Technology Roadmap

Concentrating Solar Power

International Energy Agency

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its mandate is two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply and to advise member countries on sound energy policy.

The IEA carries out a comprehensive programme of energy co-operation among 28 advanced economies, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency aims to:

- 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.

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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of CO_2 will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies.

We must – and can – change our current path; we must initiate an energy revolution in which low-carbon energy technologies play a lead role. If we are to reach our greenhouse-gas emission goals, we must promote broad deployment of energy efficiency, many types of renewable energy, carbon capture and storage, nuclear power and new transport technologies. Every major country and sector of the economy must be involved. Moreover, we must ensure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is developing a series of roadmaps for key energy technologies. These roadmaps provide solid analytical footing that enables the international community to move forward, following a well-defined growth path – from today to 2050 – that identifies the technology, financing, policy and public engagement milestones needed to realise the technology's full potential. The IEA roadmaps include special focus on technology development and deployment to emerging economies, and highlight the importance of international collaboration.

The emerging technology known as concentrating solar power, or CSP, holds much promise for countries with plenty of sunshine and clear skies. Its electrical output matches well the shifting daily demand for electricity in places where air-conditioning systems are spreading. When backed up by thermal storage facilities and combustible fuel, it offers utilities electricity that can be dispatched when required, enabling it to be used for base, shoulder and peak loads. Within about one to two decades, it will be able to compete with coal plants that emit high levels of CO_2. The sunniest regions, such as North Africa, may be able to export surplus solar electricity to neighbouring regions, such as Europe, where demand for electricity from renewable sources is strong. In the medium-to-longer term, concentrating solar facilities can also produce hydrogen, which can be blended with natural gas, and provide low-carbon liquid fuels for transport and other end-use sectors.

For CSP to claim its share of the coming energy revolution, concerted action is required over the next ten years by scientists, industry, governments, financing institutions and the public. This roadmap is intended to help drive these indispensable developments.

Nobuo Tanaka
Executive Director

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Key findings

Concentrating solar power (CSP) can provide low-carbon, renewable energy resources in countries or regions with strong direct normal irradiance (DNI), *i.e.* strong sunshine and clear skies. This roadmap envisages development and deployment of CSP along the following paths:

- By 2050, with appropriate support, CSP could provide 11.3% of global electricity, with 9.6% from solar power and 1.7% from backup fuels (fossil fuels or biomass).
- In the sunniest countries, CSP can be expected to become a competitive source of bulk power in peak and intermediate loads by 2020, and of base-load power by 2025 to 2030.
- The possibility of integrated thermal storage is an important feature of CSP plants, and virtually all of them have fuel-power backup capacity. Thus, CSP offers firm, flexible electrical production capacity to utilities and grid operators while also enabling effective management of a greater share of variable energy from other renewable sources (*e.g.* photovoltaic and wind power).
- This roadmap envisions North America as the largest producing and consuming region for CSP electricity, followed by Africa, India and the Middle East. Northern Africa has the potential to be a large exporter (mainly to Europe) as its high solar resource largely compensates for the additional cost of long transmission lines.
- CSP can also produce significant amounts of high-temperature heat for industrial processes, and in particular can help meet growing demand for water desalination in arid countries.
- Given the arid/semi-arid nature of environments that are well-suited for CSP, a key challenge is accessing the cooling water needed for CSP plants. Dry or hybrid dry/wet cooling can be used in areas with limited water resources.
- The main limitation to expansion of CSP plants is not the availability of areas suitable for power production, but the distance between these areas and many large consumption centres. This roadmap examines technologies that address this challenge through efficient, long-distance electricity transportation.
- CSP facilities could begin providing competitive solar-only or solar-enhanced gaseous or liquid fuels by 2030. By 2050, CSP could produce enough solar hydrogen to displace 3% of global natural gas consumption, and nearly 3% of the global consumption of liquid fuels.

Key actions by government in the next ten years

Concerted action by all stakeholders is critical to realising the vision laid out in this roadmap. In order to stimulate investment on the scale required to support research, development, demonstration and deployment (RDD&D), governments must take the lead role in creating a favourable climate for industry and utilities. Specifically, governments should undertake the following:

- Ensure long-term funding for additional RD&D in: all main CSP technologies; all component parts (mirrors/heliostats, receivers, heat transfer and/or working fluids, storage, power blocks, cooling, control and integration); all applications (power, heat and fuels); and at all scales (bulk power and decentralised applications).
- Facilitate the development of ground and satellite measurement/modelling of global solar resources.
- Support CSP development through long-term oriented, predictable solar-specific incentives. These could include any combination of feed-in tariffs or premiums, binding renewable energy portfolio standards with solar targets, capacity payments and fiscal incentives.
- Where appropriate, require state-controlled utilities to bid for CSP capacities.
- Avoid establishing arbitrary limitations on plant size and hybridisation ratios (but develop procedures to reward only the electricity deriving from the solar energy captured by the plant, not the portion produced by burning backup fuels).
- Streamline procedures for obtaining permits for CSP plants and access lines.

Other action items for governments, and actions recommended to other stakeholders, are outlined in the Conclusion.

Introduction

This concentrating solar power roadmap is part of a series being developed by the IEA in response to the pressing need to accelerate the development of advanced energy technologies to address the global challenges of clean energy, climate change and sustainable development. Ministers from the G8 countries, China, India and South Korea, acknowledged this need in their June 2008 meeting (Aomori, Japan) and expressed their desire to have the IEA prepare roadmaps to chart clear paths for the development and deployment of innovative energy technologies.

> *We will **establish an international initiative with the support of the IEA** to develop roadmaps for innovative technologies and cooperate upon existing and new partnerships, including carbon capture and storage (CCS) and advanced energy technologies. Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognize and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies...*

To achieve this ambitious goal, the IEA has undertaken, under international guidance and in close consultation with industry, to develop a series of global roadmaps covering 19 technologies. These are evenly divided among demand-side and supply-side technologies.

The overall aim of these roadmaps is to demonstrate the critical role of energy technologies in achieving the stated goal of halving energy-related carbon dioxide (CO_2) emissions by 2050. The roadmaps will enable governments, industry and financial partners to identify the practical steps they can take to participate fully in the collective effort required.

This process began with establishing a clear definition and the elements needed for each roadmap. Accordingly, the IEA has defined its global technology roadmaps as:

> *... a dynamic set of technical, policy, legal, financial, market and organizational requirements identified by the stakeholders involved in its development. The effort shall lead to improved and enhanced sharing and collaboration of all related technology-specific research, development, demonstration and deployment (RDD&D) information among participants. The goal is to accelerate the overall RDD&D process in order to enable earlier commercial adoption of the technology in question.*

Rationale for CSP

CSP uses renewable solar resource to generate electricity while producing very low levels of greenhouse-gas emissions. Thus, it has strong potential to be a key technology for mitigating climate change. In addition, the flexibility of CSP plants enhances energy security. Unlike solar photovoltaic (PV) technologies, CSP has an inherent capacity to store heat energy for short periods of time for later conversion to electricity. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sundown. CSP plants can also be equipped with backup power from combustible fuels.

These factors give CSP the ability to provide reliable electricity that can be dispatched to the grid when needed, including after sunset to match late evening peak demand or even around the clock to meet base-load demand. Collectively, these characteristics make CSP a promising technology for all regions with a need for clean, flexible, reliable power. Further, due to these characteristics, CSP can also be seen as an enabling technology to help integrate on grids larger amounts of variable renewable resources such as solar PV or wind power.

While the bulk of CSP electricity will come from large, on-grid power plants, these technologies also show significant potential for supplying specialised demands such as process heat for industry, co-generation of heating, cooling and power, and water desalination. CSP also holds potential for applications such as household cooking and small-scale manufacturing that are important for the developing world.

The possibility of using CSP technologies to produce concentrating solar fuels (CSF, such as hydrogen and other energy carriers), is 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.

The purpose of the roadmap

Concentrating solar power can contribute significantly to the world's energy supply. As shown in this roadmap, this decade is a critical window of opportunity during which CSP could become a competitive source of electrical power to meet peak and intermediate loads in the sunniest parts of the world.

This roadmap identifies technology, economy and policy goals and milestones needed to support the development and deployment of CSP, as well as ongoing advanced research in CSF. It also sets out the need for governments to implement strong, balanced policies that favour rapid technological progress, cost reductions and expanded industrial manufacturing of CSP equipment to enable mass deployment. Importantly, this roadmap also establishes a foundation for greater international collaboration.

The overall aim of this roadmap is to identify actions required – on the part of all stakeholders – to accelerate CSP deployment globally. Many countries, particularly in emerging regions, are only just beginning to develop CSP. Accordingly, milestone dates should be considered as indicative of urgency, rather than as absolutes.

This roadmap is a work in progress. As global CSP efforts advance and an increasing number of CSP applications are developed, new data will provide the basis for updated analysis. The IEA will continue to track the evolution of CSP technology and its impacts on markets, the power sector and regulatory environments, and will update its analysis and set additional tasks and milestones as new learning comes to light.

Roadmap process, content and structure

The IEA convened a CSP Roadmap Expert Meeting to coincide with the SolarPACES 2009 Conference (Berlin, 14 September 2009). The workshop was attended by 35 experts from ten countries, representing academic, industry, financial and policy-making circles. Sessions focused on five topics: CSP technologies; systems integration; solar fuels; economics and financing; and aspects of policy. The roadmap also takes account of other regional and national efforts to investigate the potential of CSP, including:

- The European Union's Strategic Energy Technology (SET) Plan and the Solar Thermal Electricity European Industrial Initiative (STEII)
- The Solar America Initiative (SAI)
- China's solar energy development plans
- India's Solar Mission
- Australia's Solar Flagship Initiative
- *The Solar Technology Action Plan* of the Major Economies Forum on Energy and Climate Change.

This roadmap is organised into five major sections. It starts with the status of CSP today, including considerations relative to the solar resource, current technologies and equipping CSP for grid integration. The roadmap then sketches a vision of future large-scale use of CSP, includes an overview of the economic perspectives for CSP. Milestones for technology improvements are then described. The roadmap concludes with the policy framework required to support the necessary RDD&D.

CSP status today

The basic concept of concentrating solar power is relatively simple: CSP devices concentrate energy from the sun's rays to heat a receiver to high temperatures.[1] This heat is transformed first into mechanical energy (by turbines or other engines) and then into electricity. CSP also holds potential for producing other energy carriers (solar fuels).

CSP is a proven technology. The first commercial plants began operating in California in the period 1984 to 1991, spurred by federal and state tax incentives and mandatory long-term power purchase contracts. A drop in fossil fuel prices then led the federal and state governments to dismantle the policy framework that had supported the advancement of CSP. In 2006, the market re-emerged in Spain and the United States, again in response to government measures such as feed-in tariffs (Spain) and policies obliging utilities to obtain some share of power from renewables – and from large solar in particular.

As of early 2010, the global stock of CSP plants neared 1 GW capacity. Projects now in development or under construction in more than a dozen countries (including China, India, Morocco, Spain and the United States) are expected to total 15 GW.

Parabolic troughs account for the largest share of the current CSP market, but competing technologies are emerging. Some plants now incorporate thermal storage.

1 By contrast, photovoltaics (PV) and concentrating photovoltaics (CPV) produce electricity from the sun's rays using direct conversion with semi-conductor materials.

The importance of the solar resource

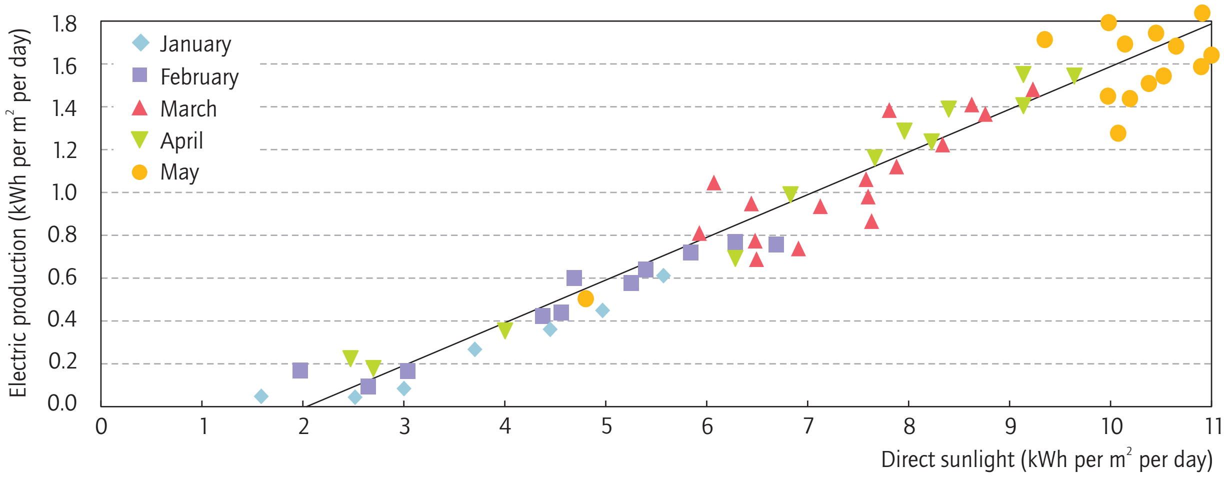
The sunlight hits the Earth's surface both directly and indirectly, through numerous reflections and deviations in the atmosphere. On clear days, direct irradiance represents 80% to 90% of the solar energy reaching the Earth's surface. On a cloudy or foggy day, the direct component is essentially zero. The direct component of solar irradiance is of the greatest interest to designers of high-temperature solar energy systems because it can be concentrated on small areas using mirrors or lenses, whereas the diffuse component cannot. Concentrating the sun's rays thus requires reliably clear skies, which are usually found in semi-arid, hot regions.

The solar energy that CSP plants use is measured as direct normal irradiance (DNI), which is the energy received on a surface tracked perpendicular to the sun's rays. It can be measured with a pyrheliometer.

DNI measures provide only a first approximation of a CSP plant's electrical output potential. In practice, what matters most is the variation in sunlight over the course of a day: below a certain threshold of daily direct sunlight, CSP plants have no net production (Figure 1), due to constant heat losses in the solar field.

