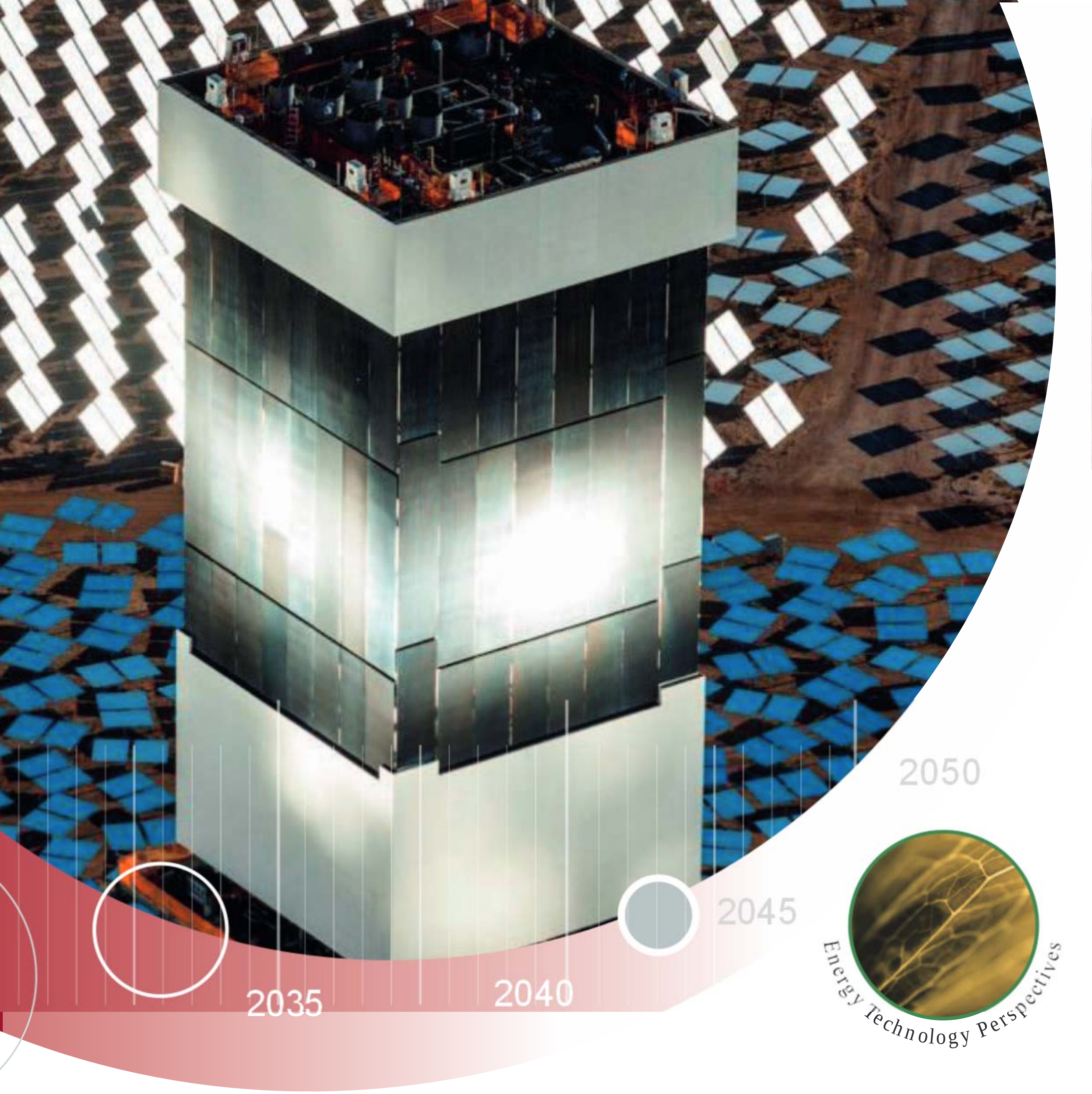


Technology Roadmap

Solar Thermal Electricity

2014 edition

International Energy Agency

Secure • Sustainable • Together

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea (Republic of)
Luxembourg
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

The European Commission also participates in the work of the IEA.

International Energy Agency 1974•2014
Secure • Sustainable • Together

International Energy Agency
9 rue de la Fédération
75739 Paris Cedex 15, France

www.iea.org

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

Table of contents

List of tables

List of figures

List of boxes

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).

For more information on this document, contact:
Technology Roadmaps
International Energy Agency
9, rue de la Fédération
75739 Paris Cedex 15
France
Email: TechnologyRoadmapsContact@iea.org

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.

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

- 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.

- 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.

