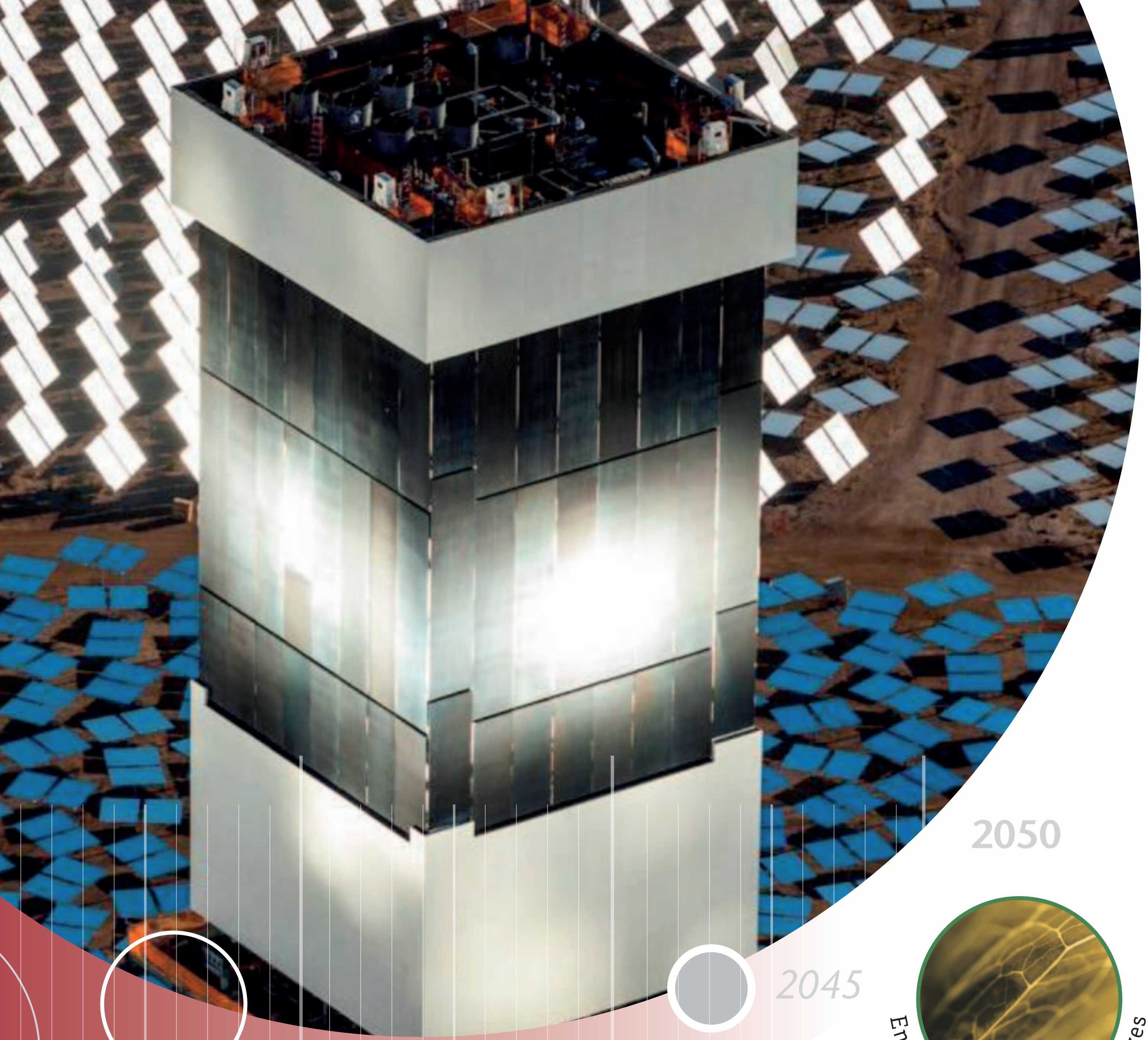

Energy Technology Perspectives

Technology Roadmap

Solar Thermal Electricity

2014 edition

International Energy Agency
Secure • Sustainable • Together

INTERNATIONAL ENERGY AGENCY

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Foreword

Current trends in energy supply and use are unsustainable – economically, environmentally and socially. Without decisive action, energy-related greenhouse-gas (GHG) emissions would lead to considerable climate degradation with an average 6°C global warming. We can and must change the path we are now on; sustainable and low-carbon energy technologies will play a crucial role in the energy revolution required to make this change happen. Energy Efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to achieve a global energy-related CO_2 target in 2050 of 50% below current levels and limit global temperature rise by 2050 to 2°C above pre-industrial levels.

This will require significant global investment into decarbonisation, which will largely be offset by reduced expenditures on fuels. Nonetheless, this supposes an important reallocation of capital. To address this challenge, the International Energy Agency (IEA) is leading the development of a series of technology roadmaps which identify the steps needed to accelerate the implementation of technology changes. These roadmaps will enable governments, industry and financial partners to make the right choices – and in turn help societies to make the right decision.

Solar thermal electricity (STE) generated by concentrating solar power (CSP) plants is one of those technologies. It has witnessed robust growth in the last four years, although less than expected in the 2010 IEA technology roadmap. More importantly, the technology is diversifying, creating pathways that promise to increase deployment by reducing costs and opening new markets. Meanwhile, the rapid deployment and the decrease in costs of solar photovoltaics (PV), as well as other important changes in the energy landscape, notably greater uncertainty in regard to nuclear power and CCS, have led the IEA to reassess the role of both solar technologies in mitigating climate change.

The interesting outcome of this reassessment is that the vision set for STE four years ago, to reach about 11% of global electricity generation by 2050, has remained unchanged – despite the increased prospects for PV deployment. Their built-in storage capabilities allow CSP plants to supply electricity on demand. This decisive asset is already being used to generate electricity when demand peaks after sunset in emerging economies with growing capacity needs. This advantage will only gain in importance as variable renewable energy sources such as PV and wind power increase their shares of global electricity. Hence this updated roadmap envisages reduced medium-term prospects for STE deployment, but almost no reduction in long-term prospects.

Countries must establish stable policy frameworks for investments in CSP plants to take place. Like most renewables or energy efficiency improvements, STE is very capital intensive: almost all expenditures are made upfront. Lowering the cost of capital is thus of primary importance for achieving the vision of this roadmap. Clear and credible signals from policy makers lower risks and inspire confidence. By contrast, where there is a record of policy incoherence, confusing signals or stop-and-go policy cycles, investors end up paying more for their investment, consumers pay more for their energy, and some projects that are needed simply will not go ahead.

I strongly hope that the analysis and recommendations in this roadmap will play a part in ensuring the continued success of STE deployment and, more broadly, a decarbonised energy system.

This publication is produced under my authority as Executive Director of the IEA.

Maria van der Hoeven
Executive Director
International Energy Agency

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Acknowledgements

This publication was prepared by the Renewable Energy Division (RED) of the International Energy Agency (IEA). Cédric Philibert was the main author of this update, based on the original 2010 roadmap. Paolo Frankl, Head of RED, provided comments and inputs. Cecilia Tam, in her role as Technology Roadmap Co-ordinator, made important contributions through the drafting process. Several other IEA colleagues provided important contributions, in particular Yasmina Abdelilah, Heymi Bahar, Simon Mueller, Uwe Remme and Michael Waldron. The author is also grateful to Keisuke Sadamori, Director of Energy Markets and Security at the IEA, for his guidance.

The author would also like to thank Andrew Johnston for editing the manuscript as well as the IEA Publication Unit, in particular Muriel Custodio, Therese Walsh and Astrid Dumond, and Bertrand Sadin for executing the layout.

Finally, this roadmap would not be effective without the comments and support received from the industry, government and non-government experts who attended the workshop at IEA headquarters in Paris in February 2013, reviewed and commented on the drafts, and provided overall guidance and support. The authors wish to thank all of those, such as workshop participants, who contributed through discussions and early comments, in particular: Jenny Chase (BNEF), Manuel Collares Pereira (Universidade de Évora), Luis Crespo (Protermosolar) Gilles Flamant (CNRS), Rémy Flandin (AREVA Solar), Yoel Gilon (BrightSource), Bill Gould (SolarReserve), Frank Lenzen (Schott Solar), Elisa Prieto (Abengoa Solar), Christoph Richter (SLR/SolarPACES), Frédéric Siros (EDF) and Winfried Hoffmann (ASE).

Review comments were received from Nikolaus Benz (Schott Solar), Fabrizio Bizzarri (Enel GreenPower), Gilbert Cohen (Eliasol); Manuel Collares Pereira (Universidade de Évrora), Luis Crespo (Protermosolar); Fengli Du (China National Solar Thermal Energy Alliance), Jayesh Goyal (AREVA Solar), David Jacobowitz (BrightSource), Daniel Kammen (University of California), Anton Meier (PSI), Paula Mints (SPV Market Research), David Mooney (NREL), Fred Morse (Abengoa Solar), Robert Pitz-Pal (DLR), Werner Platzer (Fraunhofer ISE), David Renne (NREL/ISES), Christoph Richter (DLR/SolarPACES), Christian Sattler (DLR), David Schlosberg (BrightSource), Frédéric Siros (EDF), Martin Stadelmann (Climate Policy Initiative) and Frank "Tex" Wilkins (CSP Alliance).

This publication was made possible also thanks to the support of the French government through ADEME (French Environment and Energy Management Agency).

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Key findings and actions

- Since 2010, generation of solar thermal electricity (STE) from concentrating solar power (CSP) plants has grown strongly worldwide, though more slowly than expected in the first IEA CSP roadmap (IEA, 2010). The first commercial plants were deployed in California in the 1980s. A resurgence of solar power in Spain was limited to 2.3 gigawatts (GW) by the government in the context of the financial and economic crisis. Deployment in the United States was slow until 2013 because of long lead times and competition from cheap unconventional gas and from photovoltaic (PV) energy, whose costs decreased rapidly.[1] Deployment in other places took off only recently.

- Global deployment of STE, about 4 GW at the time of publication, pales in comparison with PV (150 GW). Costs of CSP plants have dropped but less than those of PV. However, new CSP components and systems are coming to commercial maturity, holding the promise of increased efficiency, declining costs and higher value through increased dispatchability. New markets are emerging on most continents where the sun is strong and skies clear enough, including the Americas, Australia, the People's Republic of China, India, the Middle East, North Africa and South Africa.

- This roadmap envisions STE's share of global electricity to reach 11% by 2050 – almost unchanged from the goal in the 2010 roadmap. This shows that the goal for PV in the companion roadmap (IEA, 2014a) is not increased at the detriment of STE in the long term. Adding STE to PV, solar power could provide up to 27% of global electricity by 2050, and become the leading source of electricity globally as early as 2040. Achieving this roadmap's vision of 1 000 GW of installed CSP capacity by 2050 would avoid the emissions of up to 2.1 gigatonnes (Gt) of carbon dioxide (CO_2) annually.

- From a system perspective, STE offers significant advantages over PV, mostly because of its built-in thermal storage capabilities. STE is firm and can be dispatched at the request of power grid operators, in particular when demand peaks in the late afternoon, in the evening or early morning, while PV generation is at its best in the middle of the day. Both technologies, while being competitors on some projects, are ultimately complementary.

- The value of STE will increase further as PV is deployed in large amounts, which shaves mid-day peaks and creating or beefing up evening and early morning peaks. STE companies have begun marketing hybrid projects associating PV and STE to offer fully dispatchable power at lower costs to some customers.

- Combined with long lead times, this dynamic explains why deployment of CSP plants would remain slow in the next ten years compared with previous expectations. Deployment would increase rapidly after 2020 when STE becomes competitive for peak and mid-merit power in a carbon-constrained world, ranging from 30 GW to 40 GW of new-built plants per year after 2030.

- Appropriate regulatory frameworks – and well-designed electricity markets, in particular – will be critical to achieve the vision in this roadmap. Most STE costs are incurred up-front, when the power plant is built. Once built, CSP plants generate electricity almost for free. This means that investors need to be able to rely on future revenue streams so that they can recover their initial capital investments. Market structures and regulatory frameworks that fail to provide robust long-term price signals beyond a few months or years are thus unlikely to attract sufficient investment to achieve this roadmap's vision in particular and timely decarbonisation of the global energy system in general.

Key actions in the next five years

- Set long-term targets, supported by predictable mechanisms to drive investments.

- Address non-economic barriers and develop streamlined procedures for permitting.

- Remunerate STE according to its value, which depends on time of delivery.

- Implement support schemes with fair remuneration to investors but predictable decrease over time of the level of support.

- Design and implement investment markets for new-built CSP plant and other renewable energy plants, and markets for ancillary services.

- Avoid retroactive legislative changes.

1. See the companion *Technology Roadmap: Solar Photovoltaic Energy* (IEA, 2014a).

- Work with financing circles and other stakeholders to reduce financing costs for STE deployment, in particular involving private money and institutional investors.
- Reduce the costs of capital and favour innovation in providing loan guarantees, and concessional loans in emerging economies.
- Strengthen research, development and demonstration (RD&D) efforts to further reduce costs.
- Strengthen international collaboration on RD&D and exchanges of best practices.

Introduction

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of clean energy, climate change and sustainable development. To achieve the necessary reductions in energy-related CO_2 emissions, the IEA has developed a series of global technology roadmaps, under international guidance and in close consultation with industry. These technologies are evenly divided among demand-side and supply-side technologies, and include several renewable energy roadmaps (www.iea.org/roadmaps/).

The overall aim is to advance global development and uptake of key technologies to limit the global mean temperature increase to 2 degrees Celsius (°C) in the long term. The roadmaps will enable governments, industry and financial partners to identify and implement measures needed to accelerate development and uptake of the required technologies.

The roadmaps take a long-term view, but highlight the key actions that need to be taken in the next five years, which will be critical to achieving long-term emissions reductions. Existing conventional plants and those under construction may lock in CO_2 emissions, as they will be operating for decades. According to the *IEA Energy Technology Perspectives 2014* (*ETP 2014*) (IEA, 2014b), early retirement of 850 GW of existing coal capacity would be required to reach the goal of limiting climate change to 2°C. Therefore, it is crucial to build up low-carbon energy supply today.

Rationale for solar thermal electricity in the overall energy context

ETP 2014 projects that in the absence of new policies, CO_2 emissions from the energy sector would increase by 61% over 2011 levels by 2050 (IEA, 2014b). The *ETP 2014* model examines a range of technology solutions that can contribute to preventing this increase: greater energy efficiency, renewable energy, nuclear power and the near-decarbonisation of fossil fuel-based power generation. Rather than projecting the maximum possible deployment of any given solution, the *ETP 2014* model calculates the least-cost mix to achieve the CO_2 emissions reduction goal needed to limit climate change to 2°C (the *ETP 2014* 2°C Scenario [2DS]). The hi-Ren Scenario, a variant of the 2DS, envisages slower deployment of nuclear and carbon capture and storage (CCS) technologies, and more rapid deployment of renewables, notably solar and wind energy.

Based on the *ETP 2014* hi-Ren Scenario, this roadmap envisions up to 11% of global electricity by 2050, or 4 350 TWh, almost unchanged from the goal of the 2010 roadmap (which included a higher amount of fossil fuel back-up, however). This assessment includes some intercontinental energy transfers, notably between Europe and North Africa, which are regionally significant but have minor global impact.

STE generates electricity while producing no greenhouse gas emissions, so it could be a key technology for mitigating climate change. In addition, the flexibility of CSP plants enhances energy security. Unlike solar photovoltaic (PV) technologies, CSP plants use steam turbines, and thus inherently provide all the needed ancillary services. Moreover, they have an inherent capacity to store thermal energy for later conversion to electricity. CSP plants can also be equipped with backup from fossil fuels delivering additional heat to the system. When combined with thermal storage capacity of several hours of full-capacity generation, CSP plants can continue to produce electricity even when clouds block the sun, or after sundown or in early morning when power demand steps up.

The technologies deployed in CSP plants to generate electricity also show significant potential for supplying specialised demands such as process heat for industry; co-generation of heating, cooling and power; and water desalination. They could also produce concentrating solar fuels (CSF, such as hydrogen and other energy carriers) – an important area for further research and development. Solar-generated hydrogen can help decarbonise the transport and other end-use sectors by mixing hydrogen with natural gas in pipelines and distribution grids, and by producing cleaner liquid fuels. Solar fuels could also be used as zero-emission back-up fuel for generating STE.

Purpose of the roadmap update

The CSP roadmap was one of the first roadmaps developed by the IEA, in 2009-10. Since then, CSP deployment has been slower than expected. The 147 GW of cumulative capacity expected to be reached by 2020 is now likely to be achieved seven to ten years later at best. As STE becomes competitive on more markets, however, its deployment is likely to accelerate after 2020, reaching impressive growth in a carbon-constrained world.

This updated roadmap takes into account changes in the energy landscape. It shows that rapid deployment of PV has delayed the deployment of STE but is unlikely to impede it in the longer term, because STE's built-in thermal storage and synchronous generation will give it a strong advantage from a system perspective despite higher energy costs. Further, the roadmap takes stock of the progress the technology has made, and of the rapid evolution of technology concepts.