CSP developers typically set a bottom threshold for DNI of 1900 kWh/m²/year to 2100 kWh/m²/year. Below that, other solar electric technologies

Figure 1: Output of a SEGS plant in kWh/m²/day as a function of the DNI in kWh/m²/day



Source: Pharabod and Philibert, 1991.[2]

2 Unless otherwise indicated, data for tables and figures reflect IEA analysis.

that take advantage of both direct and diffuse irradiance, such as photovoltaics, are assumed to have a competitive advantage.

Distribution of the solar resource for CSP

The main differences in the direct sunlight available from place to place arise from the composition of the atmosphere and the weather. Good DNI is usually found in arid and semi-arid areas with reliably clear skies, which typically lay at latitudes from 15° to 40° North or South. Closer to the equator the atmosphere is usually too cloudy and wet in summer, and at higher latitudes the weather is usually too cloudy. DNI is also significantly better at higher altitudes, where absorption and scattering of sunlight are much lower.

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

Recent attempts to map the DNI resource worldwide are based on satellite data (Figure 2). While existing solar resource maps agree on the most favourable DNI values, their level of agreement vanishes when it comes to less favourable ones. Important differences exist, notably with respect to the suitability of northeastern China, where the most important consumption centres are found. However, precise measurements can only be achieved through ground-based monitoring; satellite results must thus be scaled with ground measurements for sufficient accuracy.

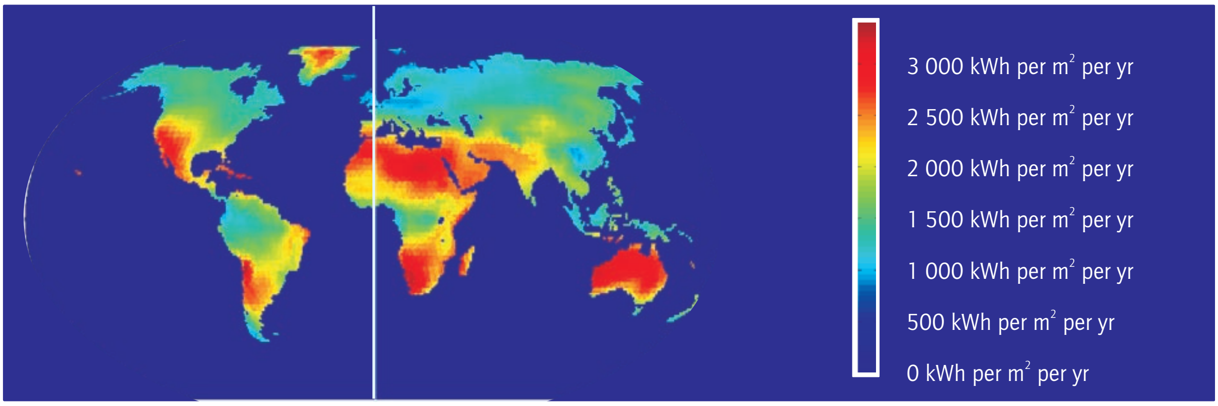
Several studies have assessed in detail the potential of key regions (notably the United States and North Africa), giving special consideration to land availability: without storage, CSP plants require around 2 hectares per MWe, depending on the DNI and the technology.

Even though the Earth's "sunbelts" are relatively narrow, the technical potential for CSP is huge. If fully developed for CSP applications, the potential in the southwestern US states would meet the electricity requirements of the entire United States several times over. Potential in the Middle East and North Africa would cover about 100 times the current consumption of the Middle East, North Africa and the European Union combined. In short, CSP would be largely capable of producing enough no-carbon or low-carbon electricity and fuels to satisfy global demand. A key challenge, however, is that electricity demand is not always situated close to the best CSP resources.

Transporting and exporting electricity from CSP

As demonstrated over decades by hydropower dams in remote regions, electricity can be transported over long distances to demand centres. When distance is greater than a few hundred kilometres, economics favour high-voltage direct-current (HVDC) technology over alternative-current technology. HVDC lines of gigawatt capacity can exceed 1 000 km and can

Figure 2: Solar resource for CSP technologies (DNI in $kWh/m^2/y$)



Source: Breyer & Knies, 2009 based on DNI data from DLR-ISIS (Lohmann, et al. 2006).

be installed across the seabed; they also have a smaller environmental footprint. Electricity losses are 3% per 1 000 km, plus 0.6% for each conversion station (as HVDC lines usually link two alternative-current areas).

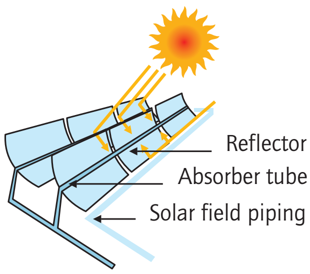
This creates opportunities for CSP plant operators to supply a larger range of consumers. However, the cost of constructing major transmission and distribution lines must be taken into account.

Current technologies for power production

At present, there are four main CSP technology families, which can be categorised by the way they *focus* the sun's rays and the technology used to *receive* the sun's energy (Table 1).

Parabolic troughs (line focus, mobile receiver)

Parabolic trough systems consist of parallel rows of mirrors (reflectors) curved in one dimension to focus the sun's rays. The mirror arrays can be more than 100 m long with the curved surface 5 m to 6 m across. Stainless steel pipes (absorber tubes) with a selective coating serve as the heat collectors. The coating is designed to allow pipes to absorb high levels of solar radiation while emitting very little infra-red radiation. The pipes are insulated in an evacuated glass envelope. The reflectors and the absorber tubes move in tandem with the sun as it crosses the sky.



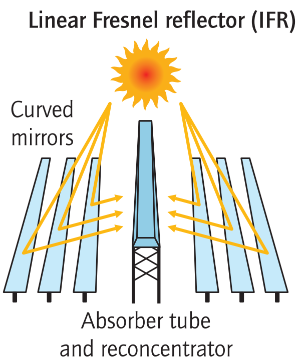
All parabolic trough plants currently in commercial operation rely on synthetic oil as the fluid that transfers heat (the heat transfer fluid) from collector pipes to heat exchangers, where water is preheated, evaporated and then superheated. The superheated steam runs a turbine, which drives a generator to produce electricity. After being cooled and condensed, the water returns to the heat exchangers.

Parabolic troughs are the most mature of the CSP technologies and form the bulk of current commercial plants. Most existing plants, however, have little or no thermal storage and rely on combustible fuel as a backup to firm capacity. For example, all CSP plants in Spain derive 12% to 15% of their annual electricity generation from burning natural gas. Some newer plants have significant thermal storage capacities.

Table 1: The four 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 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 (CRS)**
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**

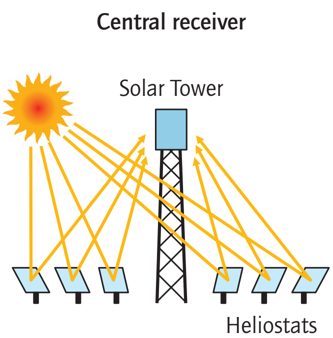
Linear Fresnel reflectors (line focus, fixed receiver)



Linear Fresnel reflectors (LFRs) approximate the parabolic shape of trough systems but by using long rows of flat or slightly curved mirrors to reflect the sun's rays onto a downward-facing linear, fixed receiver. A more recent design, known as compact linear Fresnel reflectors (CLFRs), uses two parallel receivers for each row of mirrors and thus needs less land than parabolic troughs to produce a given output.

The main advantage of LFR systems is that their simple design of flexibly bent mirrors and fixed receivers requires lower investment costs and facilitates direct steam generation (DSG), thereby eliminating the need for – and cost of – heat transfer fluids and heat exchangers. LFR plants are, however, less efficient than troughs in converting solar energy to electricity and it is more difficult to incorporate storage capacity into their design.

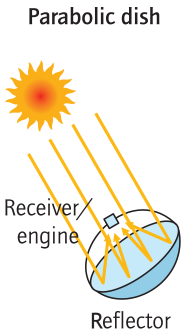
Solar towers (point focus, fixed receiver)



Solar towers, also known as central receiver systems (CRS), use hundreds or thousands of small reflectors (called heliostats) to concentrate the sun's rays on a central receiver placed atop a fixed tower. Some commercial tower plants now in operation use DSG in the receiver; others use molten salts as both the heat transfer fluid and storage medium.

The concentrating power of the tower concept achieves very high temperatures, thereby increasing the efficiency at which heat is converted into electricity and reducing the cost of thermal storage. In addition, the concept is highly flexible; designers can choose from a wide variety of heliostats, receivers, transfer fluids and power blocks. Some plants have several towers that feed one power block.

Parabolic dishes (point focus, mobile receiver)



Parabolic dishes concentrate the sun's rays at a focal point propped above the centre of the dish. The entire apparatus tracks the sun, with the dish and receiver moving in tandem. Most dishes have an independent engine/generator (such as a Stirling machine or a micro-turbine) at the focal point. This design eliminates the need for a heat transfer fluid and for cooling water.

Dishes offer the highest solar-to-electric conversion performance of any CSP system. Several features – the compact size, absence of cooling water, and low compatibility with thermal storage and hybridisation – put parabolic dishes in competition with PV modules, especially concentrating photovoltaics (CPV), as much as with other CSP technologies. Very large dishes, which have been proven compatible to thermal storage and fuel backup, are the exception. Promoters claim that mass production will allow dishes to compete with larger solar thermal systems.

Parabolic dishes are limited in size (typically tens of kW or smaller) and each produces electricity independently, which means that hundreds or thousands of them would need to be co-located to create a large-scale plant. By contrast, other CSP designs can have capacities covering a very wide range, starting as low as 1 MW. The optimal size of troughs, LFR and towers, typically from 100 MW to 250 MW, depends on the efficiency of the power block.

Other systems

Some smaller CSP devices combine fixed receivers with parabolic troughs or, more often, dishes (called "Scheffler dishes"). They are notably used in India for steam cooking devices in facilities that serve thousands meals per day. Dishes have also been used for process heat by gathering the heat collected by each dish; feeding a single power block to produce electricity this way is possible, but this option does not seem to be pursued at present.

Solar thermal electricity without concentration is also possible. Highly efficient non-concentrating solar collectors could evaporate enough steam to run specific power blocks (*e.g.* based on organic Rankine cycles). The efficiency would be relatively low in comparison to CSP technologies discussed above, but non-concentrating solar power could capture both direct and diffuse sunlight (like PV modules) and thus expand the geographic areas suitable for solar thermal electricity. Low-cost thermal storage and fuel backup could give this technology interesting features when and if it becomes commercial.

Enhancing the value of CSP capacities

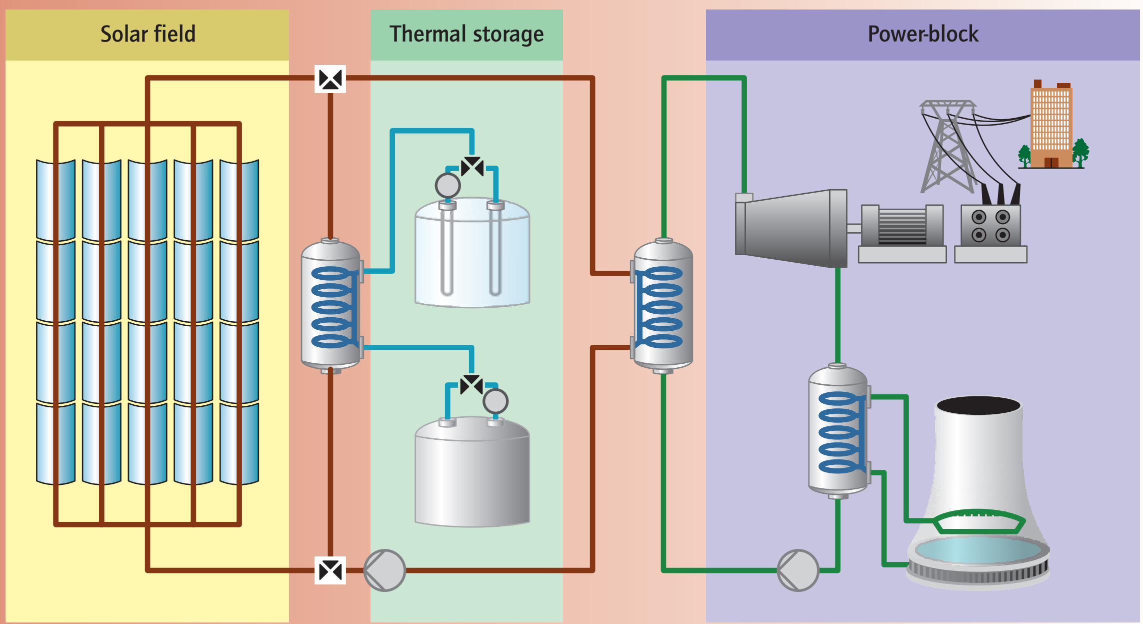
In arid and semi-arid areas suitable for CSP production, sunlight usually exhibits a good match with electricity demand and its peaks, driven by air-conditioning loads. However, the available sunlight varies somewhat even in the sunniest places. Furthermore, human activity and thermal inertia of buildings often maintain high demand for electricity several hours after sunset. To provide a larger share of clean electricity and maximise CO_2 emission reductions, CSP plants will need to provide base load power. Thermal storage and backup or hybridisation with fuels help address these issues.

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.

Recently, operators have begun to build thermal storage systems into CSP plants. 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.

Storage system in a trough solar plant



This graph shows how storage works in a CSP plant. Excess heat collected in the solar field is sent to the heat exchanger and warms the molten salts going from the cold tank to the hot tank. When needed, the heat from the hot tank can be returned to the heat transfer fluid and sent to the steam generator.

Source: SolarMillennium.

