconnecting region are sufficiently variable and/or the terrain complexity is large.

Therefore, the analysis of the balancing between solar resources (DNI) and wind energy resources in key regions is an important issue for examination.

TABLE VIII: RESEARCH PRIORITIES FOR DISPATCHABILITY

	Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Optimised operation strategy	Studies on the use of solar irradiance for very short term forecast	• Reduce instabilities in the plants • Maximise revenues at the electricity stock exchange by selling the electricity preferably at high price times rather than at low price times	**Parameter:** MBE **Target:** < 5% **Parameter:** RMSE **Target:** < 10%	X		
	Electricity production forecasting system	• Develop a prototype software that integrates all forecasting, modelling and output generation for concentrating solar technologies	**Parameter:** Deviation from planned to production **Target:** - 5%	X		
Improved solar resource assessment	Improving DNI measurement-ground base data network	• Improve solar radiation database based on ground solar radiation sensors network with extended geographical coverage of Southern Europe and other Mediterranean and North African regions	**Parameter:** Solar resource data **Action:** Extend the current solar radiation network to areas of high interest with lack of data (Northern Africa) **Action:** Extend the length of the measured data period to about 10 years	X		
	Deriving the global and beam irradiance components from meteorological satellite images	• Validate and compare different products deriving the global and beam irradiance components from meteorological satellite images for different latitudes and altitudes in Europe. • Obtain reliable and accurate knowledge of the aerosol optical depth and the beam irradiance.	**Parameter:** Accuracy of the beam irradiance **Target:** < 10%, standard deviation = 20%	X		
	DNI forecasting system	• Maximise the economic potential of the participation at premium tariffs • Reduce the solar energy yield integration costs by accurate information on expected solar irradiance	**Parameter:** MBE **Target:** < 10% **Parameter:** RMSE **Target:** < 15%	X		
	Improved Numerical Weather Prediction (NWP) Models for DNI forecasting	• Increasing the reliability of the DNI forecasts based on NWP	**Parameter:** Forecast reliability **Action:** High spatial and temporal resolution DNI forecasts provided by reference NWP models as those of the ECMWF	X		
	Analysis of the interannual variability of the DNI	• Increase the current understanding on the causes of the interannual/decadal variability of the DNI in region of interest • Analyse the relative roles of clouds and aerosols in this variability • Obtain better estimates of the expected interannual/decadal variability in the output of solar power plants in the regions of interest	**Parameter:** DNI variability **Action:** Evaluation of the relative influence of aerosol and clouds on interannual variability of the DNI in key region		X	
	Analysis of the spatial-temporal balancing between solar energy (DNI) and wind energy resources	• Evaluate the spatial balancing between solar and wind energy resources in key regions • Determine if by interconnecting advantageously-distributed wind farms and STE plants, it may be possible to achieve reduced minimum output, eventually transforming the sum of the thermal energy and wind farm energy into a reliable supply	**Parameter:** Correlation between DNI and wind **Action:** Studies on combination of weather forecast and demand at a large regional scale		X	

7.3 Objective 3: Improve Environmental Profile

7.3.1 Heat transfer fluids

7.3.1.1 Heat transfer fluids vs. environment impact

The environmental components that could be affected by leaks or emissions of HTF (heat transfer fluid) are the soil, groundwater and surface water, air and human presence. As a reference situation, the case of synthetic oil as HTF is taken and compared to other possible HTFs which are expected to be friendlier to the environment.

PT, linear Fresnel and PD technologies depend on a widespread distribution of the receivers, that is, a wide distribution of tubes or motors in the solar fields and therefore a potential involvement of large tracts of land by possible HTF leakages. Understanding this serves as a cautionary warning that the use of HTFs may be hazardous to the environment. This aspect is less problematic for the limited area devoted to the TES and to the process equipment. In this case, a proofing surface may provide a solution.

Accidental leakages could occur during the circulation of the HTF in some parts not shielded by insulation, such as a CR. In this case the pressurised fluid is sprayed outside and, due to the height of the tower the area of dispersion could be large.

Synthetic oil

Nowadays PT plants in California and Spain exhibit some leakages of the synthetic oil used as HTF. There is also a prevailing HTF smell in the installations. Leakages have been more controlled by new interconnection elements (ball joints), while soil pollution can be recovered by bacteriological decontamination or by removing and substituting large amounts of ground. Where there are superficial ponds or shallow groundwater, the synthetic oil pollutes the soil and could pass very fast to the water, where it may be highly toxic. This fact suggests that oil should be avoided in the case of very vulnerable aquifers.

The research and development of the past years have led to various new systems that do not need any more the synthetic oil, but use water/steam directly as HTF, as in DSG (direct steam generation), gases or molten salt mixtures in direct/indirect systems. The choice of the HTF has various constraints besides the environment safeguard costs, such as their impact on the performance and efficiency of the plants. This implies a compromise in order to comply with safe solutions.