This roadmap also examines numerous economic and non-economic barriers to achieving the much higher STE deployment needed to reach global emissions reduction targets, and identifies the policy actions and timeframes necessary to overcome those barriers. In some markets, certain actions have already been taken or are under way. Many countries, particularly in emerging regions, are only just beginning to develop CSP plants. Accordingly, milestone dates should be considered as indicative of urgency, rather than as absolutes. Each country will have to choose which actions to prioritise, based on its mix of energy sources and industrial policies.

This roadmap is addressed to a variety of audiences, including policy makers, industry, utilities, researchers and other interested parties. As well as providing a consistent overall picture of STE at global and continental levels, it aims to provide encouragement and information to individual countries to elaborate action plans, set or update targets, and formulate roadmaps for CSP technology and STE deployment.

Roadmap process, content and structure

This roadmap was developed with the help of contributions from representatives of the solar industry, the power sector, research and development (R&D) institutions, the finance community and government institutions. An expert workshop was held in Paris in February 2014 at IEA headquarters in Paris, focusing on technology and vision for both PV and STE.[2] A draft was then circulated to experts and interested parties for further contributions and comments.

The roadmap also takes into account other regional and national efforts to investigate the potential of STE:

- the SunShot Initiative of the US Department of Energy (US DoE)
- the EU Strategic Energy Technology Plan (Set Plan).

This roadmap is organised into five major sections. First, the current state of the STE industry and progress since 2009 is discussed, followed by a section that describes the vision for STE deployment between 2015 and 2050 based on *ETP 2014*. This discussion includes information on the regional distribution of CSP plants and the associated investment needs, as well as the potential for cost reductions.

The next two sections describe approaches and specific tasks required to address the major challenges facing large-scale STE deployment in two major areas: STE technology development; and policy framework development, public engagement and international collaboration.

The final section sets out next steps and categorises the actions in the previous sections that policy makers, industry, power system actors, and financing circles need to take to implement the roadmap's vision for STE deployment.

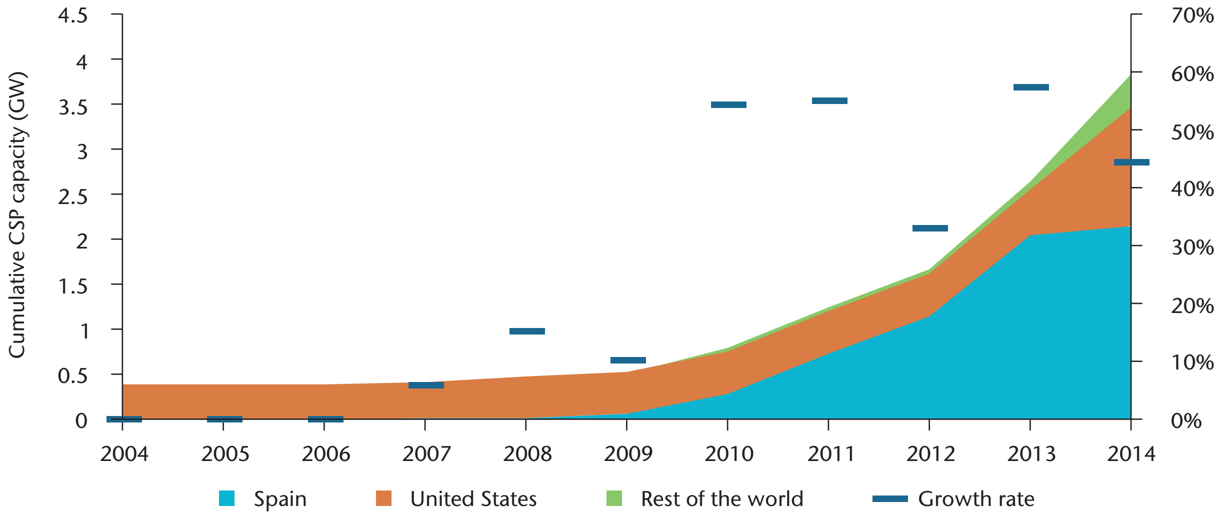
2. See www.iea.org/workshop/solarelectricityroadmapworkshop.html.

Progress since 2009

The STE industry has experienced robust growth since 2009, although from low initial levels (Figure 1). This growth has been concentrated in Spain and the United States, but has begun to be seen in many other countries. Market prices, which have been slow to diminish, finally seem to be falling. New technologies have reached commercial maturity and new concepts have emerged. Thermal storage in molten salts is routinely used in trough configurations and has been demonstrated in solar towers.

Recent market developments

Figure 1: Global cumulative growth of STE capacity



Source: Unless otherwise indicated, all tables and figures derive from IEA data and analysis.

KEY POINT: STE so far has been a tale of two countries, Spain and the United States.

Table 1: Progress in STE since 2009

	End of 2009	End of 2013
Total installed capacity	600 MW	3.6 GW
Annual installed capacity	100 MW	882 MW
Annual investment	USD 1.8 billion	USD 6.8 billion
Number of countries with 50 MW installed	2	5
STE generated during the year	0.9 TWh	5.5 TWh

With 2 304 megawatts (MW) of cumulative CSP capacity, of which 300 MW was added in 2013, Spain leads the world in STE, but will soon be overtaken by the United States.

Spain is the only country where STE is "visible" in national statistics, with close to 2% of annual electricity coming from CSP plants (REE, 2014). Maximum instantaneous contribution in 2013 was 7.6%, maximum daily contribution 4.6%, and maximum monthly contribution 3.6% (Crespo, 2014).

The United States ranks second, with 900 MW at the end of 2013 and 750 MW added in early 2014. More than 20 large projects are being promoted or are in early development but not all will survive the permitting process or negotiations with utilities for appropriate remuneration.

The largest plants in the rest of the world are in the United Arab Emirates and India, but others are in construction in Morocco and South Africa. Smaller solar fields, often integrated in larger fossil fuel plants, also exist in Algeria, Australia, Egypt, Italy, Iran and Morocco.

Box 1: Solar radiation relevant for CSP/STE

Solar energy is the most abundant energy resource on earth, with about 885 million terawatt hours (TWh) reaching the surface of the planet every year – 6 200 times the commercial primary energy consumed by humankind in 2008, and 3 500 times the energy that humankind would consume in 2050 according to the *ETP 2014* 6°C scenario, the 6 DS. (IEA, 2011; 2014b).

The solar radiation reaching the earth's surface equals about 1 kilowatt per square metre (kW/m^2) in clear conditions when the sun is near the zenith. It has two components: direct or "beam" radiation, which comes directly from the sun's disk; and diffuse radiation, which comes indirectly after being scattered in all directions by the atmosphere. Global solar radiation is the sum of the direct and diffuse components.

Global horizontal irradiance (GHI) is a measure of the density of the available solar resource per unit area on a plane horizontal to the earth's surface. Global normal irradiance (GNI) and direct normal irradiance (DNI) are measured on surfaces "normal" (i.e., perpendicular) to the direct sunbeam. GNI is relevant for two-axis, sun-tracking, "1-sun" (i.e., non-concentrating) PV devices. DNI is the only relevant metric for devices that use lenses or mirrors to concentrate the sun's rays on smaller receiving surfaces, whether concentrating photovoltaics (CPV) or CSP generating STE.

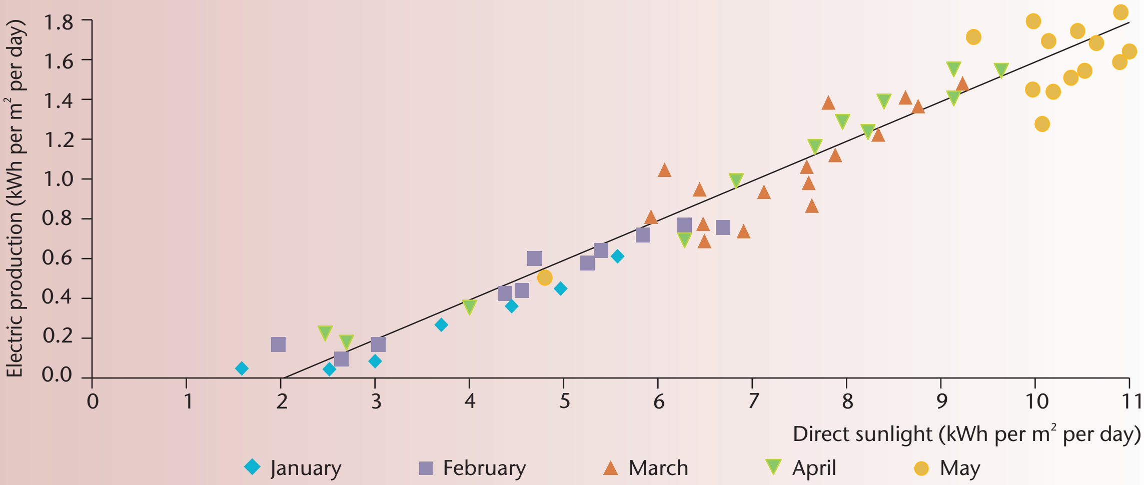
All places on earth receive 4 380 daylight hours per year — i.e., half the total duration of a year – but different areas receive different yearly average amounts of energy from the sun. When the sun is lower in the sky, its energy is spread over a larger area and energy is also lost when passing through the atmosphere, because of increased air mass; the solar energy received is therefore lower per unit horizontal surface area. Inter-tropical areas should thus receive more radiation per land area on a yearly average than places north of the Tropic of Cancer or south of the Tropic of Capricorn. However, atmospheric absorption characteristics affect the amount of this surface radiation significantly.

In humid equatorial places, the atmosphere scatters the sun's rays. DNI is much more affected by clouds and aerosols than global irradiance. The quality of DNI is more important for CSP plants than for CPV, because the thermal losses of a CSP plant's receiver and the parasitic consumption of the electric auxiliaries are essentially constant, regardless of the incoming solar flux. Below a certain level of daily DNI, the net output is null (Figure 2).

High DNI is found in hot and dry regions with reliably clear skies and low aerosol optical depths, which are typically in subtropical latitudes from 15° to 40° north or south. Closer to the equator, the atmosphere is usually too cloudy, especially during the rainy season. At higher latitudes, weather patterns also produce frequent cloudy conditions, and the sun's rays must pass through more atmosphere mass to reach the power plant. DNI is also significantly higher at higher elevations, where absorption and scattering of sunlight due to aerosols can be much lower.

Thus, the most favourable areas for CSP resource are in North Africa, southern Africa, the Middle East, north-western India, the south-western United States, northern Mexico, Peru, Chile, the western parts of China and Australia. Other areas that are suitable include the extreme south of Europe and Turkey, other southern US locations, central Asian countries, places in Brazil and Argentina, and some other parts of China.

Figure 2: Output of an early CSP plant in California as a function of daily DNI



Source: Pharabod, F. and C. Philibert (1992), *Luz solar power plants*, DLR for IEA-SSPS.

KEY POINT: Daily distribution of DNI is of primary importance for CSP plants, which have constant heat losses.

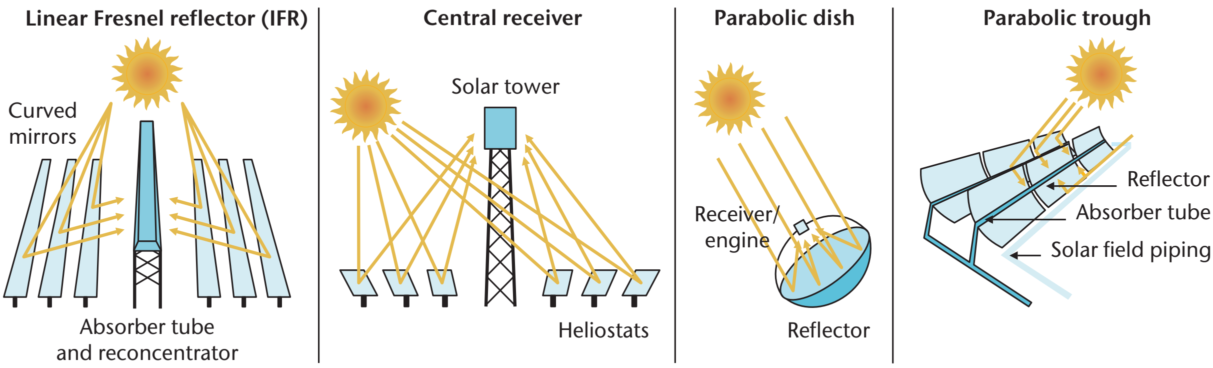
Technology improvements

CSP plants concentrate solar rays to heat a fluid, which then directly or indirectly runs a turbine and an electricity generator. Concentrating the sun's rays allows for the fluid to reach working temperatures high enough to ensure fair efficiency in turning the heat into electricity, while limiting heat losses in the receiver. The three predominant CSP technologies are parabolic troughs (PT), linear Fresnel reflectors (LFR) and towers, also known as central receiver systems (CRS). A fourth type of CSP plant is a parabolic dish, usually supporting an engine at its focus. These technologies differ with respect to optical design, shape of receiver, nature of the transfer fluid and capability to store heat before it is turned into electricity (Figure 3).

Table 2: The main CSP technology families

Focus type / *Receiver type*	***Line focus*** *Collectors track the sun along a single axis and focus irradiance on a linear receiver. This makes tracking the sun simpler.*	***Point focus*** *Collectors track the sun along two axes and focus irradiance at a single point receiver. This allows for good receiver efficiency at higher temperatures.*
Fixed Fixed receivers are stationary devices that remain independent of the plant's focusing device. This eases the transport of collected heat to the power block.	Linear Fresnel reflectors	Towers
Mobile Mobile receivers move together with the focusing device. In both line focus and point focus designs, mobile receivers collect more energy.	Parabolic troughs	Parabolic dishes

Figure 3: Main CSP technologies



KEY POINT: Most current CSP plants are based on trough technology, but tower technology is increasing and linear Fresnel installations emerging.

Most installed capacities today replicate the design of the first commercial plants built in California in the 1980s, which are still operating. Long parabolic troughs track the sun on one axis, concentrate the solar rays on linear receiver tubes isolated in an evacuated glass envelope, heat oil to 390°C, then transfer this heat to a conventional steam cycle. Almost half the capacities built in Spain since 2006 have been equipped with thermal energy storage comprised of two tanks of molten salts, with 7 hours of nominal capacity (i.e. with full storage they can run seven hours at full capacity when the sun does not shine). This is now fully mature technology. In the United States, three 280 MW (gross) plants using PT technology were built and connected to the grid in 2013 and early 2014: two without storage, the Genesis and the Mojave projects in California, another with six-hour storage, the Solana generating station in Arizona.

Other technologies have been making considerable progress since the publication of the 2010 IEA roadmap. Central receiver systems (CRS), or towers, in particular, have emerged as a major option. After Abengoa Solar built two tower plants based on direct steam generation (DSG) near Seville, Spain, two much larger plants began operating in the United States. One large plant was built by BrightSource at Ivanpah in California, totalling 377 MW (net) – the largest CSP capacity so far at a single place. The plant gathers three distinct towers – each with its own turbine – based on DSG technology and no storage. The other is the largest single tower plant ever built, with a capacity of 110 MW and 10-hour thermal storage. It was built by Solar Reserve at Crescent Dunes, Nevada, and uses molten salts as both heat transfer fluid and heat storage medium. Tower technology comes second only to parabolic dishes with respect to concentration ratio and theoretical efficiency, and offers the largest prospects for future cost reductions.

While in 2010 only a couple of prototypes using linear Fresnel reflectors were operating, a 30 MW LFR plant built in Calasparra, Spain, by the German company Novatec Solar started up in early 2012, and a 125 MW commercial LFR plant built in Rajasthan, India, by AREVA Solar, subsidiary of the French nuclear giant, began operating in 2014. None have storage. LFR approximate the parabolic shape of trough systems but use long rows of flat or slightly curved mirrors to reflect the sun's rays onto a downward-facing linear, fixed receiver. LFR are compact, and their almost flat mirrors easier to manufacture than parabolic troughs. The mirror aperture can be augmented more easily than with troughs, and secondary reflection makes possible higher concentration factors, reducing thermal losses. However, LFR have greater optical losses than troughs when the sun is low in the sky. This reduces generation in early morning and late afternoons, and also in winter, but can be overcome in part by the use of higher operating temperatures than trough plants. All LFR plants currently use DSG, as does one small parabolic trough plant in Thailand.

Parabolic dishes supporting individual heat-to-electricity engines (Stirling motors or micro-turbines) at their focus points have almost disappeared from the commercial energy landscape, despite having the best optical efficiency. It has not proved possible to reduce the higher costs and risks of the technology, which also does not easily lend itself to storage, and thereby suffers from competition by PV, including CPV. Meanwhile an alternative type, called a "Scheffler dish" after the name of its inventor, is now being used by hundreds as a source of heat in community kitchens and other service or small industry facilities in India (IEA, 2011). A Scheffler dish is less efficient but more convenient as it concentrates the sun's rays on a fixed receiver.