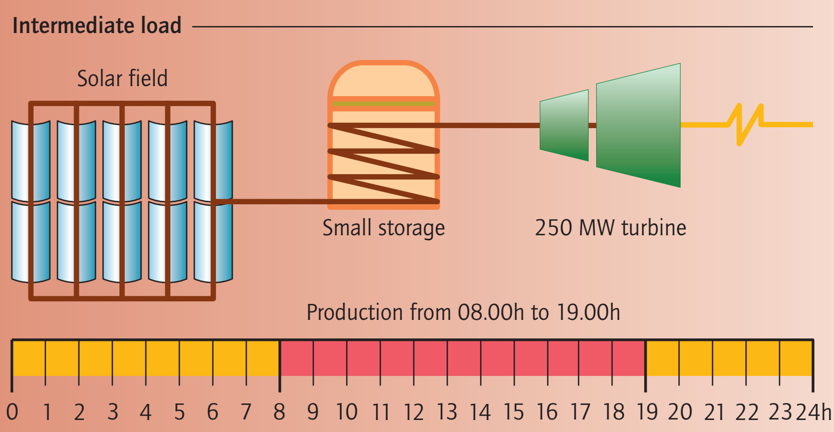
Studies show that, in locations with good sunlight (high DNI), extending electricity production to match this demand requires a storage capacity of two to four hours. In slightly less sunny areas, storage could be larger, as it also helps compensate for the somewhat less predictable resource. The solar field is somewhat larger relative to the rated electrical capacity (*i.e.* the plant has a greater solar multiple[3]), to ensure sufficient electricity production. As a result, at maximum sunlight power, solar fields produce more heat than their turbines can absorb. In the absence of storage, on the sunniest hours, plant operators would need to "defocus" some unneeded solar collectors. Storage avoids losing this energy while also allowing for extending production after sunset. For example, some trough plants in Spain store enough heat in molten salts to produce power at the rated capacity of the turbine (50 MWe) for more than 7 additional hours (See box).

3 The *solar multiple* is the ratio of the actual size of a CSP plant's solar field compared to the field size needed to feed the turbine at design capacity when solar irradiance is at its maximum (about 1 kW/m^2). Plants without storage have an optimal solar multiple of roughly 1.1 to about 1.5 (up to 2.0 for LFR), depending primarily on the amount of sunlight the plant receives and its variation through the day. Plants with large storage capacities may have solar multiples of up to 3 to 5.

Tailoring storage to serve purpose

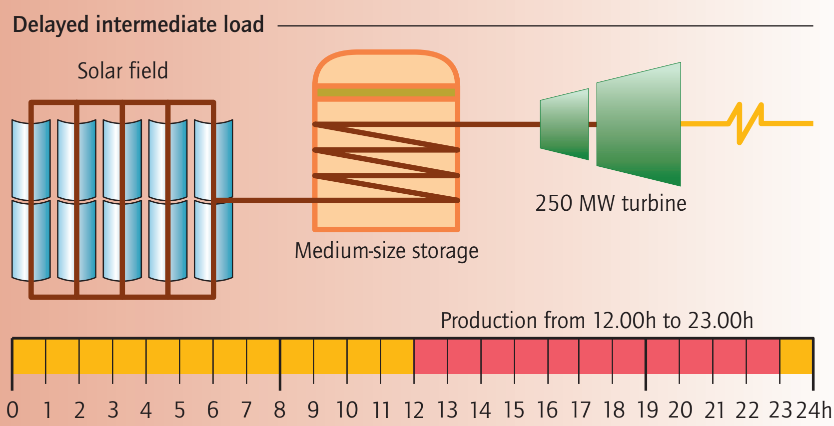
Varying the storage capacity is a means of tailoring CSP plant to meet different needs. All four hypothetical plants below have the same solar field size and produce the same amount of electricity, but at different times and different power rates.

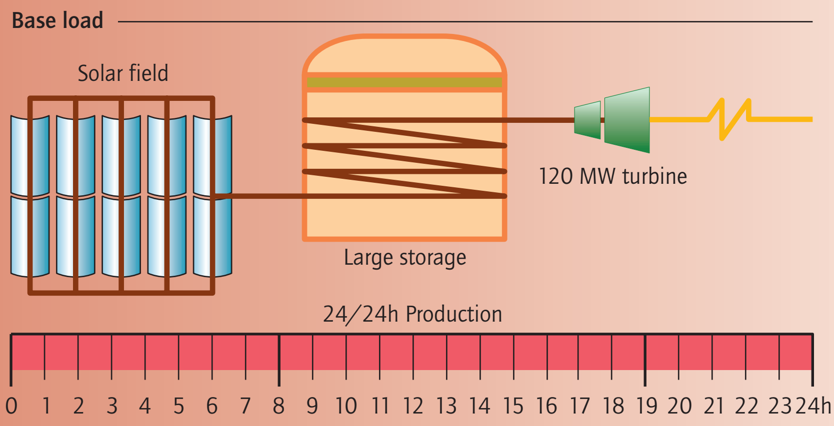
Figure 3: Four different configurations of CSP plants of a given solar field size



The intermediate load configuration is designed to produce electricity when the sunshine available covers peak and shoulder loads. It has a 250 MW turbine and requires only a small amount of storage. It has the smallest investment costs and the least-expensive electricity output.

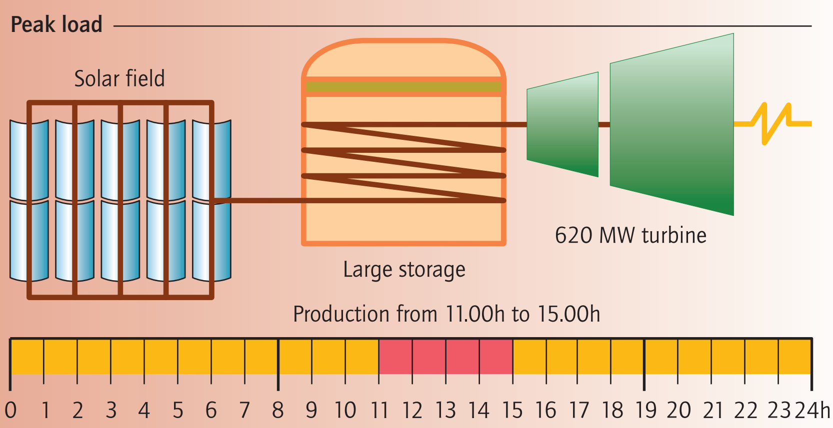
The delayed intermediate load design collects solar energy all day but produces electricity from noon on and after sunset, corresponding to peak and shoulder loads. It has the same size turbine as the intermediate load plant but requires a larger amount of storage.





The base load configuration runs 24 hours per day for most of the year; it needs a larger amount of storage and a smaller turbine. If the costs of storage capacity are lower than those of larger turbines, electricity from the base load plant is slightly cheaper than that of delayed intermediate load plant. This will likely be the case with higher working temperatures, which will allow for less-expensive storage but require more sophisticated and costly turbines.

The peak load plant is designed to provide electricity only for a few hours to meet the extreme peak load. It requires a large turbine (600 MW) and a large amount of storage. Of all four designs it produces the most expensive, but also the most valuable electricity.



Source: Julien Octobre and Frank Guihard, *Systèmes Solaires*, 2009

CSP plants with large storage capacities may be able to produce base-load solar electricity day and night, making it possible for low-carbon CSP plants to compete with coal-fired power plants that emit high levels of CO_2. For example, one 17 MW solar tower plant under construction in Spain will use molten salts as both heat transfer fluid and storage medium and store enough heat energy to run the plant at full load for 16 hours.

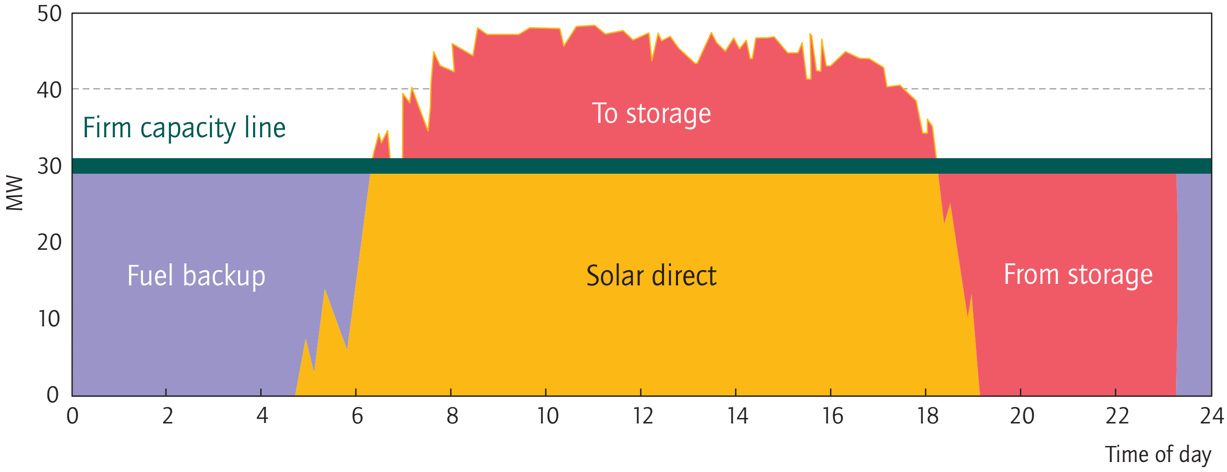
Storage has a cost, however, and cannot be expanded indefinitely to prevent rare events of solar energy shortages. A current industry focus is to significantly increase the temperature to improve overall efficiency of CSP plants and reduce storage costs. Enhanced thermal storage would help to guarantee capacity and expand production. Storage potentially makes base-load solar-only power plants possible, although fuel-powered backup and hybridisation have their own advantages and are likely to remain, as described below.

Backup and hybridisation

Virtually all CSP plants, with or without storage, are equipped with fuel-powered backup systems that help to regulate production and guarantee capacity – especially in peak and mid-peak periods. The fuel burners (which can use fossil fuel, biogas or, eventually, solar fuels) can provide energy to the heat transfer fluid or the storage medium, or directly to the power block.

In areas where DNI is less than ideal, fuel-powered backup makes it possible to almost completely guarantee the plant's production capacity at a lower cost than if the plant depended only on the solar field and thermal storage (Figure 4). Providing 100% firm capacity with only thermal storage would require significantly more investment in reserve solar field and storage capacity, which would produce little energy over the year.

Figure 4: Combination of storage and hybridisation in a solar plant



Source: Geyer, 2007, *SolarPACES Annual Report*.

Fuel burners also boost the conversion efficiency of solar heat to electricity by raising the working temperature level; in some plants, they may be used continuously in hybrid mode.

CSP can also be used in hybrid by adding a small solar field to fossil fuel plants such as coal plants or combined-cycle natural gas plants in so-called *integrated solar combined-cycle plants* (ISCC). As the solar share is limited, such hybridisation really serves to conserve fuel. A positive aspect of solar fuel savers is their relatively low cost: with the steam cycle and turbine already in place, only components specific to CSP require additional investment. Such fuel savings, with capacities ranging from a few megawatts to 75 MW, are being built adjacent to existing or new fossil fuel power plants in Algeria, Australia, Egypt, Iran, Italy and the United States (in the state of Florida).

Grid integration of CSP plants

The storage and backup capabilities of CSP plants offer significant benefits for electricity grids. Losses in thermal storage cycles are much smaller than in other existing electricity storage technologies (including pumped hydro and batteries), making the thermal storage available in CSP plants more effective and less costly.

Two examples of backup and/or hybridisation

The SEGS CSP plants, built in California between 1984 and 1991, use 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 10:00 p.m.) when mid-peak pricing applies. During the winter mid-peak pricing time (12:00 noon to 6:00 p.m.), SEGS uses natural gas to achieve rated capacity by supplementing low solar irradiance. By law, the plant is limited to using gas to produce only 25% of primary energy.

The Shams-1 trough plant (100 MW), planned in the United Arab Emirates, will combine hybridisation and backup, using natural gas and two separate burners. The plant will burn 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 will use a natural gas heater for the heat transfer fluid. This backup measure was required by the electric utility to guarantee capacity, but will be 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.

CSP plants can enhance the capacity of electricity grids to accommodate a larger share of variable energy sources, thereby increasing overall grid flexibility. As demonstrated in Spain, connecting CSP plants to some grid sub-stations facilitates a greater share of wind energy. CSP plant backup may also eliminate the need to build fossil-fired "peaking" plants purely to meet the highest loads during a few hours of the day.

Although the optimal size of CSP plant is probably 200 MW or more, many existing grids use small power lines at the ends of the grid in less-populated areas, which cannot support the addition of large amounts of electricity from solar plants. Thus, in some cases, the size of a CSP plant could be limited by the available power lines or require additional investment in larger transport lines. Furthermore, it is often easier to obtain sites, permits, grid connections and financing for smaller, scalable CSP plant designs, which can also enter production more quickly.

Plant cooling and water requirements

As in other thermal power generation plants, CSP requires water for cooling and condensing processes. CSP water requirements are relatively high: about 3 000 L/MWh for parabolic trough and LFR plants (similar to a nuclear reactor) compared to about 2 000 L/MWh for a coal plant and only 800 L/MWh for combined-cycle natural gas plants. Tower CSP plants need less water per MWh than trough plants, depending on the efficiency of the technology. Dishes are cooled by the surrounding air, and need no cooling water.

Accessing large quantities of water is an important challenge to the use of CSP in arid regions, as available water resources are highly valued by many stakeholders. Dry cooling (with air) is one effective alternative used on the ISCC plants under construction in North Africa. However, it is more costly and reduces efficiencies. Dry cooling installed on trough plants in hot deserts reduces annual electricity production by 7% and increases the cost of the produced electricity by about 10%. The "performance penalty" of dry cooling is lower for solar towers than for parabolic troughs.

Installation of hybrid wet/dry cooling systems is a more attractive option as such systems reduce water consumption while minimising the performance penalty. As water cooling is more effective but more costly, operators of hybrid systems tend to use only dry cooling in the winter when cooling needs are lower, then switch to combined wet and dry cooling during the summer. For a parabolic trough CSP plant, this approach could reduce water consumption by 50% with only a 1% drop in annual electrical energy production.

CSP for niche markets

CSP technologies can be highly effective in various niche markets. Mid-sized CSP plant can fuel remote facilities such as mines and cement factories. Even small CSP devices (typically using organic Rankine cycles or micro-turbines) can be useful on buildings to provide electricity, heat and cooling.

CSP plants can produce significant quantities of industrial process heat. For example, a solar tower will soon produce steam for enhanced oil recovery in the United States. At a smaller scale, concentrating sunlight can be used for cooking and artisanal production such as pottery. The advantages could be considerable in developing countries, ranging from independence from fossil resources, protection of ecosystems from deforestation and land degradation, more reliable pottery firing and, in the case of cooking, reduction of indoor air pollution and its resulting health impacts. The scope of this roadmap precludes a full investigation of these possibilities, barriers to their dissemination, or policies to overcome such barriers.