Advanced HTF solutions

Other options involve advanced HTFs, including:

- Pressurised gas, currently under testing, e.g. at the Plataforma Solar de Almería, Spain. Additional work is needed to improve heat transfers in the receiver tubes and to ensure control of the solar field, which is more complex than the reference oil design;
- Molten salt directly used in the solar collectors field thus simplifying the TES, because the HTF also serves as storage medium, e.g. in the Archimede demo plant, Italy. The used molten salt mixture, i.e. the less expensive "solar salt" nowadays used for TES, solidifies below 235°C; therefore auxiliary heating equipment and expenses are needed to protect the field against freezing. Other molten salt mixtures are under investigation to reduce the freezing point to as low as 100°C;
- Dense gas-particle suspensions: it is proposed to use dense gas-particle suspensions (approximately 50% of solid) in tubes as HTF. These tubes, set in a bundle, constitute the solar absorber (or receiver), placed at the top of a CR system. This new HTF behaves like a liquid with an extended working temperature range: it stays almost liquid at any temperature (there is no freezing temperature) and it permits to increase the working temperature up to 700°C and higher. Moreover, it may be used as an energy storage medium because of its good thermal capacity. It is composed of any particulate mineral that withstands high temperatures, thus reducing the environmental impact and addressing the safety concern in comparison with standard HTF;
- Adding nanoparticles to the above mentioned fluids, thus obtaining the so-called nanofluids, would greatly enhance physical and transport properties, implying a positive impact on the environment;
- Other attempts to reduce the melting point for molten salt mixtures through the use of special additives have to be considered to reduce the potential environment impact.

7.3.1.2 Heat transfer fluid characteristics

In the ANNEX III: Heat transfer fluids vs. environmental components, different HTFs are listed together with the impact of their characteristics on the possible environmental hazards. In Table 4, the various fluids are evaluated on the basis of a value scale ranging from 1 to 10 on the basis of their impact to the environment components and their technical and economic characteristics.

Among all the possible HTFs, only the most commonly employed and/or studied ones have been selected, together with some less investigated but very promising nanofluids, i.e. fluids containing nanoparticles:

- **Thermal oil:** Gilotherm, Therminol, etc;
- **Na, K (MS):** Nitrate binary mixture $NaNO_3/KNO_3$ 60:40 wt% (generally defined as "solar salt");
- **Li, Na, K (MS):** Nitrate ternary mixture containing lithium, at the "eutectic" composition: $NaNO_3/KNO_3/LiNO_3$ 18:53:30 wt%;
- **Ca, Na, K (MS):** Nitrate ternary mixture containing calcium, at the "eutectic" composition: $NaNO_3/KNO_3/Ca(NO_3)_2$ 15:42:42 wt %;
- **Hitech MS with nitrite:** Ternary mixture containing Nitrite (Coastal Hitech© salt): $NaNO_3/KNO_3/NaNO_2$ 7:53:40 wt%;
- **CO_2 and H_2O:** CO_2, air, steam;
- **Na, K (MS + nanoparticle):** Solar salt added with nanoparticles (carbon nanotubes, Al_2O_3, TiO_2);
- **CO_2 + nanoparticle:** CO_2, steam added with nanoparticles (Al_2O_3, TiO_2, CuO);
- **H_2O + nanoparticle:** Dense gas-particle suspensions of oxides or carbides, typical particle diameter, 50 μm.

TABLE 4: HTF and environmental parameters

HTFs / Parameters	Thermal oil	Na, K (MS)	Li, Na, K (MS)	Ca, Na, K (MS)	Hitech MS with nitrite	CO_2	H_2O	Na, K MS+ nanop	CO_2 + nanop	H_2O + nanop
Soil pollution	10	2	5	2	2	1	1	3	2	2
Water pollution	10	3	5	3	6	1	1	4	4	4
Air pollution	10	1	1	1	1	2	1	2	3	3
Toxicity to human presence	10	1	1	1	3	2	1	2	2	2
Cost	10	1	5	3	2	1	1	4	4	4
Freezing temperature	1	10	2	5	2	1	1	10	1	1
Cost of handling equipment and system	8	5	8	8	8	5	8	8	8	10
Upper thermal limit	10	2	2	6	6	1	1	3	2	2

The rating evaluations are assigned considering a value of 10 for the material presenting the worst level for the characteristic concerned, and assigning to the other HTFs a relative value respect to the maximum one (from 1 to 9), in particular:

- Soil, water, air pollution; toxicity for humans: thermal oils are the most potentially harmful material, and they are also flammable;
- Freezing temperature: the binary $NaNO_3/KNO_3$ 60:40 wt% exhibits the higher freezing point;
- HTF cost: thermal oils are the most expensive materials at the moment, however, the costs for nanomaterials particles, considering their preparation procedures, have to be more carefully established;
- Cost for handling equipment and systems: a system consisting of steam and nanoparticles is potentially the most expensive.

The choice to use normalised values allows a qualitative comparison of first approximation among the various HTFs, in order to define the most suitable one for a specific application. For a more precise and careful comparison it is necessary to have more data from laboratory experiments and demonstration projects.

Besides the aspects already considered, the complexity and the possibility of recovery from likely accidents, e.g. a sudden leak of HTF from a rupture of a flexible or rotating connection, have to be evaluated.