Areas with sufficient direct irradiance for CSP development are usually arid and many lack water for condenser cooling (Box 1). Dry-cooling technologies for steam turbines are commercially available, so water scarcity is not an insurmountable barrier, but it leads to an efficiency penalty and an additional cost. Wet-dry hybrid cooling can significantly improve performance, with water consumption limited to heat waves. For large CSP plants, dry cooling could be further improved and the efficiency penalty reduced or suppressed with a modified "Heller system", using condensing water in a closed system with a cooling tower tall enough to allow for natural updraft (Bonnelle et al., 2010).

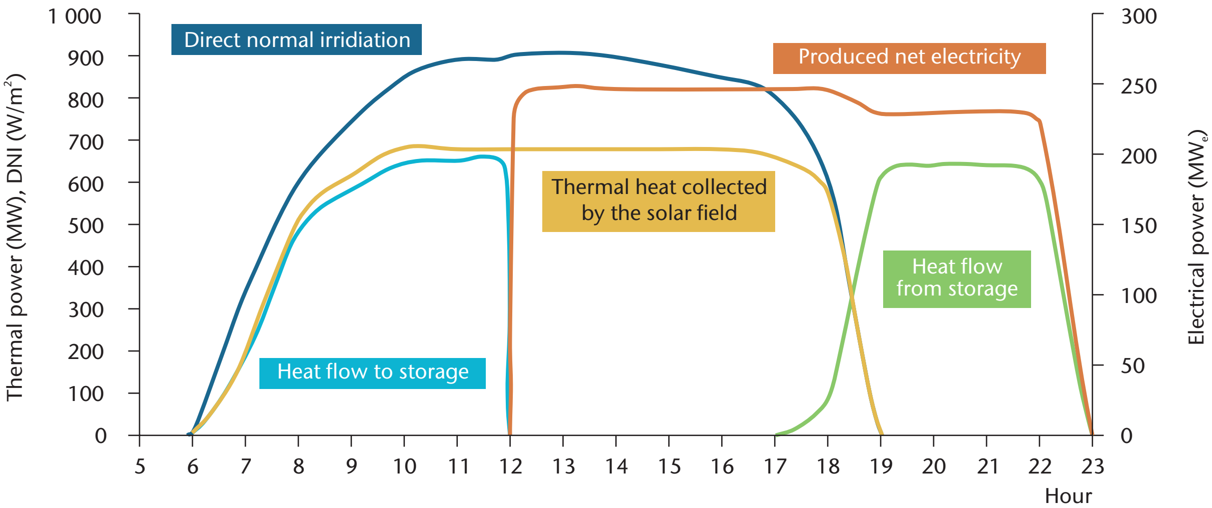
Thermal storage

All CSP plants have some ability to store heat energy for short periods of time and thus have a "buffering" capacity that allows them to smooth electricity production considerably and eliminate the short-term variations other solar technologies exhibit during cloudy days.

Since 2006, operators have built thermal storage systems into CSP plants, almost exclusively using sensible heat storage in a mixture of molten salts. The concept of thermal storage is simple: throughout the day, excess heat is diverted to a storage material (e.g. molten salts). When production is required after sunset, the stored heat is released into the steam cycle and the plant continues to produce electricity. Figure 4 illustrates the daily resource variations (DNI) and the flows from the solar field to the turbine and storage, and from the field and storage to the turbine, in a CSP plant generating STE from 12:00 to 23:00.

Storage size, technically measured in GWh_{th}, is more often expressed in "hours", meaning hours of running the plant at rated capacity from the storage only. The optimal size of storage depends on the role the plants are supposed to play. It also relates to the "solar multiple" of a plant, that is, the ratio of the actual size of the solar field to the size that would deliver the rated capacity under

Figure 4: Use of storage for shifting production to cover evening peaks



Notes: the graph shows on left scale the DNIR and the flows of thermal exchanges between solar field, storage and power block, and on the right scale electricity generation of a 250-MW (net) CSP plant with storage. Courtesy of ACS Cobra.

KEY POINT: Thermal storage uncouples electricity generation from solar energy collection.

the best conditions of the year. This ratio is always greater than one, to ensure sufficient capacity as the amount of sunlight the plant receives varies through the day. Small thermal storage avoid losses of energy that would arise on the most sunny hours or days from solar multiple being greater than one.

Plants with large storage capacities may have a solar multiple of three to five. Under similar sunshine conditions, larger solar fields and storage capabilities for a given turbine size lead to greater annual electrical output. Conversely, for a given solar field the storage size and the turbine size can be adjusted for different purposes, such as shifting or extending generation by a few hours to cover evening peaks, when the value of electricity is higher, or even generating round the clock part of the year and hence covering base load.

Since 2010, thermal storage has been routinely used in 40% of Spanish plants and in a growing number of plants in the United States and elsewhere. The rapid cost reduction of PV systems seems to have made CSP without storage almost irrelevant, while the expected roll-out of PV will increase the need for flexible, dispatchable "mid-merit" technologies, i.e. technologies that be optimally run for about 4 000 hours per year. CSP plants with five to ten hours of storage, depending on the DNI, seem best fitted to play this role.

When thermal storage is used to increase the capacity factor, it can reduce the levelised cost of solar thermal electricity (LCOE). The extra investments needed – in a larger solar field and in the storage system – are spread over more kWh, as the power block (turbine and generators), the balance of plant and the connection run for more hours. By contrast, storage that first takes electricity from the grid (such as pumped-storage hydropower, or battery storage) always increases the levelised cost of the electricity shifted in time (IEA, 2014c). Thermal storage also has remarkable "return" efficiency, especially when the storage medium is also used as heat transfer fluid. It may then achieve 98% return efficiency – i.e., energy losses are limited to about 2%.

Back-up and hybridisation

Almost all existing CSP plants use some fossil fuel as back-up, to remain dispatchable even when the solar resource is low and to guarantee an alternative thermal source that can compensate night thermal losses, prevent freezing and assure a faster start-up in the early morning. Some are full hybrids, as they routinely use a fuel (usually, but not always, a fossil fuel) or another source of heat together with solar energy.

The solar electricity generating systems (SEGS) plants built in California between 1984 and 1991 used natural gas to boost production year-round. In the summer, SEGS operators use backup in the late afternoon and run the turbine alone after sunset, corresponding to the time period (up to 22:00) when mid-peak pricing applies. During the winter mid-peak pricing time (12:00 to 18:00), SEGS uses natural gas to achieve rated capacity by supplementing low solar irradiance. By law, the plant is limited to using gas to produce 25% of primary energy. CSP plants in Spain similarly used natural gas as a backup, limited to 12% or 15% of annual energy depending on the owner's choice of support system, until the support system was modified for all existing plants, and generation from natural gas stopped receiving any premium.

The Shams-1 trough plant (100 MW) in the United Arab Emirates combines hybridisation and backup, using natural gas and two separate burners. The plant burns natural gas continuously during sunshine hours to raise the steam temperature (from 380°C to 540°C) for optimal turbine operation. Despite its continuous use, natural gas will account for only 18% of overall production of this peak and mid-peak plant. The plant also uses a natural gas heater for the heat transfer fluid. This backup measure was required by the electric utility to guarantee capacity, but is used only when power supply is low due to lack of sunshine. Over one year, this second burner could add 3% to the plant's overall energy production.

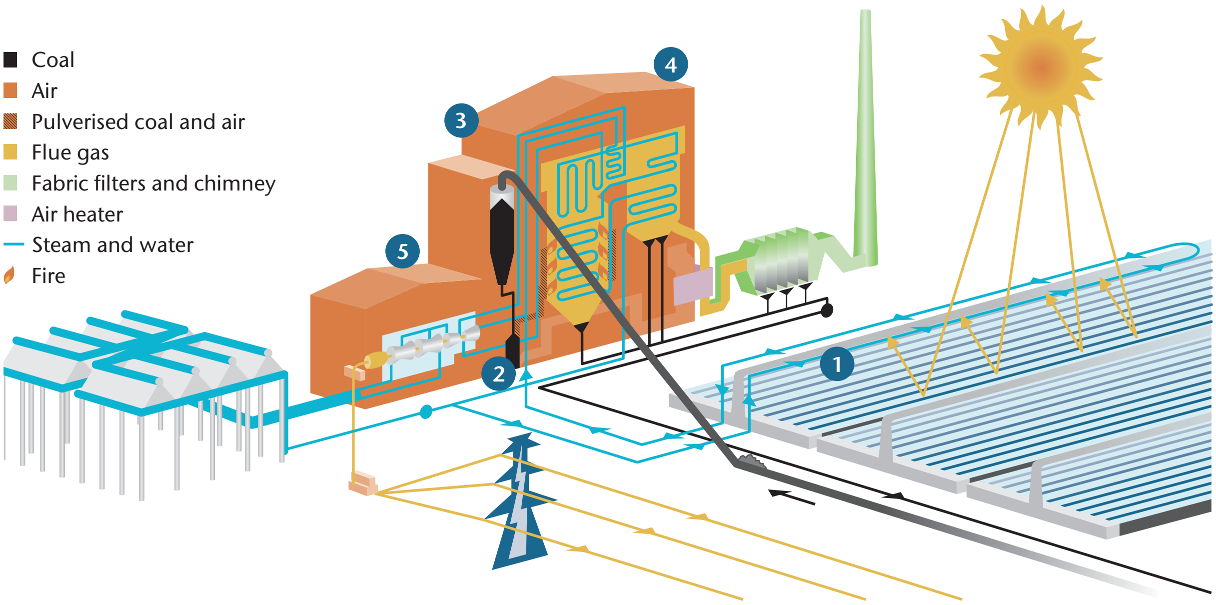
Solar-fossil hybridisation can also consist in adding a small solar field to a fossil-fired thermal power plant, either a gas-fired combined cycle or a coal-fired plant. On integrated solar combined-cycle (ISCC) plants, the solar field provides steam (preferably high-pressure steam) to the plant's steam cycle. Since the supplementary cost of the turbine (corresponding to its extra capacity) is only marginal, ISCC plants provide cheap solar thermal electricity. Such ISCC plants, with solar capacities ranging from a few megawatts to 75 MW, have been integrated into existing or new fossil fuel power plants in Algeria, Egypt, Iran, Italy, Morocco and the United States (Florida).

Solar boosters for coal plants, in particular, have emerged as an intriguing new option for solar fields. On any coal plant, the feedwater is preheated before entering the boiler in order to improve the cycle efficiency. This is achieved thanks to a train of preheaters that extract steam from the turbine at various pressure levels. Replacing the highest-pressure steam extractions with solar steam, fully or partially, maintains water preheating while expanding more steam in the turbine, thereby boosting its power output.

Some existing coal plants are particularly well suited to hybridisation because they already allow a "boost mode" by closing the highest-pressure steam extraction (with an efficiency penalty), their turbo-generator having the corresponding capacity margin. Hybridising these plants provides a power boost without extra coal consumption. If the solar potential exceeds the turbine's extra capacity, coal-saving is possible. On current solar-hybrid coal plants, solar steam feeds only the highest-pressure preheater, but other hybridisation concepts could be adopted and combined in order to increase the solar share, especially on greenfield projects (Siros et al., 2012). Such "solar boosters" increase capacity and energy generation without extra coal consumption, with virtually no other extra cost than that of the solar field. The largest solar booster so far – a 44 MW LFR plant – is under construction in Australia supplementing the supercritical coal plant at Kogan Creek (Figure 5).

Using a solar booster for existing coal plants that were modified for biomass co-firing can be even more advantageous, as the solar heat offsets the output and efficiency penalty resulting from the lower heating value of the fuel. It is also possible to combine a solar field with a thermal plant using only biomass, as has been demonstrated since the end of 2012 by the 22 MW Termosolar Borges plant in Catalonia, Spain. It associates a parabolic trough field using oil as HTF and two biomass burners, which heat the transfer fluid when sunshine is absent or insufficient. In May 2014, the Italian developer Enel Green Power announced its intention to couple a 17 MW_{th} PT solar thermal power field to its existing 33 MW_e geothermal power plant in Nevada, United States. The existing power block, based on an organic Rankine cycle, will be left unmodified. The solar field, using pressurised, demineralised water as HTF, will provide extra heat to the system in daylight, increasing the temperature of the geothermal fluid and consequently the efficiency of the whole system. The hybrid plant will be operating by the end of 2014.

Figure 5: Solar boosters for coal plants: The example of Kogan Creek



Notes: 1) cold water from the air-cooled condenser is heated using solar energy and converted to steam; 2) steam from the solar field is further heated and used to power the intermediate pressure turbine to generate electricity; 3) pulverised coal is blown and ignited in the boiler; 4) water is heated in the boiler to produce steam; 5) steam drives the turbine. Courtesy of AREVA Solar and CS Energy.

KEY POINT: The addition of the solar field makes more steam available for generating electricity.

Advancing toward competitiveness

Investment costs

Investment costs for CSP plants have remained high, from USD 4 000/kW to 9 000/kW, depending on the solar resource and the capacity factor, which also depends on the size of the storage system and the size of the solar field, as reflected by the solar multiple.

Costs were expected to decrease as CSP deployment progressed, following a learning rate of 10% (i.e., 10% cost reduction for each cumulative capacity doubling). This decrease has taken a long time to materialise, however, because market opportunities for CSP plants have diminished and the cost of materials has increased, particularly in the most mature parts of the plants, the power block and balance of plant (BOP). Other causes are the dominance of a single technology (trough plants with oil as heat transfer fluid) and a regulatory limit of a sub-optimal 50 MW of power output per plant in Spain, where most deployment occurred after 2006. The few larger plants that have been or are being built elsewhere are either the first of their find in the world, with large development costs and technology risks (e.g., in the United States), or the first of their kind in the country, with large development costs and country risks (e.g., Morocco) or both (e.g., India).

Operations and maintenance

CSP plants are steam plants in which the solar radiation is the primary source of fuel. The steam portion of the plant, or power block, is operated and maintained like all other steam plants. They are operated around the clock and local regulations usually require that a minimum number of operators be present at any given time. The solar field that tracks the sun, although highly automated, requires trained staff to perform regular maintenance tasks.

While a typical 50 MW trough plant requires about 30 employees for plant operation and 10 for field maintenance, a 300 MW plant requires about the same number of employees for operation and administration, and 20 to 30 employees for field maintenance. Operation and maintenance (O&M)

costs have been assessed in the Spanish plants at USD 50/MWh, including fuel costs for backup and water consumption for mirror cleaning, feedwater make-up and condenser cooling. As plants become larger, operation and maintenance costs per MW will decrease, and could be cut by half in large plants benefitting from better solar resource

Levelised cost of electricity

The levelised cost of electricity (LCOE)[3] of STE varies widely with the location, technology, design and intended use of plants. The location determines the quantity and quality of the solar resource (Box 1), atmospheric attenuation at ground level, variations in temperature that affect efficiency (e.g., cold at night increases self-consumption, warmth during daylight reduces heat losses but also thermodynamic cycle efficiency) and the availability of cooling water. A plant designed for peak or mid-peak generation with a large turbine for a relatively small solar field will generate electricity at a higher cost than a plant designed for base load generation with a large solar field for a relatively small turbine. LCOE, while providing useful information, does not represent the entire economic balance of a CSP plant, which depends on the value of the generated STE.

Public information about feed-in tariffs (FiT) and long-term power purchase agreements (PPA) can give an indication of LCOE but may significantly differ. In countries with significant inflation, escalating FiTs or PPAs have an initial level that may greatly differ from the LCOE – which by definition does not escalate.

Spanish plants benefited from FiTs of around EUR 300/MWh (about USD 400/MWh), and 40% of them have seven-hour storage — i.e., the capacity to generate full-load electricity only from storage for seven hours. Recent PPAs in sunnier countries are at half that level or below. One widely quoted figure is of the PPA of the first phase of the Noor 1 CSP plant at Ouarzazate in Morocco, at MAD 1.62/kWh (USD 190/MWh) for a 160 MW trough plant with three-hour storage. A recent CSP plant in the United States secured PPA at USD 135/MWh, but taking investment tax credit into account, the actual remuneration is about USD 190/MWh.

3. The LCOE represents the present value of the total cost (overnight capital cost, fuel cost, fixed and variable operation and maintenance costs, and financing costs) of building and operating a generating plant over an assumed financial life and duty cycle, converted to equal annual payments, given an assumed utilisation, and expressed in terms of real money to remove inflation.

Another difference between LCOE and FiT or PPA levels is that FiTs or initial PPAs are usually limited to 20 years, or in some cases 30, but the technical lifetime of CSP plants can be significantly greater. The nine SEGS plants built by Luz Industries in California in the 1980s are still operating. The owner of the two oldest SEGS plants, which are nearly 30 years old, is considering significant refurbishment, including adding thermal storage, to extend their lives by 20 years and to negotiate a new PPA with the company that buys the electricity, Southern California Edison. This extended plant lifetime reduces LCOE in comparison with PPAs or FiTs, everything else being equal.

