ATKEARNEY

ESTELA

Solar Thermal Electricity 2025

Clean electricity on demand: attractive STE cost stabilize energy production

June 2010

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Participating companies and interview partners in preparation of the STE industry roadmap were:

Research institutes:	CIEMAT, Plataforma Solar de Almería, CTAER, Universidad de Sevilla, CENER
Technology developers:	Abengoa Solar, Acciona, ACS Cobra, CNIM, Ferrostaal, Flagsol, SENER, Solar Reserve, Siemens, Tessera Solar, Solar Power Group, Novatec Biosol, Schlaich Bergermann und Partner, eSolar, Infinia, SkyFuel
Component manufacturers:	Archimedes Solar Energy, BASF, Cevital, Dow, Flabeg, Schott Solar, Senior Berghöfer, Siemens, Consorzio Solare XXI, SQM, RioGlass, Saint Gobain,
Plant developers:	Abengoa Solar, Acciona, ACS Cobra, CNIM, eSolar, Ferrostaal, SAMCA, Solar Millenium SolarReserve, Novatec Biosol
Utilities:	ENEL, ESB International, RWE, Veolia
Banks:	Deutsche Bank, Sarasin
Governmental institutions:	European Comission, European Parliament
International institutions:	International Energy Agency, The DESERTEC Foundation and Industrial Initiative
Industry associations:	ESTELA, ProtermoSolar

Definitions

Cost reduction potential – the study refers to project/plant costs in terms of CAPEX from the view of a project/plant developer. It includes project development, engineering and planning, technology procurement, construction costs based on current market prices. Cost considerations thus refer to component costs including sales margin from the manufacturer and EPC contractor.

Financing costs – were considered based on two different cost scenarios according to the maturity of different technologies. For Parabolic Trough with synthetic aromatic fluid a base case scenario was considered where financing duration has a period of 18 years, with a debt ratio of 70% and an interest rate of 7% p.a. For the remaining technologies, a conservative scenario with a financing period of 15 years, debt ratio of 70% and an interest rate of 8% p.a. was applied. For cost modelling purposes, from 2015 onwards, the conservative case was substituted by the base case, as commercial viability of all technologies was assumed.

Plant efficiency impact – was assessed as the net plant efficiency difference, i.e. the net plant output (excluding own consumption) for a given annual solar irradiation energy (considered as the direct normal irradiation of the sun in a given area multiplied by the aperture area of the solar field of a given plant) when using different technologies/components.

Commercial viability – refers to the period when a certain component/technology is available to be produced by a manufacturer and when independent developers would be willing to purchase/invest in that component/technology. Due to project development cycle, there is a time lag of 2 to 3 years between when a component/technology is considered commercially viable and its impact on cost and efficiency can be verified on the produced electricity.

Levelized Cost of Electricity (LCOE) – Total project CAPEX and plant efficiencies were gathered from different base plants provided by the study participants and were fed into a Levelized Cost of Electricity (LCOE) calculation based on 2010 real currency. LCOE is equivalent to the average price that would have to be paid to exactly repay the investors for capital, O&M and fuel cost with a rate of return equal to the discount rate (WACC[1]). Thus LCOE displays the minimum tariff at which energy must be sold for an energy project to break even excluding targeted Return on Equity (ROE). LCOE approach often used to help assess economic profitability of a planned electricity generation plant or to compare two or more alternative plant investment. Typically, LCOE is calculated over 20 to 40 year lifetimes and given in the units of currency per kilowatt hour, e.g. €c/kWh. For the evaluation of the STE cost position for the distinct purposes (support level requirements estimation and compassion with other RES), two different methodologies have been applied, named tariff and LCOE respectively:

Tariff – refers to the minimum required tariff that is necessary to ensure coverage of project financing, taking determined prerequisites into account (i.e. ensure a currently requested Debt Service Coverage Ratio (DSCR)[2] of 1.3 to 1.4 for banks and investors). This value indicates the target level for support, e.g. feed-in tariffs (FiT). Tariff is calculated with the LCOE methodology based on a 25 years plant runtime, which is equal to the proposed FiT runtime.

[1] *Calculated excluding tax impact – not relevant for technology comparison*
[2] *Factor by which the debt contracted to finance a STE Project has to be covered by the expected revenues of its operation*

LCOE – is applied to compare different technologies, e.g. STE against other RES. For this purpose, LCOE is calculated over the entire plant run-time, i.e. for STE plants 40 years. LCOE should not be used to drive implications on the level of support.

Reference plants – For LCOE/minimum required tariff calculations, CAPEX and plant's components costs were considered with reference to really operating plants, those under under construction respectively planned plants. Figure 1 describes considered base plants.

Figure 1: Considered base plants

	In Operation		Under Construction or in planning				
	Parabolic trough	**Parabolic trough**	**Parabolic trough**	**Solar tower**	**Solar tower**	**Dish Stirling**	**Linear Fresnel**
Capacity (megawatts)	50	50	50	50	17	50	30
Operating fluid	Synthetic aromatic fluid	Synthetic aromatic fluid	Molten salt	Superheated steam	Molten salt	Not available	Saturated steam
Aperture area (square meters)	300,000	500,000	554,000	480,000	307,000	172,000	110,000
Storage (hours)	0	7.5	12	5	15	0	0
Net efficiency (%)	13.5 – 14,0	13.5 – 14.0	15.5 – 16.0	16.0 – 17.0	16.0 - 17.0	20.0 - 23.7	10.5 – 11.0
Planned year of operation	2009	2009	2013	2013	2011	2012	2012

Note: Co-fueling has been excluded from analyses (in output, in CAPEX); solar tower with saturated steam is expected to be substituted by superheated steam and has been excluded from analyses.
Source: ESTELA project team; A.T. Kearney analysis

Executive summary

Solar Thermal Electricity (STE) comprises various technologies that convert **concentrated solar radiation into heat to produce electricity**. Mirrors focus direct solar radiation onto special receivers, in which fluids are heated up beyond 400°C. This heat is converted into mechanical energy by means of a thermodynamic cycle and then into electricity by the alternator.

After over 20 years of successful operations, STE is now entering a commercial ramp-up phase with several large scale projects ≥50MW around the world. Growth drivers for this energy source include increasing demand for Renewable Energy Sources (RES) complemented by its **unique value proposition** when **compared with other energy sources:**

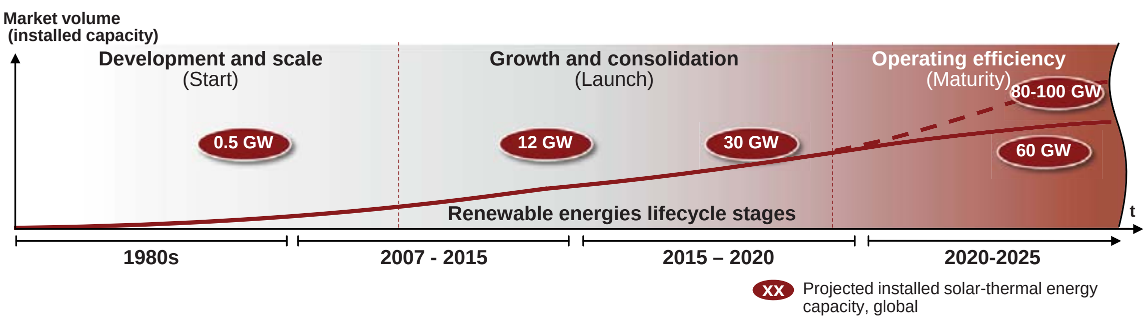
- **Predictability** and **reliability** of production
- **Dispatchability** due to proven and highly cost efficient storage and potential plant integrated back up firing
- **Grid stability** due to the inertial features of STE power blocks
- **Cost competitiveness** against other renewable energy sources
- **Large scale** deployment and **energy on demand**
- Long-term **supply security** and **independence from oil and gas prices**
- High share of **local content**

The present industry roadmap initiated by the European Solar Thermal Electricity Association (ESTELA) is based in a **collective effort to assess STE's competitiveness and** to create a common understanding within the industry about the current status and **expected evolution of the technologies**. Figure 2 provides a high level overview of the industry vision that supports this roadmap.

The **STE industry is committed to technological improvement initiatives**, focused on increasing plant efficiency and reducing

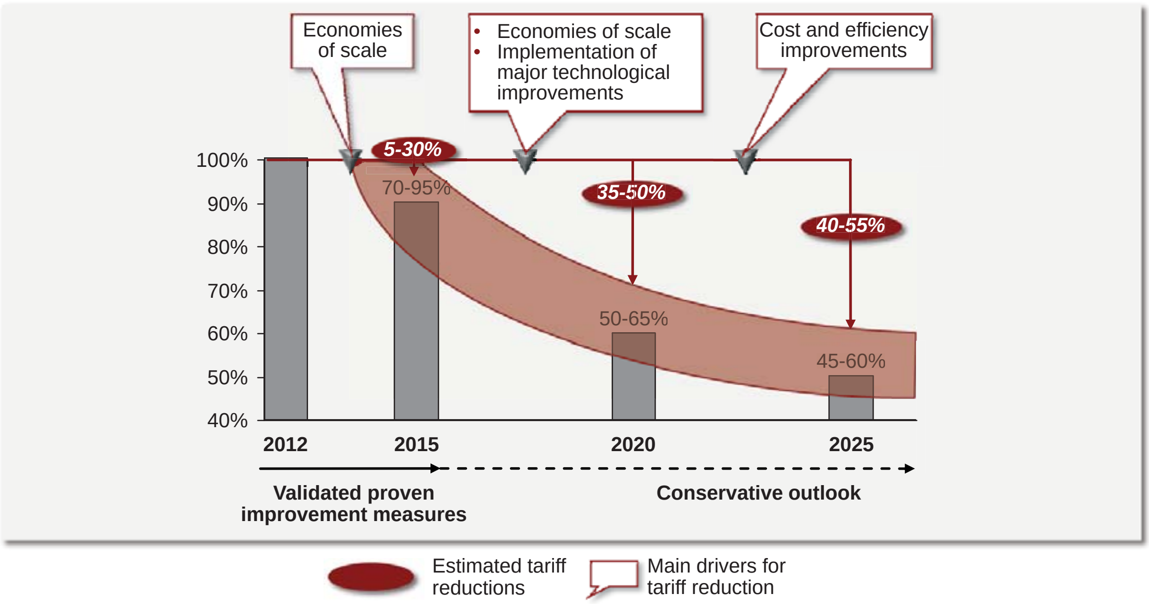
Figure 2: High-level STE industry roadmap

Pioneer phase	Commercial ramp-up	Major technology improvement	Large scale deployment
• Plant sizes 1 to 80 megawatts • Tariffs: greater than c€30	• Plant sizes 50 to 100 megawatts • Tariffs: c€27 to c€31	• Plant sizes 100 to 250 megawatts • Tariffs: c€10 to c€18	• Plant sizes greater than 250 megawatts • Tariffs: greater than c€10



Note: Tariffs are in euro cent per kilowatt hour, and equal to the minimum required tariff to ensure project break-even. Considers tariff decrease of 4.5 percent, with an increase of direct normal irradiance by 100 kilowatt hours per square meter area referent to Spanish base case
Source: ESTELA project team; A.T. Kearney analysis

Figure 3: Expected tariff reductions from 2012 to 2025



Notes: Tariffs equal the minimum required tariff, and are compared to 2012 tariffs
Source: A.T. Kearney analysis

deployment and operating costs. **By 2015**, when most of these improvements are expected 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 plant's size increase will also contribute to **reduce plants' CAPEX per MW installed up to 30%**. STE **deployment** in **locations with very high solar radiation**, such as the MENA region, **further contribute** to the achievement of **cost competitiveness** of this technology by **reducing costs of electricity up to 25%**.

All these factors can lead to **electricity generation cost savings up to 30% by 2015 and up to 50% by 2025, reaching competitive levels with conventional sources** (e.g. coal/gas with LCOE <10€c/kWh) *(see figure 3)*.

Additionally to the potential to substitute conventional sources, **STE can complement renewable energy sources portfolio as a peak to mid load provider.**

To achieve the targets pursued by the industry **it is essential that governments foster the deployment of STE** technology **by addressing** the following key energy and environmental policy **enablers:**

- **Creation and maintenance of energy policy mechanisms**, such as feed-in tariffs, and financial support schemes, such as R&D programmes, to mitigate initial investment risks and to encourage future investments and innovation
- **Revision of energy legislation** so that they do not **hinder adequate STE plant development** (e.g. limiting previously mentioned economies of scale)
- **Deployment of HVDC connections** to enable **large scale energy distribution from countries** with adequate resources for STE

to countries without enough renewable resources to fulfil the EU targets and from regions, where it can additionally leverage on **high solar irradiation** to further exploit its cost competitiveness, like MENA, to **countries with demand for green electricity** (e.g. Central Europe)

- Establishment of **national and cross-national cooperation mechanisms** for STE, which offer ideal opportunities for relationships between EU countries and from EU and MENA
- **Adjustment/establishment of market mechanisms to support the exchange of green electricity** in order to create further outlets for STE produced power

The **political conditions** addressing these topics **shall be adjusted to STE technology evolution to avoid over-subsidizing and ensure sustainability of efforts**. Sustainable support schemes must be flexible, both in the total amount of support and combination of the different elements, to reflect cost reductions and to provide the necessary effective support for the deployment of STE. Furthermore, incentives to foster an accelerated cost reduction should be put in place in order to reward more aggressive cost reduction. With such type of sustainable support schemes, governments can foster the development of this technology up to the point where it no longer needs them and can be a self-sustained energy source. According to industry expectations such situation can be achieved until 2020.

Implications of STE development further stress the political relevance of this technology. In fact, **STE can contribute to the accomplishment of climatic and environmental targets** (e.g. EU's 20/20/20). Also, for STE suitable countries, STE plants can **drive domestic economic development through local manufacturing, job creation and energy exports.** A best-case scenario of up to 100 gigawatts (GW) of global installed capacity in 2025 involves the potential creation of 100,000 to 130,000 new jobs as a result of the STE industry roadmap. Of these, 45,000 would be permanent full-time jobs in operation and maintenance. Finally, STE can contribute to **clean energy supply security and strong cross-country relationships.**

1. Introduction

Solar Thermal Electricity (STE) is a renewable energy source, which, after a demonstration period of 25 years since the first plant installations, is now entering a commercial ramp-up phase.

There are two main approaches to generate power from sun radiation. PV for instance, directly converts captured solar radiation intro electricity. STE technology is based on the principle that concentration of solar radiation – by using mirrors in a receiver developed for that purpose – enables heating-up fluids at high temperature, around 350-550 degrees with current technologies. The thermal energy can then be used to generate electricity through a proper cycle process and electrical generator system. Figure 4 breaks down STE systems into their main functionalities.

The adoption of the STE technology for power generation is driven by its unique value proposition: STE is a competitively priced, predictable, dispatchable, and reliable renewable energy source with a high share of local content. STE storage capabilities differentiate this technology from renewable sources like wind or PV. STE can store the heat produced when the sun is shining, to produce electricity when it is really needed. This allows a higher dispatchability of electricity production that is currently only available, at competitive costs, by conventional sources like coal or gas or other renewables with limited potential or high environmental impact such as hydro, biomass and geothermal. Furthermore, STE offers these advantages without conventional sources drawbacks like CO_2 emissions and requirement of fossil fuels.

The present document synthesizes the collective effort of the STE industry, to derive an industry roadmap. The study was initiated by the European Solar Thermal Electricity Association, ESTELA, with the objective to assess STE's competitiveness and to create a common understanding within the industry about the current status of the technology. It is meant to provide the basis for a dialogue with stakeholders in the energy sector, in particular between politicians, utilities and the STE industry.