Large CSP plants may also prove effective for co-generation to support water desalination. CSP plants are often located in arid or semi-arid areas where water is becoming scarcer while water demand is increasing rapidly as populations and economies grow. CSP plants could be designed so that low-pressure steam is extracted from the turbine to run multi-effect distillation (MED) stages. Such plants would produce fresh water along with electricity, but at some expense of efficiency loss in power production. Economic studies suggest that it might be preferable, however, to separate the two processes, using CSP for electricity production and reverse osmosis for desalination, when the working temperature is relatively low, as with trough plants. Co-generation of electricity and fresh water would probably work best with higher temperature levels, such as with towers.

With respect to concentrating solar fuels, current R&D efforts have shown promise in a number of necessary steps, including water splitting, fossil fuel decarbonisation and conversion of biomass and organic wastes into gaseous fuels. Success in these areas affirms the need for larger-scale experiments to support the further development of CSF as part of the global energy mix.

Vision of future deployment

Existing scenarios and proposals

The IEA publication *Energy Technology Perspectives 2008* (*ETP 2008*) includes CSP as one of the many cost-effective technologies that will lower CO_2 emissions. In the ETP BLUE Map scenario, global energy-related CO_2 emissions by 2050 are reduced to half their 2005 level, and CSP produces 2 200 TWh annually by 2050 from 630 GW of local capacities (no exports taken in account). CSP is expected to contribute 5% of the annual global electricity production in 2050 in this scenario.

In the Advanced scenario of *CSP Global Outlook 2009*, the IEA SolarPACES programme, the European Solar Thermal Electricity Association and Greenpeace estimated global CSP capacity by 2050 at 1 500 GW. The SolarPACES forecast sees large storage and solar fields that would enable capacity factors of 59% (5 200 hours per year), with a yearly output of 7 800 TWh.

In its study of the renewable energy potential in the Middle East/North Africa region, the German Aerospace Center (DLR) estimates that by 2050, CSP plants could provide about half of the region's electrical production, from a total capacity of 390 GW.

According to a recent study by PriceWaterHouse Cooper, Europe and North Africa together could by 2050 produce all their electricity from renewables if their respective grids are sufficiently interconnected. While North Africa would consume one-quarter of the total it would produce 40% of it, mostly from onshore wind and solar power. CSP plants would form the backbone of the export capacities from North Africa to Europe.

CSP deployment

This roadmap foresees a rapid expansion of CSP capacities in countries or regions with excellent DNI, and computes its electricity production as progressively growing percentages of the overall consumption forecast in IEA climate-friendly scenarios in these regions (Table 2). In neighbouring but less sunny regions, a lower contribution of CSP electricity is expected, which mixes local production and electricity from nearby sunnier areas.

Plants built before 2020 mostly respond to intermediate and peak loads, while a first set of HVDC lines is built to connect some of the CSP plants in sunny areas to large demand centres. From 2020 to 2030, as costs are reduced and performance enhanced, the deployment of CSP continues with base-load plants, thus maximising CO_2 emission reductions. After 2030, while CSP continues to develop, solar fuels enter the global energy mix. By 2050, CSP represents about 11% of global electricity production.

The overall estimated growth of CSP electricity output is represented in Figure 5 in comparison with three other scenarios: the BLUE Map scenario of *ETP 2008*, and the Advanced and Moderate scenarios of *Global CSP Outlook 2009*.

Figure 5: Growth of CSP production under four scenarios (TWh/y)

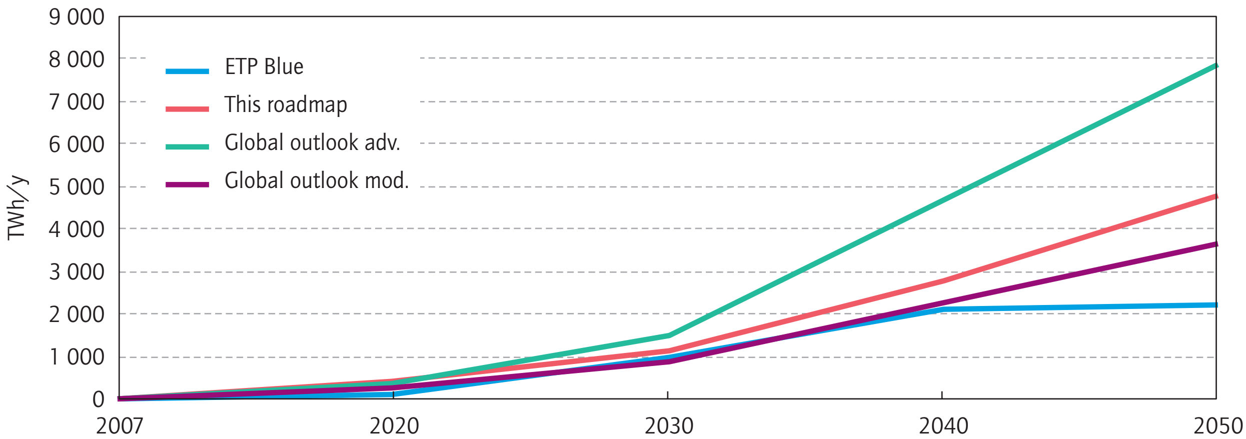


Table 2: Electricity from CSP plants as shares of total electricity consumption

Countries	2020	2030	2040	2050
Australia, Central Asia,[4] Chile, India (Gujarat, Rajasthan), Mexico, Middle East, North Africa, Peru, South Africa, United States (Southwest)	5%	12%	30%	40%
United States (remainder)	3%	6%	15%	20%
Europe (mostly from imports), Turkey	3%	6%	10%	15%
Africa (remainder), Argentina, Brazil, India (remainder)	1%	5%	8%	15%
Indonesia (from imports)	0.5%	1.5%	3%	7%
China, Russia (from imports)	0.5%	1.5%	3%	4%

4 Includes Afghanistan, Kazakhstan, Kyrgyzstan, Pakistan, Tajikistan, Turkmenistan, and Uzbekistan.

Figure 6 shows the growth of CSP electricity production by region according to this roadmap as it is further detailed below. This projection takes into account a significant amount of electricity transportation.

The vital role of transmission

This roadmap sees long-range transportation of electricity as an important way of increasing the achievable potential of CSP. Large countries such as Brazil, China, India, South Africa and the United States (Figure 7) will have to arrange for large internal transmission of CSP-generated electricity.

In other cases, high-voltage transmission lines will cross borders, opening export markets for CSP producing countries and increasing energy security for importing countries. Australia might feed Indonesia; the Central Asian countries supply Russia; Northern African countries and Turkey deliver power to the European Union; northern and southern African countries feed equatorial Africa; and Mexico provide CSP electricity to the United States.

The transfer of large amounts of solar energy from desert areas to population centres has been promoted, in particular, by the DESERTEC Foundation (Figure 8). This idea has inspired two major initiatives in Europe, the Mediterranean Solar Plan and the DESERTEC Industry Initiative. The first, developed within the framework of the Barcelona Process: Union for the Mediterranean, aims to bring about 20 GW of renewable electricity to EU countries by 2020 from the various developing economies that adhered to this recently created intergovernmental organisation.

Figure 6: Growth of CSP production by region (TWh/y)

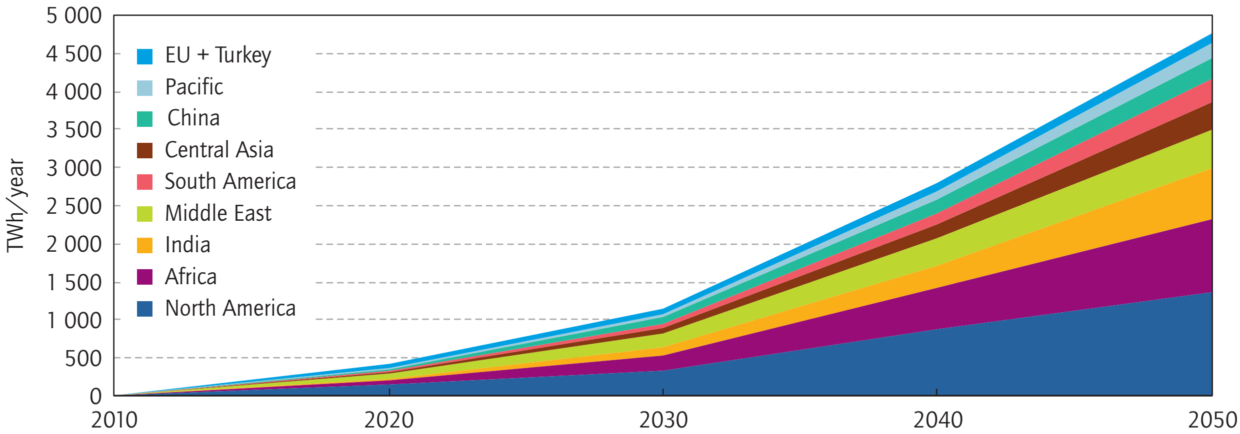
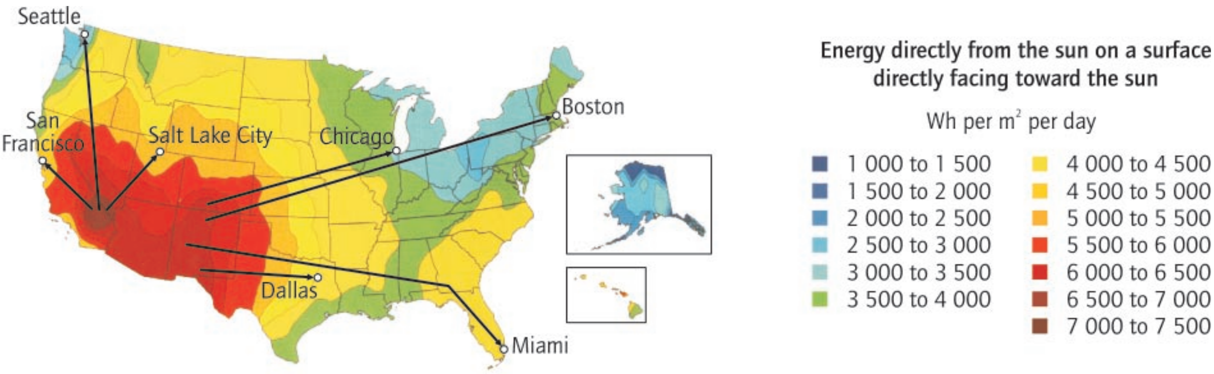
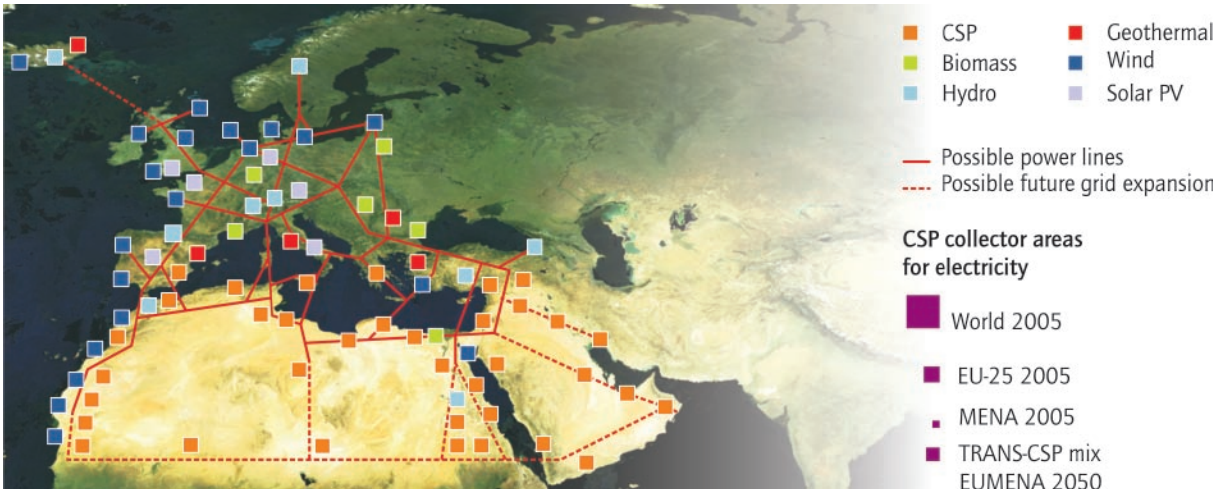


Figure 7: Vision of possible HVDC lines linking the Southwest to the rest of the United States



Source: Hank Price, US DOE, 2007.

Figure 8: The DESERTEC concept applied to EU-MENA Region



Source: the DESERTEC Foundation.

The second initiative, announced in July 2009, takes the form of a limited liability company, with 12 shareholders.[5] The DESERTEC Industry Initiative aims to establish a framework for investments to supply the Middle East, North Africa and Europe with solar and wind power. The long-term goal is to satisfy a substantial part of the energy needs of the Middle East and North Africa, and meet as much as 15% of Europe's electricity demand by 2050.

The abundant sunlight in the Middle East and North Africa will lead to lower costs, compensating for the additional expected transmission costs and electricity losses. Further, the current feed-in tariffs in Spain or France for large-scale, ground-based solar electricity would largely cover the costs of production of electricity in North Africa, assessed at USD 209 (EUR 150)/MWh on best sites, plus its transport to the south of Europe, assessed at USD 21 (EUR 15)/MWh to USD 63 (EUR 45)/MWh.

Deployment till 2020: intermediate and peak loads

From 2010 to 2020, the global rollout of CSP initiated before 2010 is expected to accelerate, thanks to ongoing industry efforts and the adoption of suitable incentives for CSP in sunny countries.

5 These are ABB, Abengoa Solar, Cevital, DESERTEC Foundation, Deutsche Bank, E.ON, HSH Nordbank, MAN Solar Millennium, Munich Re, M+W Zander, RWE, Schott Solar and Siemens.

From 2010 to 2020, the global solar resource potential is investigated more accurately due to expected advancements in satellite algorithms, which offer higher spatial resolution and better DNI maps. These estimates are validated by many high-quality solar radiation measurement stations. Such reference stations are installed in all countries and regions of interest for CSP, including those currently lacking adequate coverage, such as China, India, Turkey, Africa, the Middle East and Latin America.