7.3.1.3 Leakage consequences

In absolute, the leaks of pure gases and steam are the least complex, presenting a momentary hazard around the point of dispersion of fluid at high pressure and high temperature. Once the discharge ends, no appreciable pollution should remain. However, if nanoparticles have been added to the liquid, the pollution may be very important, depending on their noxiousness. If the material is dispersed over a large area, no realistic possibility of remediation is achievable.

Similar leaks of molten salt, other than the momentary hazard during discharge, result in a spill of liquid that solidifies very fast on the ground, avoiding penetration of the soil. Once cooled, the solidified molten salt can be removed almost completely with mechanical tools, minimising soil impact. Only in the case of concurrent rain could the soil be polluted, as well as the groundwater, if the rain is abundant. This would be more severe for a more aggressive mixture such as molten salt with lithium. While Na and K nitrates are used in agriculture as fertilisers with a definite quantity square meter of treated soil, larger dispersed quantity of molten salt mixtures with higher impact could pollute vulnerable aquifers such as shallow groundwater or ponds.

Besides the aspects already considered, the complexity and the possibility of recovery from likely accidents, e.g. a sudden leak of HTF from a rupture of a flexible or rotating connection, has to be evaluated.

7.3.2 Reduction of water consumption

7.3.2.1 Improved cooling systems

Water consumption of traditional wet-cooling systems is very high and it is a significant barrier for the commercial deployment of this technology in arid areas with a lack of water resources and high solar radiation levels. Development of new approaches with water consumption lower than current wet-cooling systems and with similar cost and efficiency is a very important R&D topic.

Although dry-cooling systems are already available, their higher cost and lower efficiency often make them non-competitive. Two examples of possible approaches to lower the water needs of STE plants with PT collectors are the use of the so-called negative gradient in desert areas, where the air temperature at night is much lower than the temperature during sun-light hours, and the implementation of hybrid cooling systems that depend on wet-cooling for the summer and dry-cooling for the winter.

7.3.2.2 Desalination

Desalination is a vital necessity to many countries. This is why it has been highly developed during the last decade, with every indication that this activity will continue to grow in the near future.

Advantages:
Desalination needs a large amount of energy and requires the association of large plants with conventional power facilities. Therefore, the combination or integration of desalination into solar thermal power plants is a very interesting issue that can provide a significant technical and economic advantage for the following reasons:

- The typical geographic coincidence of water shortage and limitation problems with the existence of high levels of solar radiation, which normally make water issues a top priority for many sunny locations and forces the use of dry cooling instead of water cooling systems for solar thermal power plants when no water is available or severe restrictions prevail;
- The possibility to reduce or theoretically eliminate the conventional cooling requirements for solar power plants;
- The reduction of financial schemes based on the synergy effect between the two technologies, solar power and desalination, due to reduced overall investments by combining two normally separated plants into one and by obtaining higher revenues thanks to the production of two different goods: electricity and water.

Drawbacks:
However, this combined concept has also some drawbacks. One drawback is that the plants need large amounts of land close to the sea, while the DNI is normally lower in coastal areas.

It should be noted that the LCOE and the levelised water costs (LWC) normally increase as a consequence of the energy losses and the efficiency reduction at local level but the combined efficiency and the integrated economics could improve significantly. This may have a positive financial impact. Therefore, in these cases, indicators such as return of investment or present net value may be better parameters than the LCOE and the LWC, considered separately.

As a consequence, the main objective of research activities in the topic is to increase the combined efficiency and lower the combined costs.

Integration

Strategic goals and objectives pursued are the following:

- Optimising heat extraction in different STE technologies to be able to drive desalination processes;
- Reducing cooling requirements of solar power cycles without penalising the thermodynamic cycle and exergy efficiency;
- Optimising the energy and exergy of combined power and seawater desalination processes;
- Optimising desalination technologies for better matching solar power cycle conditions.

Multi-effect distillation (MED)

- Inlet temperature

Multi-effect distillation (MED) is, to date, the most thermodynamically efficient thermal desalination technology, with energy consumptions between 65 and 75 kWh_{th}/m^3 of desalted water (i.e. a consumption of 65 - 75 kWh of thermal energy per cubic meter of distilled water produced by the MED unit). Typical electricity consumption of MED plants is around 1.5 kWh_e/m^3.

The main interest in using this technique is that typical enthalpy values of the exhaust steam of the power turbine are close to the ones required by the conventional MED technology with the advantage that the latent heat of this steam is very high. Therefore, the total amount of energy normally rejected is huge, thus making the desalination process very attractive. As the MED plant would also be the cooler element of the power block, the typical cooling issues could be reduced or even eliminated.

- Thermo-compression

Typical MED plants associated with power facilities include thermo-compression devices to increase the efficiency of the water production. Thus, they heavily penalise the power production. As a consequence, the challenge is to develop improved MED concepts and specific technologies dealing with some key components so as to optimise, from the thermodynamic point of view, the overall combined efficiency when combined with solar thermoelectric plants.

- Tube bundles

Using nanotechnology for the tube bundle coatings can be an interesting option to achieve an effective heat transfer. It could also have a positive impact on costs.