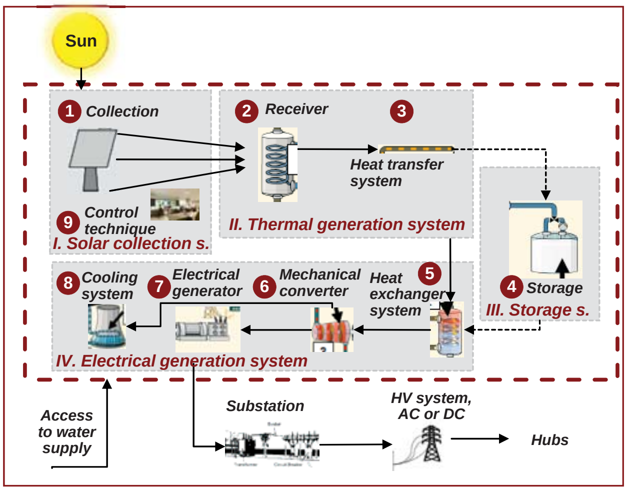
2. STE industry vision and positioning

2.1 Key milestones of STE

Already at the end of the 1970s, Sandia National Labs, in partnership with SERI, launched projects to develop a technology that would allow electricity production from sun radiation. At the same time similar initiatives were launched on Europe, like the SSPS projects and the CESA 1 in Almeria (Spain), the EURELIOS in Italy, the THEMIS in France and Nio in Japan. The inherent principle of this technology was that concentrated solar radiation could reach temperatures high enough to heat fluids. Subsequently, the first STE power plants were built in the Mojave Desert. Unfortunately, the industry came to an early stop when the sole private company developing the technology at that time went bankrupt, due to a sudden stop of political and financial support. Figure 5 shows the key milestones of the development of this technology since its establishment.

Only in very recent years, increasing global electricity needs, shortage in fossil fuels and awareness of global warming have once more made STE an attractive energy source. The STE industry has started to grow. Yet, it will still need substantial government support to establish itself as a self-sustainable energy and industry segment by 2020.

Figure 4: The nine steps of STE



1. **Receive and concentrate** solar radiation with minimum dissipation possible, ensuring maximum stability and sun exposure. Includes mirrors, support structure and tracking system
2. **Absorb** concentrated solar radiation and convert it into thermal energy
3. **Conduct** thermal energy from collectors to power block. Includes interconnection and piping structure and heat-transfer fluid
4. **Store** energy (for example thermal or electrical energy) through a storage medium (such as molten salt, flywheel or batteries) for delayed use
5. **Transmit** heat from one heat transfer medium to another (for example, using a steam generator)
6. **Transform** thermal energy into mechanical energy
7. **Convert** mechanical energy into electricity
8. **Reduce** temperature and condense working fluid
9. **Control** STE system function

Source: A.T. Kearney analysis

Figure 5: Key STE historical milestones

Period	Key milestones
1970's	▪ Research efforts for the development of STE technology
1980's	▪ In 1981 the two SSPS projects of the IEA were connected to the grid ▪ Other projects like Solar 1 in Barstow California, CESA 1 in Almeria Spain, THEMIS in France, EURELIOS in Italy and Nio in Japan were connected in the early 80's ▪ In 1984, the first commercial plant for parabolic troughs started operating – SEGS I (14MW) ▪ Continued research efforts for alternative STE technologies (solar tower, dish Stirling and linear Fresnel)
1990's	▪ By 1990, 9 SEGS plants have been deployed with a total capacity of 354 MW ▪ In 1991, the sole developer of the parabolic trough technology went bankrupt which drastically slowed down STE technology development ▪ During the 90's two pilot molten salt solar towers were deployed – Solar One and Solar Two ▪ In 1998, the first roadmap for parabolic trough technology was developed
2000-2005	▪ In 2004, construction of the first 150kW Dish Stirling pilot plant at Sandia Labs deployment of pilot molten salt solar towers – Solar One and Solar Two ▪ Also in 2004, Spanish legislation considerably improved the incentives for the first 200MW of STE, fostering the development of this technology ▪ Launch of Solar PACES by IEA contributed to greater awareness of STE technology
2006-2010	▪ Creation of FiT mechanisms in several European Union countries further contributed to foster the deployment of this technology ▪ In 2007, deployment of the first commercial solar tower plant (PS10 with 10 MW) and the large Nevada Solar One (60MW) parabolic trough plant marked the beginning of STE's commercial ramp-up stage ▪ In 2008, Andasol I plant was commissioned (50MW) proving commercial viability of thermal storage system for STE technologies; also in that year, the first Fresnel thermal power plant, Kimberlina, was installed (15MW) ▪ In 2009, the deployment of further plants in Spain like the PS20 20MW (Solar tower), Puertollano, Andasol II, La Risca, all three parabolic trough 50 MW and PE1(1,4 MW Linear Fresnel), and the Sierra Sun Tower of 5 MW in the USA, enabled STE technology to reach close to 600MW ▪ So far in 2010, 12 additional 50 MW STE plants have been either put into operation or will be shortly commissioned in Spain, and a commercial scale Dish Stirling power plant has been deployed in the USA (Maricopa, 5MW)

Following project development pipelines and announcements by utilities, STE is expected to have deployed more than 1GW of installed capacity worldwide by the end of 2010. Looking at the current project pipeline (2.5 GW already authorized in Spain), significant growth can be expected until 2015 leading to the deployment of more than 11GW *(see figure 6)*.

2.2 STE value proposition and target positioning within generation mix

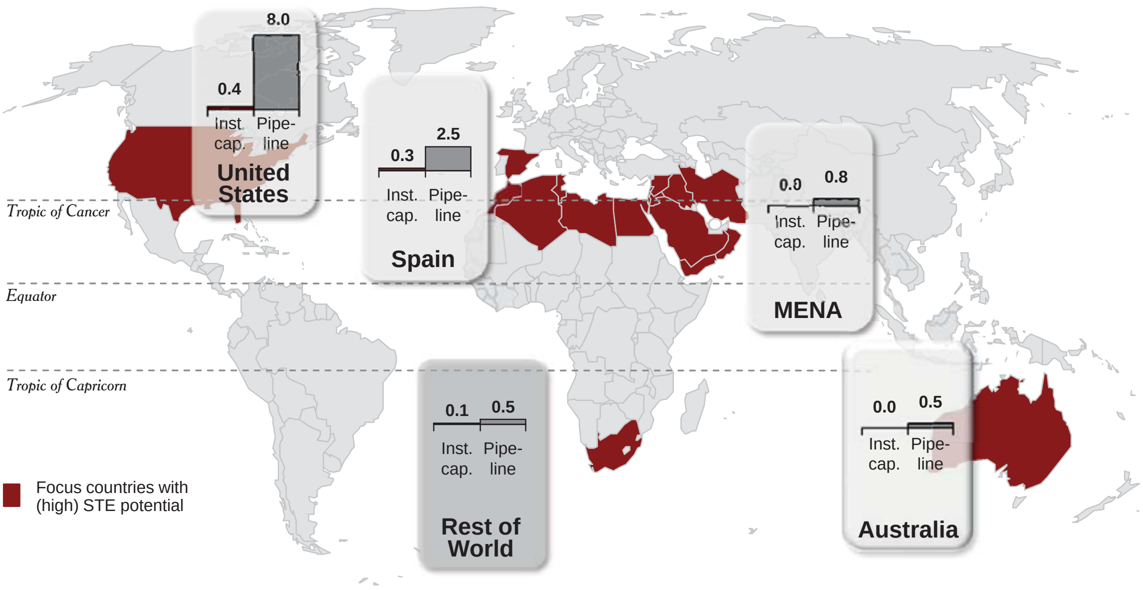
Due to its technical characteristics, STE offers a unique value proposition:

- Predictability and reliability of production
- Dispatchability due to proven and highly cost efficient storage and potential plant integrated back up firing
- Grid stability due to the inertial features of STE power blocks
- Cost competitiveness compared to other RES
- Large scale deployment and energy on demand
- Long-term supply security and independence from oil and gas prices
- High share of local content

Operational characteristics of STE plants enable thermal energy storage. For high-capacity applications, thermal storage is technologically proven and much feasible cheaper than electrical storage, which makes STE a highly cost efficient technology. As energy can be stored, electricity can be produced on demand and dispatched to the distribution network when it is needed and not only when resources are available. Because of this, STE differentiates itself from renewable energy sources like wind or PV.

Locations with high solar irradiation and large plants sizes pose significant levers for STE competitiveness. Considering ideal conditions for STE deployment (e.g. >250MW plant in Chile

Figure 6: Existing and planned STE capacity through 2015



Note: Totals are for gross weight. MENA stands for Middle East and North Africa.
Source: Interviews with industry experts; A.T. Kearney analysis; NREL

under ideal conditions) cost of electricity (LCOE) could already today reach the 13-15c€/kWh range. This already shows STE's cost competitiveness compared with other renewables. Considering expected improvements, STE's LCOE could be below 10c€/kWh by 2025, as further discussed in this document.

Another distinct characteristic of STE is that construction and operation of STE plants require a significant amount of labour force and components that can be locally manufactured. Thus, STE offers an opportunity to explore endogenous natural energy resources while employing local labour.

STE has a significant long-term edge over conventional energy sources and complements the renewable energy sources portfolio with a dispatchable and predictable energy source. STE can fill the gaps left by other renewables which can only intermittently generate electricity. In the short and midterm, STE is suitable as a peak and mid load provider. In hybrid configurations, and with the technical evolution suggested by the present roadmap, STE can contribute significantly to the progressive replacement of conventional and fossil fuel generation by a flexible "beyond base load" of mix of renewables with STE occupying a strong position.

Although STE's technological improvements present a significant opportunity for improving economies of STE projects, cost evolutions are not solely dependent on technology. Uncertainty of future projects and business instability both lead developers and manufacturers to temporarily inflate their prices in order to manage the risk of their investment. As such, demand currently plays a key role in respect of the cost of electricity from this technology. Government support that fosters the deployment of this technology is of utmost importance for the STE industry.

As an up-side for government support, the STE value proposition can be directly related to today's economical and political developments:

- STE has proven commercial viability as technologies are becoming mature and cost competitive
- Greenhouse gas emission reduction targets drive demand for CO_2-neutral energy supply
- STE can contribute significantly to achieve EU targets to source 20% of energy from renewable energy sources in 2020

2.3 The STE industry vision

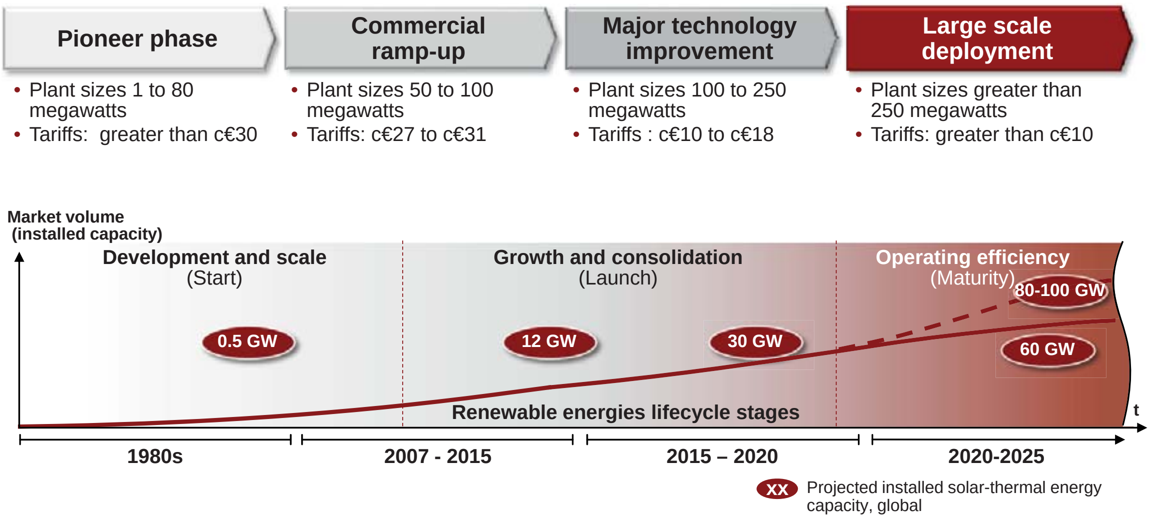
Demonstrated commercial viability, its unique value proposition and cost competitiveness[3] alongside with the growing demand for renewable energies are the key drivers for STE growth. Taking all these factors into consideration, the STE industry shares the following collective vision:

Establish STE as mainstream renewable energy technology so that it can become competitive compared to conventional energy sources, replacing them in the long-term, and complement the current renewables portfolio with a proven and highly cost efficient dispatchable solution

The execution of the industry roadmap, detailed in this report, complemented by proper support, is expected to enable the achievement of this vision. Figure 7 illustrates the various steps comprised by the industry roadmap and how they influence STE installed capacity and its cost evolution.

The STE evolution, implied in this vision, can be broken down into 4 phases: pioneer phase, commercial ramp-up, major technology improvement and large scale deployment. The first phase had already taken place with the SEGS and Solar 1 and 2 demonstration plants.

Figure 7: High-level STE industry roadmap



Note: Tariffs are euros per kilowatt hour, and equal the minimum required tariff. Tariffs will decrease by 4.5 percent, with an increase of direct normal irradiance by 100 kilowatt hours per square meter.
Source: ESTELA project team; A.T. Kearney analysis

As suggested by the existing project pipeline, the STE industry is currently in the commercial ramp-up phase with a focus on the US, Spain, and likely South Europe countries, and MENA regions. The current phase is characterized by still relatively high minimum tariffs when compared with other renewable sources.

Between 2013 and 2020 a wave of technology improvements is expected to be implemented and deployed on large scale plants (100 to 250 MW) which can allow significant cost reductions resulting either directly from the technology improvements or from economies of scale enabled by large sized plants. With both of these factors, associated with deployment in high irradiation areas, minimum required tariffs may reach the 10€c/kWh which will provide STE with a significant cost competitive positioning against other conventional energy sources (gas and coal). Sunbelt countries provide STE with an edge over other renewable sources, resulting from high solar irradiation[4]. Proper grid infrastructure deployment, connecting sunbelt countries through a super-grid, can drastically increase the ramp-up of STE. As such STE penetration could well reach the 30GW by 2020 as results of this ramp-up.

After 2020 and until 2025, further cost reductions may be expected as well as an increase on the average plant size to around 250-350 MW. Under these circumstances, STE becomes cheaper than conventional energy sources, replacing them in countries' energy mix. By 2025, resulting from a high deployment penetration in sunbelt countries, 60 GW of STE installed capacity could well be reached. With the proper support, in the best case scenario, by 2025 STE could even reach a global capacity of 80 to 100 GW worldwide.

Announced project pipeline and the technology improvements currently being developed by the STE industry indicate that although still in the beginning of the commercial ramp-up phase, the realization of the STE industry vision is already happening.