The deployment of CSP takes many forms, from assisting fossil-fuel plants in fuel savings to solar-only CSP plants in regions with excellent sunlight. Some off-grid or remote-grid CSP systems are built, but large on-grid plants comprise more than 90% of overall CSP capacity.

Thermal storage is further developed but in most cases remains limited to what is necessary to cover almost all intermediate and peak loads from solar resources only. CSP is not yet fully competitive with coal power plants for base load, as CO_2 emissions are not yet priced highly enough.

Backup, usually from natural gas, is used in some cases to enhance the efficiency of the conversion of solar thermal energy to electricity. In other cases, it is used only to guarantee the plant's production capacity – during the day in summer to compensate for cloud cover, but also in the evening or at night, essentially to compensate for variability of a growing share of wind power on most grids.

Dedicated HVDC lines are developed and built to bring solar electricity from distant regions to consumption centres. Some lines link North African countries to Europe. A north-south line links Lagos to plants in Mali or Niger. Other HVDC lines are built within large countries. In India, Mumbai and Delhi – as well as Lahore in Pakistan – could be supplied from Rajasthan. In the United States, Atlanta could be reached from the Southwest. In Brazil, Sao Paulo and Rio de Janeiro; in China, Xining, Chengdu and Chongqing could be supplied with CSP electricity.

The global installed capacity reaches 148 GW by 2020, with an average capacity factor of 32% (2 800 hours per year), thereby providing 414 TWh annually. Primary energy from fossil-fuel backup or hybridisation in CSP plants accounts for 18% of this amount; the "solar share" in CSP electricity is thus 82% or 340 TWh. This represents 1.3% of the global electricity production expected by 2020. The limiting factor for deployment during this period is the global capacity of the industry, which must rapidly increase from about 1 GW per year in 2010 to more than 20 GW per year by 2020.

Deployment till 2030: base loads and CO_2 reductions

CSP technologies will become competitive with coal-fired base-load power, maximising CO_2 reductions around 2020 as CO_2 prices increase and costs fall for solar fields and storage, due to higher-temperature technologies (540 °C and above). Many newly built CSP plants will have larger solar fields and storage systems to produce electricity on a continuous basis for most of the year. Incentives will vanish rapidly in most countries, as they are no longer required to support the deployment of CSP capacities.

Furthermore, investors in CSP plants built after 2010 will progressively come to the end of their reimbursement period, and begin to enjoy significantly higher benefits as the costs of CSP electricity will now derive only from operation and maintenance expenses.

Further HVDC line extensions, up to 3 000 km long, could be considered at this stage. Moscow could be supplied from Kazakhstan. Existing lines will need to be reinforced or augmented as their

Big cities near deserts

Most CSP plants will be built on sites with good or excellent sunshine – including deserts – close to significant consumption centres. The largest metropolitan areas likely to benefit from CSP electricity by 2020 are Ahmadabad, Alexandria, Algiers, Amman, Athens, Baghdad, Barcelona, Cairo, Casablanca, Houston, Istanbul, Jaipur, Johannesburg, Karachi, Las Vegas, Lima, Los Angeles, Madrid, Mexico City, Miami, Riyadh, San Diego, Santiago (Chile), Sydney, Tashkent, Tehran, Tripoli, Tunis and Urumqi.

Mid-sized biomass/CSP plants in developing countries

In countries where electrification of households is not complete, small-scale or mid-scale CSP plants offer co-generation of electricity for remote or weakly interconnected grids, and process heat for some local manufacturing. Where DNI is good but not excellent, and large amounts of biomass (notably animal residues) are available for gasification, these CSP plants are often hybridised with biogas. While the main driver is the availability of the resource in Africa, Brazil, China, India and other developing economies, these plants entail no CO_2 emissions at all.

capacities are progressively saturated. In Europe, investments in local CSP plants will vanish as the technical potential, taking into account land availability, is almost totally utilised. However, European investors will continue to finance CSP plants abroad, particularly on the southern shore of the Mediterranean.

The global installed capacity reaches 337 GW, with an average capacity factor of 39% (3 400 hours per year), thereby providing 1 140 TWh annually. The solar share will be 85%, or 970 TWh, thanks to improvements in storage. This represents 3.8% of the global electricity production by 2030.

Meanwhile, the first demonstration plants for solar-assisted natural gas reforming are built in southern Europe, California and the Middle East for manufacturing fertilisers. On some refinery sites, solar tower plants recycle the hydrogen that extracts sulphur from petroleum. Solar-assisted coal gasification for the production of coal-to-liquid fuels with a smaller carbon footprint is being developed in Australia, China, India, South Africa and the United States.

Deployment beyond 2030: power and fuels

CSP continues its expansion as CO_2 pricing makes it fully competitive with fossil fuels. CSP imports help electricity grids handle a growing share of variable energy sources in many regions. However, a limit to electricity imports is set at 15% of consumption of importing countries, as governments prefer local renewable resources. Meanwhile, solar fuels are progressively introduced to the global energy mix.

By 2040, the global installed CSP capacity reaches 715 GW, with an average capacity factor of 45% (3 900 hours per year), thereby providing 2 790 TWh annually. The solar share of 85%, or 2 370 TWh, represents 8.3% of global electricity generation.

By 2050, the global installed capacity reaches 1 089 GW, with an average capacity factor of 50% (4 380 hours per year), thereby providing 4 770 TWh annually, or 11.3% of the estimated global electricity production in the *ETP 2008* BLUE Map scenario. As the global electricity system becomes decarbonised, biogas and solar fuels become the main source of backup and hybridisation in CSP plants from 2030 to 2050. There is thus no greater reason than before to attempt to build solar-only plants. Therefore, the roadmap foresees the same solar share of 85% or 4 050 TWh in 2050, representing 9.6% of global electricity production.

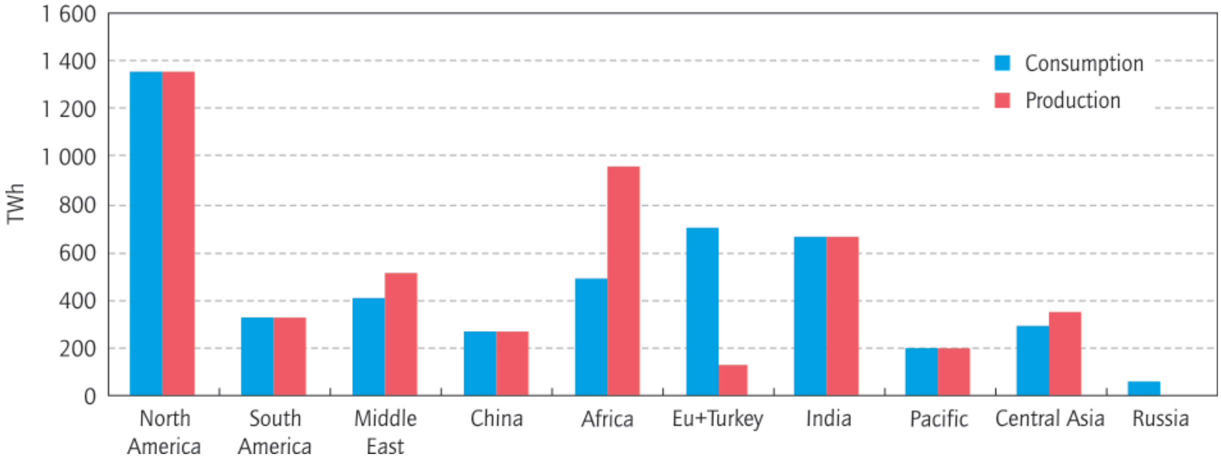
Figure 9 shows where CSP electricity will be produced and consumed by 2050. North America would be the largest producing region, followed by Africa, India and the Middle East. Africa would be by far the largest exporter, and Europe the largest importer. The Middle East and North Africa considered together, however, would produce almost as much as North America (the United States and Mexico). Indeed, the Middle East-North Africa region is the largest producer when all solar products are considered, including gaseous and liquid fuels.

Concentrated solar fuels

Full-scale, solar-assisted natural gas reforming plants will be progressively built in the Middle East and North Africa, Central Asia and the US Southwest from 2030. Hydrogen will be blended with the natural gas in existing gas pipelines and distribution networks, including for exports (in particular to Europe) to be ultimately used in houses, industrial or power plants. In this first step, the blend is limited to about 12% in volume to minimise the required adaptation in transport systems and end-use devices.

Oil prices are expected to make both coal-to-liquid and solar fuels competitive, but the former have huge upstream carbon content if carbon capture

Figure 9: Production and consumption of CSP electricity by 2050 (in TWh)

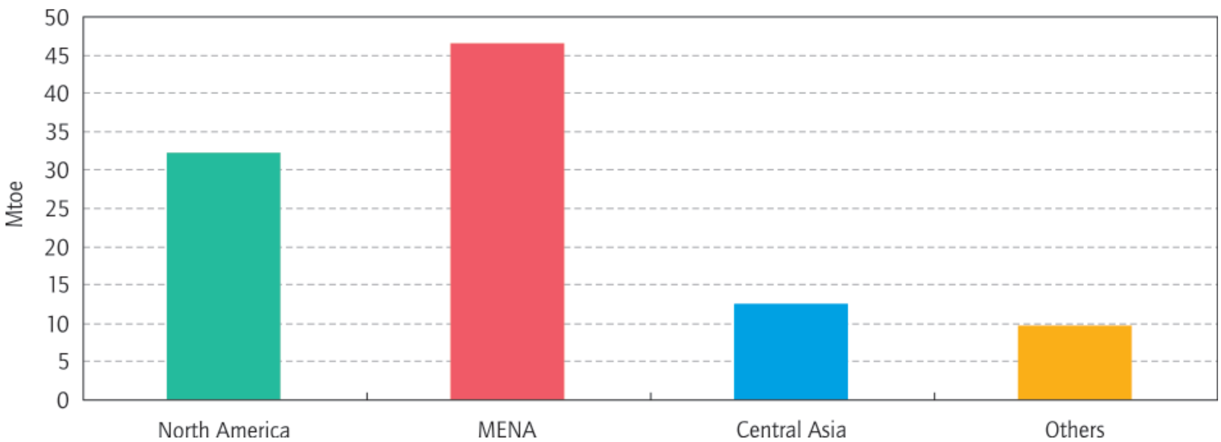


and storage are not deployed at liquefaction plants. Liquid solar fuels are introduced as transport fuels to prevent increased upstream CO_2 emissions. Solar fuels will not substitute for second- and third-generation biofuels that have a lower carbon footprint on a life-cycle basis, but will complement them.

In the following decade, the blend of hydrogen in natural gas will rise to 25% of volume (at normal pressure) with a second phase of adaptation at system and end-use levels. This is roughly comparable with the changes customers experienced when they had to adapt from town gas to natural gas. This reduces the specific consumption of natural gas by about 6%, as the energy content of hydrogen, while greater than that of natural gas per mass, is significantly smaller by volume. This substitution takes place only in the sunniest countries that produce natural gas, thus avoiding the need to transport pure hydrogen. Solar hydrogen blended in natural gas thus accounts for 86 million tonnes oil equivalent (Mtoe) by 2050, or over 3% of the estimated global consumption of natural gas. Figure 10 shows the geographical distribution under that forecast.

Similarly, about 3% of the global market for liquid fuels is taken by fuels derived from solar hydrogen. Some CSF plants are used to produce the hydrogen required to remove sulphur from petroleum products in refineries. Others produce coal-to-liquid or gas-to-liquid processes with much lower CO_2 emissions using concentrating solar heat.

Figure 10: Roadmap vision of hydrogen production blended in natural gas (Mtoe) by 2050



CO_2 reductions from concentrating solar power and fuels by 2050

The 4 050 TWh of solar electricity generated by CSP plants in 2050 are expected to avoid around 2.5 gigatonnes (Gt) of CO_2 emissions per year worldwide with respect to the ETP Baseline scenario. The 86 Mtoe savings on natural gas would yield another 560 million tonnes (Mt) of CO_2 reduction. Together, emission reductions due to CSP electricity and gaseous fuels can be assessed around 3 Gt of CO_2, or about 7% of the CO_2 reductions from unabated trends necessary to halve global energy-related CO_2 emissions by 2050.

The perspectives offered by this vision would not exhaust the global potential for CSP, which could essentially run the world's economy by itself, at least with respect to electricity, with low or no CO_2 emissions. However, energy policies will also favour other resources, notably renewable energy sources, which in places are less expensive or closer to end-users, and obviously have a more "domestic" nature in less sunny countries. Furthermore, these perspectives rest on policy support, especially in this decade.

Economic perspectives

Although CSP currently requires higher capital investments than some other energy sources, it offers considerable long-term benefits because of minimum fuel costs for backup/hybridisation. Moreover, initial investment costs are likely to fall steadily as plants get bigger, competition increases, equipment is mass produced, technology improves and the financial community gains confidence in CSP. In the near term, the economics of CSP will remain more favourable for peak and intermediate loads than for base loads, for reasons explained in this section.

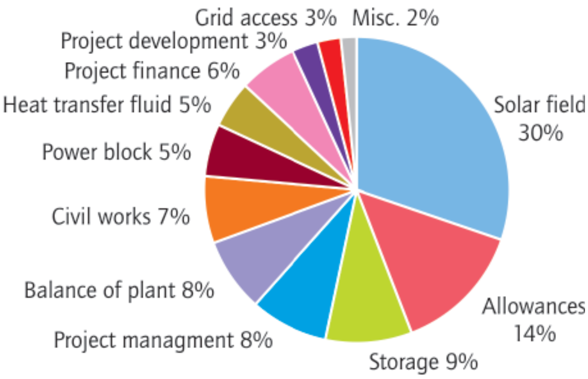
Milestones for cost reductions	Dates
1. Achieve competitiveness for peak and intermediate loads	2020
2. Achieve competitiveness for base loads	2025 to 2030

Investment costs

For large, state-of-the-art trough plants, current investment costs are USD 4.2/W to USD 8.4/W depending on labour and land costs, technologies, the amount and distribution of DNI and, above all, the amount of storage and the size of the solar field. Plants without storage that benefit from excellent DNI are on the low side of the investment cost range; plants with large storage and a higher load factor but at locations with lower DNI (around 2000 kWh/m²/year) are on the high side. Figure 11 breaks down investment costs of a trough plant with storage under Spanish skies. These investments costs are slightly higher than those of PV devices, but CSP plants have a greater energy output per MW capacity.