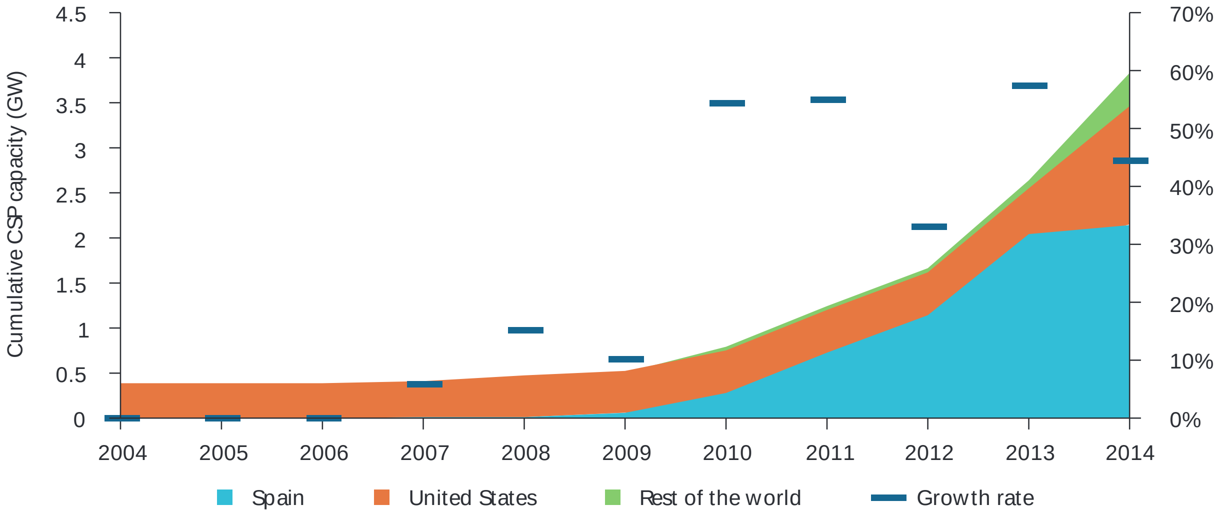
2. See www.iea.org/workshop/solarelectricityroadmapworkshop.html.

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.

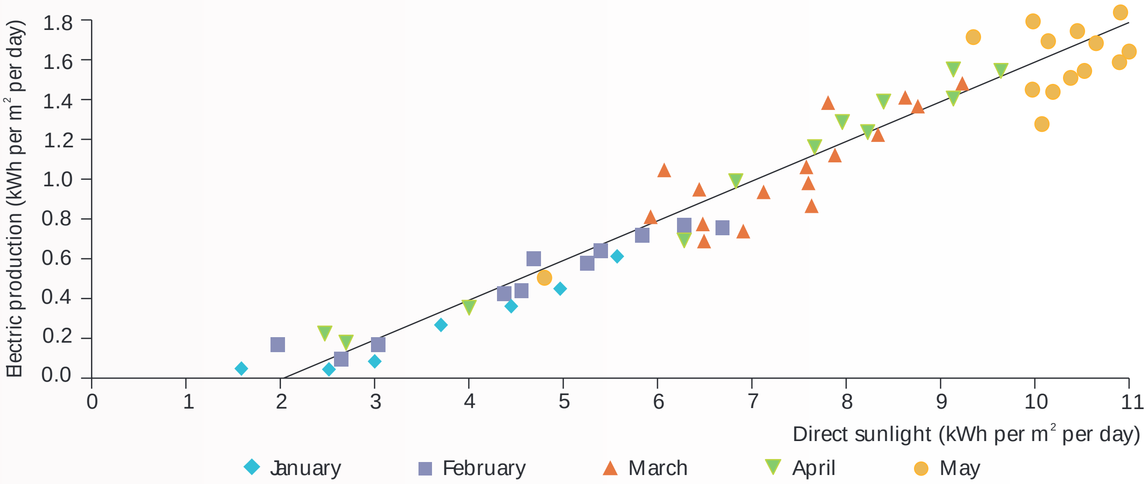
All places on earth receive 4 380 daylight hours per year — i.e., half the total duration of a year – but different areas receive different yearly average amounts of energy from the sun. When the sun is lower in the sky, its energy is spread over a larger area and energy is also lost when passing through 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.

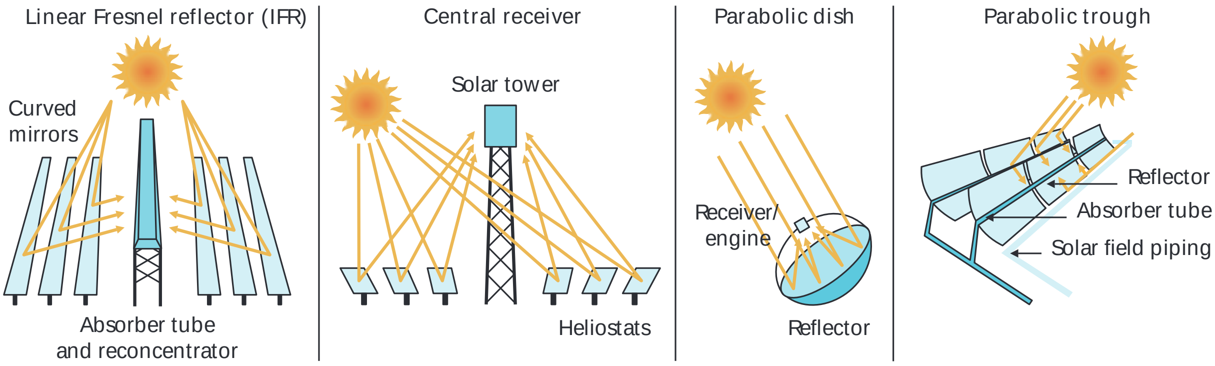
Technology improvements

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).