[3] *Further elaborated on the following chapters*
[4] *Further elaborated on the following chapters*

3. Achieving STE vision: technology and cost road-map

3.1 The STE technology landscape and main evolution axis

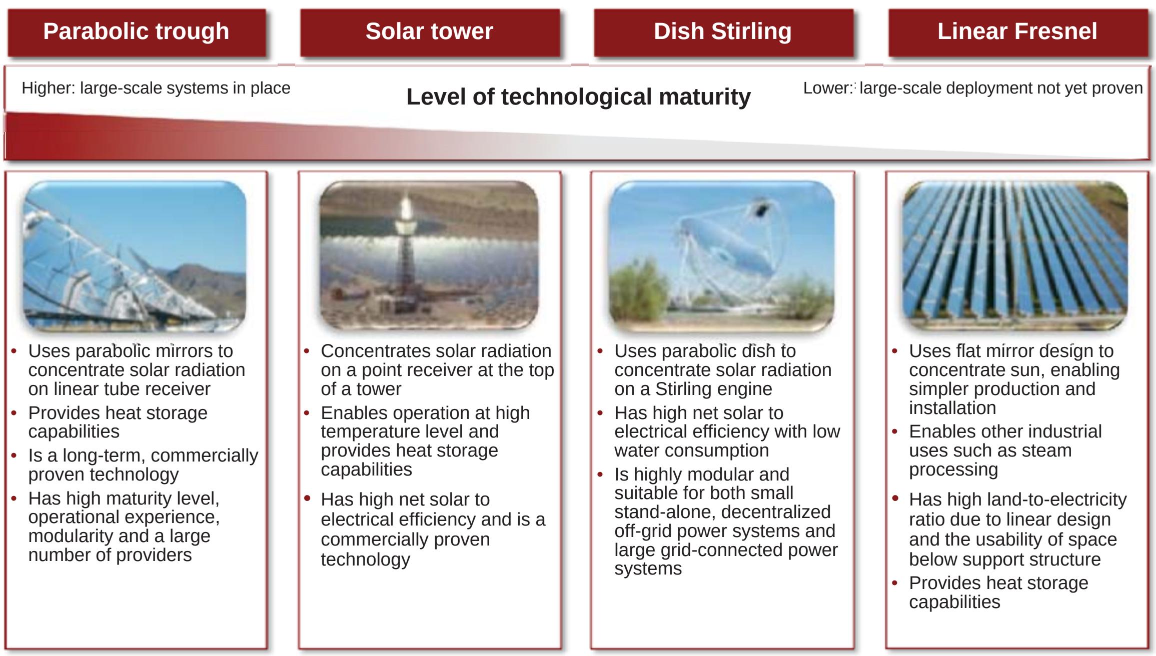
Although all STE technologies share the same set of basic principles, they have been implemented through different approaches. For this reason the STE technology landscape is currently comprised of four main technologies. Each has a different set of characteristics and each is in a different degree of technological maturity as shown in Figure 8.

STE technologies can be used to supply electricity both in centralized grid access locations or decentralized off-grid power systems. Also, STE can leverage on hybridization possibilities with other type of energy sources like gas or biomass which can push overall efficiencies of STE plants. Steam processing for industrial activities can also be a possible application of STE technologies which can drive its growth near industrial zones.

Despite entering a commercial ramp-up phase, STE technology is still in a development stage, displaying high potential for technical improvements. The industry is already focused on the research and development of the next stage of technology improvements, which shall have great impact on costs and efficiency of STE plants. These improvements, which can be either technology specific or horizontal to most technologies, are centred on three axes:

- Increase power generation efficiency, mainly through the rise of the operating temperature leading to higher turbine efficiency, but also

Figure 8: Types of STE technologies



Source: A.T. Kearney analysis

Figure 9: Overview of main technological and efficiency improvement measures

Technology \ Functionalities	Solar collection	Thermal generation	Storage	Electrical generation
Parabolic trough	• Mirror size and accuracy • Optimized support structure design	• Receiver characteristics • Alternative working fluid • Higher operating temperature	• Alternative storage reservoir designs and storage medium compositions	• Turbine efficiency
Solar tower	• Field configuration and heliostat size optimization • Optimized tracking system costs	• Alternative working fluid • Higher operating temperature • Improved cycle technology	• Alternative storage reservoir designs and storage medium compositions	• Turbine efficiency
Dish Stirling	• Optimized support structure design • Optimized mirror sizes for various solar resources		• Storage development	• Engine efficiency and capacity
Linear Fresnel	• Automatic mirror assembly • Optimized mirrors	• Receiver characteristics • Higher operating temperature	• Storage development	• Turbine efficiency

Initiative improvement potential: High Medium Low

Source: A.T. Kearney analysis

through improvements in reflecting facets[5] and receivers

- Reduce solar field costs by minimizing costs and through design optimizations that can lead to more cost effective solar fields deployment
- Reduce internal resources consumption through reduction of needed water and auxiliary parasitic consumption[6]

Figure 9 illustrates and summarizes the expected impact and main improvement initiatives according to these axes, across the several STE system functionalities:

Besides the technological improvements, cost developments resulting from the evolution of the components' price are also expected to impact STE plant costs. Finally, scale effects resulting from larger STE plants can also contribute to the reduction of these technology costs.

In the following sections, these technological and cost drivers will be explained in more detail, with a specific focus on industry's technological improvement initiatives, Furthermore, their impact on the expected LCOE/tariff evolution will be analyzed.

3.2 Technology roadmap

In this section, the several identified technological improvements which are currently being developed by STE industry companies are described. Each technological improvement is presented with its expected impact on cost and efficiency as well as the year after which it becomes commercially viable[7].

3.2.1 Parabolic Trough technology improvements

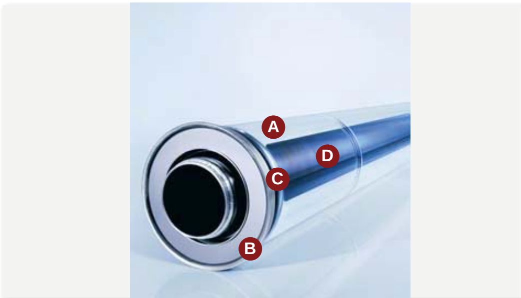
A parabolic trough employs parabolic shaped mirrors to concentrate the solar radiation onto a tubular receiver (see figure 10). The heat is gener-

[5] *Mirror's capacity to reflect sun radiation*
[6] *Plant operations require consumption of electricity (e.g. to pump fluids). This type of consumption is called parasitic consumption*
[7] *Refer to Definitions section for further explanation*

Figure 10: The parts of a parabolic trough collector

Parabolic trough collector

Receiver detail



1 Receiver 2 Parabolic shaped mirror
3 Ball joints 4 Support structure

A External glass B Expansion bellow
C Glass-to-metal seal D Internal pipe

ated in long parallel rows of individually tracked collectors with a total mirror area of more than 3.000 m² per loop. Due to its high maturity level, improvement opportunities for parabolic trough have been intensively studied by developers, and improvements across all system functionalities can be expected.

New support structure design

SEGS plant's original support structure design had a torque box to support trough's mirrors and was made of steel with a galvanized layer. Currently, second generation support structures still follow a similar design philosophy, but a few variations are emerging. Torque tubes with cantilever arms (Sener, Solar Millennium's HelioTrough, TechInt) or struts and geo hubs[8] (Acciona, Gossamer) designs have been developed (see figure 11). Applied as well are alternative materials like stamped steel or aluminum which combined with the new designs have contributed to a significant cost decrease, on the order of 25% since the first generation.

Looking forward, by 2012 new design concepts are expected to be rolled-out. 10% steel usage reduction and on-site labor optimization are the main targets. Also, larger trough dimensions can contribute to the decrease of the total number of rows for the same solar field aperture, resulting in a cost decrease per area of solar field. HelioTrough design already demonstrated support structure savings of 8% through the enlargement of collectors.

Considering these factors, the third generation support structure expected for 2012 can drive a cost reduction for this component of up to 12%. Improved resistance to external forces can drive an increase in sun concentration precision. Due to this fact, a boost in efficiency up to 2% can be achieved by this third generation. After 2015, breakthrough design concepts and alternative materials (e.g. composite materials) are expected to further drive down costs by 33%. Further increases in precision can originate additional gains of 1% in plant efficiency.

Alternative mirror materials[9]

As a cheaper and reflectivity enhanced mirror alternative to current parabolic thick glass mir-

[8] *Also known as space frameworks*
[9] *Alternative mirror manufacturing processes (e.g. tempered glass mirrors) were also studied and although suggested improved mirror properties, quantifiable impact could not be assessed*

Figure 11: Parabolic trough support structure designs

Torque box | **Torque tube with cantilever arms** | **Geo struts and hubs**

rors (93,5% reflectivity) some manufacturers[10] are exploring alternative mirror materials. Those alternatives include: thin glass mirrors, front surfaced aluminized reflectors, polymer reflector on aluminum substrate, all-polymeric reflectors and front surface mirror.

- Thin glass mirrors have higher reflectivity (up to 95%) and are cheaper (less ~25%). However, requirements of supporting substrate and durability pose some cost tradeoffs
- Front surface aluminized reflectors are considerably cheaper than glass mirrors (costing less than 40%) although presenting lower reflectivity values (<90%).
- Polymer reflectors on aluminum substrate might also lead to some cost advantages (less ~25%) but light dissipation and degradation emerge as main drawbacks
- All-polymeric based reflectors are expected to be a very cheap reflector material (~2/3 cheaper) potentially achieving reflectivity values up to 97%. However, further development testing is still needed to prove reflectivity as well as durability
- Front surface mirrors, with reflective silver surface on top of a glass substrate (which normally is placed behind it), may enable reflectivity up to 96% because radiation would not have to go through the glass material. Front surface reflective coatings, to protect the silver layer, are the main enabler for this technique and are currently being studied by mirror manufacturers. Due to early stage of development results are only expected after 2015.

Assuming all the current alternatives under development, it can be expected that after 2015 a proven reflective material that enables a reflectivity of 95% (increasing plant efficiency by 3.5%) and 25% cheaper will be available.

Solar collectors size increase

In order to capture solar radiation, STE plants cover a determined area (aperture). In the parabolic trough technology, the size of the aperture depends on the number of trough rows. Larger solar collectors with bigger mirror facets and larger tube diameters can lead to a reduction in the total number of trough rows, for a solar field with the same aperture. This leads to significant costs savings on the number of mirrors, and on the specific receiver cost per square meter as

[10] *Examples of manufacturers pursuing these alternatives include: Flabeg, RioGlass, Saint Gobain, Guardian, Hirtz, Paneltec, Ronda Reflex, Alucoil, Alanod, Refletech, 3M*

Figure 12: Solar collector increase impact

	Operative	Testing	Commercially viable in 2012	Commercially viable after 2015
Pipe diameter (centimeters)	**7**	**8**	**9**	**10-12**
Length (millimeters)	4,060	4,300	4,700	5,000 – 6,000
Collector's aperture area increase (%)	0%	21%	50%	75-150%
Unit cost variation (% per receiver unit)	0%	15%	33%	50%
Solar field cost variation, including new mirrors area (% of total plant cost)	0%	-1.5%	-3.3%	-5.0%
Plant efficiency increase (%)	0.0%	0.6%	1.0%	1.2%

Sources: Interviews with receiver manufacturers; A.T. Kearney analysis

well as in the required piping and tracking system drives. Both mirror and receiver manufacturers are already planning next generation sizes of components that can lead to larger solar collectors.

Current mirror dimensions range from 1.57x1.4m to 1.6x1.9m. By 2012, dimensions are expected to range from 1.7x1.641m to 1.8x1.9m and after 2020 a further increase in mirror sizes is expected. Larger mirrors enable the construction of larger trough rows with fewer mirrors, reducing the cost per mirror surface area for a given plant. Mirrors saving up to 7.5% in 2012 and up to 13% after 2020 can be achieved this way.

Following the same trend, receiver sizes are also expected to increase. A first wave of larger receivers is expected to be available by 2012, and further enlargement can be expected after 2015. Although receivers size increases have a cost increase impact on each unitary receiver, the total number of receivers per plant will be reduced, since there will be less trough rows to cover the same area. In addition to the cost savings, larger receivers also lead to reduced pressure drops which contribute to an increase in plant efficiency. A summary of solar collector size increases is depicted in figure 12.

Improved receiver characteristics

Parabolic trough's receiver pipes are covered with special selective coatings. These coatings enable high solar spectrum radiation absorptance, high transmittance through the glass envelope to the pipe, and a low infra-red emittance which altogether ensures that solar radiation is efficiently converted in order to heat up the working fluid. These optical and thermal characteristics, are already reaching their physical limit. Although, slight improvements of optical properties can still be expected for the years to come based on developments focusing on high temperature stability

Figure 13: Evolution of parabolic trough receiver characteristics

	Absorptance	Emittance	Transmittance	Active aperture	Pipe maximum temperature	Coating maximum temperature
Current	Greater than 95-96%	Greater than 10%for 400º Greater than 14% for 580º	Greater than 96%	95% to 96.2%	400º to 550º	550º to 600º
Next generation	Greater than 96%	9%for 400º 10% for 450º Greater than14% for 580º	Greater than 97%	Greater than 97%	550º	600º

Note: All temperatures are in Celsius.
Sources: Interviews with receiver manufacturers; A.T. Kearney analysis

to enable higher operating temperatures. Receivers' manufacturers like Schott Solar, Siemens and Archimedes Solar Energy are currently working on these improvements. Figure 13 shows the current technical specification of receivers and the expected improvements. Receivers with these characteristics can be expected to be commercially available by 2011 and when deployed in plants can contribute to a plant efficiency increase up to 4%.

Alternative working fluids

Currently operating parabolic trough plants use a synthetic aromatic fluid (SAF) as heat transfer fluid. This fluid is organic (benzene) based and as such cannot reach temperatures above 400ºC with acceptable performance due to its decomposition at higher temperatures. At temperatures higher than 400°C, fluid degradation is so high that it becomes inoperable. As such, this limited temperature range is capping overall steam cycle efficiency.

To overcome this obstacle, developers are focusing on the development of alternative fluid technology, namely: molten salt, direct steam generation, nanotechnology improved fluids and alternative inorganic fluids.

Molten salt, which is currently used as a heat storage medium, can be used as a working fluid without the 400°C cap of regular SAF, reaching temperatures up to 550°C. Using molten salt as heat transfer fluid enables a new plant configuration which can lead to savings at several levels:

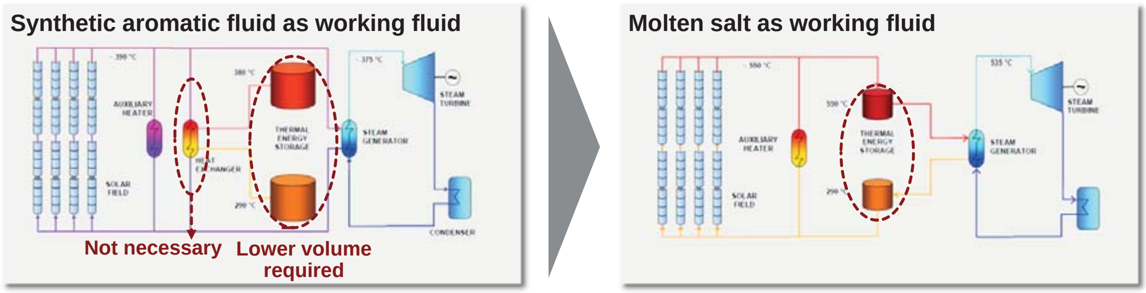
1. storage system's heat exchanger can be eliminated since the fluid that goes from the solar field to the storage system is the same *(see figure 14)*;
2. with operation at higher temperatures, the molten salt volume for the storage system can be reduced by 2/3 which also leads to a reduction in size of the storage tanks with an impact of 30% in costs.

These savings represent an approximate 20% technology procurement cost decrease when compared with normal SAF plants with storage. Also, due to the higher operating temperature plant efficiency can increase up to 6%. Despite being one of the most promising technology improvements, molten salt carries a technological risk due to its high freezing point at 230ºC at which the currently used salt becomes solid and requires a plant operation stop. A 5MW molten salt demonstration plant, developed by ENEL and ENEA, is under commissioning process and is expected to be operational by June 2010. This plant will provide real O&M costs data to analyze technological viability of this technology. Large, commercial scale molten salt parabolic trough plants can be expected to be operating by 2013.

Direct steam generation (DSG) on parabolic trough's receiver can also be attainable through the development of special receivers which can withstand higher pressures. Such receivers are already being developed and are expected to cost 20% more than regular receivers. Direct steam generation would enable higher operating temperatures, increasing plant efficiency, and a plant design simplification by eliminating SAF to water heat exchangers *(see figure 15)*. Considering receiver's price increase and impact of simplifications, this approach would reduce total plant costs by about 5% while increasing efficiency up to 7%, compared with current SAF plants. Main drawback of such solution is that an efficient and high capacity storage solution has yet to be developed to work with steam[11]. DSG for parabolic trough is still under development and is not expected to be available before 2015.