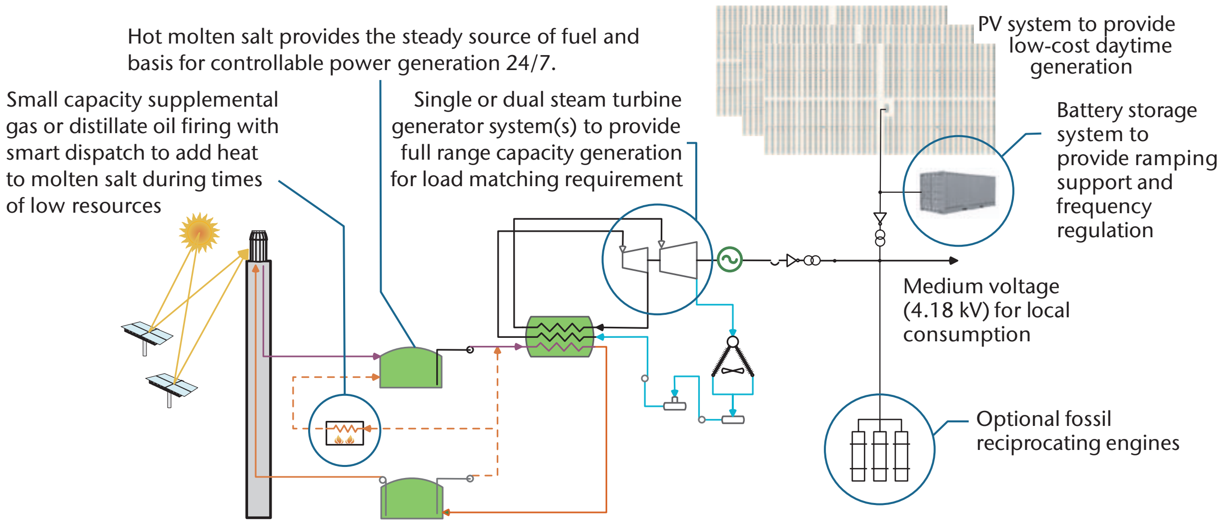
Barriers encountered, overcome or outstanding

Developers have encountered several barriers to establishing CSP plants. These include insufficiently accurate DNI data; inaccurate environmental data; policy uncertainty; difficulties in securing land, water and connections; permitting issues; and expensive financing, leading to difficult financial closureInaccurate DNI data can lead to significant design errors. Ground-level atmospheric turbidity, dirt, sand storms and other weather characteristics or events may seriously interfere with CSP technologies. Permits for plants have been challenged in courts because of concerns about their effects on wildlife, biodiversity and water use. Some countries prohibit the large-scale use as HTF of synthetic oil or some molten salts, or both.

The most significant barrier is the large up-front investment required. The most mature technology, PT with oil as HTF, with over 200 cumulative years of running, may have limited room for further cost reductions, as the maximum temperature of the HTF limits the possible increase in efficiency and imposes high costs to thermal storage systems. Other technologies offer greater prospects for cost reductions but are less mature and therefore more difficult to obtain finance for. In countries with no or little experience of the technology, financing circles fear risks specific to each country.

In the United States, the loan guarantee programme of the DoE has played a key role in overcoming financing difficulties and facilitating technology innovation. National and international development banks have helped finance CSP plants in developing countries, such as Morocco.

Figure 6: STE and PV can be combined in a single offer



Source: Gould, W. (2014), *SolarReserve, Brief Status and R&D Directions*, presentation at the IEA workshop on solar electricity roadmaps, Paris, 3 February.

KEY POINT: Turnkey 24/7 dispatchable solar plants may mix PV and STE to achieve lowest cost in high DNI areas.

The rapid decrease of the cost of PV modules and systems has led some project developers to consider switching from STE to PV, especially in California, where PV offers a good match with consumption peaks, so that the value of thermal storage is less. This has in turn led some CSP technology providers to broaden their offer and sell hybrid PV-STE plants (Figure 6) (Green, Diep and Dunn, 2014).

Medium-term outlook

There are no new CSP projects in Spain, as incentives have been cut, even though the national renewable energy action plan (NREAP) envisages CSP capacity of 5 GW by 2020. New projects would have to be designed for export to other European countries in the framework of reaching the European Union's 20% renewable energy target. Italy has a 600 MW target in its NREAP and has put in place a specific FiT, which has survived the extinction of FiTs for PV systems. France has a 540 MW CSP capacity target in its NREAP. Plants in the approval process or ready to start construction represent 20 MW in France and 115 MW in Italy, while other projects are under development. The Italian environment legislation does not allow for extensive use of oil in trough plants, however, limiting the technology options to more innovative designs, such as DSG or molten salts as HTF.

Projects that would produce several gigawatts are still under consideration or development in the United States, although not all will succeed in obtaining the required permits, PPAs, connections, and financing.

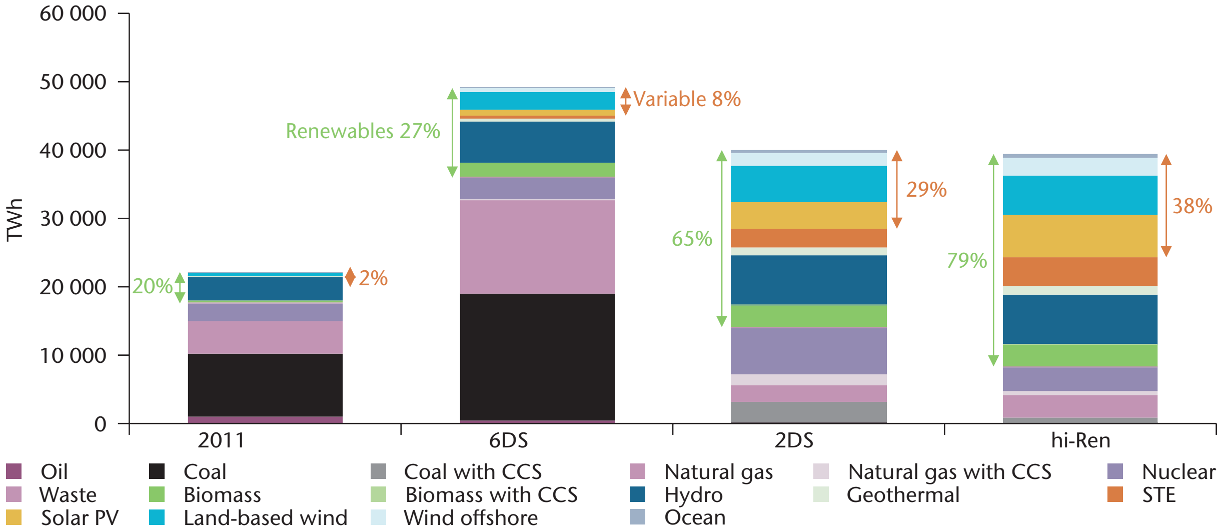
Besides Spain and the United States, and a few countries where small solar fields are used as boosters in larger-scale fossil fuel plants, very few countries have installations of commercial size, say above 50 MW. India and the United Arab Emirates have plants already synced to the grid; Morocco and South Africa are finalising their first plants. Other countries are implementing or have announced ambitious development plans, including India, Israel, Jordan, Kuwait, Morocco, Saudi Arabia and South Africa, while in northern Chile development is taking place on a market basis. In 2012 Saudi Arabia announced that it would build CSP plants generating 32 GW by 2032, creating considerable hope in the industry. Some early achievements in these countries will come to fruition before the end of the decade.

A detailed examination of the main markets and project pipelines anticipates the deployment of 11 GW of CSP plants by 2020 (IEA, 2014d). While this is well below the expectations in the 2010 roadmap (IEA, 2010), it nevertheless represents a dramatic increase over the installed capacities at the end of 2009, of about 600 MW.

Vision for deployment

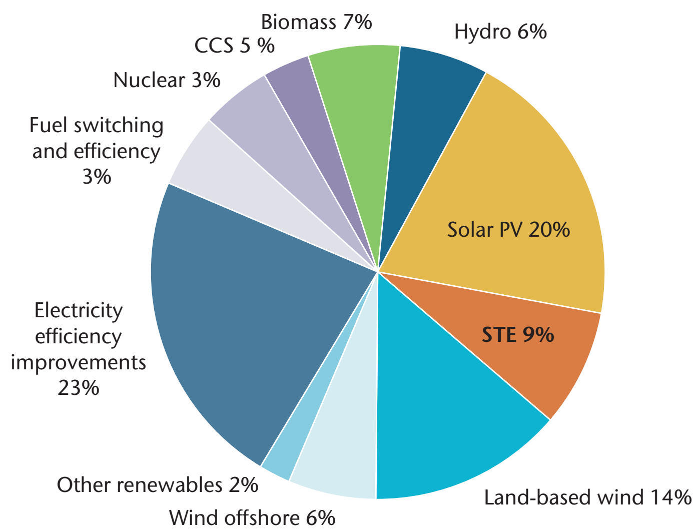
Since the original roadmap was published in 2010, deployment of CSP plants has been slower than expected, but technological improvements have been significant. Like the original roadmap, this roadmap envisages STE representing about 11% of total electricity generation by 2050. In this scenario, global electricity production in 2050 is almost entirely based on zero-carbon emitting technologies, mostly renewables (Figure 7).

Figure 7: Global electricity mix in 2011 and in 2050 in three *ETP 2014* scenarios



KEY POINT: In the hi-Ren Scenario, renewables provide 79% of global electricity by 2050, variable renewables 38%, and STE 11%.

Figure 8: Cumulative technology contributions to power sector emission reductions in *ETP 2014* hi-Ren Scenario relative to 6DS up to 2050



KEY POINT: STE from CSP plants contributes to 9% of CO_2 emission reductions from power sector over the next 35 years in the hi-Ren Scenario.

CO_2 reduction targets from the *ETP 2014* Scenarios

CSP plants installed by the end of 2013 are estimated to generate 9 TWh/yr, saving 8 $MtCO_2$/yr. In the *ETP 2014* 6DS, annual emissions from the power sector would increase from 13 $GtCO_2$ in 2011 to about 22 $GtCO_2$ in 2050 (IEA, 2014b) (Box 2). By contrast, in the hi-Ren Scenario, they would fall to a mere 1 $GtCO_2$ in 2050. STE from CSP plants would be responsible for emission reductions of 2.1 $GtCO_2$, and 9% of cumulative emission reductions over the entire scenario period (Figure 7). This is about half the contribution from PV electricity (IEA, 2014a), mainly because of the lower amount of STE generated but also because on average PV displaces electricity with greater carbon intensity.

The regional repartition of additional CO_2 emission reductions in 2050 due to STE in the hi-Ren Scenario over the 6DS (Figure 8), seems to reflect on the carbon intensity of the electricity mixes of various regions, and the size of their electricity generation, as much as the share of STE in these mixes, as discussed below. India comes first because Africa and Middle East, despite higher shares of STE, have less coal in their 6DS generation mixes, and lower total electricity demands. China comes second due to its electricity consumption and high carbon intensity, although its generation mix in the hi-Ren Scenario has a relatively small share of STE, only greater than that of coal.

Box 2: *ETP* Scenarios: 6DS, 2DS, hi-Ren

This roadmap takes as a starting point the vision in the IEA *ETP 2014* analysis, which describes several scenarios for the global energy system in 2050.

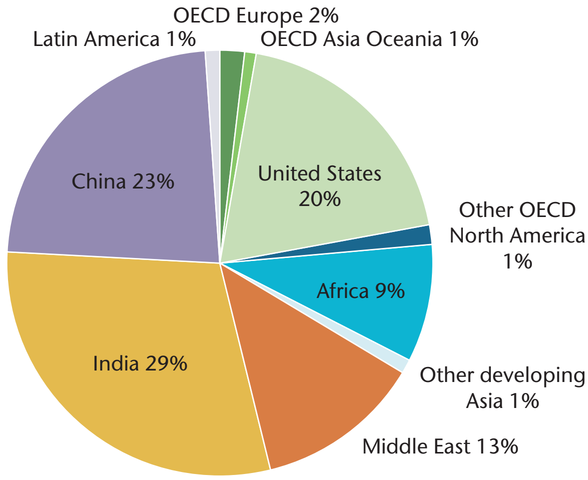
The 6°C Scenario (6DS) is a base-case scenario, in which current trends continue. It projects that energy demand would increase by more than two-thirds between 2011 and 2050. Associated CO_2 emissions would rise even more rapidly, pushing the global mean temperature up by 6°C.

The 2°C Scenario (2DS) sees energy systems radically transformed to achieve the goal of limiting the global mean temperature increase to 2°C. The High-Renewables Scenario (hi-Ren Scenario) achieves the target with a larger share of renewables, which requires faster and stronger deployment of PV, as well as wind power and STE, to compensate for the assumed slower progress in the development of CCS and deployment of nuclear than in 2DS.

The *ETP 2014* analysis is based on a bottom-up TIMES* model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. Covering 28 world regions, the model permits the analysis of fuel and technology choices throughout the energy system, representing about 1 000 individual technologies. It has been developed over several years and used in many analyses of the global energy sector. The *ETP* model is supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

* TIMES = The Integrated MARKAL (Market Allocation)-EFOM (energy flow optimisation model) System.

Figure 9: Additional CO_2 emission reductions due to STE in 2050 in the hi-Ren Scenario (over the 6DS)



KEY POINT: China and India combined account for over half the additional emission reductions due to STE.

Updated STE goals

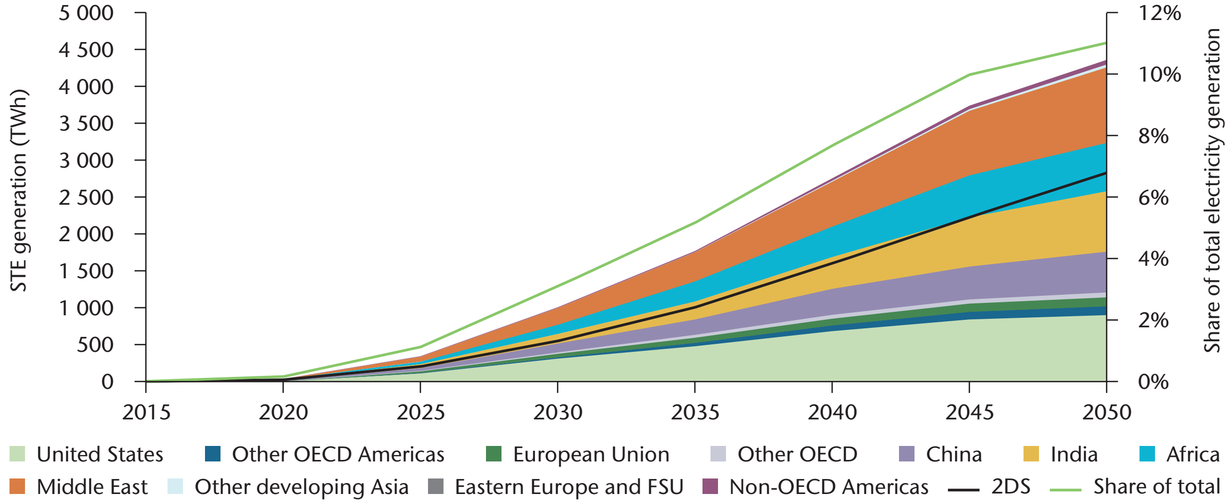
The path leading to the large CSP deployment envisioned in this roadmap differs significantly from the path in the original roadmap. In the most recent hi-Ren Scenario (IEA, 2014b), deployment is much slower until 2020, as technologies gradually mature and investment costs gradually fall. Global capacities jump to 260 GW by 2030 (vs. 337 GW in the original roadmap). By 2050 they reach 980 GW (vs. 1089 GW in the original roadmap).

This represents capacity increases of 27 GW per year on average, with a five-year peak of 40 GW per year from 2040 to 2045. Table 3 shows the CSP capacities by region that this roadmap targets. Thermal storage is a key feature of CSP plants all along, and capacity factors grow regularly with increased solar field sizes and storage capacities, reaching on average 45% in 2030, a decade earlier than in the 2010 roadmap. This allows the amount of STE to reach about 1 000 TWh by 2030, and 4 380 TWh by 2050, thus providing 11% of the global electricity mix.

Table 3: CSP capacities by region in 2030 and 2050 forecast in this roadmap

GW	United States	Other OECD Americas	European Union	Other OECD	China	India	Africa	Middle East	Other developing Asia	Non-OECD Americas	World
2013	1.3	0.01	2.31	0.01	0.02	0.06	0.06	0.10	0.02	0	4.1
2030	87	6	15	4	29	34	32	52	0.3	2	261
2040	174	18	23	12	88	103	106	131	3	7	664
2050	229	28	28	19	118	186	147	204	9	15	982

Figure 10: Regional production of STE envisioned in this roadmap



KEY POINT: In the hi-Ren Scenario, STE represents 11% of global electricity; the Middle East, India and the United States are the largest contributors.