Investment costs per watt are expected to decrease for larger trough plants, going down by 12% when moving from 50 MW to 100 MW, and by about 20% when scaling up to 200 MW. Costs associated with power blocks, balance of plant and grid connection are expected to drop by 20% to 25% as plant capacity doubles. Investment costs are also likely to be driven down by increased competition among technology providers, mass production of components and greater experience in the financial community of investing in CSP projects. Investment costs for trough plants could fall by 10% to 20% if DSG were implemented, which allows higher working temperatures and better efficiencies. Turbine manufacturers will need to develop effective power blocks for the CSP industry. In total, investment costs have the potential to be reduced by 30% to 40% in the next decade.

Figure 11: Investment costs of a 50 MW trough plant with 7-hour storage



CSP: a plentiful supply of raw materials

The perspectives presented in this roadmap are unlikely to be impaired by a scarcity of raw materials. Large mirror areas will be required, which may exceed current global production by a factor of two to four, so timely investment in production capacity of mirrors will be necessary. This production would only account for a few percentage points of the global production of flat glasses, however. Similarly, accelerated deployment of trough plants would require investment in production of heat collector elements. Receivers for towers are a variety of high-temperature heat exchanger, which industry has largely deployed throughout the world.

Only molten salts for thermal storage may raise some production problems. They are used in large quantities as fertilisers for agriculture, but their use as a storage medium requires a high degree of purity.

For solar towers, investment costs are more difficult to estimate, but are generally higher than for trough plants. However, increasing efficiency from 15% to 25% will allow a 40% reduction in investment in solar-specific parts of the plants, or 20% of overall investment costs. The recent trend toward numerous mass-produced, small, flat mirrors promises to bring costs down further, as the problems of wind resistance and precision in pointing are resolved using computers. As the solar tower industry rapidly matures, investment costs could fall by 40% to 75%.

The costs of CSP electricity should go down even more. Some experts see a greater potential in developing countries for local fabrication of towers than of troughs, leading to lower costs in emerging economies.

Operation and maintenance costs

Operation and maintenance costs for CSP include plant operation, fuel expenses in the case of hybridisation or backup, feed and cooling water, and field maintenance costs. A typical 50 MW trough plant requires about 30 employees for plant operation and 10 for field maintenance. Operation and maintenance costs have been assessed from USD 13/MWh to USD 30/MWh, including fuel costs for backup. As plants become larger, operation and maintenance costs will decrease.

Costs of providing finance for CSP plants

Financing schemes can differ markedly from one investment and legal environment to another, with significant consequences for the costs of generating electricity and the expected rates of return on investment. Large utilities building their own plants with available cash do not incur the costs that utilities or investors face when combining equity and loans from various sources to finance plants. Differences among fiscal regimes, in particular with respect to corporate taxes, have an impact on the turnkey costs (the expenditures necessary before a plant is ready for use) depending on how long it takes to secure financing and build the plant. This impact might be significant for CSP plants that may require one to two years of construction. The same parameters will have an even greater impact on the electricity generating costs, as capital expenses are much larger for CSP plants than for, say, fossil-fuel plants.

Generating costs

Levelised energy costs, which estimate a plant's annualised lifetime cost per unit of electricity generation, range from USD 200/MWh to USD 295/MWh for large trough plants, the technology for which figures are most readily available. The actual cost depends mostly on the available sunlight.[6]

The impact of storage on generating costs is not as simple as it may seem. When there is storage capacity, the investment costs increase with the size of the solar field and the added storage but so do the capacity factor and the yearly electrical output (*e.g.* up to 6 600 hours in Spain with 15 hours of storage), thus the energy cost changes only marginally.

In any case, the main merit of storage is not to reduce the cost of electricity but to increase the value of the plant to the utility in making its capacity firm and dispatchable, allowing solar plants to compete with fossil-fuel plants by supplying base-load power in the not-too-distant future.

Towards competitiveness

In the regions where CSP plants can be installed, peak and intermediate loads are more often driven by air-conditioning than by electric heating demands, corresponding to the optimal daily and seasonal operation periods for CSP plants. This explains why the economics of CSP will remain more favourable for peak and intermediate loads than for base loads in the coming decade, unless or until CO_2 emissions are heavily priced. Competing energy sources have significantly higher generation costs for peak and mid-peak demand, while the cost of CSP electricity is about the same for peak and base load.

Peak loads are usually considered as cumulating 10% of the yearly consumption of electricity, intermediate loads 50% and base loads the remaining 40%. This indicates that there will

6 For this analysis, the following assumptions were used: equity capital, 30 years economic lifetime, 10% discount rate. The lower end corresponds to excellent DNI and little storage, the upper end corresponds to larger storage and higher capacity factor but lower DNI.

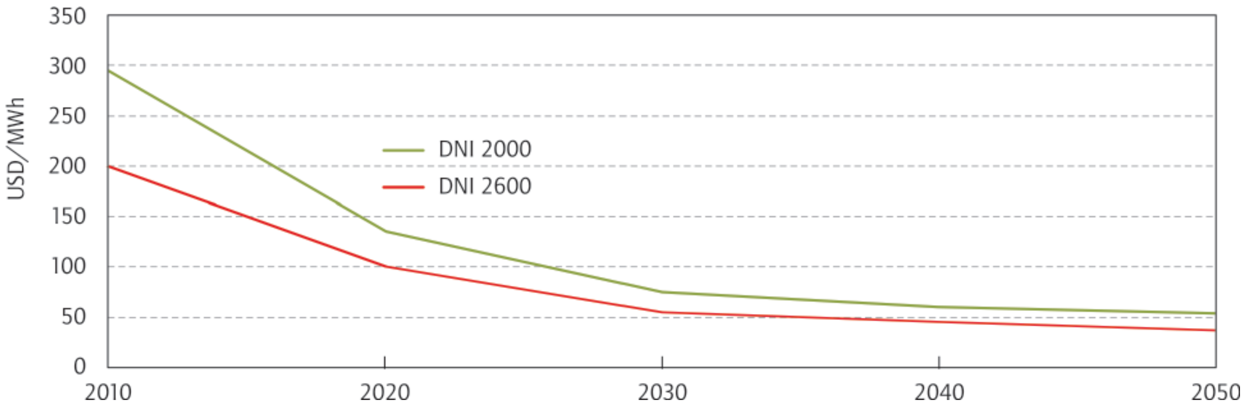
be an ample market for CSP with peak and intermediate loads, and no need to rush into base-load production. The US Department of Energy has set an objective for its CSP programme to reach competitiveness with fossil fuels by 2015 for intermediate loads, at around USD 100/MWh, and by 2020 for base loads, at around USD 50/MWh. According to the evolution of levelised electricity costs envisioned in this roadmap (Figure 12), competitiveness is more likely to be achieved by 2020 for intermediate loads and 2025 to 2030 for base loads.

Assuming an average 10% learning ratio,[7] CSP investment costs would fall by about 50% from 2010 to 2020, as cumulative capacities would double seven times according to the vision proposed in this roadmap – if all stakeholders undertake the actions it recommends. Electricity costs would decrease even faster thanks to progressively greater capacity factors, making CSP technology competitive with conventional technologies for peak and intermediate loads in the sunniest countries by about 2020. This perspective is fully consistent with the potential for improvement for the various technologies identified in the next section.

Solar thermal hydrogen production costs are expected to be USD 2/kg to USD 4/kg by 2020 for efficient solar thermodynamic cycles (detailed below), significantly lower than costs of solar electricity coupled with electrolysis, which are expected to be USD 6/kg to USD 8/kg when solar electricity cost is down to USD 80/MWh. Solar-assisted steam reforming of natural gas would become competitive with natural gas (as an energy source) at prices of about USD 11/MBtu.

7 A 10% learning ratio means a 10% decrease in investment costs when cumulative installed capacities double.

Figure 12: Projected evolution of the levelised electricity cost from CSP plants, in USD/MWh, under two different DNI levels in kWh/m²/y



Note: DNI = direct normal irradiance

Milestones for technology improvements

Table 3 summarises the main features of different CSP technologies and their outlook for improvements.

Technology advances are under development that will enable CSP to boost electricity production and reduce costs, notably through higher temperatures that bring greater efficiency. Other technologies now under development will enable the production of liquid or gaseous fuels by concentrating solar energy. With concerted effort, these milestones can be achieved in the next two to five years.

Milestones for technology improvements	Dates
1. Demonstrate direct steam generation (DSG) in parabolic trough plants	2015 - 2020
2. Large-scale solar tower with molten salts as heat transfer fluids and storage	2010 - 2015
3. Mass-produced parabolic dishes with Stirling engines	2010 - 2015
4. Demonstrate three-step thermal storage for DSG solar plants	2015 - 2020
5. Demonstrate solar tower with supercritical steam cycle	2020 - 2030
6. Demonstrate solar tower with air receiver and gas turbine	2020 - 2030

Troughs and LFR

In an ongoing effort to increase performance and lower costs, all components of parabolic troughs need to continue to make incremental improvements, particularly solar field elements. Effective but costly back-silvered, thick-glass curved mirrors could be replaced with troughs based on less expensive technologies such as acrylic substrates coated with silver, flexible aluminium sheets covered with silver or aluminium, or aluminium sheets glued to a glass-fibre substrate. Wider troughs, with apertures close to 7 m (versus 5 m to 6 m currently) are under development, and offer the potential for incremental cost reductions.

Other proposed innovations are more speculative, but merit further research. The current glass-to-metal welding of the evacuated tubes that collect solar energy could be replaced with a mechanical seal, if it proved capable of preserving the necessary vacuum for 20 years or more. Selective coating of the tubes could also make small performance improvements.

More fundamental advances should be pursued as well, including replacing the costly heat transfer fluid currently used by trough plants; synthetic oil limits the steam temperature to about 380°C as it degrades at higher temperatures. The challenge is to enable the next generation of trough plants

Table 3: Comparison of main CSP technologies

Technology	Optical efficiency	Annual solar-to-electric efficiency	Land occupancy	Water cooling (L/MWh)	Storage possible	Possible backup/hydrid mode	Solar fuels	Outlook for improvements
Parabolic troughs	**	15%	Large	3 000 or dry	Yes, but not yet with DSG	Yes	No	Limited
Linear Fresnel receivers	*	8-10%	Medium	3 000 or dry	Yes, but not yet with DSG	Yes	No	Significant
Towers (central receiver systems)	**	20-35% (concepts)	Medium	2 000 or dry	Depends on plant configuration	Yes	Yes	Very significant
Parabolic dishes	***	25-30%	Small	none	Depends on plant configuration	Yes, but in limited cases	Yes	Through mass production

Note: Optical efficiency is the ratio of the energy absorbed by the solar receiver over the solar energy received in the entire device.

to produce steam at temperatures close to 500°C, thereby feeding state-of-the-art turbines without continuous backup from fuel.

Direct steam generation (DSG) in the collector fields would allow high working temperatures and reduce investment costs, as no heat transfer fluid and heat exchangers would be necessary. DSG needs to be demonstrated in troughs on a large scale, but more work is needed to design specific options for storage with DSG, ensure the separation of water and steam, and handle the circulation of high-temperature, high-pressure working fluids, which is a challenge with mobile receivers.

Other options involve advanced heat transfer fluids, including:

- **pressurised gas**, currently under testing at the Plataforma Solar de Almeria, Spain. Additional work is needed to improve heat transfers in the receiver tubes, and to ensure control of the solar field, which is more complex than the standard design.
- **molten salts** used in the collector field simplify storage, as the heat transfer fluid becomes the storage medium. Salt mixtures usually solidify below 200°C, however, so work is needed to reduce the pumping and heating expenses needed to protect the field against freezing.
- **new liquid fluids**, in particular nanofluids, should actively be investigated.

Linear Fresnel reflectors (LFR) are a nascent technology with large room for improvement. Although LFR lend themselves to DSG because of their fixed receivers, LFR developers should explore options similar to those being considered for trough plants.

Towers and dishes

CSP towers, which already reach high working temperature levels, can achieve higher temperatures still, opening the door to better power cycle efficiencies. Storage costs can also be drastically reduced with higher temperatures, which allow more heat to be converted into electricity and less lost due to limited storage capacity. Improved efficiency also means a lower cooling load, thus reducing water consumption by wet cooling in plants in arid areas. It would also reduce the performance penalty of dry cooling.

The possibilities of these higher temperatures should be explored using different receiver technologies. One option is supercritical steam (or carbon dioxide) cycles such as those used in modern coal-fired power plants, which reach thermal-to-electric efficiency levels of 42% to 46% with supercritical and ultra-supercritical designs.[8] The application of this technology to solar towers, however, requires that it be adapted.

Direct steam generation (DSG) will pose particular challenges in synchronising solar fields with receivers and supercritical steam turbines. A continuous management of solar collectors will be needed to avoid problems during start-up and variations caused by clouds and at sunset. Solar towers with high-temperature heat transfer fluids and storage may prove more capable of fulfilling these requirements, as they disconnect solar heat collection and power generation.[9] Superheating with some fuel could also help address these challenges.

High-temperature tower concepts also include atmospheric air as the heat transfer fluid (tested in Germany with the Jülich solar tower project) with solid material storage. Solar-to-electricity efficiencies of up to about 25% can be delivered by such towers, but for supercritical steam turbines below 400 MW, the gain in efficiency may not compensate for the cost and complication of the cycle.

Solar-based 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. Excess heat could be sent to a steam cycle running a second generator. The solar-to-electricity efficiency could be as high as 35%.[10] Heat storage, however, is still an unresolved issue for such plants, while fossil-fuel (or biomass) backup is more straightforward. Backup fuel heating the air from the solar receiver could be used to manage solar energy variations, and if necessary continuously raise the temperature level.

8 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 efficiencies approaching 50%.

9 Another advantage is that high-temperature heat transfer fluids such as molten salts are low pressure liquids, which allow for thinner wall tubes in heat exchangers and thus facilitate heat transfers.