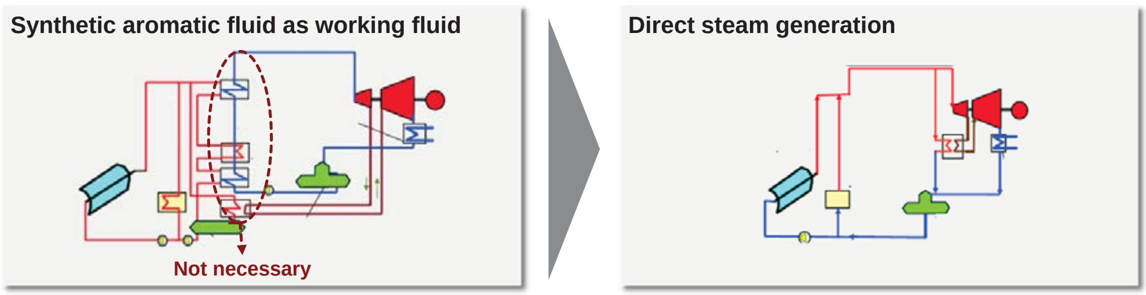
[11] *However, efforts are being developed to fulfill this need as explained ahead*

Figure 14: Molten salt can be used to simplify parabolic trough plants



Source: A.T. Kearney analysis

Figure 15: Direct steam generation can also simplify parabolic trough plants



Source: A.T. Kearney analysis

Usage of **nanotechnology** could contribute to the improvement of fluids heat absorptance at a constant temperature leading to an increase in cycle efficiency. However, this option is still in a very early stage of development and further testing and research is needed in order to become commercially viable. Therefore, no impact could be estimated at the time this roadmap is written.

Alternative inorganic fluid formulations that can withstand higher temperatures and do not have high freezing points[12] like molten salt are also being studied by developers. Such fluid can have an impact similar to the molten salt on plant's costs and efficiency. Development of fluid formulations has a life-cycle of about 6 years before it reaches a state of commercial availability. As such, a potential inorganic fluid without the drawbacks of molten salt cannot be expected before 2015.

Improved synthetic aromatic fluid

Despite the development of alternative working fluids, improvements for currently used SAF can also be expected in the near future that can have an impact on total plants costs.

Producers like Dow are currently developing SAF with a better heat transfer coefficient, meaning a better distribution of the heat within the fluid becomes possible. Such an improvement

[12] *See Glossary*

would enable a reduction of the required heat transfer surfaces within the heat exchangers of the plant. Smaller, and cheaper heat exchangers could be used in the storage system as well as in the power block resulting in a 10% cost reduction for storage heat exchanger and a 15% cost reduction by steam generator and solar pre-heaters. Despite a possible price increase resulting from such improvement, a plant cost reduction can still be materialized for SAF plants. SAF development with the characteristics mentioned above can be expected by 2015.

Additional incremental improvements

Additionally to the most critical technological developments previously discussed, several other incremental improvements initiatives can be expected in the near term. Summed up they still contribute in a significant way to cost reduction or efficiency increase:

The definition of a specific support structure design code can contribute to a more objective and less conservative design approach for support structures. This way, a significant reduction of the required support structure steel weight can be realized. An estimated cost reduction of 10% on support structure can be expected with the development of such codes (range aligned with impact in other RES, like wind). Development of a new design code would take at least 3 years.

Receiver product differentiation for cold and end loops of the solar field might lead to a cost reduction of 1% for total plant receivers and an increase of 1% in efficiency. Due to fluid's flow, with heating and cooling phases, the different areas of the solar field have different operation temperature requirements. As such, installation of specifically tailored receiver pipes, with different properties for specific areas of the solar field with lower operating temperature could reduce total receiver' costs, since colder areas do not need such specialized receiver properties. Also, this design solution could increase plant efficiency since on end loops of the solar field better temperature maintenance could be ensured through better receivers. Receiver manufacturers expect this receiver's product differentiation to be available by 2012.

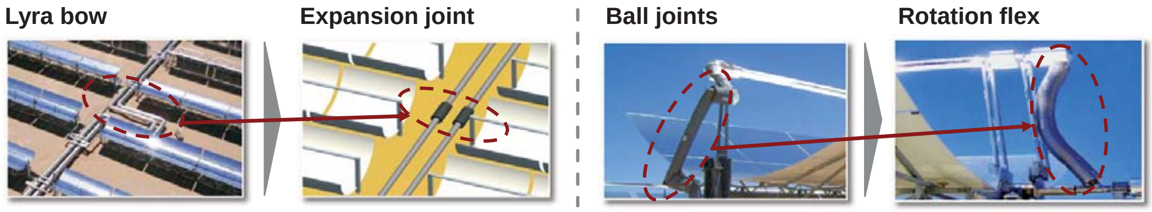
The glass envelope of a receiver tube has to be airtight-bonded to the steel pipe in order to maintain receiver's vacuum that prevents a loss of heat from the steel pipe and protects its special coating. Improvements of glass to metal seal, through enhancement of production steps and materials, or potential change to mechanical seal[13], are options currently being studied by developers. These improvements can be expected to be commercially available until 2014 and would lead to a 2-5% receiver unitary cost decrease.

Parabolic trough's loops are usually connected through flexible hoses and ball joints system (see figure 16). Metal hoses manufacturers like Senior Berghöfer have devised a system which replaces lyra bows by expansion joints and ball joints by a rotation flex hose. This design change reduces the required piping by 18% and the fluid volume associated with number of elbows by 80%. Joints and flexible hoses expenditures can then be reduced by 60% and 40% respectively, reducing the total plant cost in 0.4%. As an additional advantage, pressure drops can be reduced with this system. Currently in operation in one of the SEGS plant, this system shall be soon installed in new plants in Spain proving its commercial viability.

Parabolic Trough's mirrors accuracy is measured by the focal deviation which expresses by how many millimeters, reflected solar radiation can be distributed. The smaller the focal deviation, the more precise mirrors become, ensuring a

[13] Still in a very early stage of development

Figure 16: Piping and interconnection system details



more efficient light concentration. Current mirrors have a focal deviation of 10mm. Mirror manufacturers are working on improving the bending precision for Parabolic Trough mirrors which can lead to a decrease of the focal deviation up to 6mm by 2020. Such improvement would result of up to 2% increase in plant efficiency.

3.2.2 Solar Tower specific technological improvement initiatives

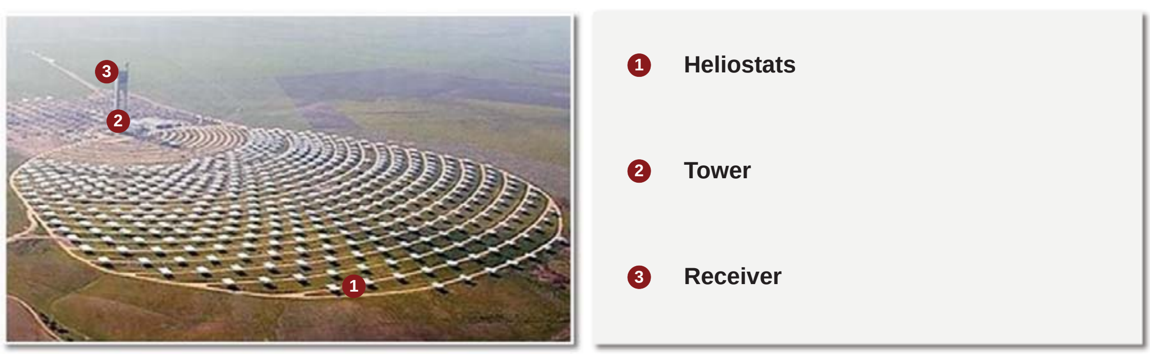
Solar Tower technology uses a field of flat (or slightly bended) mirrors to reflect and point solar radiation to a receiver placed on the top of a tower (*see figure 17*). Despite being a more recent technology than parabolic trough it is already well established since the launch of the commercial plant PS10. Several improvements are also expected for this technology across its main components.

Heliostat design improvements

Heliostats are comprised by a structure that holds a panel in which mirror facets are fixed. They reflect and direct the sun radiation to the receiver located on the top of the tower. There are currently two design philosophies being developed: small and large heliostats

Large heliostats have aperture areas of 62 to 120m² and multiple mirror facets. Sizes for large heliostats are expected to increase up to 150m² until 2012. With this size increase, the total number of tracking system drives would decrease, reducing tracking system costs per m². Since they are one of the most relevant cost factors for tower's solar fields, achievement in these dimensions for heliostats can yield a cost reduction of 7% per solar field area.

Figure 17: Components of a solar tower field



Small heliostats have aperture areas of 1 to 7m² and have 1 or 2 mirror facets. Such dimensions enable lower foundation and installation costs, low cost tracking systems since heliostats have to withstand small wind forces and a better land use factor. These factors contribute for small heliostats having capital costs of less 16% than larger ones (considering current dimensions). However, a more complex control system, plant scaling limitations and potentially higher lifetime O&M costs resulting from the larger number of components, which increases failures probabilities, make this alternative yet to be viably proven.

Study of medium sized heliostats is also being currently undertaken by some developers. However they are still in a very early stage of research and impact cannot be estimated.

Tracking system improvement

Tracking system scheme for small heliostat fields can be further improved. Current tracking system is based on the use of one drive per heliostat. However, small heliostat developers are developing a system based on a common row tracking with micro-robotic drives that couple at each heliostat individually. Such a system can effect in a total tracking system cost reduction by 40%. However, reliability and maintenance cost of a new tracking system have yet to be proven. Expected roll-out year for this technology is 2012.

Solar field optimizations

Solar field layouts can be tailored in order to optimize sun shading and blocking produced by heliostats. This can be achieved by different heliostat designs according to their location on the solar field. This mix of different heliostat types in a given solar field might contribute to the reduction of the total cost of the field up to 10% and an efficiency improvement of 3% when compared with currently employed designs.

Multi-tower fields

Multi-tower configuration appears to present a promising potential for cost reduction. It consists of installing more than one tower for the same turbine and, eventually, for the same heliostat field. This enables an increase in the efficiency of each tower (up to 5%) by the reduced distance between heliostats and towers which mitigates light dissipation issues. Additionally, smaller towers have lesser construction requirements (high towers are exposed to higher wind forces) which can reduce costs by ~25%. However, due to higher pressure drops and thermal losses of the piping system resulting from the sharing of a single power block, and an increased control complexity, its competitiveness at high-capacity plants is yet to be established. Multi-tower fields can be expected to be commercial available in 2013.

Alternative receivers

One of the most promising developments for towers relies on the development of receivers that can operate with alternative fluids which can lead to higher operating temperatures. Current towers in commercial scale operation like the PS10, work with saturated steam that can reach temperatures in the order of 250ºC. This value is far from the maximum temperature that can be achieved with alternative receivers for towers. Main alternatives for solar tower receivers currently under development include: superheated steam, molten salt, open air, pressurized air and solar fuels. Considering the vast number of alternatives, and their stage of development, solid efficiency improvement for tower can be achieved and is expected to have great impact on the cost of electricity.

Superheated steam[14] towers can reach temperatures up to 540°C and can boost plant efficiency by 28%. Brightsource and Abengoa Solar

[14] *Please refer to Glossary for further explanations*

are currently developing receivers to operate with superheated steam. Tower receivers capable of working with superheated steam are expected to be commercially available in 2013. For steam based towers, superheated steam, once developed will render saturated steam obsolete in which case further saturated steam towers cannot be expected to be built for large commercial use. Abengoa Solar has been testing a superheated steam tower since December 2008 with very good results in terms of efficiency.

Molten salt towers, which have already been demonstrated by projects like Solar Two, also present a significant efficiency improvement over the saturated steam tower. Operation with molten salt may lead to operating temperatures around 560°C and may allow an efficiency improvement of 24% compared with saturated steam. A molten salt tower is currently being developed in Spain by Sener (Gemasolar) and is expected to start operation in 2010. Adoption of this technology for large tower deployment can be expected for 2013. Operation with molten salt also means a significant advantage for storage development, since it can ensure low storage cost and high capacity efficiency.

In a more long-term horizon, receivers to operate with air and solar fuels can also be expected. These, however, are still in a very early stage of development, and commercial availability can only be expected after 2015. Pilot plants with open air receivers are being developed in Germany and in Spain. Expected operating temperatures range between 500 and 800°C with an efficiency increase of 13%. Further improvements to open air lies in the use of pressurized air which can reach temperatures of 700 to 1,000°C leading to an efficiency increase of up to 42% by using combined cycles (gas and steam turbines). Solar fuels which derive from solar and chemical reactions can also be used in towers enabling operating temperatures from 900°C to 1,500°C with an efficiency improvement of 37%.

Due to the higher operating temperatures, materials with better properties must be used to build these receivers, which can drive up their costs by 20-40%. However, it is worth noting that the significant increase in efficiency of these alternative receivers outweighs their corresponding cost increase. With the consequent production of these new receiver technologies, cost decreases by learning curve effects[15] can be expected which will further offset their initial disadvantage.

3.2.3 Dish Stirling specific technological improvement initiatives

Dish Stirling technology uses a parabolic dish mirror (which can be comprised by one or several facets) to concentrate solar radiation in a Stirling engine (see figure 18). Temperatures reached in the Stirling engine receiver surfaces lead the engine internals to produce a compress and expand cycle which can be used to produce electricity. Several technological improvements are already being studied by developers of this technology like Tessera Solar, Infinia Solar systems or Schlaich Bergermann und Partner.

New support structure design

Since the first prototype and pilot designs of Dish Stirling systems, significant cost reductions have been accomplished with structure redesigns. Following this pattern, the first generation of commercial scale Dish Stirling systems, expected for 2010 to 2015, can still experience further reductions in the number of parts and in the amount of steel. The structures as well as the leverage of components from large volume supply

[15] *See explanation ahead*

Figure 18: Components of a dish Stirling system

1. **Mirror facets**
2. **Support structure**
3. **Stirling engine**

chains (e.g. automotive) can contribute to a cost reduction of 20%. After 2015, alternative dish sizes and further reductions of steel with employment of alternative composite materials and the set up of supply chains in low labour cost countries can decrease dish structure costs by another 35%.

Mirror optimizations

Improvements in the shaping of mirror facets to enable faster assembly on site as well as the adoption of high volume manufacturing mirrors, like thick glass mirrors, can reduce costs for Dish Stirling mirrors by 20% until 2015. Until 2025, usage of composite materials for the backing of the facets and leverage of supply chains established in low cost countries may further drive down costs for dish mirrors' up to 35%.

Storage system development

There are currently two alternatives being pursued to develop storage solutions for the Dish Stirling technology: electro-mechanical and 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.

[16] *Please refer to Glossary section for further information*

Optimize engine design

There are currently two types of Stirling engines: kinematic and free piston[16]. Both engine types are expected to evolve in order to materialize significant cost savings.

Kinematic engines operate with hydrogen as a working fluid and have higher efficiencies than the free piston engines. Improvements for cost reduction of kinematic engines include:

1) improved engine production techniques
2) increased share of "off the shelf" components engine
3) new designs with higher capacity
4) simplified gas management system

Free piston engines work with helium and do not produce friction during operation which enables a reduction in required maintenance. Development of multi-cylinder free piston engine is seen as one of the most promising improvements for this type of engine, as it would enable a significant cost reduction and an overall simplification of the engine concept. Multi-cylinder engines are expected to be rolled out in 2012.

According to Stirling engine manufacturers improvements under development may contribute to an engine cost reduction of 20% by 2015 and 35% until 2025.