Box 3: The hi-Ren Scenario and electricity trade between North Africa and Europe

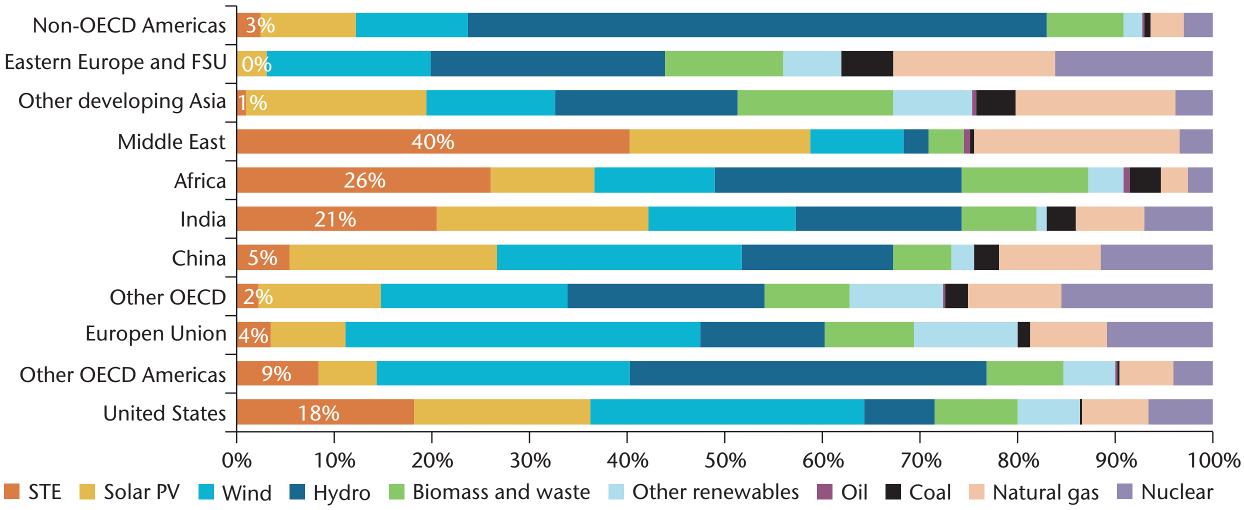
The 2010 roadmap integrated the possible role of "exports" of STE from one continent to another, and in particular from North Africa to Europe, reshuffling CSP capacities on both sides of the Mediterranean Sea. Such trade was at the core of the Desertec concept (DII, 2013). For this roadmap, however, the ETP model was complemented with the possibility of building trans-continental HVDC lines. A few other assumptions were updated after the publication of *ETP 2014*.

At a global level, the resulting changes are minor – the total CSP capacity by 2035 increases from about 430 GW to about 460 GW, and this gap persists up to 2050. In North Africa the difference is more significant. In 2030, installed capacity is 25 GW instead of a mere 10 GW, then the difference grows to about 30 GW, while the overall capacity in North Africa reaches 120 GW by 2050. Increased STE generation represents only about half the net exports from North Africa to Europe, followed by wind power and PV. This may explain the capacity of the interconnections selected by the model, of 23 GW in 2025, 35 GW in 2030 and 53 GW in 2050. Although net exports from North Africa to Europe eventually appear, the lines are likely to serve both ways at different times of the day or year. For example, overcapacities in gas plants in Spain currently provide power to Morocco in its peak hours after sunset, and this may persist.

In Europe, the imports from North Africa lead to reduction of generation (mostly from wind power and natural gas) but by less than the amount of imported electricity, as imports from non-EU parts of the continent are displaced. Net electricity imports from North Africa account for slightly less than 10% of European consumption.

While CSP plants are limited in their possible extension in Europe, the United States becomes the largest contributor up to 2040, followed by the Middle East, India, China and Africa (Figure 9). By 2050, the Middle East overtakes the United States as the leading contributor, and India distances both Africa and China. The Middle East is also in first position when it comes to STE's share of electricity generation in each region (Figure 11), followed by Africa, India and the United States.

Figure 11: Generation mix by 2050 in the hi-Ren Scenario, by region



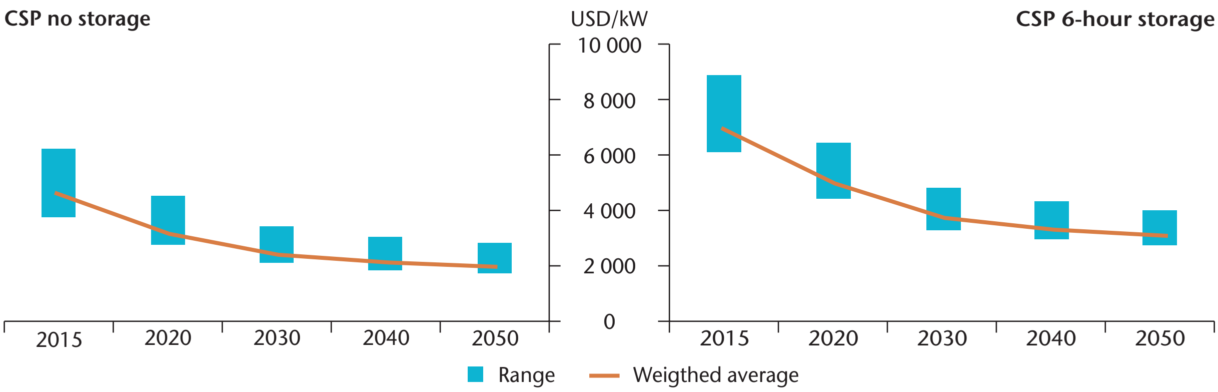
KEY POINT: In the hi-Ren Scenario, STE is the largest source of electricity in Africa and the Middle East by 2050.

Potential for cost reductions

For all three predominant CSP technologies — PT, LFR and towers — novel optic designs are being considered, as well as new mirror materials and receiver designs. A few project are experiencing cheaper parabolic troughs of a laminated reflective components glued on aluminium sheets (Frazier, 2013). Tower designers are also exploring choices relating to the type of receivers (cavity or external), the number and size of heliostats, the number of towers associated with each turbine, and the size and shape of solar fields. New thermodynamic cycles (supercritical steam cycles, Brayton cycles with a gas turbine or supercritical CO_2) can be envisioned. Scaling up plants would allow reduction in the specific costs of turbines and BOP. Greater standardisation as markets mature would reduce development costs.

Investment costs would follow a 10% learning rate (i.e., diminish by 10% for each doubling of cumulative capacities), and in the hi-Ren Scenario fall by 2050 to a range of USD 2 800/kW to USD 4 100/kW for a plant with six-hour storage — allowing for up to 4 500 full-load hours. The weighted average would be about USD 3 100/kW by 2050 (Figure 12).

Figure 12: CSP investment cost projections in the hi-Ren Scenario



KEY POINT: The cost of CSP plants is expected to halve by 2030 as technologies mature.

Reduced capital expenditure, increased performance and economies of scale are not the only factors reducing LCOE. Current average LCOE is high because most existing plants have been built in Spain, which has relatively weak DNI. As deployment intensifies in the southwestern United States and spreads to North Africa, South Africa, Chile, Australia and the Middle East, better resources will be used, improving performance. Furthermore, as technology matures and becomes more mainstream, technology risks will be reduced, also reducing the cost of capital and facilitating financial closure of projects. In the hi-Ren Scenario, LCOE falls by 55% from 2015 to 2050 (Table 4). STE progressively reaches competitive levels compared with electricity from most competing (new-built) technologies, apart from wind and PV, taking CO_2 prices into account. The US DoE's Sunshot programme expects more rapid cost reductions based on current trends, and even aims for LCOE of USD 60/MWh as soon as 2020.

Table 4: Projections of LCOE for new-built CSP plants with storage in the hi-Ren Scenario

USD/MWh	2015	2020	2025	2030	2035	2040	2045	2050
Minimum	146	116	96	86	72	69	66	64
Average	**168**	**130**	**109**	**98**	**80**	**77**	**72**	**71**
Maximum	213	169	124	112	105	101	96	94

Note: All LCOE calculations in this table are based on 8% real discount rates as in *ETP 2014* (IEA, 2014b).

The possible role of small-scale CSP devices – from 100 kW to a few MW – off-grid or serving in mini-grids, has not been included in the ETP model. There is too little industrial experience of such systems to make informed cost assumptions, whether the systems are based on PT, LFR, parabolic dishes, Scheffler dishes or small towers, using organic Rankin cycle turbines, micro gas-turbines or various reciprocating engines. If they allow thermal storage[4] or fuel backup, small-scale CSP systems have to compete against PV with battery storage or fuel backup. They may find a role, although the fact that CSP technology seems to benefit more than PV from economies of scale suggests that small-scale CSP systems may face a greater competitive challenge than large-scale ones. Finding local skills for maintenance may also be challenging in remote, off-grid areas.

For a given site, where irradiation is given (apart from manmade air pollution), and disregarding performance ratio and its evolution over time, the most significant ways of reducing costs are lower capital expenditures and lower costs of capital. The LCOE projections in this roadmap rest on WACC of 8%. Actual projects may experience higher or lower WACC, depending on the lenders and investors' appreciation of the technology, country, exchange rate, policy and other risks. As the technology and local markets mature, and possibly also as other types of investors step in (e.g., pension funds, private equity and sovereign wealth funds), one might expect some reduction of the average WACC.

Global investment to 2050

To decarbonise the entire energy system in the 2DS by 2050 will require about USD 44 trillion in additional costs. This investment is more than offset by over USD 115 trillion in fuel savings – resulting in net savings of USD 71 trillion. Even with a 10% discount rate, the net savings are more than USD 5 trillion (IEA, 2014b).

The hi-Ren Scenario requires additional, cumulative investments for power generation of USD 4.5 trillion more than the 2DS, including CSP plants but also wind power and PV. The lower consumption of fossil fuels in this variant, corresponding to fuel cost savings of USD 2.6 trillion, partly offsets the additional investment needs, however, so that overall the hi-Ren Scenario results in additional costs

4. Such as this 1-MW trough plant with 15-h molten-salt storage was built in end 2013 in Sicily (Italy).

Table 5: CO_2 prices in the climate-friendly scenarios of *ETP 2014*

USD/CO_2	***2020***	***2030***	***2040***	***2050***
2°C Scenario	46	90	142	160
Hi-Ren Scenario	46	115	152	160

of USD 1.9 trillion. This represents a 3% increase in total cumulative costs for power generation over the 2DS, and only 1% over the 6DS.

However, investments are more significant in the next two decades of the hi-Ren Scenario. This is reflected in the implicit carbon prices in both variants, which differ significantly by 2030 (Table 5)

Total investments in CSP/STE over the modelling period, including limited repowering, would be about USD 4.3 trillion (undiscounted) in the hi-Ren Scenario.

Beyond 2050

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) is to stabilise atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Whatever this exact level turns out to be, CO_2 stabilisation will eventually require zero net emissions or below to compensate for the rebound effect – the release into the atmosphere of CO_2 from natural reservoirs that accumulate part of the anthropogenic emissions (see chapters 6 and 12, IPCC, 2014).

Longer-term climate change mitigation studies tend to show significantly higher CSP deployment beyond 2050 – or even by 2050, due to their longer-term perspective. For example, IEA (2011) offers a global perspective for hypothetical longer-term reduction of global energy-related CO_2 emissions – beyond 2060 – to about a tenth of current levels. It rests on a much stronger penetration of electricity in final energy demand, and has global installed CSP capacity six times larger than this roadmap assumes by 2050, generating up to 25 000 TWh of STE.

Technology development: Actions and milestones

	Time frames
1. Demonstrate using molten salts as HTF in linear systems (PT and LFR).) at large scale.	Complete by 2018
2. Develop light-weight, low-cost reflector optics.	Complete by 2018
3. Optimise heliostat size, solar field design, central receiver design, number of towers per turbine for 6 to 18 hours of storage.	Complete by 2018
4. Introduce supercritical steam turbines in CSP plants.	Complete by 2025
5. Increase the energy in receiver tubes with innovative non-imaging optics for linear systems.	Complete by 2020
6. Introduce innovative HTF: air, gas, nano-fluids in linear systems, fluoride liquid salts, air and particles in towers.	Complete by 2025
7. Introduce closed-loop multi-reheat Brayton turbines.	Complete by 2025
8.Develop and introduce supercritical CO_2 cycles.	Complete by 2030
9. Develop hybrid PV-CSP via spectrum-splitting or PV topping.	Complete by 2030
10. Intensify R&D on solar fuels (gaseous, liquid or solid).	2015-2050

Efforts to improve linear systems (parabolic troughs and linear Fresnel reflectors) and point-focus systems, mostly towers, strive to increase efficiency in converting the energy from the sun into electricity, while reducing investment costs. Higher working temperatures are key to increasing efficiency in converting the heat into electricity. Storage costs can also be drastically reduced with higher temperatures. Improved efficiency also lowers the cooling load and the performance penalty caused by dry cooling. Higher temperatures increase the thermal losses of the receiver through convection and radiation, however, and may require more expensive materials. The trade-offs are likely to differ with the concentration ratio.

Linear systems

Parabolic troughs (PT) with oil as heat transfer fluid (HTF) is the most mature technology, but still has room for improvement. Troughs themselves can further increase their dimensions. Reflecting films may replace glass, making troughs lighter and cheaper. Heat receiver tubes have been constantly improving. At the same time, other HTFs are being investigated.

Direct steam generation (DSG) is one option. It saves heat exchangers and some specific equipment ensuring the quality stabilisation of HTF, but high pressure makes other components more expensive. It enables the steam temperature and pressure to be increased if the steam generation process in the solar field is well managed, which could be a complex undertaking. The largest commercial PT plant so far based on DSG has a capacity of only 5 MW, but LFR and tower plants of more than 100 MW use DSG.

However, storage is a particular challenge in CSP plants that use DSG. Because water evaporation is isothermal, unlike sensible heat addition or removal in the salt, a round-trip storage cycle would result in severe steam temperature and pressure drops, thereby destroying the efficiency of the thermodynamic cycle in discharge mode. Storing latent heat of saturated steam in pressurised vessels is expensive and provides no scale effect on cost. One option would use three-stage storage devices that preheat the water, evaporate the water and superheat the steam. Stages 1 and 3 would be sensible heat storage, in which the temperature of the storage medium changes. Stage 2 would best be latent heat storage, in which the state of the storage medium changes, using some phase-change material. Another option could be to use liquid phase-change materials.

The growing relevance of thermal storage in the context of intense competition from cheap PV favours using molten salts as both the heat transfer fluid and the storage medium (termed “direct storage”). If DSG spares heat exchangers for steam generation, the use of molten salts as HTF spares heat exchangers for storage. Salts are less costly than oil. Using salts allows raising the temperature and pressure of the steam, from 380°C to 530-550°C and from 10 to 12-15 megapascals (MPa) in comparison with oil as HTF, increasing the efficiency of the power block from 39% to 44-45% (Lenzen, 2014).

Thanks to higher temperature differences between hot and cold salts (currently used salt mixtures usually solidify below 238°C), plants using molten salts as HTF need three times less salts than trough plants using oil as HTF, for the same storage capacity. This lowers the storage system costs, which represent about 12% of the overall plant cost for seven-hour storage of a trough plant. Also, the “return efficiency” of thermal storage, at about 93% with indirect storage (in which heat exchangers reduce the working temperature), is increased to 98% with direct storage. Finally, another advantage of molten salts as HTF over steam is that heat transfer can be carried out at low pressure with thin-wall solar receivers, which are cheaper and more effective. Overall, the substitution of molten salts for oil in CSP would allow for 30% LCOE reduction, according to Schott, the lead manufacturer of solar receiver tubes (Lenzen, 2014).

Several companies are developing the use of molten salts as HTF in linear systems, and have built or are building experimental or demonstration devices. One challenge is to reduce the expense required to keep the salts warm enough (usually above 290°C) for better viscosity in long tubes at all times and protect the field against freezing. The 5 MW Archimede plant in Sicily uses this technology, developed by ENEL with the Italian government agency ENEA. It is an ISCC plant using PT technology with molten salts as HTF and heat storage medium.

Addressing this challenge may be easier in LFR plants thanks to their fixed receivers (sometimes called “linear towers” for that reason), than in trough plants, with mobile receivers linked with flexible joints and pipes. AREVA has developed a LFR solution using molten salts as HTF, which enables efficient storage and temperatures up to 565°C, and this technology has been demonstrated at the Sandia National Laboratories molten-salt test facility in New Mexico, United States. In any case, the challenge is less in towers because the central receiver is compact and can more easily be drained by gravity; and it is easier to keep salts hot in tanks. Molten-salt towers are already in operation in Spain and in the United States.