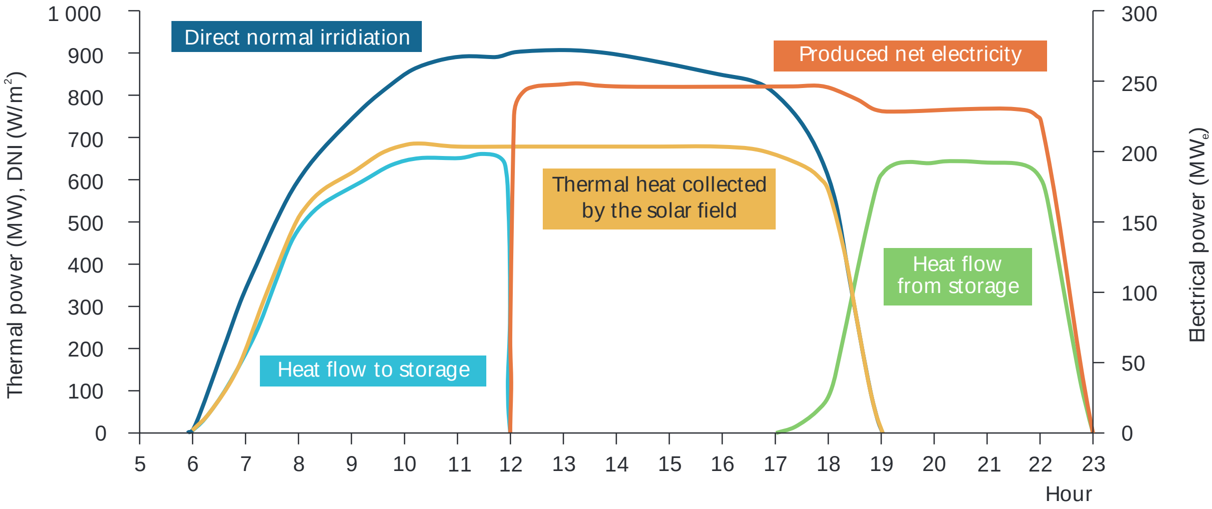
Thermal storage

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.

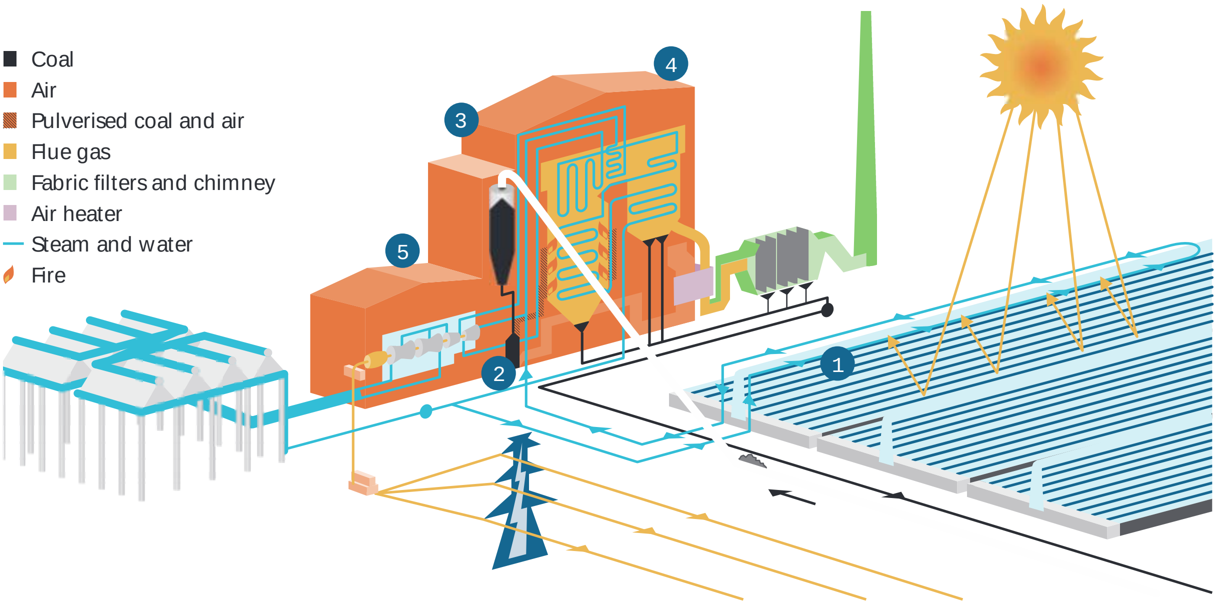
Solar-fossil hybridisation can also consist in adding a small solar field to a fossil-fired thermal power plant, either a gas-fired combined cycle or a coal-fired plant. On integrated solar combined-cycle (ISCC) plants, the solar field provides steam (preferably high-pressure steam) to the plant's steam 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 ½eld 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.