Improve engine efficiency and increase output capacity

Dish Stirling technology presents the highest efficiency among STE systems - average annual engine efficiency for medium DNI locations (like Spain) is expected to be above 23%. Some prototype engines even have surpassed the 31% peak efficiency and on high DNI locations register (like the US) have registered an average efficiency of 27%. Despite this fact, further improvements can be expected that can lead to even higher efficiencies. Until 2015 reduction in parasitic losses and improvements in gas circuit materials can enable efficiency to reach an annual average of 25%. Further developments can be expected which can allow efficiency to reach 27% until 2025, namely:

1) usage of alternative materials for improved thermal cycling;
2) alternative engine configurations

Apart from the improved engine's efficiency, some Dish Stirling developers are also developing engines with larger output capacity. This would enable a greater electricity output per unit area, and enable Dish Stirling systems to access lower DNI areas.

3.2.4 Linear Fresnel specific technological improvement initiatives

Linear Fresnel uses modules of almost flat mirrors which concentrate solar radiation in a linear receiver placed above these mirrors (*see figure 19*). Most commonly, Linear Fresnel plants are devised to work with water/steam as the heat transfer fluid. Despite the early stage of this technology, there are already several improvements being studied.

Support structure improvements

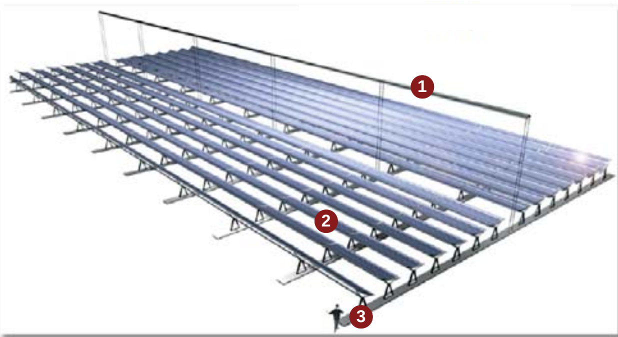
There are currently two types of support structure designs for Linear Fresnel technology that were created by different developers: bench bar and ring design (*see figure 20*). Despite their technical differences and characteristics, current Fresnel support structures are designed to be cost effective and provide adequate precision. Improvements (like removing parts) can contribute to an additional cost decrease up to 10% until 2015. However, the cost development of Fresnel support structures is highly dependent on raw material prices and economies of scale.

Primary reflector automatic installation

For some Fresnel technologies, primary reflectors are still manually fabricated. This can be opti-

Figure 19: Components of a Linear Fresnel solar field

Linear fresnel solar field



1 **Receiver**

2 **Reflective panels**

3 **Support structure**

Figure 20: Linear Fresnel support structure designs

Bench bar design

Ring design

mized by the usage of automation as some Fresnel developers already demonstrated (e.g. Novatec). Cost savings in primary reflectors of up to 17% could be materialized with this approach. Additionally, automation of primary reflector assembly and installation could also improve overall efficiency due to increased stability and bending precision of the reflector surface resulting in an increase of 1% in produced energy. Additionally, efforts are being developed in order to create robots that would enable automatic mirror installation. However, commercial roll-out is not expected until 2015.

Increase operating temperatures

One of the most important efficiency leaps for Linear Fresnel stems from the possibility of working with superheated steam. Superheated steam might reach operating temperatures of up to 500°C which can drastically boost turbine cycle efficiency compared with currently applied saturated steam (270°C).

In order to operate with superheated steam, Fresnel receivers are currently being improved in order to withstand the higher operating temperatures. These improvements include an enhancement of receiver's absorptance, emittance and design as well as more resistant receiver pipes that can withstand higher pressures (100bars for superheated steam).

A 800kW Linear Fresnel pilot operating at 450°C has already been tested in Plataforma Solar de Almería with components developed by Solar Power Group, and the technology is expected to be commercially available by 2012, according to several developers (Novatec Biosol, Solar Power Group). By 2015, Linear Fresnel can be expected to be operating with superheated steam at 500°C yielding an efficiency improvement of up to 18.1%[17] relative to current saturated steam operation at 270°C.

Storage system development

Commercialization of Linear Fresnel power plants with storage system has yet to be demonstrated. However, phase change materials and high capacity direct steam storage are options currently being pursued by the industry. These options strongly indicate the need for the development of a thermal storage solution for Linear Fresnel starting in 2015.

3.2.5 Horizontal technological improvement initiatives

Alongside with the specific technological improvements of each technology, there are some initiatives that can be applied to all technologies[18]. Those are introduced in this subsection.

Improved mirrors reflectivity

Mirrors' reflectivity conditions the total solar radiation that is captured and concentrated on receivers. There are two ways to improve reflec-

[17] *Considering receiver's efficiency increase*

[18] *Some storage improvements are not applicable to Dish Stirling technology*

tivity in glass mirrors: usage of thinner mirrors and usage of mirrors with the same thickness but with less iron concentration.

Thinner mirrors have better reflectivity due to the reduced layer of glass which radiation has to pass in order to reach the reflective surface which hence reduces absorption losses. On average a 1% reflectivity increase can be achieved by the reduction of 1mm in glass thickness. This way, plant efficiencies can be increased by the adoption of such mirrors. As previously mentioned, thin glass mirrors require a self-supporting substrate which increases its cost.

On the other hand, thicker glass mirrors with less iron concentration, also have reduced absorptance since iron is one of the most important elements in this phenomenon. Thick glass mirrors have currently an average reflectivity of 93.5% and according to mirror manufacturers, that number can be increased up to 94.5% until 2015, leading to an increase of 1% in plant efficiency. Despite higher purity of the glass, cost shall not be relevantly impacted.

Improved mirror maintenance

Special coatings like anti-soiling and hydro-phobic are being tested by mirror manufacturers like Flabeg and Saint Gobain in order to decrease mirror's cleaning requirements. Anti-soiling coatings prevent the accumulation of dirt and dust on mirror's surface which can reduce the number of washing cycles by 50% with estimated OPEX reduction of 150 k€/a[19]. Hydro-phobic coatings can reduce the amount of required water for cleaning mirrors by 30% leading to an OPEX reduction of 25 k€/a. Anti-soiling coatings are expected to be available just in 2010, whereas hydrophobic coatings can only be expected for 2012.

[19] *For a 500.000m² solar field*

In parallel to the development of mirror coatings, further efforts are undergone to reduce the labour costs of mirror cleaning with the development of special cleaning robots. Linear Fresnel and some tower technologies already possess such robots. The development of such mechanisms for remaining technologies can be expected before 2015.

Alternative tanks configuration

Current STE plants use a two-tank system with molten salt to store thermal energy. The two-tank system has demonstrated commercial viability with the Andasol I, Andasol II, and Extresol I plants (developed by ACS/Cobra) (*see figure 21*). Alternative designs are currently being studied which can yield significant savings:

- For small to medium sized plants (up to 30MW) thermocline tanks pose a significant improvement opportunity. Following this approach, energy is stored in a single tank which combines a cold section at the bottom and a hot one at the top. Different prototypes are being tested but the expected savings are estimated to be around 30% for storage medium and 25% for tank costs when compared to the two-tank system. This solution is still under development and is only expected after 2015.
- For large scale plants, the two-tank system design is also expected to be improved through reconfiguration and the usage of alternative materials which can lead to a tank cost reduction of 12% and a molten salt volume decrease of 10% by 2015. After 2015 further savings can be materialized, namely a 15% decrease in molten salt quantity and 20% tank costs considering the 2010 costs.

Figure 21: The two-tank storage system

Storage medium composition

Alternative molten salt compositions are being tested (both by producers like SQM and research institutions like Sandia) in order to explore cost savings and operational improvements. The roll-out of these alternatives is not expected before 2015.

- Introduction of ceramic (refractory) material in storage tanks could enable a reduction in the amount of required molten salt by 30 to 40%, while ensuring thermal properties
- Lithium based molten salt formulation could contribute to increase the current maximum operating temperature and reduce the freezing point from 230ºC to 130ºC. This would reduce freezing risk and the plant's parasitic costs. Lithium based molten salt formulation could be more expensive due to the Lithium scarcity.
- Formulations based on Calcium Nitrate, may allow even lower freezing point of 100ºC but be potentially less stable and with higher viscosity impacting a plant's pumping requirements.
- Reducing the purity of the molten salt could yield a cost reduction of up to 10% of this medium. However, current storage tank materials (carbon steel and stainless steel) might not afford the corrosion produced at operating temperature. Also, less pure salts contain other non-desired components which specific treatments impact total plant's CAPEX.

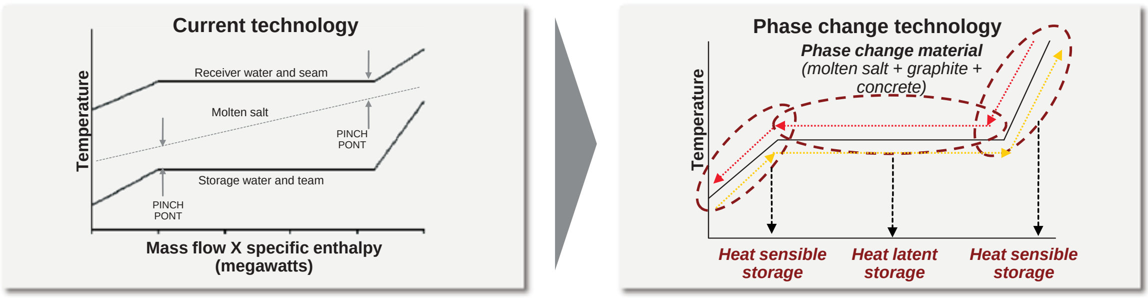
Phase change materials

Usage of steam as a working fluid poses significant efficiency challenges to current salt technology, limiting the efficiency of the storage system to 80%. This is due to the temperature differences between the water during the changing phase and the molten salt (*see figure 22*). Phase change materials currently being developed reduce these differences by using three different storage phases (two sensible and one latent, the phase change). The objective is to achieve an efficiency of 95% for steam based cycles, enabling an efficient storage solution for these technologies. Such storage materials are only expected to be deployed in large scale commercial plants after 2015 and might carry a storage medium cost increase of 18%.

Direct steam storage

Direct steam storage in a pressurized steam tank has been deployed as an operation storage solution for saturated steam tower plants like PS20. Storage capacity depends on steam drum size and while currently only short duration storage is sup-

Figure 22: Details of phase change technology



ported, in the long-term larger drum sizes and capacities are expected to emerge increasing storage periods.

Turbine improvements

Given the expected growth of STE, turbine manufacturers (e.g. Siemens) are currently developing improved turbines for STE plants. These improvements include enhanced internal seals to decrease leakage, improved blade designs and manufacturing methods. Turbines with these enhancements implemented can be expected for 2015. When deployed at plants they contribute to an efficiency increase of 0.6%, for current temperatures.

3.3 Cost roadmap

Apart from the technological improvements mentioned in the previous section, the development expected for STE also comprises cost developments. Those are discussed in this section.

3.3.1 Expected component cost developments

According to the forecasted demand for STE, some cost developments for STE plants are expected.

Cheaper mirrors

Due to the growth of STE technology and the stabilization of demand volumes for mirrors, price reductions can be expected. As such, for parabolic trough, the current price can be reduced more than 10% by 2015 and up to 20% by 2020. For flat mirrors employed in Tower and Fresnel, prices can drop up to 25% until 2025.

Increased scale and competition of receiver's market

As demand for parabolic trough receivers increases, it is expected that low labour cost countries like China and India will enter the receiver producing market significantly driving down prices for this component. Until 2025, and including previously mentioned improvements, procurement costs for receivers could be as low as 45% compared to today's costs.

Molten salt price evolution

Prices for molten salt are strongly driven by supply and demand. The price for nitrate salts has historically experienced a high volatility leading to price escalations in certain periods. Maturity of storage technology and demand for dispatchable renewable energies will drive growth of STE plants with storage. As such, molten salt demand is expected to range between 395,000 metric tons to 420,000 metric tons between 2012 and 2015, 600,000-800,000 metric tons between 2016 and 2020 and 900,000-1,000,000 metric tons after 2020. Ensuring stable demand for molten salt can lead to proper scale-up of supply capacity and would result in a stabilization of prices in the near future.

Dish Stirling volume ramp-up

One of the most important drivers for Dish Stirling costs is the volume of the demand. According to the forecasted demand for STE technologies and the expected Dish Stirling market share, dish cost reductions of 30% by 2015 and 50% by 2025 can be attainable. This expectation is realistic taking into account not only the discussed technology improvements but also the scale effects that can be leveraged from the Dish Stirling supply chains.

Learning curve effects

Volume effects resulting from mass manufacturing also have an impact on the production cost development of STE components. As demonstrated by other manufacturing industries, production costs of components tend to decrease by a certain amount whenever production is doubled. When producing a second component, a learning effect resulting from the production of the first component, shall also have an impact on the manufacturing costs of the latter. This effect tends to be lower as component maturity increases. Experience curves and the associated concept of progress ratio quantify the effect of cost decrease for increasing experience in production/ volume. These curves can be expected to be applicable for STE components as well. Cost decreases from 5% up to 40% can be expected for STE components until 2025 depending on component maturity and level of demand.

3.3.2 Economies of scale impact on STE plants

A key cost driver for STE plants are economies of scale. STE technology favours large power plant configurations. This fact results from several characteristics inherent to STE plant development:

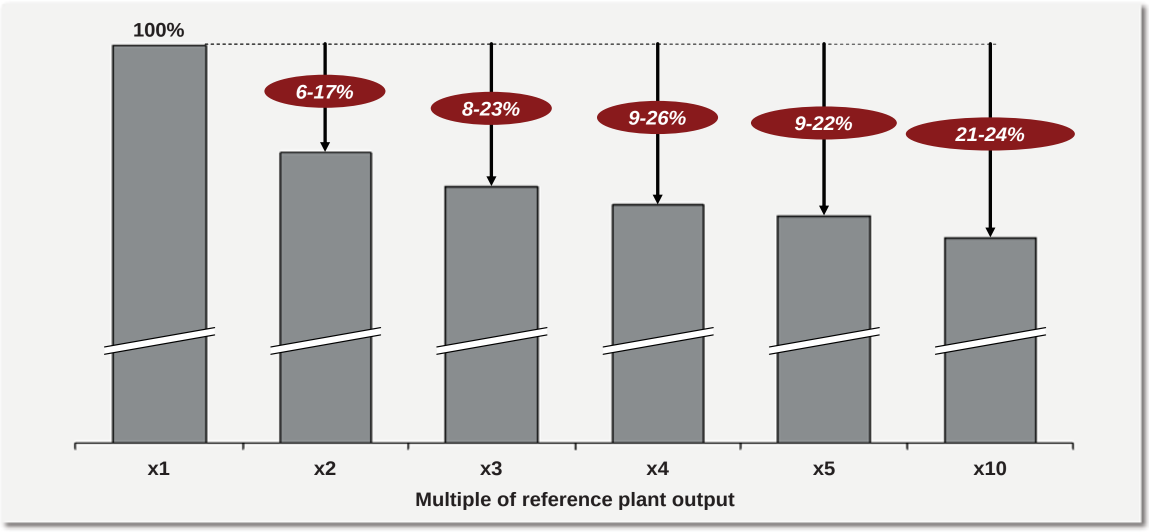
- Large volume procurement of solar field components can lead to order discounts that can only be materialized on large power plants
- Engineering and planning costs as well as project development costs are practically independent from the scale of the plant. This makes them cheaper on an electricity production basis for large scale plants since these can produce more power at practically the same cost on the mentioned categories
- The construction of larger solar fields to capture a higher volume of solar radiation could also enable the use of power blocks with higher capacity. As cost of power blocks are not directly proportional to their capacity, and taking into account the higher output enabled by larger power blocks, significant cost savings can be achieved this way

Based on these three levers, savings on plant's CAPEX per annual output could reach 24% considering a plant scale-up from 50MW to 500MW as illustrated in figure 23.