10 Such solar combined-cycle plants should not be confused with the ISCC plants currently under construction, which have a small solar share compared with the fossil-fuel share.

The main ongoing work on dishes aims at reducing costs through mass production and demonstrating long-term reliability, consolidating their specific advantages of excellent efficiency and no need for cooling water. They could also be improved by making them more compatible with thermal storage and hybridisation, as has been experimentally demonstrated on a few large dishes.

Improvements in storage technologies

Increasing the overall working temperatures of plants is the best means of reducing storage costs.[11] Several types of storage-specific research are promising, including the use of inexpensive recycled materials such as vitrified wastes (*e.g.* asbestos wastes) with a glass or ceramic structure. Adding nanoparticles to increase the heat capacity of molten salts is another option. A third possibility is to use thermocline separation between hot and cold molten salts in a single tank, but leakage risks are more difficult to manage in this case.

Storage is a particular challenge in CSP plants that use DSG. Small amounts of saturated steam can be stored in accumulators, but this is costly and difficult to scale up. Effective full-scale storage for DSG plants is likely to require 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 (PCM). Sodium nitrate ($NaNO_3$), with a melting temperature of 306°C, is a primary candidate for this function.

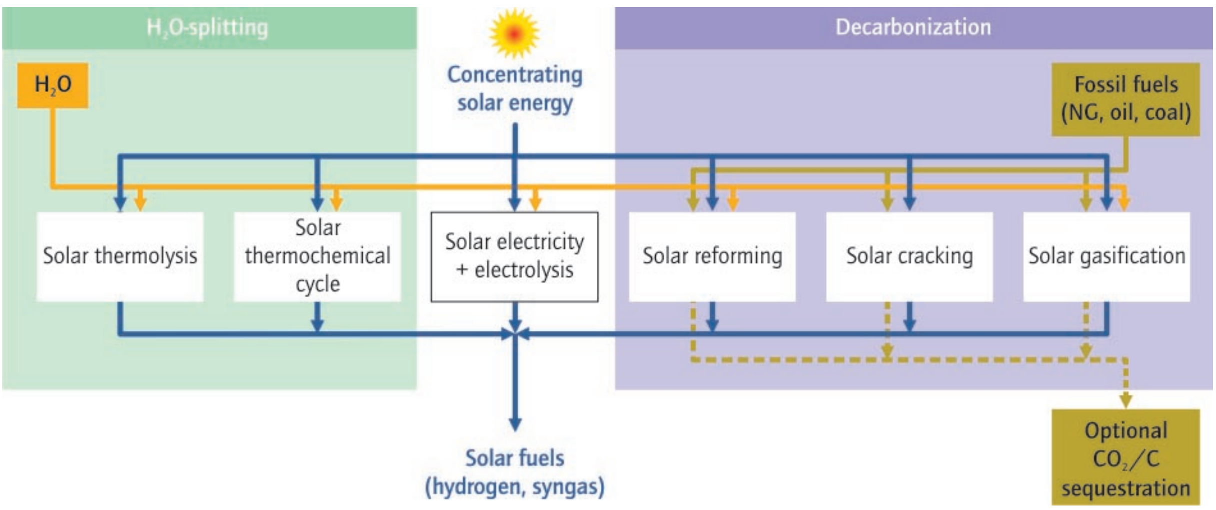
11 For example, if the temperature difference between the hot and cold working or transfer fluids is 300°K instead of 100°K, the same volume of storage material will store three times as much heat.

Emerging solar fuel technologies

Concentrating solar thermal technologies also allow the production of hydrogen (H_2), which forms the basis of fuels, or carriers, that can help store solar energy and distribute it to industry, households and transportation, substituting fossil-based fuels with low-emission solar energy. Solar towers and large dishes are capable of delivering the required amount of heat at the appropriate temperatures.

Producing solar hydrogen via electrolysis of water using solar-generated electricity offers an overall solar-to-hydrogen efficiency of about 10% with current technologies. High-temperature heat from CSP could reduce electricity needs. CSP also offers several other promising options for solar fuel production (Figure 13).

Figure 13: Different thermochemical routes to producing fuels with concentrating solar energy



Source: PSI/ETH-Zürich.

Short-term options would reduce CO_2 emissions but not eliminate them. In the presence of carbon from fossil fuels or biomass, the carbo-thermal reduction of metals could take place at lower temperatures, but the output, instead of pure hydrogen, would be a syngas mixture of H_2 and carbon monoxide (CO). Similarly, solar-assisted steam reforming of natural gas, and steam gasification of coal or solid biomass, can yield syngas. Another option would be natural gas reforming using CO_2 instead of steam. CO_2 could be directly captured from flue gases at coal power plants, and recycled in a solar-enhanced gaseous or liquid fuel.

Syngas can also be used in the well-known water-gas shift process to give H_2 and CO_2, which can be separated easily, or for producing liquid synthetic transportation fuels (as well as methanol and ammonia) through commercially available Fischer-Tropsch processes. Solar pyrolysis or gasification of biomass would greatly reduce the CO_2 emissions involved in the manufacturing of biofuels.

Hydrogen from CSP could be used in today's energy system by being blended in natural gas networks up to 20% of volume. This blend could be used for various purposes in industry, households and transportation, reducing emissions of CO_2 and nitrous oxides.

Solar hydrogen could also find niche markets today in replacing hydrogen production from steam reforming of natural gas in its current uses, such as manufacturing fertilizers and removing sulphur from petroleum products. Solar-assisted steam reforming of natural gas would eliminate the emissions associated with the 40% or more of natural gas used as energy source, not feedstock, in the former use. Concentrated sunlight could also provide process heat for the thermo-chemical decomposition of hydrogen sulphide into hydrogen and sulphur.

Solar-assisted production of hydrogen from fossil fuel could be deemed transitional, because it uses the exhaustible resource as feedstock only, and not as energy source. Also, solar liquid fuels produced from a fossil feedstock would contain carbon atoms, with small but net emissions of CO_2 when combusted. In the long term, however, they will result in much lower emissions than state-of-the-art coal liquefaction processes, which risk rapidly increasing upstream emissions associated with fuels in transportation when oil becomes scarcer and more costly.

The production of pure hydrogen from water or from both water and biomass would be considered a superior form of solar hydrogen since it is based on an extremely abundant and fully renewable resource (hydrogen is recombined in water when used as a fuel) with no CO_2 emissions. It requires, however, much longer research efforts.

Solar thermolysis requires temperatures above 2 200°C, and raises difficult challenges. Water-splitting thermo-chemical cycles allow operation at lower temperature levels (some less than 1 000°C), but require several chemical reaction steps, and there are inefficiencies associated with heat transfer and product separation at each step. Thermal cracking of natural gas will directly produce hydrogen and marketable carbon black. These options require long-term research efforts.

Above 1 200°C, more efficient two-step cycles using reversible reduction-oxidation (redox) reactions can be used. The two steps can be separated in time and place, offering interesting possibilities for their use in transportation. Dedicated concentrated solar fuel plants de-oxidise light elements, which are easily transported to customer stations or even within vehicles, where their oxidation with water produces hydrogen. Oxides are then returned to the solar plants. Aluminium, magnesium and non-metallic elements such as boron are good candidates as energy carriers in such schemes.

Policy framework: roadmap actions and milestones

Overcoming economic barriers

CSP today is usually not competitive in wholesale bulk electricity markets, except perhaps in isolated locations such as islands or remote grids, so in the short term its deployment depends on incentives. A number of regions, including Spain, Algeria, some Indian states, Israel and South Africa, have put in place feed-in tariffs or premium payments. Spain, for example, lets the producers choose between a tariff of EUR 270 (USD 375)/MWh, or a premium of EUR 250 (USD 348)/MWh that adds to the market price, with a minimum guaranteed revenue of EUR 250/MWh and a maximum of EUR 340 (USD 473)/MWh. This approach has proven effective, as it offers developers and banks long-term price certainty, and makes CSP one of the less risky investments in the power sector.

In the United States, the federal government recently created the Renewable Energy Grant Program, as well as a Federal Loan Guarantee Program designed to foster innovation. BrightSource became the first CSP provider to benefit from this programme, securing USD 1.4 billion from the US Department of Energy in February 2010 for several projects.

In the long term, however, financing of CSP plants may become difficult if investors in technology companies do not supply some equity capital. Prices for capacity and energy are only guaranteed by utilities on a case-by-case basis under renewable portfolio standards (the regulations that require increased production of energy from renewable sources) and these standards are not always binding.

Financing innovation

As pointed out earlier in this roadmap, many different technical approaches to CSP have been proposed, each showing expected benefits and potential challenges. All these options have to be tested in pilot plants to reveal their benefits and constraints, so strong government support for innovative small pilot plants is direly needed. Small 5 MW pilot plants are essential as a step towards developing commercial plants.

Once a prototype has been tested through small-scale demonstration, it is conceivable to build a full-scale, first-of-its-kind commercial plant. This is a risky step for private investors. Managing first-of-their-kind plants draws upon public knowledge while also providing lessons to the global CSP community, so public R&D institutes should take part in these efforts.

The US Loan Guarantee Program is one example of a strong incentive designed to foster innovation by private investors. Another useful procedure could be for utilities bidding for capacities to specify that some degree of innovation is required.

This roadmap recommends the following actions:	***Milestones***
Governments	
1. Establish an equitable environment for CSP development through feed-in tariffs or binding renewable energy standards on a par with ground-mounted PV	2010 - 2020
2. Avoid arbitrary limitations on plant size and hybridisation ratios; develop procedures to reward solar-only share	2010 - 2020
3. Streamline permit procedures for CSP plants and access lines	2010 - 2040
4. Consider offering suitable land and access to grid or water resources, and waiving land property and other taxes for quick-start deployment	2010 - 2020
5. Develop incentive schemes for solar process heat	2010 - 2020
6. Progressively eliminate subsidies to fossil fuels and price CO_2 emissions	2010 - 2030
7. Develop incentive schemes for solar process fuels	2020 - 2040
Utilities	
8. Provide certainty to investors with long-term power purchase agreements or bidding procedures	2010 - 2025
9. Reward CSP plants that have firm capacities	2020 - 2050
10. Facilitate grid access for CSP developers	2010 - 2040
11. Participate actively in project development	2015 - 2025

Incentives for deployment

To support CSP deployment, it is vital to build investor confidence by setting a sufficiently high price for the electricity generated, and in a predictable manner. Feed-in tariffs and premiums have proven effective for CSP deployment in Spain, and for other renewable energy technologies in many countries. The levels of feed-in tariffs or premiums must be carefully studied and agreed upon with everyone involved, however, as they are ineffective if too low and economically inefficient if too generous. Renewable energy standards might be effective if they are sufficiently ambitious and "binding" for utilities – that is, if the financial penalties or safety valves are set at appropriate levels in case of no or limited compliance.

While incentives need to be gradually reduced to foster less expensive CSP electricity, revisions need to be announced in advance to enable producers to adapt. Furthermore, while governments may want to limit the benefit of incentives to specified overall project capacities, they should not arbitrarily limit plant size, as scaling up plant size is one important way of reducing costs.

Similarly, governments should avoid arbitrarily setting hybridisation rates; instead, they should establish ways to limit incentives to the solar fraction of CSP power. As PV power and CSP use the same resource, they should enjoy the same incentives so that choices efficiently match the quality of the solar resource with energy needs.

Governments should also design and implement incentives for solar process heat for industrial applications of all kinds and, at a later stage, for the various solar fuels that concentrating solar plants can deliver.

Regardless of whether the electricity sector belongs to state-owned or partially state-owned monopolies or is fully deregulated, governments could encourage all utilities to bid for CSP capacities. Governments should also consider other options to help initiate or develop CSP capacities, such as: offering suitable land or connection to the grid or to water resources; waiving land property taxes; and helping ensure the availability of low-cost or at least reasonably priced loans.

Utilities, for their part, should reward the flexibility of CSP plants, *i.e.* their ability to dispatch electricity when needed. Capacity payments represent a simple option for doing this. Storage has a cost, and should be valued at grid level, not plant level. Policy frameworks should encourage this necessary evolution.

Addressing non-economic barriers

Obtaining permits and grid access are the main challenges for new CSP plants. Access to water or gas networks for backup may be difficult in some locations, and will certainly become important if large numbers of CSP plants are deployed in desert regions.

Nearby residents do not usually object to permits, although the synthetic oil of trough plants and molten salts are classified as hazardous material in some jurisdictions. Before permits are given, however, all environmental impacts must be evaluated, including loss of animal habitat, water use, visual impact and effects on endangered species. The pace of the permitting process is the most frequent problem. In California, for example, environmental analyses on federal or state land can take 18 to 24 months.

Similarly, grid access problems are not caused by utilities, which like the guaranteed, dispatchable nature of CSP, but by slow planning and permitting processes.

Governments must act decisively to streamline procedures and permits for CSP plants and transmission lines. It is especially important to build a network of HVDC lines to transmit electricity from CSP plants in sunny regions to less sunny regions with large electricity demand. The global success of CSP depends on interested countries, producers and consumers sharing a common vision.

Research, development and demonstration support

Over the last three decades, public RD&D efforts have taken place mostly in Australia, Europe and the United States. Russia and Ukraine seem to be less involved than in the past but China and South Korea are building new R&D programmes, while other countries have expressed interest, in particular Abu Dhabi through Masdar.

This roadmap recommends the following RD&D actions:	Milestones
1. Governments to ensure increased and sustained funding for public and private RD&D of CSP	2010 - 2040
2. Governments to develop ground and satellite measurement/modelling of solar resources	2010 - 2020
3. Research centres to develop air receivers for solar towers	2010 - 2020
4. Develop three-step thermal storage for all DSG solar plants	2010 - 2020
5. Seek new heat transfer fluids and storage media for line-focus solar plants	2012 - 2020
6. Develop solar-assisted hydrogen production	2010 - 2020
7. Develop solar tower with supercritical steam cycle	2015 - 2030
8. Develop solar tower with air receiver and Brayton cycle	2010 - 2020
9. Develop solar-only hydrogen production	2020 - 2030
10. Develop solar-assisted liquid fuel production	2020 - 2030

Recent global public RD&D investments in CSP have been assessed at less than USD 100 million per year. The CSP deployment in the BLUE Map scenario would imply building about 20 GW of new CSP capacity each year on average during the next four decades. This represents investment expenses of about USD 56 billion per year. R&D expenditures are typically 1% of total investments, giving USD 560 million as the necessary level of public and private RD&D expenditures. Even if 50% of this were to come from industry, the global public RD&D expenses still need to be almost tripled.