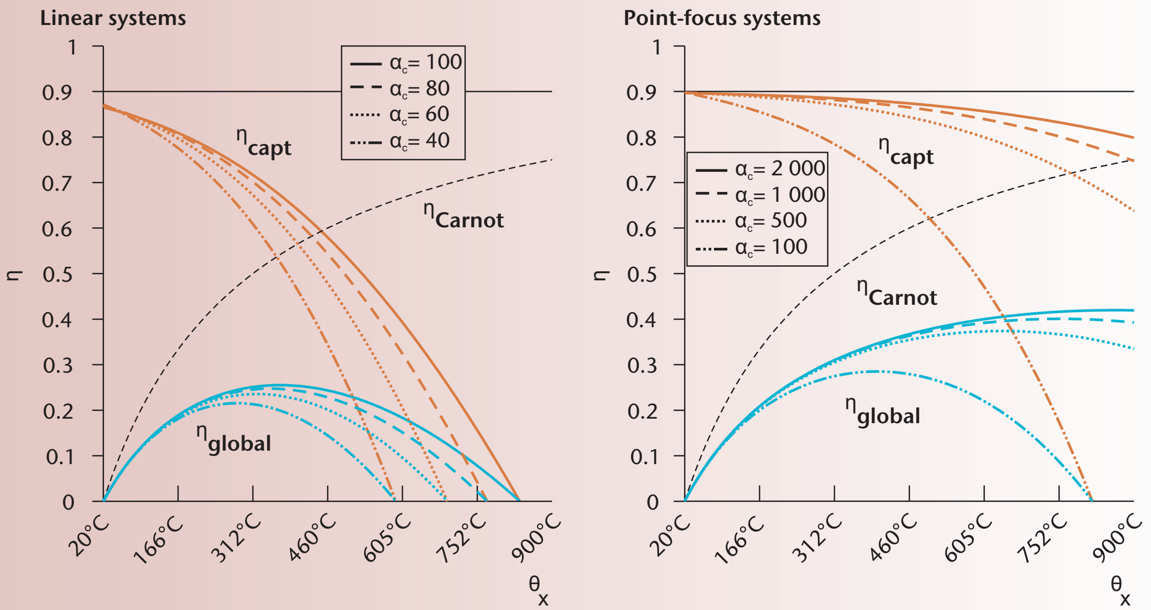
Solar towers

In theory, solar towers offer a more efficient design than linear systems, as higher temperatures, key for better efficiency of the power block, require greater concentration factors to minimise heat losses in the receiver (Box 4). In reality, however, the actual efficiency of receivers varies. In linear plants, receivers can be insulated in an evacuated glass envelope, which is not the case in towers. Towers are less sensitive to seasonal variations than linear systems, which have greater optical losses in winter.

Box 4: Concentrating solar rays: Linear vs. point-focus systems

Concentrating the sun’s rays allows higher working temperatures with good efficiency at collector level. This, in turn, allows better efficiency in converting heat into mechanical motion and, thus, electricity, as a consequence of the Carnot theorem. The ideal Carnot efficiency is defined by the ratio of the difference in temperatures of the hot and the cold source, divided by the absolute temperature (in Kelvin) of the hot source. Receiver efficiencies, Carnot efficiencies of the conversion into electricity, and total solar to electric efficiencies, are shown on Figure 12 in function of the working temperature for various concentration ratios or “suns”. In the left-hand diagram, ratios of 40 to 100 suns are representative of linear concentration systems (PT or LFR). In the right-hand diagram, ratios of 100 to 2 000 suns are representative of point-focus systems (towers or dishes). The efficiency of the receiver depends on the state of the technology, while the Carnot efficiency represents a physical law and expresses the maximum possible efficiency of the conversion. The global efficiency is the product of the efficiency of the collector by the Carnot efficiency and a fixed coefficient, set at 0.7, expressing the imperfection of the thermodynamic engine. As Figure 13 shows, point-focus systems can convert into electricity a larger fraction of the energy that falls on the receiver than linear systems. For each concentration level, there is an optimal temperature level with current receiver technology, which maximises the global efficiency. It is around 400°C for concentration ratios of 100, and around 750°C for concentration of 1000.

Figure 13: Efficiencies as a function of temperature for various concentration ratios



Note: a_c= concentration ratio; $\square_{cap}$= efficiency of the collector; $\square_{Carnot}$= efficiency of the conversion of heat into electricity; $\square_{global}$= global efficiency. Values are indicated for an ambient temperature of 20°C.

Source: Tardieu Alaphilippe, M. (2007*), Recherche d'un Nouveau Procédé de Conversion Thermodynamique de l'Energie Solaire, en Vue de son Application à la Cogénération de Petite Puissance*, dissertation presented to the l'Université de Pau et des Pays de l'Adour, Pau, France.

KEY POINT: There is an optimal working temperature for any given concentration ratio.

Apart from the fundamental choice between DSG and molten salts for HTF, towers currently also offer a great diversity of designs – and present various trade-offs. The first relates to the size (and number) of heliostats that reflect the sunlight onto the receivers atop the tower. Heliostats vary greatly in size, from about 1 m² to 160 m². The small ones can be flat and offer little surface to winds. The larger ones need several mirrors that are curved to send a focused image of the sun to the central receiver, and need strong support structures and motors to resist winds. For similar collected energy ranges, however, small heliostats need to be grouped by the thousand, multiplying the number of motors and connections. Manufacturers and experts still have divided views about the optimum size. Heliostats need to be distanced from one another to reduce losses arising when a heliostat intercepts part of the flux received (“shading”) or reflected (“blocking”) by another.

While linear systems require flat land areas, central receiver systems may accommodate some slope, or even benefit from it as it could reduce blocking and shadowing, and allow increasing heliostat density. Algorithmic field optimisation may help reduce environmental impacts and required ground levelling work while maximising output (Gilon, 2014). In low latitudes heliostat fields tend to be circular and surround the central receiver, while in higher latitudes they tend to be more concentrated to the polar side of the tower. Larger fields tend to be more circular to limit the maximum receiver heliostat distance and minimise atmospheric attenuation.

There are two basic receiver designs: external and cavity. External receivers offer vertical pipes to the concentrated solar flux from the heliostats, in which a heat transfer or working fluid circulates. In the cavity design, the solar flux enters the cavity, ideally closed by a window, though this raises significant material challenges. The cavity design is thought to be more efficient, reducing heat losses, but accepts a limited angle of incoming light, so towers surrounded with large heliostat fields need to support several receivers.

Proper aiming strategy must be ensured by the heliostat field's control system in order to optimise the solar flux map on the receiver, thereby allowing the highest solar input while avoiding any local overheating of the receiver tubes. This is more difficult with DSG receivers. The heat flux on the different types of solar panel of a DSG receiver differs significantly: superheater panels (poorly cooled by superheated steam) receive a much lower flux than evaporator and preheater panels.

Another important design choice relates to the number of towers for one turbine. Heliostats that are in the last rows far from the tower need to be very precisely pointed towards it, and lose efficiency as the light must make a long trip near ground level. They also have greater geometrical ("cosine") optical losses. At over 1 million m^2, the solar field associated with the 110 MW tower built by SolarReserve with 10-hour storage at Crescent Dunes, (Nevada, United States) is perhaps close to the maximum efficient size.

To limit optical absorption but benefit from higher efficiency and economies of scale of large turbines, several towers can be linked to one turbine. This design may also facilitate the choice of cavity receiver over external receivers. If towers use molten salts as low-pressure HTF, transporting the HTF of several towers to one single turbine in well-insulated self-draining pipes should be relatively straightforward. The additional costs of building several towers may be made up for by the greater optical and thermal efficiencies of multi-tower design (Wieghardt et al., 2014). However, the optimal field size and number of towers may depend on the atmospheric turbidity of the site considered, which varies greatly among areas suitable for CSP plants. The Californian company eSolar proposes 100 MW molten salt power plants based on 14 solar fields and 14 receivers on top of monopole towers (similar to current large wind turbine masts) for one central dry-cooled power block with 13-hour thermal storage and 75% capacity factor (Tyner, 2013).

The possibilities of even higher temperatures should be explored using different receiver technologies. One option is supercritical steam cycles, such as those used in modern coal-fired power plants, which reach overall efficiencies of 42% to 46% with supercritical and ultra-supercritical designs (thermal-to-electric efficiencies of 45% to 50%). Typically, modern coal-fired power plants use steam at up to 620°C and 24 MPa to 30 MPa, but by 2020 could reach 700°C and 35 MPa, using nickel-based alloys to achieve overall efficiencies approaching 50%. The application of this technology to solar towers, however, will require some adaptation. Supercritical turbines are currently available at 400 MW capacity and beyond. Unless turbine manufacturers decide to commercialise smaller turbines, such capacity would require at least two towers, or more as it would probably involve significant storage capacities. BrightSource is considering a different association – that of a DSG tower, cheaper for providing heat when daylight is available, with a molten-salt tower providing heat, through thermal storage, at sunset or dawn (Gilon, 2014). Reaching the high steam temperatures allowed by towers while providing about 75% of the heat input with cheap LFR has also been envisaged (Goffe et al., 2009).

Finally, some new concepts emerge from rethinking the options in the context of an ever-changing electricity mix. As the share of variable energy increases, base load plants, even if technically flexible (which all are not) will become less economically efficient as their utilisation rate diminishes. At the same time, more peaking and mid-merit plants become necessary. Below a certain load factor – about 2 000 full load hours – open-cycle gas turbines become a better economic choice than combined-cycle plants, but they are less energy-efficient as they generate large amounts of waste heat. Open-cycle gas turbines could be integrated with a CSP plant with storage, however, of which the steam turbine is not being used with a very high capacity factor. When the sun does not shine, the otherwise wasted heat could be collected to a large extent in the hot tank of a two-tank molten-salt system. This energy could afterwards be directed to the steam turbine to deliver electricity whenever requested. If more power is needed when the sun shines sufficiently to run the steam turbine by itself, the heat from the gas turbine could be directed to the thermal storage. In both cases, a large part of the waste heat will be used. This concept differs from the existing ISCC in which solar only provides a complement, as the presence of thermal storage allows for a complete reversal of the proportion of solar and gas, which remains a backup, though a more efficient one (Crespo, 2014). The Hysol project, funded by the European Union's Seventh Programme for research, technological development and demonstration, aims to demonstrate the viability of the concept. Similarly, in areas with both high wind penetration and CSP plants, some thermal storage, which is equipped with electric heaters for security reasons, could be used in winter to reduce curtailment from excess wind power.

Beyond incremental improvements

Research aimed at improving efficiency and reducing generation costs is investigating a vast number of new options, including optical systems, receivers, HTF and storage systems.

Innovative, non-imaging optics may allow troughs or Fresnel reflectors to be redesigned, enabling greater concentration ratios and efficiencies while using state-of-the-art receiver tubes, such as those now being commercialised for using molten salts as HTF. While the overall optical efficiency would be diminished due to multiple reflections, 70% more energy would be delivered to the receiving tubes, reducing by a factor of about two the number of receivers, pipes, pumps, heat transfer fluid volume, and associated losses. Larger parabolas could also enable the centre of the mass of the mirror-receiver system to be brought closes to the centre of the tube, allowing for the tube to remain fixed while the mirrors track the sun without considerable mechanical efforts. (Collares Pereira, 2014).

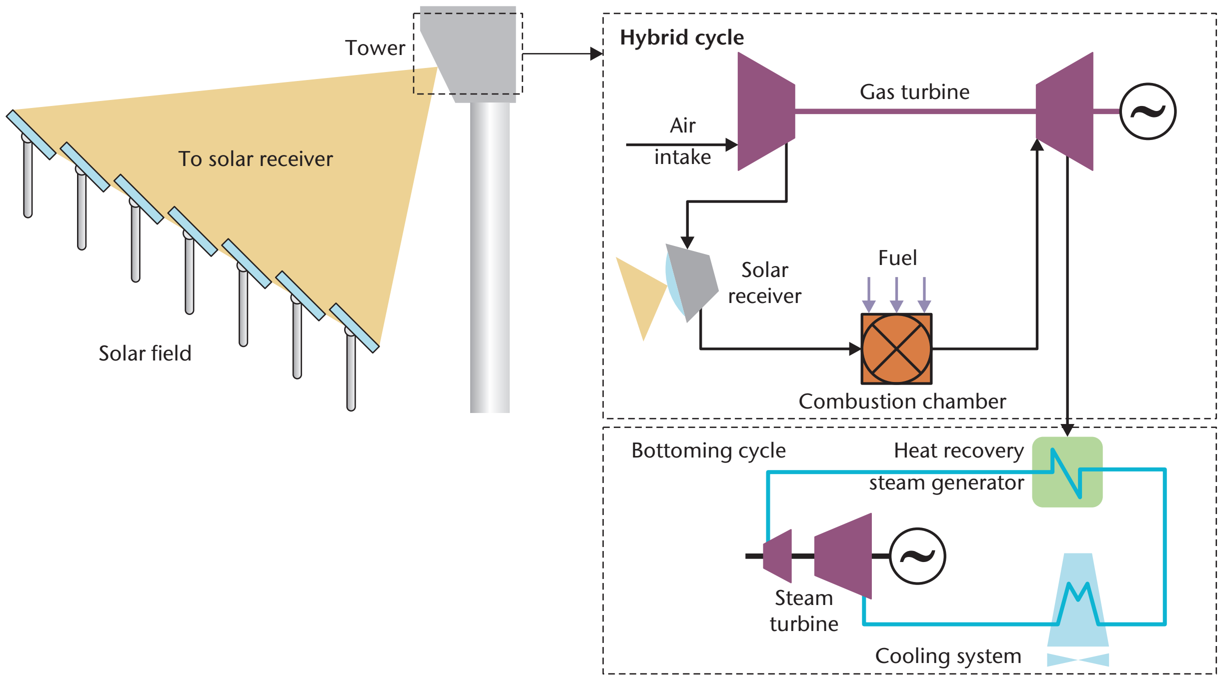
Molten salts decompose at higher temperatures, while corrosion limits the temperatures of steam turbines. Higher temperatures and efficiencies could rest on the use of fluoride liquid salts as HTFs up to temperatures of 700°C to 850°C, with closed-loop multi-reheat Brayton cycles using helium or nitrogen, which were initially developed for high-temperature nuclear reactors. As well as enabling higher plant efficiency, such power systems operate at relatively high pressure and power densities that requires smaller equipment than for steam cycles, so they could cost less.

Innovative HTF for future linear CSP plants may include nano-fluids. Dispersing solid particles in fluids enhances thermal conductivity, but particles settle rapidly in fluids. Nano-particles, possibly enhanced with surfactants/stabilisers, could remain in suspension almost indefinitely, and have a surface area per unit volume a million times larger than that of micro particles, offering improved heat transfer properties. Pressurised gas, currently being tested at the Plataforma Solar de Almeria, Spain, is another option for future HTF.

High-temperature tower concepts include atmospheric air as the HTF (tested in Germany with the 1.5 MW Jülich solar tower project) with solid material storage. A combination of such a system with a gas turbine to provide high load flexibility is considered as the next step in scaling up a project in Algeria. With air temperatures of up to 800°C, the system is also suitable for process heat or chemical applications. Solar-to-electricity efficiencies of up to about 25% can be delivered by such towers, but it is not yet clear if the gain in efficiency will compensate for the cost and complication of the cycle.

Solar-based open Brayton cycles offer a completely different way of exploiting the higher working temperatures that towers can achieve. Pressurised air would be heated in the solar receivers, and then sent directly to a gas turbine, at a temperature exceeding 800°C. Excess heat after running the gas turbine could be sent to a steam cycle running a second generator. The solar-to-electricity efficiency could be higher than 30%. Heat storage concepts have been developed based on adiabatic heat storage in combination with a pressurised air storage system. This concept was developed through the 100 kW Solgate project led by DLR (the German Aerospace Center). A more powerful 4.6 MW project along the same lines, Solugas, has been installed and operated on a new tower at

Figure 14: Concept of hybrid solar and gas tower plant with pressurised air receiver



Note: Courtesy of Pegase/CNRS.

KEY POINT: Scaling up air receivers for towers remains challenging.

the Abengoa Solar test facility near Seville, Spain (Abengoa Solar, 2013). Aora, in Israel, is operating a 100 kW tower that uses biomass as backup fuel.

The 2 MW Pegase demonstration project set up by the French research centre CNRS will use the Themis solar tower in the Pyrenees, with a different receiver design (Flamant, 2014). An optimal configuration would include a bottoming steam turbine (Figure 14).

Pressurised air receivers can be surface receivers – i.e., heat exchangers irradiated by the concentrated solar flux – or volumetric. On volumetric receivers, the air goes through a porous material that also absorbs the concentrated radiation. They are more efficient than surface receivers but require a transparent quartz window that must resist the air pressure: therefore, scaling up such receivers to MW scale or above does not seem feasible. At lower temperatures, a tubular concept using high-temperature alloys is suitable. Using supercritical CO_2 instead of pressurised air may thus become an option. Such a concept could provide high efficiencies at a temperature below 800°C in a single cycleAnother option would be to use particles to form a special kind of heat transfer "fluid", such as ceramic particles. In a recent experiment by DLR, a rotating drum filled with ceramic particles was inserted in the receiver. The particles are held inside by centrifugal force. After being heated by the focused solar radiation, the particles fall from the drum into thermally insulated containers. There, the heated particles can be used either for immediate power generation or stored for later use.

Safety advances in the nuclear sector in the last decade have led to a revival of the idea of using liquid metals like sodium or a combination of lead and bismuth as advanced HTF at temperatures above the temperature limit of molten salts. Initial laboratory-scale installations are under preparation.