Reverse osmosis (RO)

- Energy recovery

Reverse osmosis (RO) is the leading worldwide desalination technology today, due to its low energy consumption (from 3.0 to 4.5 kWh_e/m^3 depending on seawater conditions; even lower consumption is possible with brackish water) . This has resulted from significant advancements with membranes and energy recovery devices. As RO only uses electricity, the coupling with solar thermoelectric plants does not provide any particular synergy effects, as the desalination plant can be at a different location and therefore be considered like any other power consumption source.

- Mechanical energy

In addition, there are some interesting concepts that deserve to be explored. RO needs mechanical energy to reach the required pressure (around 70 bar), which can be provided by the solar steam cycle at a higher efficiency than conventional electrically driven pumps. In theory, this could avoid the inefficiencies (implying economic savings) due to the electricity conversion. The saved electricity can then be used to produce the additional mechanical energy necessary for the reverse osmosis process. This approach could also permit the exploration of other promising ideas related to the improvement of current energy recovery devices, thus increasing the overall efficiency.

Other desalination technologies

- Humidification-dehumidification (HDH)

The HDH is a desalination process where distillation is achieved under atmospheric conditions by an air loop saturated with steam. HDH is based on the principle of mass diffusion using dry air to evaporate saline water, thus humidifying the air. The humidification cycle is a combination of evaporator and condenser: the airflow is humidified in the former and dehumidified in the latter. Air circulates by natural or forced convection. Airflow extracts the steam from salt water. Sensible heat and freshwater is produced by condensing out the steam, which results in the dehumidification of the air. The condensation occurs in another exchanger in which salt water is preheated by latent heat recovery. Solar energy is externally provided to compensate for the sensible heat loss.

- Membrane distillation (MD)

Membrane Distillation (MD) is an evaporative process in which the steam, driven by a difference in steam pressure, permeates through a hydrophobic membrane, thus separating the water phase from the salt. Once the steam has passed through the membrane (pore diameter in the range of MF between 100 nm and 1 μm, with typical values around 0.3 μm) it can be extracted or directly condensed in the channel on the other side of the membrane. The separation effect of these membranes is based on the hydrophobicity of the polymer material constituting the membrane, as molecular water in the form of steam can pass through the membrane but not the liquid. However, this is true up to a certain limiting pressure, the liquid entry pressure, which, if exceeded, wets the membrane, thus losing its properties.

The research and development efforts in these technologies are of special interest with view to the adaptation of specific turbine exhaust steam conditions which limit or avoid any power production penalty at the power block.

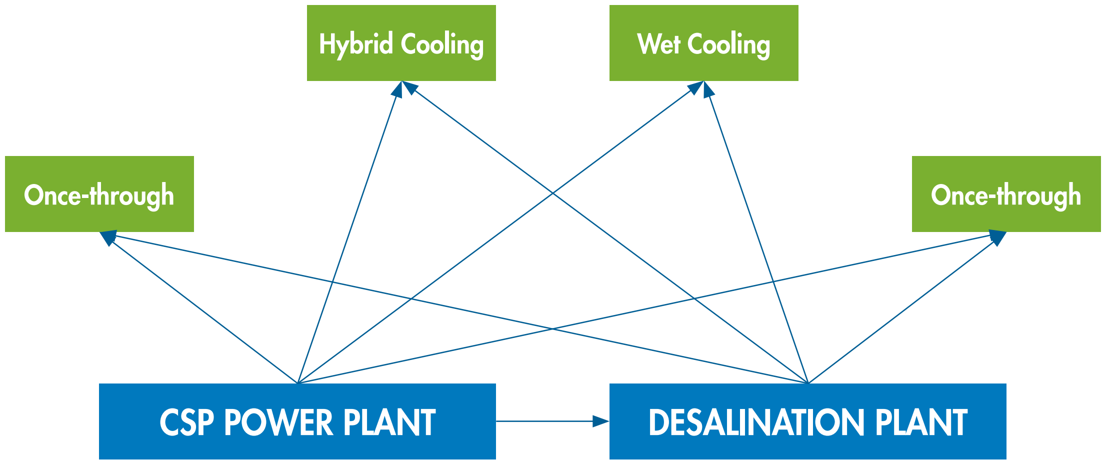
Cooling implications

- Thermo-electric plant cooling

Another research topic of interest to the coupling of solar thermal electricity and desalination is related to the implication that all these possible combinations and technologies could have over the cooling of the power block. The topic is of special interest as water is one of the major issues when solar plants are located in water scarcity areas, which are the most common locations in desert or semi-desert environments.

Considering that the desalination unit can be the "cooler" of the conventional power block and that most desalination technologies also needs cooling, another important area of research is the optimisation of the integrated or combined cooling process, which is summarised in the following figure.

FIGURE 18: Interactions and possible cooling options between solar thermal and desalination plants



7.3.2.3 Solutions for desert locations

Plants isolated in desert locations suffer from technical difficulties: the anti-soiling coating should not jeopardise the reflectivity of mirrors and should possibly enhance the transmissivity of cover glasses. The challenges can be alleviated by the reduction of soiling by surface coatings, the analysis of site specific dusting, the management of cleaning cycle and the development of cleaning technologies with low water use and with a high automation.