There is a need for more open access to RD&D tower facilities like those at the Plataforma Solar de Almeria (Spain), as the few others available are all overloaded in experiments.[12] Scalable demonstration plants in the 5 MW range also need to be built, possibly via public-private partnerships. These developments would easily add another USD 300 million per year to the public RD&D funding already mentioned.

For these reasons, public RD&D and small-scale demonstration support to CSP worldwide should be increased rapidly from USD 100 million to USD 500 million per year, and perhaps further increased to USD 1 billion per year in a second stage. It should be noted that these sums remain modest compared with the support already enjoyed by other power or fuel technologies.

Collaboration in RD&D and deployment

Since its inception in 1977, the IEA Implementing Agreement SolarPACES[13] has been an effective vehicle for international collaboration in all CSP fields. Of all IEA Implementing Agreements, SolarPACES has the largest participation from 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 SolarPACES START teams (Solar Thermal Analysis, Review and Training) have carried out missions to support the introduction of CSP to developing countries. By sending international teams of experts, independent technical advice was made available to interested countries, including Egypt, Jordan, Brazil and Mexico. In solar chemistry research, where the commercialisation goals are more long term, SolarPACES has succeeded in building up and supporting international interest, defining research priorities and facilitating co-operative international research.

The current work programme of SolarPACES includes five tasks:

- I: Solar Thermal Electric Systems;
- II: Solar Chemistry Research;
- III: Solar Technologies and Applications;
- V: Solar Resource Knowledge Management (in common with the IEA Solar Heating and Cooling Implementing Agreement); and
- VI: Solar Energy & Water Processes and Applications.

12 These include Odeillo and Themis (France), the Weizmann Institute (Switzerland), Sandia National Laboratory (USA), Jülich (Germany) and the CSIRO Energy Centre (Australia).

13 Solar Power and Chemical Energy Systems, formerly SSPS – Small Solar Power Systems.

Task IV, Solar Heat for Industrial Processes, a collaborative task with the IEA Solar Heating and Cooling (SHC) Implementing Agreement, ended in 2007.

The annual CSP Symposium run by SolarPACES is by far the largest 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.

Deployment in developing economies

The full potential for global CSP deployment requires particular attention to the needs of developing economies. While some would, under this roadmap, build CSP plants for their own needs (*e.g.* China and India), others would build more for exports, notably North African countries.

Governments of developing countries have come to realise that CSP technology, which in a few years could have extensive local content, is a productive investment. Some governments are making considerable investments in CSP, as it offers a strategy to reduce energy imports and protection against spikes in the costs of fossil fuels. Algeria and South Africa have established feed-in tariffs for CSP, and India recently set aside USD 930 million to launch its Solar Mission with the aim to build 20 GW of solar capacities (PV and CSP) by 2022. Morocco has established a detailed plan for building 2 GW of solar plants on five sites from 2010 to 2019, representing 38% of the current installed electric capacity of the country. One US company recently contracted with partners to build solar towers in India and China with overall capacities of 1 GW and 2 GW, respectively.

There are several ways of helping developing countries cover the cost difference between CSP and more conventional power sources in the first decade. These include the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change, which offers a mechanism for industrialised nations to pay for CO_2 reductions in developing countries. The Shams-1 project is an example of a CDM project that has already been registered. The World Bank's Clean Technology Fund has also set aside USD 750 million to cover 10% of the investment costs of CSP plants in the Middle East and North Africa. Such investments may also receive attractive loans from regional development banks and, according to their proportion of imported material, from export credit agencies.

For North African countries and, to a lesser extent Middle East and Central Asian countries, electricity exports are expected to be a catalyst to the development of CSP. The marginal cost of electricity production is already higher in several potential importing countries, notably in Europe. Furthermore, Europeans may accept an even higher price for imported renewable electricity to help achieve the ambitious objective of obtaining 20% of Europe's final energy from renewable sources.

It is too early to estimate the marginal cost of renewable electricity needed in Europe to achieve these targets, but if the level of feed-in tariffs is an indication, the price paid by European countries could cover the cost of CSP electricity in North Africa and its transport to Europe. Cross-border incentives have thus to be set to facilitate integration. In the importing country, priority grid connection should be offered to all renewable energy projects, independent of origin. In both

This roadmap recommends the following government actions:	***Milestones***
1. Explore alternative business models for promoting CSP deployment for distributed generation and rural electrification	2010 - 2020
2. Negotiate cross-border incentives for CSP electricity transfers	2010 - 2015
3. Expand international mechanisms to foster the development of CSP plants for local consumption in developing countries	2010 - 2020
4. Plan, finance and build cross-border HVDC lines for CSP expansion	2015 - 2040

EU renewable energy targets and CSP plants in the Middle East-North Africa region

The Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 gives all member states a share of renewable energy to be achieved by 2020. However, it allows these targets to include renewable energy that is consumed in a member state but produced in any non-member country from new installations. Furthermore, it allows two or more member countries to agree to share, with respect to their renewable energy targets, the energy produced in a non-member country and consumed in only one EU member state. This opens up new options for financing CSP expansion in potential exporting countries.

exporting and importing countries, laws and regulations should allow fast-track approval of new transmission lines.

Such projects need to result in win-win situations. It would seem unacceptable, for example, if all solar electricity were exported overseas while local populations and economies lacked sufficient power resources. Newly built plants will have to fulfil the needs of the local population and help develop local economies. Meanwhile, the returns from exporting clean, highly valued renewable electricity to industrialised countries could help cover the high initial investment costs of CSP beyond the share devoted to exports. CSP would thus represent a welcome diversification from oil and gas exports, and help develop local economies by providing income, electricity, knowledge, technology and qualified jobs.

Possible energy security risks for importing countries must also be carefully assessed. Large exports would require many HVDC lines following various pathways. The largest transfers envisioned in this roadmap, from North Africa to Europe, would require by 2050 over 125 GW of HVDC lines with 50% capacity factor – *i.e.* 25 distinct 5 GW lines following various paths. If some were out of order for technical reasons, or as a result of an attack, others would still operate – and, if the grid within importing and exporting countries permits, possibly take over. In any case, utilities usually operate with significant generating capacity reserves, which could be brought on line in case of supply disruptions, albeit at some cost. Furthermore, the loss of revenue for supply countries would be unrecoverable, as electricity cannot be stored, unlike fossil fuels. Thus, exporting countries, even more than importing ones, would be willing to safeguard against supply disruptions.

Conclusion and role of stakeholders

This roadmap has responded to requests from the G8 and other government leaders for more detailed analysis of the growth pathway for CSP, a key climate-change mitigation technology. It describes approaches and specific tasks regarding RDD&D; financing mechanisms; grid integration; legal and regulatory frameworks; public engagement; and international collaboration. It provides regional projections for CSP deployment from 2010 to 2050. Finally, this roadmap details actions and milestones (see below) to aid policy makers, industry and power-system actors, as well as non-governmental organisations (NGOs), intergovernmental organisations (IGOs) and multilateral banks, in their efforts to successfully implement CSP.

The CSP roadmap is meant to be a process, one that evolves to take into account new technology developments, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that CSP energy development efforts are on track to achieve the reductions in greenhouse-gas emissions that are required by 2050. The IEA, together with government, industry and NGO stakeholders, will report regularly on the progress achieved toward this roadmap's vision. For more information about the CSP roadmap actions and implementation, visit www.iea.org/roadmaps.

Stakeholder	Action Items
National Governments	• Ensure increased and sustained funding for public and private RD&D of CSP • Develop on-the-ground and satellite measurement/modelling of solar resources • Establish an equitable environment for CSP development through feed-in tariffs or binding renewable energy portfolio standards, on a par with large-scale ground-mounted photovoltaic plants • Encourage state-controlled utilities to bid for CSP capacities • Avoid arbitrary limitations on plant size and hybridisation ratios; instead develop procedures to reward solar electricity only • Streamline permit procedures for CSP plants and access lines • Consider offering suitable land and access to grid or water resources, and waiving land property and other taxes, as additional means for quick-start deployment • Develop incentive schemes for solar process heat and fuels, not just electricity • Explore alternative business models for promoting CSP deployment for distributed generation, notably in developing countries • Progressively eliminate subsidies to fossil fuels and price CO_2 emissions • Join SolarPACES as members

CSP Industry	• Pursue cost reduction potential for line-focus systems:
	  ○ New components (troughs, mirrors, heat collector elements)
	  ○ New transfer fluids
	  ○ Master direct steam generation (DSG) in parabolic trough plants
	  ○ Raise working temperatures in Linear Fresnel Reflector plants
	• Pursue cost reduction potential for parabolic dishes and relevant thermodynamic engines, in particular through mass production
	• Pursue cost reduction potential of heliostat (mirror) fields with immediate control loop from receivers and power blocks to address transients
	• Further develop heat storage, in particular three-step storage systems for direct steam generation solar plants, whether LFR, troughs, or towers
	• Further develop central receiver concepts, notably for superheated steam, molten salts and air receivers; increase temperature levels to reduce storage costs and increase efficiency
	• Work collaboratively with turbine manufacturers to develop new turbines in the capacity range convenient for CSP plants with greater efficiency, in particular through supercritical and ultra-supercritical designs
	• Consider all options for cooling systems in warm and water-scarce environments

Stakeholder	Action Items
CSP Industry (continued)	• Develop new concepts for small and mid-scale plants for remote or weakly interconnected grids, and isolated end-users. • Join SolarPACES as sponsors
Utilities	• Provide certainty to investors with long-term power purchase agreements or bidding procedures • Reward CSP plants that have firm capacities • Facilitate grid access for CSP developers • Participate actively in project development • In the long run, own and operate CSP plants as part of own generating assets portfolio • Join SolarPACES as sponsors
Non-governmental Organisations	• Help obtain local public acceptance of CSP projects through fair assessment of pros and cons
Intergovernmental Organisations and Multilateral Development Agencies	• Call for and organise negotiations between potential importing and exporting countries to establish cross-border incentive regimes for CSP electricity transfers between countries • Develop international mechanisms to foster the development of CSP plants for local consumption in sunny developing countries • Help organise the planning, financing and achievement of cross-border HVDC lines mainly associated with CSP expansion

Units, acronyms, abbreviations and references

Units of measure

°C	Celsius degrees (temperature)
°K	Kelvin degrees (temperature)
GW	gigawatts; or billion watts (power)
GWh	gigawatt hours; or million kWh (energy)
GWh_{th}	gigawatt hours thermal; or million kWh thermal (thermal energy)
kW	kilowatts; or thousand watts (power)
kWh	kilowatt hours (energy)
MBtu	million British thermal units (energy); one MBtu is roughly the energy content of 1 00 cubic feet of natural gas
MPa	megapascal; or one million pascals (pressure)
Mtoe	million tonnes oil equivalent
MW	megawatt; or one million watts (power)
MWe	megawatt electric; or one million watts electric (power)
MW_{th}	megawatt thermal; or one million watts thermal (thermal power)
TWh	terawatt hour; or one billion kilowatt hours

Acronyms and abbreviations

AC	alternative current
ANU	Australian National University
CCS	carbon (dioxide) capture and storage
Cener	Centro Nacional de Energias Renovables (Spain)
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
CLFR	compact linear Fresnel reflectors
CNRS	Centre national de la recherche scientifique (France)
CO_2	carbon dioxide; the most important man-made greenhouse gas
CPV	concentrating photovoltaics; usually not included in CSP
CRS	central receiver systems; solar towers
CSF	concentrating solar fuels
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CSP	concentrating solar power; usually meant to designate only concentrating solar thermal electricity or heat (*i.e.* excluding concentrating photovoltaics or CPV)
DC	direct current
Dish	parabolic reflectors
DLR	Deutschen Zentrums für Luft - und Raumfahrt (German Aerospace Centre)
DNI	direct normal irradiance
DSG	direct steam generation
EDF R&D	Electricité de France, Recherche et Développement
EIB	European Investment Bank
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
ENS	Ecole normale supérieure (France)

ESTELA	European Solar Thermal Electricity Association
ETH-Zürich	Eldgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology)
ETP	*Energy Technology Perspectives*; an IEA publication
EU	European Union
Fischer-Tropsch	process for transforming gaseous fuels into liquid fuels
G8	Group of Eight (A forum gathering Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States)
H_2	hydrogen
HTF	heat transfer fluid
HVAC	high-voltage alternative-current
HVDC	high-voltage direct-current
IEA	International Energy Agency
IGO	intergovernmental organisation
INTA	Instituto Nacional de Técnica Aeroespacial (Spain)
ISCC	integrated solar combined cycle
KfW	Kreditanstalt für Wiederaufbau (German public bank group)
KNO_3	potassium nitrate
LFR	linear Fresnel reflectors; the most recent CSP technology
MEF	Major Emitters Forum
$NaNO_3$	sodium nitrate
NEF	New Energy Finance
NREL	National Renewable Energy Laboratory (United States)
O_2	oxygen
PSA	Plataforma Solar de Almeria (Spain)
PSI	Paul Scherrer Institute (Switzerland)
PT	parabolic trough
PV	photovoltaics; some say it can produce electricity from sunlight
PwC	PricewaterhouseCoopers
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
SAI	Solar America Initiative
SEGS	Solar Electricity Generating Systems; CSP plants built by Luz from 1984 to 1991 in California, still operating
SET	Strategic Energy Technology (Europe Union)
SHC	Solar Heating and Cooling; an Implementing Agreement of the IEA
SolarPACES	Solar Power and Chemical Energy Systems; an Implementing Agreement of the International Energy Agency
SSPS	Small Solar Power Systems; former name of SolarPACES
START	Solar Thermal Analysis, Review and Training
STE	solar thermal electricity; sometimes preferred to CSP as it does not include CPV but allows for the (today, non-commercial) possibility of non-concentrating solar thermal electricity
STEII	Solar Thermal Electricity European Industrial Initiative
troughs	cylindro-parabolic reflectors
UK DECC	Department of Energy and Climate Change, United Kingdom
US DOE	Department of Energy (United States)
USD	United States dollar
Zn	zinc
ZnO	zinc oxide

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