In order to materialize such savings, plants are expected to realize a scale-up across all technologies. For instance, parabolic trough plants, currently with an average capacity of 50 MW are expected to reach 500MW by 2025. Single solar tower plants, with an average capacity of 50 MW are also expected to scale-up and reach 200MW by 2025. Dish Stirling and Linear Fresnel, expected to demonstrate commercial viability at 25-50MW and 50MW respectively, will also follow similar scale-up patterns to Parabolic Troughs and Tower. Figure 24 illustrates expected plant size development.

However, to enable the scale-up effects, country governments must ensure that legal conditions fit with these objectives. In Spain for instance, legislation for renewable energies keep STE power plants within a 50MW limit. Artificially imposed capacity caps, such as these, erect significant barriers to STE competitiveness.

Figure 23: The impact of economies of scale



Notes: Percentages equal percentage reduction of capital expenditures and GWh annual output. Plant scaling refers to plant sizes from 50-500MW; 15MW Linear Fresnel plant has been excluded from overview; solar tower only scaled up from 50-200MW, Linear Fresnel from 15-250MW
Sources: Interviews with industry experts; A.T. Kearney analysis

In order to foster STE development, legal and political frameworks should avoid such limitations.

4. Attaining competitiveness: achievable tariff reductions

Given the outlined development for STE technologies including cost and scale development which impact plant's CAPEX and efficiency, it is possible to mathematically derive their impact on the minimum required tariff for STE projects over the following years. Figure 25 illustrates the development.

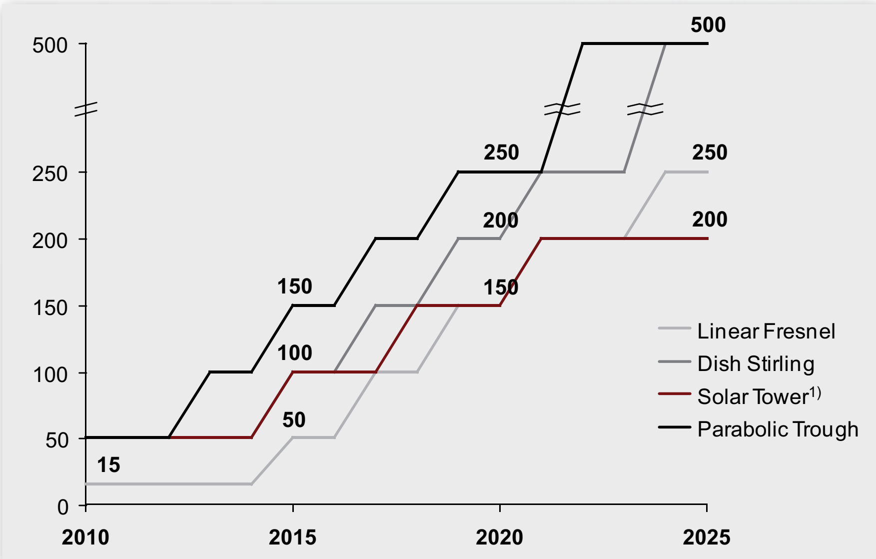
Due to the plant's procurement and construction lead times of 2 to 3 years, no tariff reductions can be materialized from 2010 to 2012 (*see figure 26*). Technical improvements and cost developments occurring during this period can only be considered for plants being constructed starting in 2012 if they are available and can be purchased to integrate into the new plants.

From 2013 onward, however, significant required tariffs/generation cost reductions can be expected for STE plants driven by size increase, which enables the mentioned economies of scale and the deployment of technological improvements. By 2015, a reduction ranging from 5 to 30% can be expected, depending on STE technology and dispatchability of the plant.

Between 2015 and 2020 with the implementation of the remaining technical improvements 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 technology to become self-sustained without the need for support schemes for newly installed plants.

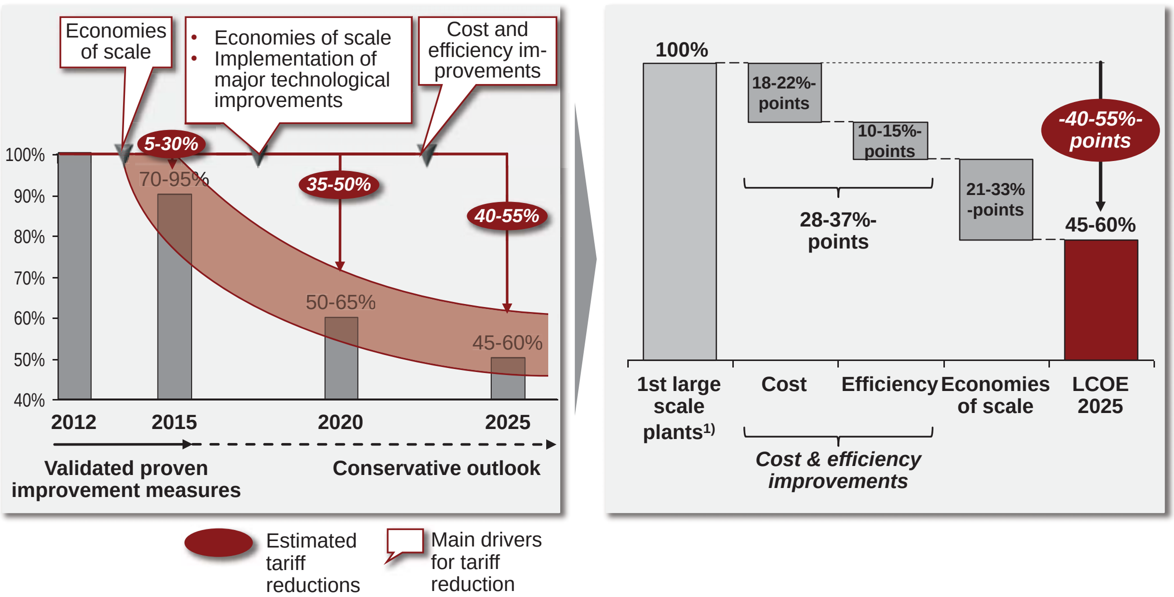
Figure 24: Expected plant's scale up

Global expected plant size development (MW)



1) Solar Tower only considered in single tower setup, capacity limited to 200MW – multi tower plants out of analysis scope multi tower setup for Solar Tower plants – out of scope
Source: A.T. Kearney projection; CENER; interviews with ESTELA project team members

Figure 25: Expected tariff reductions from 2012 to 2025



Notes: Tariffs equal the minimum required tariff, and are compared to 2012 tariffs
1) Referring to 2010-2013 according to planned commercialization date of each technology (reference plants)
Source: A.T. Kearney analysis

Another factor that can further drive down required tariff for STE projects is the solar irradiation level of the deployment location. Empirically, the larger the available solar resource is, the bigger the annual output will be, and, as such, for the same plant's CAPEX, the required tariff would be lower. Figure 27 shows how the DNI level of a specific location can influence the minimum required tariff.

On average, tariffs can decrease up to 4.5% per each additional 100kWh/m^{2}a of DNI. This means that for high DNI locations like in the MENA region or in California/US a STE project requires less 25% of minimum tariff to break-even when compared with the same project in Spain. It is worth noting that on this calculation, only DNI variation was considered. Country specific risk, financing and labour costs variations also play a significant part in defining the minimum required tariff.

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

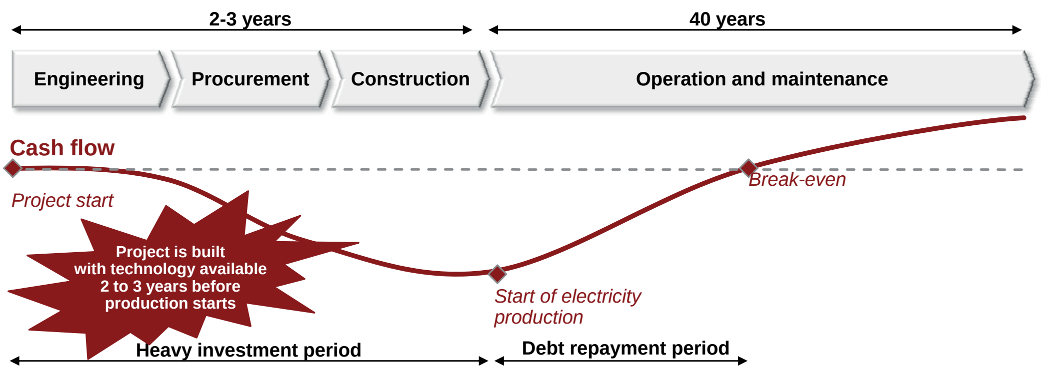
Also, according to the defined technological and cost roadmap, STE technology can achieve its positioning within the energy sources portfolio mix which shall be discussed next.

4.1 STE evolution vs. other energy sources

Previously discussed STE technology and cost roadmap can also be used to extrapolate the expected LCOE evolution of STE and compare it with other energy sources in order to conclude about long-term STE positioning in energy source mix.

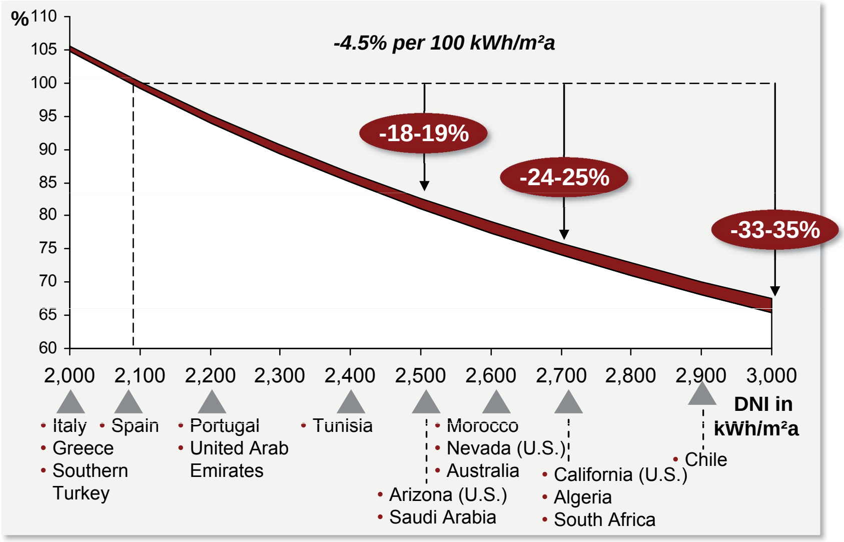
Some conventional technologies – like gas turbines – are able to produce electricity on demand by the process of burning gas. These are the currently most used power plants for providing electricity for peak and mid load. Dispatchable STE technologies, i.e., technologies with storage capabilities, also share these characteristics – they can produce power on demand in order to serve peak and mid load periods, with the advantage of CO_2 neutrality which are not achievable by coal or gas. Renewable energy supply for peak and

Figure 26: STE project lifecycle



Source: A.T. Kearney analysis

Figure 27: Tariff and levelized cost of energy development above direct normal insolation (DNI) level



[1]Reference plant location has a DNI of 2,084 kWh/m²a at 100 percent
Source: A.T. Kearney analysis

mid loads cannot currently be fulfilled by current RES, like PV or wind.

Current LCOE for STE technologies is still not competitive with these conventional energy sources. However, considering the forecasted STE LCOE evolution and the expected cost developments for gas and coal, as well as CO_2 penalties, STE is expected to compete against these conventional energy sources as shown in figure 28.

In the long run, STE can substitute CCGT as peak to mid load provider. Further hybridization can support cost competitive dispatchability. Introduction of additional CO_2-penalties would further drive competiveness of STE.

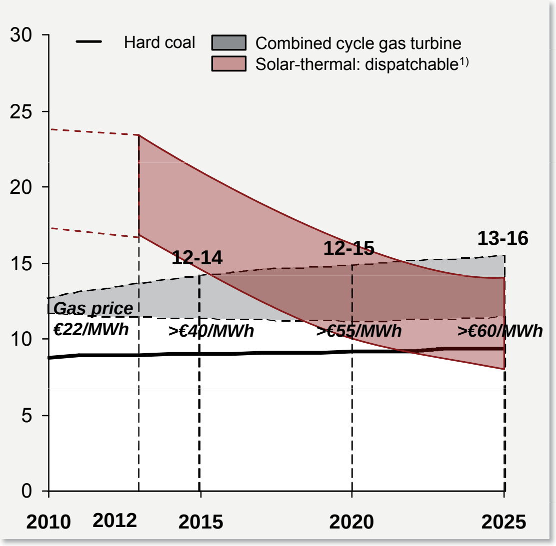
It can also be observed on the right-side chart that, within the RES portfolio, non-dispatchable STE technologies are expected to compete against non-dispatchable RES, namely against PV. STE is not expected to compete against wind, not only due to wind's cost advantage, but also because wind and solar resource availability is broadly complementary, i.e., regions with high DNI generally coincide with low average wind speed locations (in these regions however, considering the high DNIs, STE can be cost competitive against wind).

When compared with PV, STE might appear at a slight cost disadvantage in regions of medium irradiation. However, dispatchable and non-dispatchable STE technologies still provide some grid advantages that make it an alternative to consider. Due to fluids operating temperatures which do not cool down immediately as a result of transient clouds (flywheel effect), STE plants can continue to operate in such conditions. The same does not hold true for PV systems.

Figure 28:

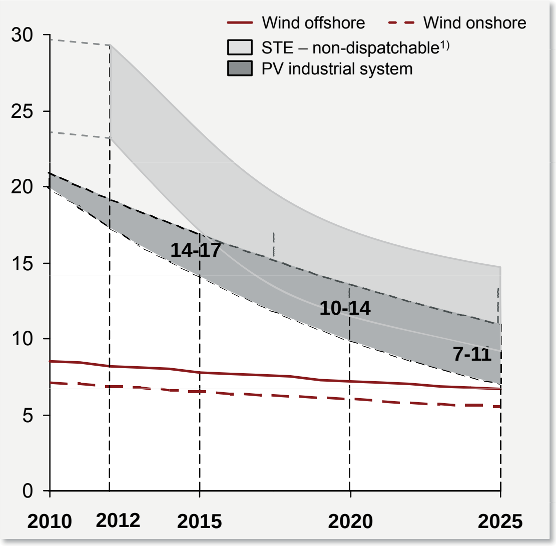
LCOE comparison of solar-thermal energy versus conventional sources

Levelized cost of electricity (€c/kWh)



Non-dispatchable renewable energy sources compared with traditional sources

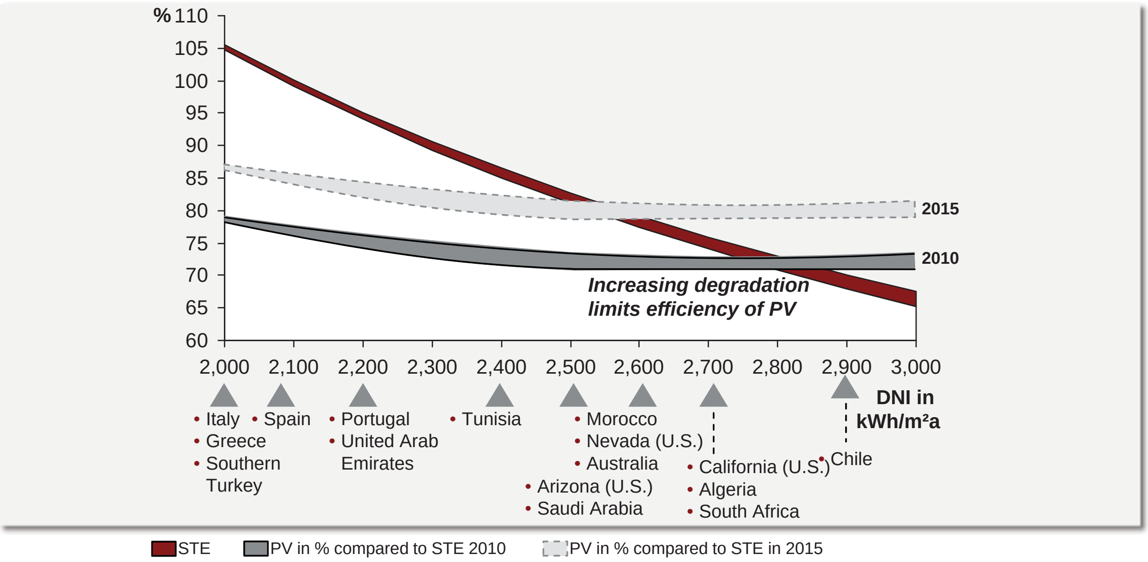
Levelized cost of electricity (€c/kWh)