This topic has aspects that are shared with other technologies, but given the particular geometry of linear Fresnel primary mirrors; there is room for research and demonstration of solutions adapted to long almost-flat mirrors. Primary linear Fresnel mirrors can also be turned face down at night, reducing condensation problems associated with radiative cooling of the mirror surface at night.

35- The GOR (Gain Output Ratio) is the ratio between the amount of (latent) heat needed for the evaporation of the water produced and the input energy supplied to the system. The GOR is a measure of the amount of thermal energy consumed in a desalination process and therefore translates the efficiency of the process.

TABLE IX: RESEARCH PRIORITIES FOR ENVIRONMENTAL PROFILE

		Topics	Objectives	Parameter/Target/Action	Short	Mid	Long
Heat transfer fluids		Heat transfer fluids vs. environment impact	• Reduce the impact on the environment from emissions and accidental leaks of HTFs, maintaining a reasonable equilibrium with costs and efficiency	**Parameter:** Level of risk towards water and land (R) **Target:** R = Medium Assuming the regulation EC N° 1272/2008, and 91/155/CEE) ,the substance to be considered should be not classified as very toxic, toxic and harmful (Xn)		X	
		Heat transfer fluid characteristics	• Reduce the cost of the HTF and of equipment and system necessary for its handling with respect of oil	**Parameter:** Cost of equipment and system for HTF handling **Target 1:** 50% **Target 2:** 30%		X	
		Leakage consequences	• For the feasible new HTFs shall be issued procedures and devices for remediation of pollutant accidents	**Parameter:** cost of remediation (C) in the respect of actual one for the accident with oil leakage (e.g. full break of a metallic hose) **Target:** C < 40% **Action:** Any procedure of remediation will ensure the full restoration of the previous situation		X	
Improved cooling systems			• Lower the water consumption in order to achieve a better sustainability	**Parameter:** Power block water consumption per kWh of electricity produced kg/kWhe **Target 1:** < 2.5 kg/kWh$_e$	X		
				Target 2: < 2 kg/kWh$_e$		X	
Desalination	Integration	Mechanical energy	• Optimise the integration of MED desalination into thermoelectric solar power plants	**Parameter:** Power block investment **Target:** - 10% in the whole investment against the independent installation of equivalent solar power and desalination plants	X		
		Intermittent desalination system operation	• Optimise the intermittence of desalination plant operations to avoid any negative interaction with power cycle	**Parameter:** Time for start up of thermally driven desalination unit **Target:** < 1 hour		X	
	Multi-Effect Distillation (MED)	Inlet temperature	• Design innovative MED systems reducing inlet temperature to better matching with exhaust turbine steam	**Parameter:** Combined power and water production thermodynamic efficiency **Target:** + 5%		X	
		Thermo-compression	• Optimise the thermo-compression to the effective use of exhaust turbine steam to MED energy feeding	**Parameter:** Conventional cooling requirements of steam power cycle **Target:** at least - 50%	X		
		Tube bundles	• Increase the effective heat transfer surface by nanotechnology coating	**Parameter 1:** Costs of tube bundles materials and other metallic surfaces **Target 1:** - 30% **Parameter 2:** MED investment costs **Target 2:** - 10%		X	
	Reverse Osmosis (RO)	Energy recovery	• Integrate energy recovery into direct high pressure mechanical system => reduction of net mechanical energy supply needed	**Parameter:** Achievement of mechanical energy recovery **Target:** > 98%		X	
		Mechanical energy	• Use steam from turbine extraction to produce the mechanical energy needed by the high pressure RO pumps	**Parameter:** Direct pressure production (p) and exergy efficiencies (η) **Target:** p = 70 bar and η > 90%		X	
	Other desalination technologies	Humidification-Dehumidification (HDH)	• Develop adequate HDH technologies to the effective use of exhaust turbine steam	**Parameter 1:** Achievement of effective seawater desalination (GOR[32]) and associated inlet temperature (T) **Target 1:** GOR > 4 and T < 60°C **Parameter 2:** Power block normal cooling requirements **Target 2:** - 25%		X	
		Membrane Distillation (MD)	• Develop adequate MD technologies to the effective use of exhaust turbine steam	**Parameter 1:** Achievement of effective seawater desalination (GOR) and associated inlet temperature (T) **Target 1:** GOR > 4 and T < 60°C **Parameter 2:** Power block normal cooling requirements **Target 2:** - 25%		X	
	Cooling implications	Thermo-electric plant cooling	• Deduction of external active cooling needs	**Parameter:** Overall thermal energy removal from the integrated power and desalination plant **Target:** - 50%		X	
Solutions for desert locations			• Reduction of operation and maintenance cost	**Parameter:** Water requirements for washing **Target:** Reduction of typically 1,500 m^3/(MW*a) by a factor of 10 (90% reduction)		X	X

CONCLUSION

Barring an unthinkable catastrophe, the expansion of the world population will not abate in the near or medium term, and neither will the legitimate demands of that population for more energy to meet basic physical needs. To meet those needs at all, immediate challenges must be addressed, and few are as critical as the challenge to generate electricity reliably without adding to greenhouse gas emissions.