The current commercially available storage solution – two-tank molten-salt sensible heat storage – is not the only option. As mentioned, DSG seem to require other options – but other plant designs may also benefit from advanced storage technologies. Phase-changed materials could be inserted in storage tanks. A single-tank "thermocline" system is still being considered by some developers, as well as the possibility of inserting steam generators into molten-salt tanks. Thermochemical storage, which may offer new ways of storing heat through reversible chemical reactions, is still being studied.

Finally, the ultimate evolution could be to hybridise STE technology with PV technology in fully integrated receivers – and take advantage of the entire solar spectrum efficiently, reducing overall electricity costs - with about half the electricity available for dispatch when needed. The Full-spectrum Optimised Conversion and Utilisation of Sunlight (Focus) programme of the US Advanced Research Projects Agency – Energy (ARPA-E) is supporting 12 such projects (Branz et al, 2014).

Full hybridisation of PV and STE could be done in various ways: splitting the solar spectrum at different points on its path from mirrors to receivers, or collecting losses from high-temperature "topping" solar cells. For example, a PV layer targeting some high-energy photons could be deposited at some point in the path of sunlight in a concentrating device, presumably on mirrors, either primary or secondary (if several reflection stages are used). This PV layer would only absorb some of the wavelengths that constitute the light from the sun. Others would be left to heat a fluid. If the PV layer is deposited directly on the thermal receiver, the PV conversion losses would be collected as heat for use in a thermal cycle – if one can develop PV materials sufficiently efficient at temperatures of 400°C or above.

Box 5: Solar fuels

Solar energy can be efficiently stored in liquid or gaseous fuels using concentrated solar radiation as the source of high-temperature heat for endothermic thermochemical processes.

There are a number of potential pathways to solar fuels. The straightforward thermolysis of water is the most difficult, as it requires temperatures above 2 200°C and may produce an explosive mixture of hydrogen and oxygen. The division of the single-step water-splitting reaction into a number of sub-reactions opens up the field of so called thermochemical cycles for H_2 production. The necessary reaction temperature can be decreased even below 1 000°C, resulting in intermediate solid products like metals (e.g., aluminium, magnesium, or zinc), metal oxides, metal halides or sulphur oxides. The different reaction steps can be separated in time and place, offering possibilities for long-term storage of the solids and their use in transportation. These thermochemical cycles are also able to split CO_2 into CO and oxygen. If mixtures of water and CO_2 are used, even synthesis gas (mainly H_2 and CO) can be produced, which can be further processed to synfuels, for example by the Fischer-Tropsch process. Thermochemical cycles are reported to have theoretical efficiencies above 60%. If coupled to a solar tower, efficiencies up to 25% are expected.

In a similar way, high- temperature solid oxide electrolysers can be used to generate hydrogen and synthesis gas. Coupled to a solar tower, solar-to-hydrogen efficiencies above 20% seem possible, a significant improvement over using solar electricity in low- temperature steam electrolysers, which achieves an efficiency of only about 12%.

All the solar thermochemical and electrochemical processes described above offer an additional environmental benefit if water and atmospheric CO_2 are used to produce H_2 and synthesis gas, thus making the products CO_2 emission- neutral.

Concentrated solar radiation can also be used to upgrade carbonaceous materials. The most developed process is the steam reforming of methane to produce synthesis gas. Sources are either natural gas or biogas. Methane can also be cracked into hydrogen and carbon, thus producing a gaseous and a solid product. However, the required process temperature is extremely high and a homogeneous carbon product is unlikely to be produced because of the intermittent solar radiation conditions. Additionally, there is a discrepancy between the huge demand for hydrogen and the low demand for high-value carbon, such as carbon black or advanced carbon nano-tubes.

Another environmentally beneficial use of concentrated solar radiation is the gasification of biomass or carbonaceous waste material to produce synthesis gas more efficiently than by burning part of the biomass or waste for providing high-temperature process heat. Using concentrating solar gasification technologies in sunny countries would reduce the land and water requirement of current or future advanced biofuels. Solid and liquid biofuels enhanced from solar heat could be used in virtually all transport and industry applications.

Hydrogen produced in concentrating solar chemical plants could be blended with natural gas and thus used in today's energy system. Town gas, which prevailed before natural gas spread out, included hydrogen up to 60% in volume or about 20% in energy content. This blend could be used for various purposes in industry, households and transportation, reducing emissions of CO_2 and nitrous oxides. Gas turbines in integrated gasification combined cycle (IGCC) power plants can burn a mix of gases with 90% hydrogen in volume. Many existing pipelines could, with some adaptation, transport such a blend from sunny places to large consumption centres (e.g. from North Africa to Europe).

Solar-produced hydrogen could also find niche markets today in replacing hydrogen production from steam-reforming of natural gas in its current uses, such as manufacturing fertilisers and removing sulphur from petroleum products. Regenerating hydrogen with heat from concentrated sunlight to decompose hydrogen sulphide into hydrogen and sulphur could save significant amounts of still gas in refineries for other purposes.

Coal could be used together with methane gas as feedstock, and deliver dimethyl ether (DME), after solar-assisted steam reforming of natural gas, coal gasification under oxygen, and two-step water splitting. DME could be used as a liquid fuel, and its combustion would entail similar CO_2 emissions to those from burning conventional petroleum products, but significantly less than the life-cycle emissions of other coal-to-liquid fuels.

Besides solar fuels, CSP technology could find a great variety of uses in providing high-temperature process heat or steam, such as for enhanced oil recovery, and mining applications (where CSP is already in use), smelting of aluminium and other metals, and in industries such as food and beverages, textiles and pharmaceuticals. Various forms of cogeneration with STE can also be considered. For example, sugar plants require high-temperature steam in spring, when the solar resource is maximal but electricity demand minimal. Solar fields providing steam for sugar plants could run a turbine and generate STE for the rest of the year.

Policy, finance and international collaboration: Actions and milestones

STE is not broadly competitive today, and will not become so until it benefits from strong and stable frameworks, and appropriate support to minimise investors' risks and reduce capital costs.

Deploying STE according to the vision of this roadmap requires strong, consistent and balanced policy support. The main areas of policy intervention include:

- Removing or alleviating non-economic barriers such as costly, lengthy and heavy permitting and connecting procedures.
- Recognising the value of STE for electric systems, due to its dispatchability, and ensuring it is duly rewarded.
- Creating or updating a policy framework for market deployment, including tailoring incentive schemes and reconsidering electricity market design to accompany the transition to market competitiveness; basing policy frameworks on targets for deployment set at country level; making regulatory changes that are as predictable as possible; and avoiding retroactive changes.
- Providing innovative financing schemes to reduce costs of capital for a great variety of potential customers.

Removing non-economic barriers

This roadmap recommends the following actions	*Time frames*
1. Streamline permitting and connecting.	Complete by 2015-2018
2. Communicate on the pros and cons of the various energy technologies with respect to the environment, and put problems in perspective.	Complete by 2015-2018

As with any large industrial projects, STE projects require several permissions, often delivered by many different government jurisdictions at various geographical levels, as well as many branches or agencies of each – local, regional, state, federal or national. Each may protect different interests, all of them legitimate. At some point, however, trade-offs need to be assessed, advantages and disadvantages put in balance, and decisions taken. It is important that developers gain a clearer view of all relevant processes and likely outcomes. The southwestern United States, in particular, has provided good examples of teamwork, with a great variety of federal and State agencies joining forces to streamline permitting processes, and reduce or avoid duplication of paperwork and hearings.

Developers also have difficulty understanding significant differences in environmental legislation from one country to another – and sometimes, in the European Union, different interpretations of European legislation in various countries. Configurations that are standard in Spain seem to be forbidden in Italy from an industrial risk perspective. Governments should regularly revise the way they apply legislation in light of their neighbours' experience.

Finally, relatively minor issues seem able to create disproportionate concerns. One example is that of birds killed by solar heat in CRS configurations in the southwestern United States. If killing birds had to be avoided at all costs, windows, pet cats and roads should all be prohibited, for they all kill birds every year in numbers that are several orders of magnitude greater than those that might be killed by solar towers. Not only the industry, but government agencies and responsible environmental NGOs should educate the public and the media about the advantages of STE with respect to climate change and associated biodiversity losses, and help them put its disadvantages in perspective.

Recognise the value of STE

This roadmap recommends the following actions	*Time frames*
1. Assess the value of STE at system level.	Complete by 2015-2018
2. Ensure time-of-delivery payment for STE reflecting the structure of avoided costs at system level, including capacity and energy costs.	Complete by 2015-2018

STE from CSP plants is not broadly competitive today, but on-demand STE has higher value than PV electricity. Even in areas where afternoon peak time matches well with PV output, CSP plants offer a variety of ancillary services that are becoming increasingly valuable as shares of PV and wind (both variable renewables) increase in the electricity mix (Box 6).

Box 6: Future values of PV and STE in California

Researchers at the National Laboratory of Renewable Energy (NREL) in the United States have studied the future total values (operational value plus capacity value) of STE with storage and PV plants in California in two scenarios: one with 33% renewables in the mix (the renewable portfolio standard by end 2020), including about 11% PV, another with 40% renewables (under consideration by California's governor), including about 14% PV. In both cases there is over 1 GW of electricity storage available on the grid. The main results indicate that at 33% renewable penetration, the bulk of the gap in favour of STE comes from its greater capacity value, which avoids the costs of building additional thermal generators to meet demand (Table 5). At 40% renewable penetration, the value of STE increases slightly, but the value of PV drops significantly, mostly reflecting the drop of its own capacity value (Jorgenson et al., 2014). For investment decisions and planning, system values are as much important as LCOE.

Table 6: Total value in two scenarios of renewables penetration in California

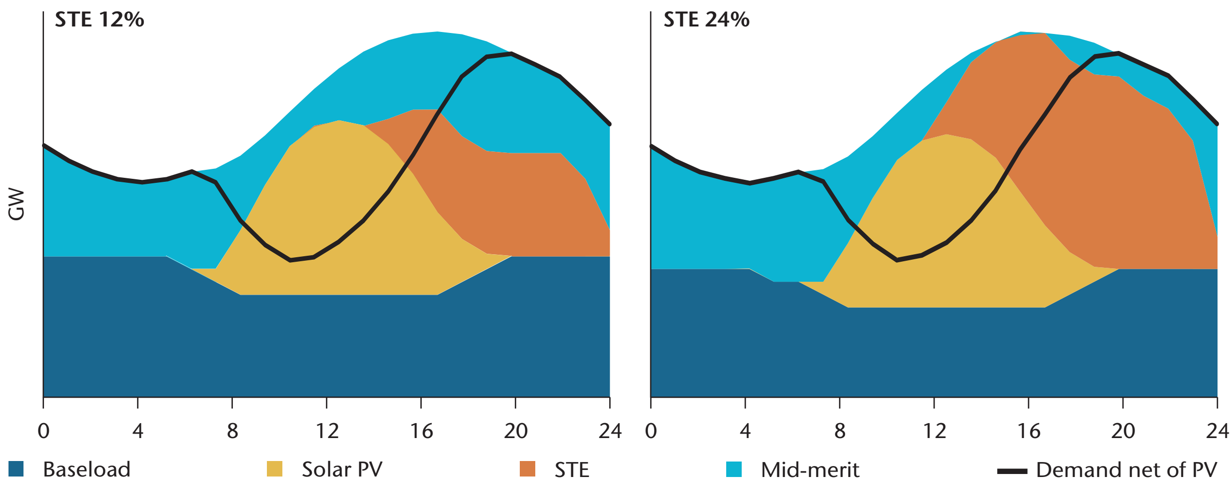
	33% renewables		*40% renewables*	
Value component	*STE with storage value (USD/MWh)*	*PV Value (USD/MWh)*	*STE with storage value (USD/MWh)*	*PV Value (USD/MWh)*
Operational	46.6	31.9	46.2	29.8
Capacity	47.9-60.8	15.2-26.3	49.8-63.1	2.4-17.6
Total	**94.6-107**	**47.1-58.2**	**96.0-109**	**32.2-47.4**

CSP plants' thermal inertia and relatively small storage capacities are likely to be sufficient for them to provide these services. To some extent, these added values are able to compensate for higher costs. Utilities in the southwestern United States that are choosing CSP plants to comply with renewable energy portfolio standards appear to be aware of these advantages of STE — and adverse to the potential risks arising from the variable output of PV systems that have been deployed too rapidly.

CSP can generate electricity when PV cannot, in the absence of affordable electricity storage capacities. The built-in storage capability of CSP is cheaper and more effective (with over 95% return efficiency, versus about 80% for most competing technologies) than battery storage and pumped-hydropower storage. Thermal storage allows separating the collection of the heat (during the day) and the generation of electricity (at will). This capability has immediate value in countries having significant increase in power demand when the sun sets, in part driven by lighting requirements. In many such countries, the electricity mix, which during daytime is often dominated by coal, becomes dominated by peaking technologies, often based on natural gas or oil products. In developing economies, which often have very tight electric capacity, peaks stretch the electric system to its limits. At such times, the marginal value of electricity can skyrocket — often to twice or three times the normal high.

In countries with demand peaks during the afternoon and early evenings, the largest share might be accessible to PV. After some PV deployment has taken place, however, the load curve net of PV becomes more favourable to CSP, when evening peaks increase. CSP is well placed to respond to these evolutions (Figure 15).

Figure 15: Daily dispatch for a stylised system with annual PV electricity share of 18% and various CSP shares (left: 12%; right: 24%)



KEY POINT: CSP plants would generate electricity for peak and mid-peak demand; after sunset, their capacity complements PV generation from earlier in the day.

This potential explains the growing interest in STE in countries such as China, India, Morocco, Saudi Arabia and South Africa. The ability of CSP plants to deliver electricity at will also helps to explain, together with current higher costs, why in long-term scenarios STE electricity initially lags behind PV electricity but eventually gains shares as PV capacities level off. Although both technology families compete on some markets today, in the longer term the synergies prevail.

The greatest possible expansion of PV, which implies its dominance over all other sources during a significant part of the day, creates difficult technical and economic challenges to low-carbon base-load technologies such as nuclear power and fossil fuel with CCS. Natural gas is more suited to daily "stop-and-go" with rapid ramps up and down, and is more economical for mid-merit operations (between about 2 000 and 4 000 full-load hours). But as the CO_2 constraints grow stricter and the carbon price rises, the share of natural gas must progressively recede. In hot and dry regions, PV deployment thus paves the way for CSP expansion in leaving untouched or aggravating demand peaks at dark.

Several recent examples highlight ways CSP could be used to support electricity system operation and planning. In Morocco, the CSP plants being built to run mostly during daytime will require continuous support from the government, despite low financing costs provided by multilateral and bilateral development banks. Yet a mix of CSP mostly used after sunset and PV used during daytime would save the government money; these technologies are less costly than the marginal cost of alternatives currently forecast — natural gas during daytime plus diesel oil after sunset.

In South Africa, while base load electricity is generated from inexpensive coal, growing demand peaks call for the deployment of additional peaking capacities. To this end, building 5 GW of new open-cycle gas turbines (OCGT) to be run on diesel oil is currently planned, while gas is not available. This offers significant opportunities for CSP plants with storage, which could deliver 80% of the electricity at peak times, with the OCGT producing the remaining 20% (Silinga and Gauché, 2013).

The South African Department of Energy (DoE) offers an excellent policy example of how to encourage CSP with storage to generate energy during peak time. The DoE recently introduced a time-of-delivery (TOD) tariff in the third round of procurement for renewable capacities. A base tariff applies during the day, and a higher tariff — the base tariff multiplied by 2.7 — will be applied for supplying energy during peak time, between 4:30 p.m. and 9:30 p.m. Competitors need only bid for one price — the price during peak hours being the simple product of the bidding price by the multiplier. Thus, the TOD ensures a simple process for selecting the best bids.

Time-of-delivery tariffs are not new, however: CSP technology might not be commercially available today without the TOD PPA under which first commercial CSP plants were built in California in the 1980s. Based on the notion of avoided costs as defined under the Public Utility Regulatory Policies Act of 1978, including "energy" and "capacity" payments, these PPA provided remuneration levels varying in large proportion with seasons and hours of the day), ranging from about USD 60/MWh during winter off-peak times to USD 360/MWh during summer peaks, reflecting avoided costs to the utility (Pharabod and Philibert, 1992).

