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.

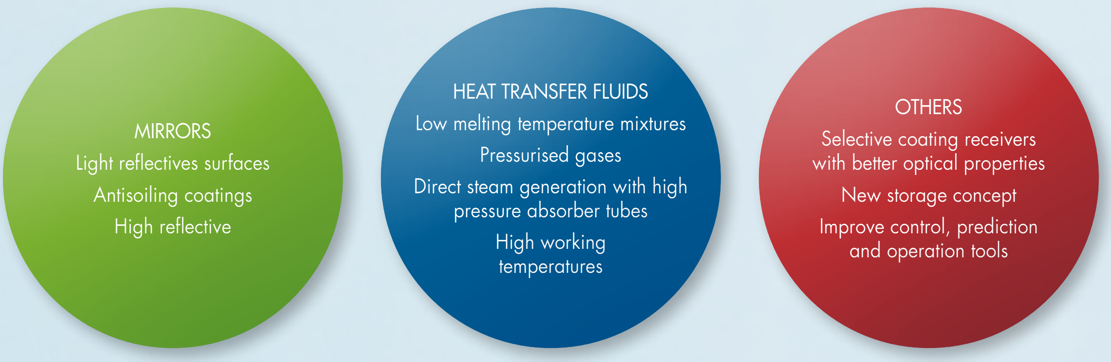
Standardisation:

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

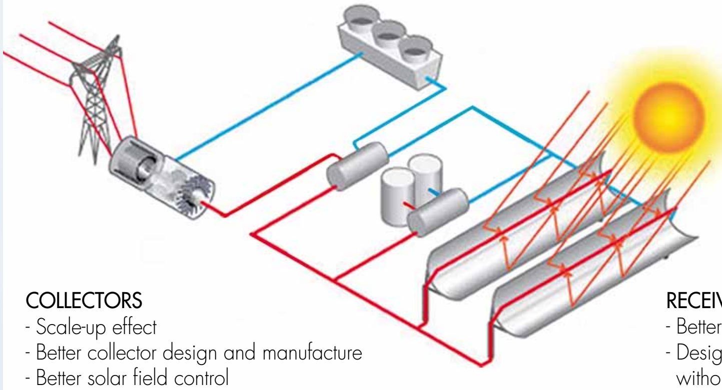
The different targets to reach the first objective ('Improve efficiency and reduce costs') are listed for each technology in the schemes on next page. However, cross-cutting issues exist between the different technologies and need to be taken into consideration. The transversal research topics to be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

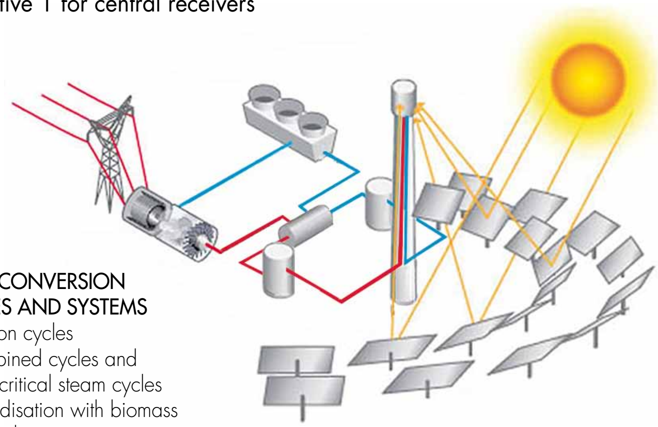
COLLECTORS
- Scale-up effect
- Better collector design and manufacture
- Better solar field control
- Autonomous drive units and local controls (wireless)

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

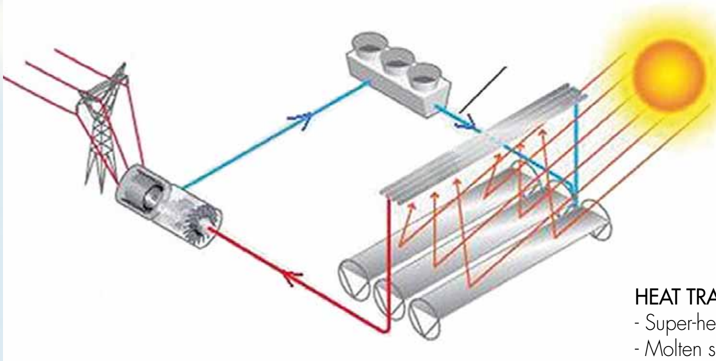
HELIOSTAT FIELD
- Multiple small towers configuration
- Reliable wireless heliostat control systems
- Optimised heliostat field
- Improve drive mechanisms
- Autonomous drive units and local controls (wireless)

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

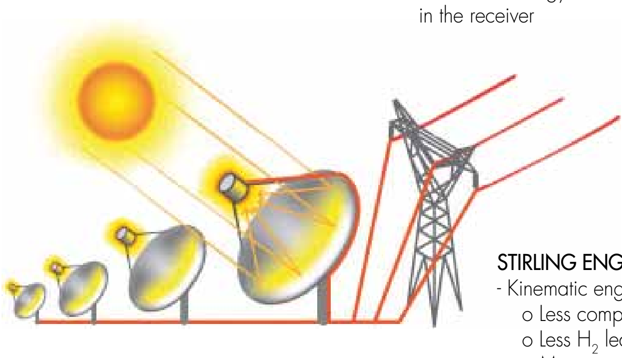
PARABOLIC DISHES

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

DISPATCHABILITY
- Electromechanical and thermal storage
- Alternative energy source (biomass) in the receiver

GAS TURBINES
- Hybridisation with natural gas or biogas
- Combination of dish turbine with CAES systems

RECEIVERS
- Reflux receivers against the lower thermal inertia



STIRLING ENGINE
- Kinematic engine
  - o Less component failures
  - o Less H_2 leakage
  - o Mass production
- Free piston engine
  - o Better control and design of linear generator

SYSTEM COMPONENTS
- Synergies with car manufacturing industry
- Improved tracking system

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.

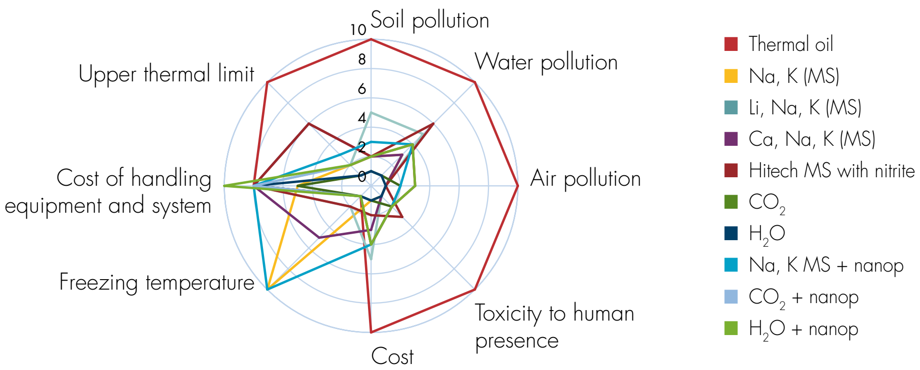
Improve forecasting:

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.