Fortunately, the solar source incident on Earth is more than enough to meet those needs in the near and medium term, if it can be converted with a reasonable efficiency and at a reasonable cost. Several options hold the promise to meet this need: thermal conversion (STE) and direct conversion (notably PV) are two of the most promising. It is likely that both of these options will have an important role as humans learn to address the challenges they face, but some characteristics of STE make this option of particular interest.

One of these characteristics is "dispatchability" – a properly designed STE plant can provide energy in the form of electricity when and if needed. The other very important characteristic is the efficiency of conversion of the solar resource. Thermodynamic limits can be very generous when the thermal source is one at very high temperature.

Great progress has been achieved in STE in a very short time frame with relatively modest government support, but past results give only a hint of what is possible with a longer learning curve and with a firm commitment from government and decision makers. Some of this commitment must take the form of support for R&D.

ESTELA has generated this document to identify, within each of the SET technologies those areas where R&D holds the most promise to further the shared goals to improve performance and lower costs. Some of the promised improvements may lead to incremental improvements by themselves. Together, they may lead to major breakthroughs and even to disruptive technologies.

A major advantage of STE is that there are many options that have been identified and that these options may serve different niches of energy generation. Two major technologies discussed in this report have been parabolic troughs and central receivers: both of these options led themselves to integration within a generating system with storage. The other two options discussed have been parabolic dishes and Fresnel lenses, which can meet the needs of high efficiency of conversion and very low cost, respectively. Improvements and areas of R&D have been identified for all options.

They have also been compared in terms of the potential for the alleviation of environmental impact, the development of local industry and the creation of jobs.

The variety of STE options also poses a challenge, because resources are finite and decisions on R&D resource allocation may unwittingly penalise disruptive options with a great potential. Even when considering financial incentives in support of the renewable industry, decisions may penalise some options. In addition to identifying the paths open for R&D for components, subsystems and systems, and areas where external support may be needed, this document has suggested possible tools to assist decision makers.

Important recommendations from this report are that support must be given to sustain demonstration projects for less mature technologies, as well as for R&D in components and systems to draw on an undeniable albeit short history of success to bridge the gap to a fully sustainable future. Another important recommendation is that some support must also be given to R&D in scientifically sound innovative STE options with the potential to successfully combate climate change, save the Earth and meet human energy needs for the foreseeable future.

BIBLIOGRAPHY

- ANEST. **CSP in Italy: 2012-2014 the age of accomplishments.** Presentation. Brussels, June 2012
- A.T.Kearney/ESTELA. **Solar Thermal Electricity 2025 - Clean electricity on demand: attractive STE cost stabilise energy production,** June 2010
- Deloitte/Protermosolar. **Macroeconomic impact of the Solar Thermal Electricity Industry in Spain,** October 2011
- EREC. **Mapping Renewable Energy Pathways towards 2020**. EU Roadmap. Brussels, March 2011
- ESFRI. **Strategy Report on Research Infrastructures**. Roadmap. 2010
- ESTELA. **Solar Thermal Electricity European Industrial Initiative (STE-EII) - Implementing Plan 2010-2012**. Brussels, May 2010
- ESTELA. **'Solar Power from Europe's Sunbelt', A European Solar Thermo-Electric Industry Initiative Contributing to the European Commission - 'Strategic Energy Technology Plan'**. Brussels, June 2009
- ESTELA. **The Essential Role of Solar Thermal Electricity - A real Opportunity for Europe**. Position Paper - Brussels, October 2012
- ESTELA. **The First 5 Years of ESTELA**. Brussels, February 2012
- ESTELA. **Workshop on Financing the SET-Plan**. Presentation. Brussels, June 2011
- European Academies Science Advisory Council. **Concentrating solar power: its potential contribution to a sustainable energy future**. EASAC policy report 16, November 2011
- GDF SUEZ Energy Iberia. **Portugal as a living lab for RES pilot project**. Presentation for the EU sustainable Energy Week. Brussels, June 2012
- IEA. **Technology Roadmap. Concentrated Solar Power**.Paris, 2010
- SETIS – EPIA – ESTELA. **Key Performance Indicators for the Solar Europe Industrial Initiative**. Version 1, Brussels, October 2011

INDEX FIGURES AND TABLES

ANNEXES

ANNEX I: KEY PERFORMANCE INDICATORS

ESTELA developed a set of KPI in order to follow the progress in innovation of the STE industry.