Setting predictable financial schemes and regulatory frameworks

Attract investment to STE	*Time frames*
1. Implement or update incentives and support mechanisms that provide sufficient confidence to investors; create a stable, predictable financing environment to lower costs for financing. These may notably include FiTs and auctions for long-term PPAs.	Complete by 2015
2. Avoid retroactive changes, which undermine the confidence of investors and the credibility of policies.	2014-50
3. Work with financing circles and other stakeholders to reduce financing costs for STE deployment, in particular developing large-scale refinancing of STE (and other clean energy) loans with private money and institutional investors.	2015-30
4. In countries (or smaller jurisdictions, such as islands) with highly subsidised retail electricity prices, progressively reduce these subsidies while developing alternative energy sources and implementing more targeted financial support to help the poor.	2015-20

Most often, STE will not be competitive in the short term. Current investments must be considered in part as learning investments, required to bring down the costs of this still young technology. They will thus need support, which can take a variety of forms. However, recognising the true value of STE in time and location, and rewarding it fully, is an important step, as it will reduce the extra burden of subsidies in any support schemes. It will also drive the development and the deployment of the technology so as to maximise its value for the whole system (e.g., in selecting the most appropriate ratio of solar field size, storage capacity and turbine size), through a proven method – maximising the return on investment for developers.

In some countries, price signals are heavily distorted by subsidies at various levels. In Morocco, for example, generating electricity at peak time after sunset was heavily subsidised until mid-2014, not so much by the Office National de l'Electricité et de l'Eau (ONEE – the national grid operator and utility) but through another mechanism at government level, the Caisse de Compensation, which subsidised imported petroleum products ("special" fuel and diesel fuel) used in thermal plants during peaks. This did not allow delivering to the developer of CSP plants, the Moroccan Agency for Solar Energy (MASEN), price signals that reflect the cost to the entire country of generating electricity during peaks.

Policy options

There are a great variety of policy options and incentive schemes to consider. Feed-in tariffs (FiTs), feed-in-premiums (FiPs), and auctions have prevailed for renewable energy in Europe, Australia, Canada, and Japan. In the United States, long-term power-purchase agreements (PPA) have been signed by utilities to respond to renewable energy portfolio standards (RPS), with or without solar carve-outs. Auctions are common in many emerging economies, from Brazil to South Africa. Up-front subsidies, directly addressing the large impediment of CSP plants' very capital-intensive cost structure, could be very helpful, but should not offset incentives to generate electricity.

Well-managed FiTs have proven effective in stimulating deployment, while providing fair but not excessive remuneration to investors. However, they have been unevenly successful in driving cost reductions: very effective for PV in Germany, much less so for STE in Spain. FiT levels must decline over time, in a predictable manner.

Furthermore, FiTs do not deliver any incentive to generate electricity when and where it is most useful for the entire electric system. **FiPs** are being implemented or suggested as possible transition tools toward greater market exposure. Premiums are added to the market prices to remunerate renewable electricity. One should however distinguish fixed ("ex ante") FiPs from sliding ("ex post") FiPs. Fixed FiPs are set once for all. The total remuneration thus depends on the market prices. Sliding FiPs are set at regular intervals, typically months, to fill the gap between the average market price perceived by all generators of a given technology and a pre-determined strike price. The United Kingdom's "contract for difference" can be considered as a sliding FiP.

With fixed FiPs, CSP plants compete with all other generating technologies on wholesale markets. Their total remuneration is therefore more uncertain, which raises investors' risk and ultimately increases the cost of capital and LCOE. With sliding FiPs, CSP plants compete with one another. Those performing better than average in delivering power when the electricity prices are high, get higher returns. Those performing worse than average get lower returns. The difference in returns is more modest than with ex-ante FiPs, and the increases in risk and costs of capital are less pronounced.

Time-of-delivery PPAs would likely be the instrument of choice for CSP projects. To preserve competition as much as possible, they could result from auctioning processes. Most emerging economies – including Brazil, India and South Africa – but also industrialised countries such as Chile, or developing countries such as Morocco, have used auction procedures to select projects and developers, with variable success.

Several lessons emerged in particular from the difficulties met in India: bidders should know the exact status of the DNI information that is made available to them; imposing large penalties for delayed projects does not help much; and some earlier experience in the field must be part of the selecting process, to encourage inexperienced potential bidders to team up with more experienced companies.

Retroactive laws

Except for criminal laws, retroactive laws are not unconstitutional in most jurisdictions. With respect to fiscal decisions, they are even relatively common. Limited retroactivity usually gets approved by constitutional judges if the retroactive legislation has a rational legislative purpose and is not arbitrary, and if the period of retroactivity is not excessive.

However, changes in the rules applicable to investments already being made or in process can have long-lasting deterrent effects on investments if they significantly modify the prospects for economic returns. This is precisely what has happened over the last few years in Spain, where a series of measures aimed at reducing the return on investment on existing CSP plants. The high risk of losing investors' confidence may have been deemed acceptable, as these measures followed the decision to stop CSP deployment. However it may have detrimental effects for future investments in CSP plants; for other investments in the energy sector; for other investments in any other sector that requires government involvement; and for investments in other countries.

Financing

CSP plants, like most renewable energy plants, are very capital-intensive, requiring large up-front expenditures. Financing is thus difficult, especially in new, immature markets, and for new, emerging sub-technologies. In the United States, some private investors have large amounts of money available and might be willing to invest in clean energy for a variety of reasons; but even in this context the risks may have appeared too high for large, innovative CSP projects – costing around USD 1 billion – to materialise, without the loan guarantee programme of the US DoE. This programme has been essential to the renaissance of CSP in the United States, in allowing projects to access debt at very low cost from a US government bank and facilitating financial closure at acceptable WACC of large projects. Perhaps more important, it has allowed innovation and scaling up of innovation to take place, opening the door for significant cost reductions. As significant potential for further cost reduction through innovation is obvious in the case of CSP, the programme has recently been reopened. Refinancing completed projects with investors seeking long-term, secure opportunities could also help accelerate the rotation of capital for more rapid deployment.

In other countries, such as India, Morocco and South Africa, public low-cost lending has been essential for jump-starting the deployment of CSP. In India and South Africa, private banks would have not provided capital for the very long maturity involved. In Morocco, the presence of a government agency as equity partner significantly reduced the perception of policy risks among other partners. In Morocco and South Africa, international finance institutions provided concessional grants that reduced the overall costs of large CSP projects. In Morocco, a syndicate of European lenders and donors (European Investment Bank, Kredit-Anstalt fur Wiederaubfau, Agence Française de Développement) saved the developer part of the burden of addressing many different loan rates, conditions and procedures (Stadelmann et al., 2014). However, currency risks may largely offset the benefits of lower rates. This can be mitigated if part of the FiT or PPA is in foreign currency (Nelson and Shrimali, 2014).

Subsidising renewable energy projects through long-term and/or low-cost debt-related policies could reduce the total subsidies compared with per-kWh support. However, this only transfers the burden of high capital-intensivity to governments, which may not have enough money at hand, and this carries a risk of slowing deployment. Interest subsidies and/or accelerated depreciation have much higher one-year budget efficiency. For solar in India, an interest subsidy of 10.2% would result in a total subsidy reduction of 11% and would support 30% more deployment in one year than the current generation-based incentive (Shrimali et al., 2014)

Of course, providing incentives only for investment always carries the risk that generation is neglected. A mix of policies is ultimately most likely to strike the right balance between incentives for deployment and incentives for generation in due time and place, at the lowest possible costs for ratepayers and taxpayers.

R&D support and international collaboration

Research is under way to test and evaluate methods of measuring DNI accurately using lower-cost instrumentation, and for producing long-term, high-quality DNI data sets by merging long-term, satellite-derived data of moderate accuracy with high-quality, highly accurate ground-based measurements that may only cover a year or less. This research also includes important studies on sunshape and circumsolar radiation, and how these factor into both DNI measurements and STE system performance. In addition, satellite-based methods for estimating DNI are constantly improving and represent a reliable and viable way of choosing the best sites for STE plants. Furthermore, the ability to accurately forecast DNI levels – from a few hours ahead to a few days ahead – is constantly improving, and will be an important tool for utilities operating STE systems. Bringing these research results to fruition as a means of developing "bankable" STE projects would be a public good and requires public support.

Public R&D efforts and public support for private R&D in the field of STE technologies remains low. The need for more open access to RD&D tower facilities like those at the Plataforma Solar de Almeria (Spain), identified in the 2010 roadmap, remains pressing, as the few others available are all overloaded with experiments.

International collaboration

Since its inception in 1977, the IEA Implementing Agreement SolarPACES has been an effective vehicle for international collaboration in all CSP fields. Of all IEA implementing agreements (IA), SolarPACES has the largest participation by non-IEA members. It has been a privileged place for exchanging information, sharing tasks and, above all – through the Plataforma Solar de Almeria run by CIEMAT – for sharing experience.

The current work programme of SolarPACES includes six tasks:

Task I: Solar thermal electric systems; Task I addresses the design, testing, demonstration, evaluation, and application of STE systems. This includes parabolic troughs, linear Fresnel collectors, power towers and dish/engine systems.

Task II: Solar chemistry research; The primary objective of Task II – Solar Chemistry R&D – is to develop and optimize solar-driven thermochemical processes and to demonstrate their technical and economic feasibility at an industrial scale:

- Production of energy carriers: conversion of solar energy into chemical fuels that can be stored long-term and transported long-range.
- Processing of chemical commodities: use of solar energy for processing energy-intensive, high-temperature materials.
- Detoxification and recycling of waste materials.

Task III: Solar technology and advanced applications; the objectives of this task deal with the advancement of technical and economic viability of emerging solar thermal technologies and their validation with suitable tools by proper theoretical analyses and simulation codes as well as by experiments in special arrangements and adapted facilities.

Task IV: Solar heat for industrial processes. The purpose of the project is to provide the knowledge and technology necessary to foster installation of solar thermal plants for industrial process heat.

Task V: Solar resource assessment and forecasting (in common with the Solar Heating and Cooling IA); The task focuses primarily on the two most important topics in the field of solar radiation for solar energy applications: for financing the projects sound solar resource assessments are important. And for operation of the many MW installed power forecasting of solar radiation is receiving high attention from plant and grid operators.

Task VI: Solar energy and water processes and applications. The task was created to provide the solar energy industry, the water sector and electricity sectors, governments, renewable energy organisations and related institutions in general with the most suitable and accurate information on the technical possibilities for effectively applying solar radiation to water processes, replacing the use of conventional energies.

The annual SolarPACES Conference is by far the largest STE/CSP scientific conference, and attracts more and more industry, finance and policy representatives.

There seems to be no need to create any new international structure supervising RDD&D for CSP. Participation by all countries sunny enough for CSP, whether IEA members or not, would further strengthen SolarPACES, however. The IEA Technology Platform currently under development inside the IEA Secretariat will co-operate closely with SolarPACES on all relevant aspects of CSP development.

As noted above, research to establish publicly available credible DNI data is an area for government action. It requires good international collaboration, such as that initiated by the Multilateral Solar and Wind Working Group, which is a project under the Clean Energy Ministerial leadership. It led to the creation of a global atlas for renewable energy by the International Renewable Energy Agency (IRENA) (see http://globalatlas.irena.org).

Roadmap action plan

To reach a share of global electricity of as much as 11% in 2050, this roadmap implies a set of milestones by different stakeholders over 35 years. In a nutshell, they are the following:

- Governments establishing or updating targets for CSP deployment and implementing stable regulatory and market framework ensuring predictable financing environment and remuneration reflecting the value of STE at time of delivery.
- Industry further reducing STE costs through technology improvements.
- Industry and research institutions making R&D efforts commensurate with the potential role of STE and CSP technologies in climate-friendly energy future.

Near-term actions for stakeholders

The most immediate actions are listed below by lead actors.

Governments include policy makers at international, national, regional and local levels. Their underlying roles are to: remove deployment barriers; establish frameworks that promote close collaboration between the CSP industry and the wider power sector; and encourage private sector investment alongside increased public investment.

Governments should take the lead on the following actions:

- Set or update long-term targets for CSP deployment, including short-term milestones consistent with national energy strategies and with expected contributions to global climate mitigation.
- Address existing or potential barriers to deployment, in particular from permitting and connecting procedures.
- Ensure a stable, predictable financing environment. Where market arrangements and cost competitiveness do not provide sufficient incentives for investors, make sure that predictable, long-term support mechanisms exist; the level of support should, however, be progressively reduced.
- Ensure that the remuneration structure reflects the current and foreseeable structure of overall power system costs, so that developers adjust the size of solar fields, thermal storage and turbines to each country's needs for dispatchable power in the coming decades.
- Do not arbitrarily limit the size of individual plants.
- Do not arbitrarily set the level of fossil fuel backup or solar hybridisation in fossil fuel plants, but provide STE remuneration to all – and only – solar sourced kWh for new-built plants.
- Avoid retroactive changes in legislation and support frameworks.
- Identify and provide a suitable level of public funding for CSP R&D, including STE, high-temperature solar heat for industrial processes, and solar fuels, proportionate to the cost reduction targets and potential of the technology in terms of electricity production and CO_2 abatement targets.
- Enable increasing international R&D collaboration to make best use of national competencies.
- Strengthen international collaboration on best practices, and the development of resource databases open to the public.

CSP industry includes technology providers, manufacturers, developers, engineering, procurement and construction (EPC) contractors, for STE and other uses of CSP technologies.

CSP industry action in the short term, with support from research institutions, should focus on:

- Develop new light-weight low-cost reflector optics.
- Demonstrate large-scale use of molten salts as HTF in linear systems.
- Further develop and optimise solar tower concepts.
- Introduce supercritical steam turbines in CSP plants.
- Market CSP technologies for high-temperature process heat.

Implementation

The implementation of this roadmap could take place through national roadmaps, targets, subsidies and R&D efforts. Based on its energy and industrial policies, a country could develop a set of relevant actions.

Ultimately, international collaboration will be important and can enhance the success of national efforts. This updated roadmap identifies approaches and specific tasks regarding CSP/STE research, development and deployment, financing, planning, legal and regulatory framework development, and international collaboration. It also updates regional projections for STE deployment from 2015 to 2050 based on *ETP 2014*. Finally, this roadmap details actions and milestones to aid policy makers, industry and power system actors in their efforts to successfully deploy STE technologies.

The STE roadmap is meant to be a process, one that evolves to take into account new developments from demonstration projects, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that CSP/STE development efforts are on track to achieve the GHG emission reductions required by 2050. As such, the IEA, together with government, industry and other interested parties, will report regularly on the progress that has been achieved toward this roadmap's vision. For more information about the STE roadmap inputs and implementation, visit www.iea.org/roadmaps.

Abbreviations and acronyms

2DS	2°C Scenario
6DS	6°C Scenario
AC	alternative current
ARPA-E	Advanced Research Project Agency - Energy
ARRA	American recovery and reinvestment Act
CCS	carbon capture and storage
CO_2	carbon dioxide
CPI	Climate Policy Initiative
CSF	concentrated solar fuels
CSP	concentrating solar power
CPV	concentrating photovoltaic
CRS	central receiver system
CTF	Clean Technology Fund
DC	direct current
DII	Desertec Industry Initiative
DLR	Forschungszentrum der Bundesrepublik Deutschland für Luft- und Raumfahrt (German Aerospace Centre)
DME	Dimethyl ether
DNI	direct normal irradiance
DSG	direct steam generation
EDF	Électricité de France
EIB	European Investment Bank
EPC	engineering, procurement and construction
ETP:	*Energy Technology Perspectives*
EU	European Union
EUR	euro
FiT	feed-in tariff
FiP	feed-in premium
G8	Group of Eight
GHG	greenhouse gas(es)
GHI	global horizontal irradiance
GNI	global normal irradiance
Gt	gigatonnes
GW	gigawatt (1 million kW)
GWh	gigawatt hour (1 million kWh)
Hi-Ren	high renewables (Scenario)
HTF	heat transfer fluid
HVDC	high-voltage direct current
IA	implementing agreement
IEA	International Energy Agency
IFI	international financial institution
IGCC	integrated gasification combined cycle
IRENA	International Renewable Energy Agency
ISCC	Integrated Solar Combined-Cycle (plant)
JRC	Joint Research Centre
kW	kilowatt
kWh	kilowatt hour
LCOE	levelised cost of electricity
LFR	linear Fresnel reflectors
MW	megawatt (1 thousand kW)
MW_e	megawatt electrical
MWh	megawatt hour (1 thousand kWh)
MW_{th}	megawatt thermal
NGO	non-governmental organisation
NREAP	national renewable energy action plan
NREL	National Renewable Energy Laboratory (United States)
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
PPA	power purchase agreement
PT	parabolic trough
PUC	Public Utility Commission
PV	photovoltaic
R&D	research and development
RD&D	research, development and demonstration
RPS	renewable energy portfolio standard
SEGS	solar electricity generating systems
STE	solar thermal electricity
T&D	transmission and distribution
TOD	time of delivery
TIMES	The Integrated MARKAL (Marketing and Allocation Model)-EFOM (energy flow optimisation model) System.
TSO	transmission system operator
TWh	terawatthour (1 billion KWh)
US	United States (of America)
USD	United States dollar
US DOE	United States Department of Energy
vRE	variable renewables
VOST	value-of-solar tariff
VSC	voltage source converter
WACC	weighted average cost of capital

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IEA Publications, 9 rue de la Fédération, 75739 PARIS CEDEX 15
TYPESETTED BY IEA AND PRINTED IN FRANCE BY CORLET, SEPTEMBER 2014

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Technology Roadmap Solar Thermal Electricity

2014

2015

2020

2025

2030

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