1) Includes cost and efficiency improvements and economies of scale
Source: A.T. Kearney analysis

Figure 29: Costs for photovoltaic and solar-thermal energy

LCOE (% compared to reference plant location Spain)



Sources: ESTELA project team; A.T. Kearney analysis

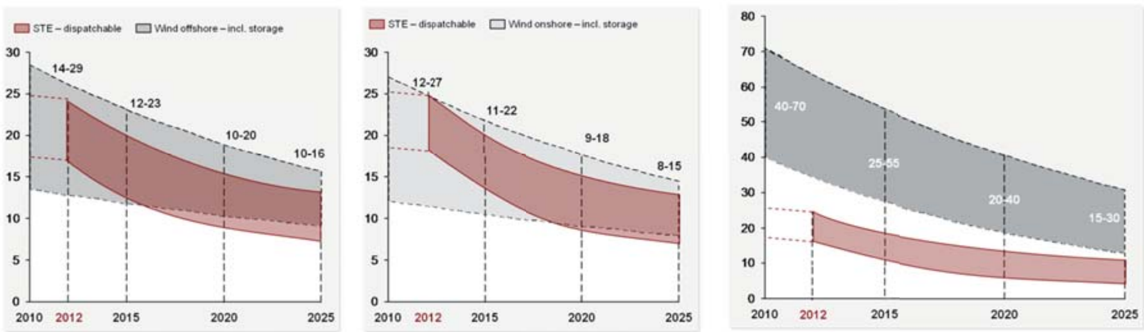
Figure 30:

LCOE for onshore and offshore wind, including storage costs

Cost (€c/kWh); wind onshore **Cost (€c/kWh); wind offshore**

Photovoltaic costs including battery storage

In Spain (€c/kWh)



In areas of high irradiation STE is expected to be competitive as non-dispatchable RES against PV as shown in figure 29.

As previously discussed, STE plant's efficiency increases in location with higher DNI levels. These regions generally bear high outside temperature levels which limit the efficient deployment of PV. This is due to a phenomenon verified in PV cells which produce less electricity at higher temperatures. As such, STE is expected to be the more cost efficient deployment alternative, for both dispatchable and non-dispatchable solar power, in areas of high irradiation and with high temperatures, e.g. US Southwest, North Africa.

LCOE of dispatchable STE technologies can also be compared against RES with storage solutions as shown in figure 30.

High storage costs solution for other RES reveal a significant competitive advantage of STE. In the case of wind, due to its base cost without storage, LCOE including storage are expected to range at a comparative cost level as dispatchable STE technologies, even though in the long-term, STE can be more cost competitive. However, it should also be noted that storage methods such as pump storage stations and pressurized air are limited to certain, small regions, where the necessary geological formations (caverns / valleys) are available and are realizable (in case of pump) only with considerable side effects on the environment where they are to be built (dams, artificial lakes, etc.). Additionally storage capacity for wind is hardly available in a sufficient scale to store enough energy to compensate longer periods (days, weeks) with no / little wind. In the case of PV, base cost penalizes competitiveness for dispatchable PV systems and it is not expected to become more cost efficient than dispatchable STE plants.

As demonstrated, STE technologies are expected to replace conventional CO_2 emitting energy sources like gas and coal. They complement the RES portfolio with a cost competitive dispatchable alternative that can make the most out of the climate in regions with high solar radiation. These facts enable the achievement of the STE target positioning.

5. Energy policy enablers for STE large scale development

The STE industry roadmap illustrates the actions that the industry is taking and the potential that STE technology comprises. These are expected to allow STE to become competitive compared to some other energy sources. However, to achieve the targets estimated by the industry, it is critical that governments foster the deployment of the STE technology. Management of investment risks and fulfilment of structural requirements are the areas where policy makers play their part in the concretization of the STE vision. In order to help create proper legal and energy policy favourable conditions, in this section a policy framework targeted at the STE industry is proposed.

The following framework identifies enablers that need to be addressed for large scale STE deployment, defines basic pre-requisites for a comprehensive support scheme to foster the deployment of STE, and addresses country specific needs and drivers for the adoption of STE.

5.1 Key energy policy enablers for STE

In order to create suitable conditions for the adoption of the STE technology and foster its growth, five key enablers need to be addressed:

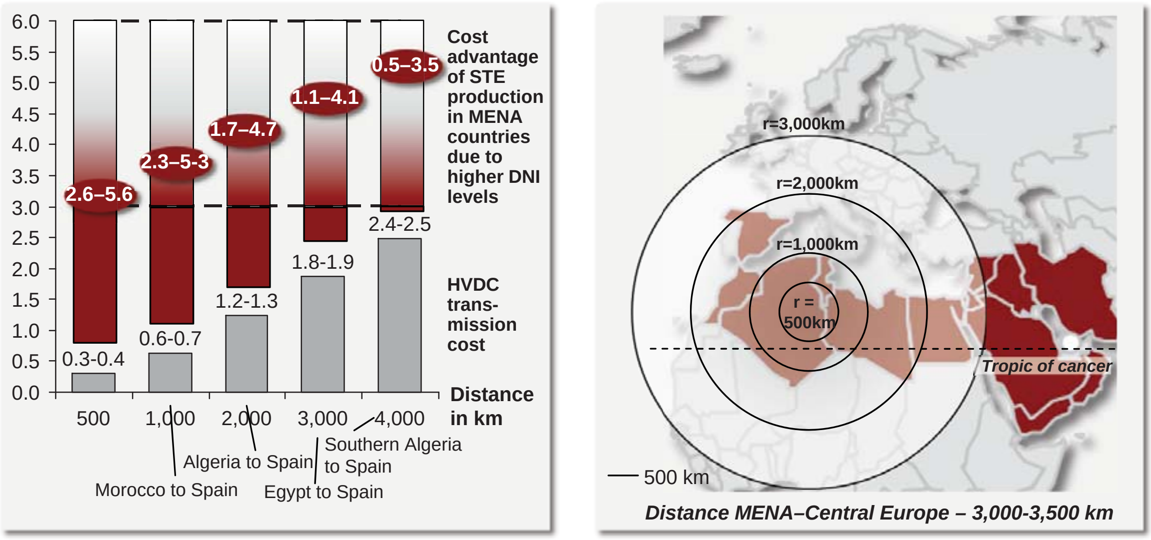
- Favourable energy policy mechanisms and financial support schemes to mitigate initial investment risks and foster innovation
- Suitability of country's energy legislation to STE technology requirements
- National and cross-national cooperation mechanisms for STE deployment
- Grid integration through HVDC connections to enable large energy exchanges between STE producing countries and green electricity demanding countries
- Adjustment/establishment of market mechanisms to support the exchange of green electricity

The implementation of these political levers constitutes a pre-requisite to support the STE industry in realizing its vision.

Creation of financial support schemes

As previously shown, the costs of electricity production through STE technology are still at a higher level than certain other energy sources. This creates a gap between production cost and the average price for green electricity. Financial support schemes can close this gap and enable STE project viability by compensating green electricity production. Also, the development of STE plants carries a significant amount of initial investment (in the order of hundreds of millions of Euros). To finance such investment, plant developers must rely on bank loans. Despite banks showing a pre-disposition to invest in green energy projects, like STE plants construction, and verbal agreements which are getting a lot of public visibility, actual financing of projects has been less visible. Creation of financial support schemes, like feed-in tariffs or tax credits, which provide plant developers with a predictable level of revenues, allows them to ensure debt repayment to financial institutions. This way financing access is easier to obtain, enabling STE plant development. Additionally, lending based support schemes like loan guarantees can also ensure proper STE plant financing in case banks do not make themselves available. In order to make STE plant developments feasible and to create confidence for investors, financial support schemes should have a long term perspective and be stable, i.e., they should not contemplate retroactive cuts or changes other crucial parameters.

Figure 31: HVDC transmission costs



(1)Includes cost of transmission losses –
Note: transmission cost for HVAC not considered; cost efficient HVDC connection considered as prerequisite for large scale deployment STE in MENA region;
Sources: A.T. Kearney analysis; Industry analysis

Suitability of country's energy legislation

Legislation of STE target countries is an important enabler for this technology. Energy laws and regulatory regimes should not pose artificial limits that may hinder STE competitiveness. A specific example is Spain where plant size limitation caps the achievement of increased cost competitiveness through economies of scale, as previously discussed. Such regulatory measures should be avoided / reviewed.

Grid integration through HVDC connections

The MENA region possesses excellent DNI levels which favor STE. One way for countries with demand for green electricity, like in Europe, to leverage on this, and gain access to competitive dispatchable green electricity, would be to import this STE generated electricity from MENA countries. In order to enable this, a suitable large distance transportation grid would have to be installed. Commonly used HVAC lines are not viable for transporting electricity over distances above a few hundred kilometers.

However, high-voltage direct-current (HVDC) technology can be competitive for long-distance transportation. Long distance HVDC lines of high capacity already exist around the world (e.g. Inga-Shaba with a 1.700km HVDC line of 600MW in the Democratic republic of Congo). They link producing areas to large consumption centers. Despite the higher cable costs and the 3% to 5% conversion losses, the business case for HVDC deployment is sound and ensures returns as already demonstrated in Europe. Figure 31 demonstrates how HVDC can be competitively used to provide STE electricity for Europe which has been produced in the MENA region:

HVDC infrastructure can boost STE deployment in MENA and provide a cost competitive renewable energy source for Europe. HVDC connections should not only focus on the MENA and European regions but rather link all sunbelt countries which have good solar resources for STE deployment, creating a worldwide super-grid, in order to increase redundancy of supply and further create the conditions for renewable energy source trading.

It is also obvious that HVDC infrastructure can be leveraged, not only by STE, but by other renewable as well, with the same cost structure. As such, HVDC installation can be seen as an enabler lever not only for STE, but for renewable energies in general.

Cooperation mechanisms

Private-public agreements or international protocols in favour of green electricity supply present an opportunity to foster STE development. These types of cooperation mechanisms enable a stabilization of expected demand for STE projects. Joint project development initiatives between public entities, governments and private partners not only provide a lever for growth for this technology. But they are also an opportunity to foster commercial trading relations between countries, especially between the regions of Europe and MENA. The development of HVDC lines, for instance, presents a relevant opportunity for cross-country collaboration.

Green market mechanisms development

A green energy exchange platform could provide an additional outlet for STE generated electricity, thus driving STE growth. Adjustment/establishment of market mechanisms to support green electricity trading, similar to the PowerNext trading platform, could be considered as a lever to address this enabler. A market driven STE industry would reward most competitive STE solutions, fostering competition. Harmonization of support schemes however, is key to develop this enabler.

5.2 Overview of support schemes for STE and support level requirements

There are several support schemes that have already demonstrated to be successful in contributing to the development of STE and other RES. Most relevant and effective support schemes to foster STE deployment are the following:

Feed-in tariff (FiT) – feed-in tariffs are electricity price supplements that governments establish through long-term contracts to encourage the adoption of renewable energy based on the cost of electricity production for the technology in question. Most EU countries with STE production potential already have a FiT systems in place, hence inclusion of STE is a very straightforward option, where not already employed;

FiT / PPA for imported energy – in order to facilitate the import of STE produced energy, a negotiated / tendered FiT for imported electricity could be implemented by a reverse auctions process, where governments invite bids from STE investors regarding the minimum FiT at which they would agree to deliver power;

Direct subsidies – attribution of subsidies to project developers for STE plant construction is another way to support the development of STE;

Build-operate-transfer (BOT) contracts – launch of STE BOT contracts for power supply in areas where energy is required is an additional mechanism to attract investment and justify subsidization;

RES Portfolio Standards – creation of required targets for share of STE and other renewable sources can provide long-term governmental target setting for state-owned and private power generators. To implement portfolio standards, utilities could be permitted to roll over some additional cost to end-consumers where possible;

Investment tax credits – Attribution of tax credits for the development of STE plants can allow improved project economics without requiring direct government subsidies;

Loan guarantees – Ensuring access for STE project financing is very important to for instance overcome current financing obstacles for private financial institutions like banks;

Clean Development Mechanism (CDM) – CDM are comprised of a legislatory framework that demands investment in clean energy sources to offset effects of fossil fuel combustion. Specific CDM can be created to direct investment for STE projects;

R&D Support – Grants, Soft loan guarantees and risk sharing mechanisms can be used to develop innovative technologies as well as further speed-up the rate of cost reductions resulting from technological improvements (e.g. EU and national R&D programs, EU SET Plan);

Direct infrastructure investment – Exports of STE generated electricity requires strengthening of transmission capacities. Directly investing in the deployment of the required infrastructure is an important option to foster its development. Creation of public-private protocols and cross-national cooperation may complement public investment;

Market mechanisms – Market oriented support schemes reward most competitive STE solutions by realizing additional margin in the market;

Multilateral supports – Multilateral institutions like the EIB, World Bank or European Commission bodies, can provide financing tools to mitigate financial/technology risk (e.g. first lost instruments, debt guarantees and grants) which assist in mobilizing capital not only from Governments but from other public and private sources

Above list only includes the most relevant methods of supporting the STE industry. However, the list is by no means exhaustive and further political initiatives can also be applied for STE, e.g.: accelerated depreciation, lower green power import tariffs, export credits carbon price trading system, level playing field (no subsidies for coal, gas or further taxes on fossil fuels), green certificates, etc.

The development of an effective support framework for STE cannot be based on a single support scheme. Discussed methods provide complementary support (e.g. fixed and variable) and a combination of those ensures that the set of STE development requirements are met.

6. Conclusion:

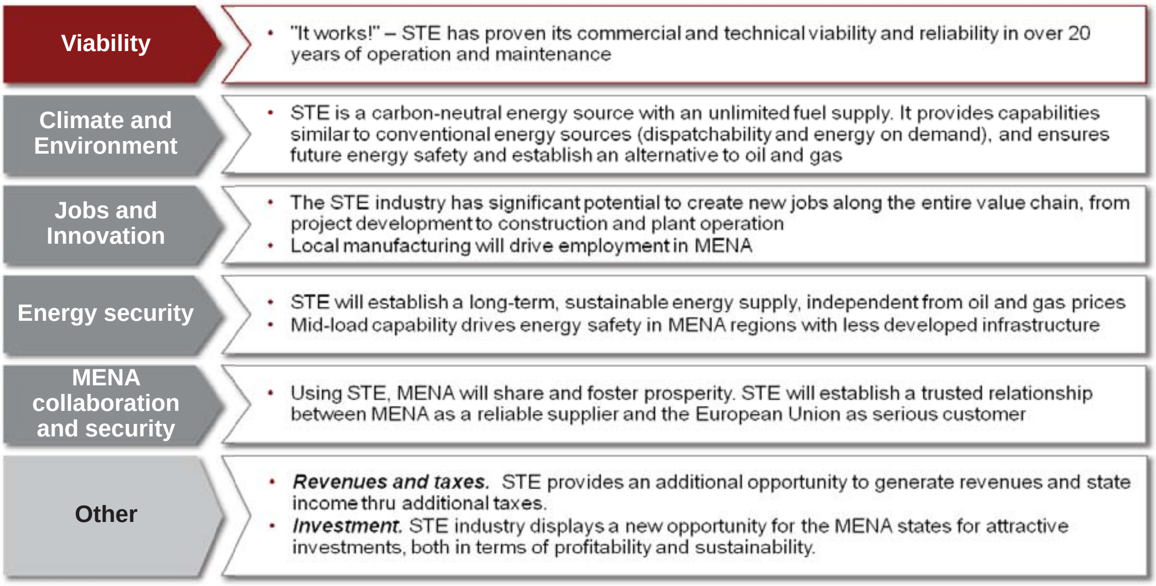
As substantiated by this report, STE possesses a unique value proposition. Since the operation of its first plants, STE has acquired a distinctive maturity and viability status among renewable energy sources as a predictable, dispatchable and reliable green electricity alternative. STE industry is committed to further improve the technology in order to bring it to competitive levels against conventional non-renewable energy sources as demonstrated by the several improvement initiatives currently being pursued by the research and development of STE industry participants.