OVER-ARCHING KPI

Description	Metric		Values		
			BASELINE	TARGETS	
			2010	2015	2020/2025
Competitiveness	KPI-1	Levelised cost of electricity (c€/kWh) for a 50 MW plant located in southern Europe with a local DNI of 2,050 kWh/m².	22 c€/kWh	- 15%	- 45%

ACTIVITY KPIs

Description	Metric		BASELINE	TARGETS	
			2010	2015	2020/2025
1. Increase efficiency and reduce costs	KPI-2	Increased solar-to-electricity conversion efficiency	15% Trough 8.5% Fresnel 17% Dish 12.5% Tower	(relative to baseline) + 5% Trough + 15% Fresnel + 15% Dish + 50% Tower[36]	(relative to baseline) + 20% Trough + 30% Fresnel + 30% Dish + 65% Tower
	KPI-3	Increase HTF Temperature	400°C Trough 280°C Fresnel 650°C Dish 250°C Tower	560°C Tower 420°C Fresnel	> 500°C Trough 500°C Fresnel > 900°C Dish > 900°C Tower
	KPI-4	Reduce cost of installed products and O&M for state-of-the-art commercial plants	2% of CAPEX	- 10%	- 20%
	KPI-5	Reduce power block costs	1,300 €/kWp Trough with thermal oil	1,300 €/kWp Molten Salt as HTF 1,000 €/kWp Hybrid plant	1,200 €/kWp Advanced HTF 800 €/kWp Advanced hybrid plant
	KPI-6	Reduce collector costs	250 €/m² Trough with thermal oil	250 €/m² Molten Salt or hybrid plant	200 €/m² Advanced hybrid plant
	KPI-7	Reduce the specific cost of the HTF system	330 €/kW_{th} Trough with thermal oil	295 €/kW_{th} Molten Salt as HTF 165 €/kW_{th} Hybrid plant	120 €/kW_{th} Advanced HTF 100 €/kW_{th} Advanced hybrid plant
2. Improve dispatchability [Figures concerning storage are based only on molten salt technology]	KPI-8	Investment cost of storage	35,000 €/MWh_{th}	20,000 €/MWh_{th}	15,000 €/MWh_{th}
	KPI-9	Increase efficiency of storage	94%		96%
3. Improve the environmental profile	KPI-10	Substantial reduction of water consumption with only minor loss of performance relative to current water cooling system	3.5 liters/kWh		< 1 liter/kWh

At a first stage, a set of KPI has been elaborated for the STE Solar European Industrial Initiative (SEII) in order to ensure the monitoring of the SET-Plan Information System (SETIS). The KPI have been reviewed for the Strategic Research Agenda and some parameters have been included.

The levelised cost of electricity (LCOE) could be considered as the main indicator to monitor the overall progress of the SEII towards increased cost competitiveness.

The LCOE can be expressed by the following standard formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1 + r_t)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1 + r_t)^t}}$$

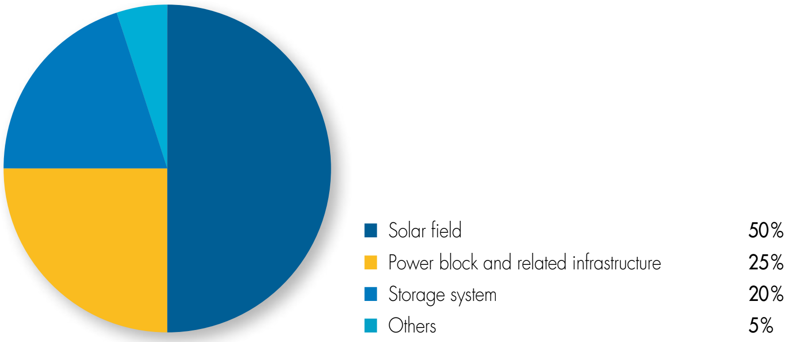
36- After Gemasolar breakthrough

Annex I

Where I_t, M_t and F_t are the expenditures on investments, maintenance and interests in year t, E_t is the electricity generated in year t, r_t is the cost of capital in year t and n is the life span of the plant in years.

It is essentially the result of dividing the present value of the costs by the present value of the energy produced. Each cost is converted into its present value, depending on the year in which this cost is incurred and the same happens to the electricity produced. Therefore, the way in which the capital is invested plays a very important role in determining the LCOE along with the O&M and financial costs.

The simplified cost breakdown structure of a 50 MW STE plant with 7.5 hours of storage is considered as follows:



This breakdown is used in order to calculate the impact of the cost reduction targets at subsystem level in the LCOE.

For the purpose of monitoring, at a first stage, reference STE plants and their respective LCOEs will be considered as 50 MW PT plant located in the South of Europe – DNI around 2,050 kWh/m². The reference plant assumptions for calculation of the LCOE KPI are indicated in this table for 2010:

CSP reference system	
DNI	2,050 kWh/m²
Total plant capacity	50 MW
Capital investment cost	300 M€
O&M costs (in percentage of investment costs)	2 %
Capacity factor	42 %
Cost of capital	9 %
Project lifetime	40 years
Baseline LCOE for 2010	22 c€/kWh