STE has the potential to become an important lever on the achievement of key economic, energy and environmental policy targets.

6.1 Relevance of STE for the achievement of political targets

Environmental, climatic and energetic issues are currently of utmost importance on global and local politics. The new EU RES Directive establishes binding targets for all member states, e.g. to increase the share of renewable energies in the EU up to 20%

Figure 32: Political issues addressed by STE



by 2020. Also, during the 2009 Copenhagen summit, world countries restated their target to significantly reduce CO_2 emissions up to 30% until 2025[20].

Launch of initiatives as the Mediterranean Solar Plan (MSP)), which was strongly supported by ESTELA has already placed STE on top of utilities', governments' and decision makers' agendas. Political implications of the development of STE further stress the relevance of this technology for energy policy. Figure 32 summarizes the key political issues for which STE can be leveraged.

The first completed SEGS plants, developed during the 1980s, are still operating and producing green electricity which demonstrates that STE is a reliable and viable technology for supplying energy. Governments and utilities can rely on it as a long-term solution to address its political issues.

Due to its technical characteristics and operational principles, STE technologies are CO_2 neutral. Government supported STE fostering can contribute to the achievement of carbon emission reduction targets while still contributing to energy supply security, particularly for mid load which is currently only fulfilled by conventional energy sources. Also, harnessing the power of the sun, STE relies on an unlimited 'fuel' supply which is independent from fossil fuel prices, like gas and oil, ensuring this way predictability of the cost of electricity which enables better political decision-making regarding energy supply.

Not only environmental and energetic issues can be addressed by STE. Due to the high share of local content, STE project development, construction and operation can drive significant domestic economical development through job creation. Figure 33 illustrates the demand in man-power for the construction and operation of a 100MW project along the several steps of the project value chain. A best-case scenario of up to 100 gigawatts (GW) of global installed capacity in 2025 involves the potential creation of 100,000 to 130,000 new jobs as a result of the STE industry roadmap. Of these, 45,000 would be permanent full-time jobs in operation and maintenance.

In addition to job creation, STE can further

[20] *EU is currently considering to reduce emission by 30% vs. 1990 levels by 2020*

Figure 33: Local content of STE plant installation and operation

	Local content	Foreign share	Local manpower demand	
Project development	0-10%	90-100%	**6-20 MY**	Planning and construction phase (2 years temporary demand)
Engineering planning	30-50%	50-70%	**75-95 MY**	
Technology (procurement)	30-60%	40-70%	**145 -220 MY**	
Construction and site improvement	100%	0%	**320 MY**	
Operations and maintenance	90-100%	0-10%	**40-45 FTE**	Permanent jobs

Notes: 1 MY (man year) equals 1,760 man hours; FTE stands for full-time equivalent; the reference is a 100-MW plant installation in MENA
Source: Industry analysis; A.T. Kearney analysis

contribute to countries' economic value creation by providing an additional source of public income and revenues and providing sustainable and potentially very profitable investment opportunities.

From an international policy view point, cross-country cooperation under the scope of collaborative STE related project developments like HVDC connection deployment, creation of a green energy market mechanism or energy supply agreements, can contribute to the strengthening of trustful relationships between countries which will further drive common prosperity. For MENA region countries, like for instance Iran, STE also poses the opportunity to install energy producing capabilities without relying on politically arguable energy sources, like nuclear power.

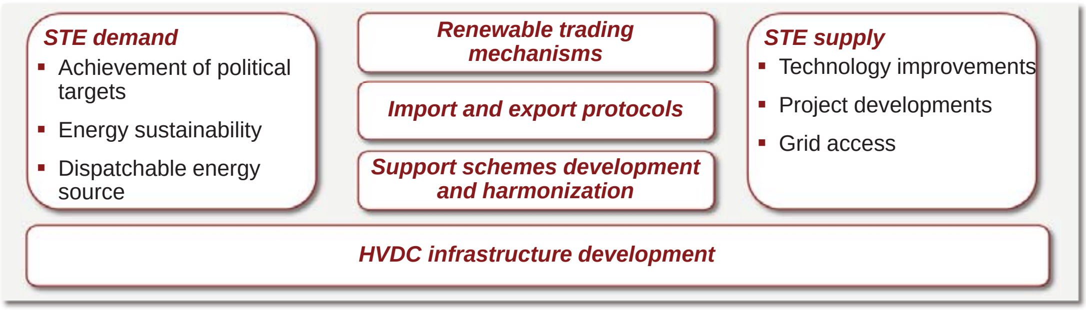
6.2 Recommended action plan per key stakeholder group

Several entities will have a role in the future development of STE. To ensure that the most effective actions are put into place, and that a collective and aligned effort is developed to tackle the challenges of this energy source, a set of recommended actions is proposed for the key stakeholder groups, including:

- Policy makers which have the capability to create a suitable political framework
- The STE industry as responsible for the improvement of the technology
- Utilities and other off-takers which should adopt STE as a main energy source for electricity supply
- Other organizations which should mobilize acceptance and negotiations of STE related projects

Actions to be taken should focus on the fulfilment of the STE industry vision by addressing previously discussed enablers for STE. Required HVDC infrastructure should be deployed, connecting sunbelt STE producing countries with centres of consumption. Creation of harmonized support schemes along with necessary import/ export mechanisms and renewable energy trad-

Figure 34: The focus for near-term actions



Source: A.T. Kearney analysis

ing mechanisms should be in place to balance STE supply and demand. Action to ensure both supply and demand development should also be put in place. Figure 34 summarizes the high-level focus of these actions to ensure realization of STE industry vision.

According to the identified stakeholder groups and the proposed action focus, the following actions are recommended: *see Figure 35.*

Organizations like ESTELA are already adopting suggested next steps and addressing several of the current STE challenges. These include: creating the conditions for STE in the MENA region, develop investment guidelines and goals for the establishment of a cross-country STE energy supply concept and starting the development of demonstration projects as proof of concepts to encourage further independent adopters.

Figure 35: Key recommended actions per stakeholder group

Stakeholder group	Recommended actions
Policy makers	• Create the mechanism and incentives to ensure STE financing • Review legislations to eliminate STE hindering laws • Ensure required support schemes for STE deployment • Fund STE innovation initiatives • Provide trans-national opportunities to use support schemes • Install cooperation mechanisms between EU countries to enable the trade of green electricity • Create cross-national agreements for the development of STE related projects • Foster deployment of HVDC connections • Facilitate permitting procedures for STE • Foster STE projects realization
STE industry	• Implement STE technology improvements • Pursue further technological innovation • Continue to launch pilot and commercial projects
Utilities	• Launch PPAs for STE produced electricity • Embrace STE project developments • Ensure grid access for STE • Contribute to dispatchability of STE • Participate in the development of local/cross-country HVDC infrastructure
Other organizations	• Create awareness for STE value proposition • Foster cross-national collaboration for development of STE related projects (e.g. HVDC, trading mechanism) • Develop investment and financing solutions for STE (e.g. multilaterals)

Methodology

The analysis that supports this report was developed by an independent consulting firm – A.T. Kearney – which worked very closely with leading experts of the STE industry. For the technology road map A.T. Kearney contracted the Spanish National Renewable Energy Centre CENER. Participating members represent all steps of the STE industry's value chain – R&D institutes, technology developers, component manufacturers, utilities, governmental agencies, banks. Participating companies and interview partners in preparation of the STE Industry roadmap were:

- Research institutes: CIEMAT, Plataformar Solar de Almería, CTAER, Universidad de Sevilla
- Technology developers: Abengoa Solar, Acciona, ACS Cobra, CNIM, Ferrostaal, Flagsol, SENER, Solar Reserve, Siemens, Tessera Solar, Solar Power Group, Novatec Biosol, Schlaich Bergermann und Partner, eSolar, Infinia, SkyFuel
- Component manufacturers: Archimedes Solar Energy, BASF, Cevital, Dow, Flabeg, Schott Solar, Senior Berghöfer, Siemens, Consorzio Solare XXI, SQM, RioGlass, Saint Gobain,
- Plant developers: Abengoa Solar, Acciona, ACS Cobra, CNIM, eSolar, Ferrostaal, SAMCA, Solar Millenium SolarReserve, Novatec Biosol
- Utilities: ENEL, ESB International, RWE, Veolia
- Banks: Deutsche Bank, Sarasin
- Governmental Institutions: European Comission, European Parliament
- International Institutions: International Energy Agency, the DESERTEC Foundation and Industrial Initiative
- Industry associations: ESTELA, ProtermoSolar

The roadmap was developed following a bottom-up approach. Technological improvements and cost reduction potential was assessed by more than one hundred interviews.

To ensure the creation of a solid and bankable technology roadmap, the main focus of the analysis was on technical developments expected until 2015. These improvements are currently under development by STE companies, and quantifiable impacts can be reliably derived. To contribute to an independent vision of the study, all feedback received from participants was challenged by CENER. Further improvement potential that can be expected between 2015 and 2025 was also taken into account, although with the respective degree of uncertainty and caution.

After identifying and quantifying improvements and cost reduction potential, their total impact was transferred to a financial model which simulated the expected electricity cost developments.

Four collective workshop sessions were also held in order to further challenge the results and to create a common understanding between participating members about the development of the STE industry.

Due to the number and profiles of the companies participating in roadmap development and also due to the approach employed, the study is highly representative for the STE industry. It is considered a solid and realistic STE technology roadmap by all participants.

Abbreviations

Throughout this report the following abbreviations have been used:

BOT	build, operate, transfer
CAPEX	Capital Expenditure
CDM	clean development mechanism
DNI	Direct normal irradiation
DS	Dish Stirling
DSCR	Debt service coverage ratio
EPC	engineering, procurement, construction
FiT	Feed-in tariff
HVDC, HVAC	high voltage direct current, high voltage alternating current
kW, MW, GW	Power: kilowatt, megawatt, gigawatt
kWh, MWh, GWh	Energy: kilowatt-hour, megawatt-hour, gigawatt-hour
LCOE	Levelized cost of electricity
LF	Linear Fresnel
m, m^2	meter, square meter
MENA	Middle East and North Africa
PT	Parabolic Trough
PV	photovoltaics
RES	Renewable energy source
SAF	synthetic aromatic fluid
ST	Solar Tower
STE	Solar Thermal Electricity
WACC	weighted average cost of capital

Glossary

Absorptance	Optical characteristics of surfaces which measure the share of solar radiation that is successfully captured by a surface
Aperture	Total area over which sun radiation can be captured by a solar field
Direct Normal Irradiation	Corresponds to the direct part of the energy carried by sun rays on a given area measured as KWh/m2 per area
Dispatchability	Ability to dispatch on-demand produced electricity to the distribution grid
Emittance	Thermal characteristic of a surface which measures the thermal radiation emitted in comparison to a black body
Freezing point	Temperature at which a given material passes from liquid to solid state
Hybridization	Combination of more than one energy source to produce electricity
Molten salt	Salt mixture which due to chemical characteristics is suitable for thermal storage applications as well as heat transfer fluid (today liquid mixture of sodium nitrate and potassium nitrate)
Saturated/superheated steam	When water is boiled, it starts to produce steam. Saturated steam corresponds to the steam heated at a temperature at which the liquid water and the vapour are in equilibrium, meaning that there is no vapour-liquid conversion. Superheated steam is steam at a temperature higher than the water's boiling point. If saturated steam is heated at constant pressure, its temperature will rise, producing superheated steam.
Stirling engine	Heat engine that operates by cyclic compression and expansion of a determined working fluid. There are several types of stirling engines. For STE applications two are used: kinematic and free piston. The main difference between those is the existence of a piston interfacing with the displacer piece (moving part that creates fluid's compression/expansion).
Transmittance	Optical characteristic of a material that measures the fraction of incident solar radiation that passes through a sample of that material

Appendix: List of STE project pipeline per technology

Status	Name	Technology	Capacity (MW)	Location	Country
Operating	SEGS I	Parabolic Trough	13,8	California	US
	SEGS II	Parabolic Trough	30	California	US
	SEGS III	Parabolic Trough	30	California	US
	SEGS IV	Parabolic Trough	30	California	US
	SEGS V	Parabolic Trough	30	California	US
	SEGS VI	Parabolic Trough	30	California	US
	SEGS VII	Parabolic Trough	30	California	US
	SEGS VIII	Parabolic Trough	80	California	US
	SEGS IX	Parabolic Trough	80	California	US
	Saguaro	Parabolic Trough	1	Arizona	US
	PS10	Solar Tower	11	Seville	Spain
	Nevada Solar 1	Parabolic Trough	64	Nevada	US
	Kimberlina	Linear Fresnel	5	California	US
	Andasol-1[21, 22]	Parabolic Trough	50	Granada	Spain
	PS20	Solar Tower	20	Seville	Spain
	Puertollano	Parabolic Trough	50	Ciudad Real	Spain
	PE1	Linear Fresnel	1,4	Murcia	Spain
	Maricopa	Dish Stirling	1,5	California	US
	La Risca	Parabolic Trough	50	Badajoz	Spain
	Andasol-2[21, 22]	Parabolic Trough	50	Granada	Spain
	Extresol-I[21]	Parabolic Trough	50	Badajoz	Spain
	Solnova 1	Parabolic Trough	50	Sevilla	Spain
	Solnova 3	Parabolic Trough	50	Sevilla	Spain
Under construction	Archimede[21]	Parabolic Trough	4,7	Sicily	Italy
	El Reboso II	Parabolic Trough	50	Seville	Spain
	Andasol-III[21, 23]	Parabolic Trough	50	Granada	Spain
	Majadas	Parabolic Trough	50	Cáceres	Spain
	Extresol-II[21]	Parabolic Trough	50	Badajoz	Spain
	Extresol-III[21]	Parabolic Trough	50	Badajoz	Spain
	Gemasolar[21]	Solar Tower	17	Seville	Spain
	Helioenergy 1	Parabolic Trough	50	Ciudad Real	Spain
	Helioenergy 2	Parabolic Trough	50	Ciudad Real	Spain
	ISCC Argelia	Parabolic Trough	150	Hassi R'mel	Algeria
	ISCC Kuraymat 1	Parabolic Trough	150	Kuraymat	Egypt
	ISCC Morocco	Parabolic Trough	470	At Ain Beni Mathar	Morocco
	La Dehesa	Parabolic Trough	50	Badajoz	Spain
	La Florida	Parabolic Trough	50	Badajoz	Spain
	Lebrija 1	Parabolic Trough	50	Sevilla	Spain
	Majadas I	Parabolic Trough	50	Caceres	Spain
	Manchasol-I[21]	Parabolic Trough	50	Ciudad Real	Spain
	Manchasol-II[21]	Parabolic Trough	50	Ciudad Real	Spain
	MNGSEC	Parabolic Trough	75	Florida	US

[21] *Includes storage*
[22] *Plants developed by ACS/Cobra*
[23] *Plant developed by Ferrostaal and Solar Millenium*

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