ANNEX II: PAST AND PRESENT EU-FUNDED PROJECTS

FP	Topic description	Projects	EC contribution (€)
	Demonstration Plants		
FP 5	PS10 First solar thermal tower plant	PS10	5.000.000
FP 5	Main CSP components for high-temperature operation	AndaSol	5.000.000
FP 5	Solar Tres solar thermal power plant with storage	SOLARTRES/GEMASOLAR	5.000.000
FP 7	Demonstration of innovative multi-purpose solar power plant	MATS	11.755.552
	Systems, Components and Storage		
FP 5	Direct Solar Steam generation	DISS	2.000.000
FP 5	Solar volumetric air receiver for commercial solar plants	SOLAIR	1.497.092
FP 6	Cost reduction for dish Stirling systems	EURODISH	750.000
FP 6	Energy storage for Direct Steam Solar power plants	DISTOR	2.228.917
FP 6	European CSP road-mapping	ECOSTAR	223.129
FP 7	Using CSP for water desalination	MED-CSD	999.960
FP 7	Improve the environmental profile of the CSP installations	SOLUGAS	5.997.752
FP 7	Using CSP for water desalination	DIGESPO	3.280.000
FP 7	Energy production by a combined solar thermionic-thermoelectric system	E2PHEST2US	1.980.000
FP 7	Dry-cooling methods for multi-MW sized concentrated solar power plants	MACCSOL	4.088.546
FP 7	Main CSP components for high-temperature operation	HITECO	3.440.194
FP 7	Thermochemical Energy Storage for Concentrated Solar Power Plants	TCSPOWER	2.850.000
FP 7	Advanced heat transfer fluids for CSP technology	CSP2	2.260.000
FP7	New system for thermal energy storage using molten salt	OPTS	8.650.000
	Solar Hybrid Plants		
FP 5	Solar hybrid gas turbine electric power system	SOLGATE	1.498.772
FP 5	Dish Stirling hybrid system	HYPHIRE	971.894
FP 5	Desalination and process heat collector	EUROTHROUGH	1.199.899
FP 6	Solar-Hybrid Power and Cogeneration plants	SOLHYCO	1.599.988
FP 7	Novel solar-assisted fuel-driven power system	SOLASYS	1.568.320
FP7	PT hybridised with biomass producing electricity and fresh water	ARCHETYPE SW550	14.385.217
FP7	Innovative configuration for a fully renewable hybrid CSP plant	HYSOL	6.168.484
	Solar Chemistry		
FP 5	Solar carbothermic production of zinc	SOLZINC	1.284.282
FP 5 / 6	Solar hydrogen via water splitting	HYDROSOL I and II	3.499.849
FP 6	Solar steam re-forming of methane-rich gas	SOLREF	2.100.000
FP 6	Hydrogen from solar thermal energy	SOLHYCARB	1.997.300
	Research Infrastructure		
FP 6	High flux solar facilities for Europe	SOLFACE	345.000
	TOTAL		**103.620.147**

ANNEX III: HEAT TRANSFER FLUIDS VS. ENVIRONMENTAL COMPONENTS

HTF	Melting (liquid) point	Risk for environment (according to regulation (EC) No 1272/2008, and 91/155/CEE)	Toxicity (according to regulation (EC) Nº 1272/2008, and 91/155/CEE)	Compatibility with air	Upper thermal point (°C)	Approximate cost, taking as unity the value for thermal oils
Nitrates containing mixtures	≈ 90°C - 235°C	• Water and land environment: low risk (medium if lithium is employed) • Oxidising agent • Very toxic for fishes • Lithium is extremely toxic for plants	• Relatively low acute oral toxicity • Causes serious eye irritation	Stable	≈ 600°C, ≈ 430°C if calcium is employed	From 1/7 (Na/K 60/40 wt% mixture) to 1/2 (if lithium is employed)
Nitrates and nitrites containing mixtures	≥ 142°C	• Water and land environment: medium risk • Oxidising agent • Very toxic to aquatic life, especially for algae	• Medium-high oral toxicity • Causes serious eye irritation	Possible oxidation	450 (under air) 538 (under nitrogen)	1/3
Thermal oils (biphenyl-diphenyl oxide mixtures, also terphenyl and phenantrene)	- 18°C - 12°C	• Water and land environment: high risk • Very toxic to aquatic life with long lasting effects • Marine pollutant • Very toxic for algae, fishes, crustaceans	• Harmful if inhaled • Causes eye burns, irritation to respiratory tract and skin • Contains material which can cause liver and nerve damage	Fire point: 127°C - 143°C Autoignition Temperature (ASTM D-2155) 585°C - 621°C	≤ 440 (under nitrogen pressure)	1
Gases/steam	Gas					1/10
Nanoparticles materials (nanoparticles additive to gases or liquids)	Ceramic nanoparticles: $Al2O_3$, TiO_2	Practically insoluble in water, can be considered ecologically safe.	Few data available, but probably low toxic effects.	Depends on nanoparticles and carrier fluid chemical nature. Ni nanoparticles is a flammable substance.	Risk of particles size growing at high temperatures	Depends on nanoparticles and carrier fluid chemical nature
	Metal oxides nanoparticles	CuO: Very toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment. SnO_2: No particular ecological problems expected.	CuO: Harmful for ingestion. SnO_2: If parenteral administered tin compounds are highly toxic.			
	Metallic nanoparticles: Ni	Harmful to aquatic organisms, may cause long-term adverse effects in the aquatic environment.	Danger of serious damage to health by prolonged exposure through inhalation. May cause sensitisation by skin contact			
	Carbon nanotubes	No particular ecological problems expected.	Causes serious eye irritation and respiratory tract irritation			

NOTES

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