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.
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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

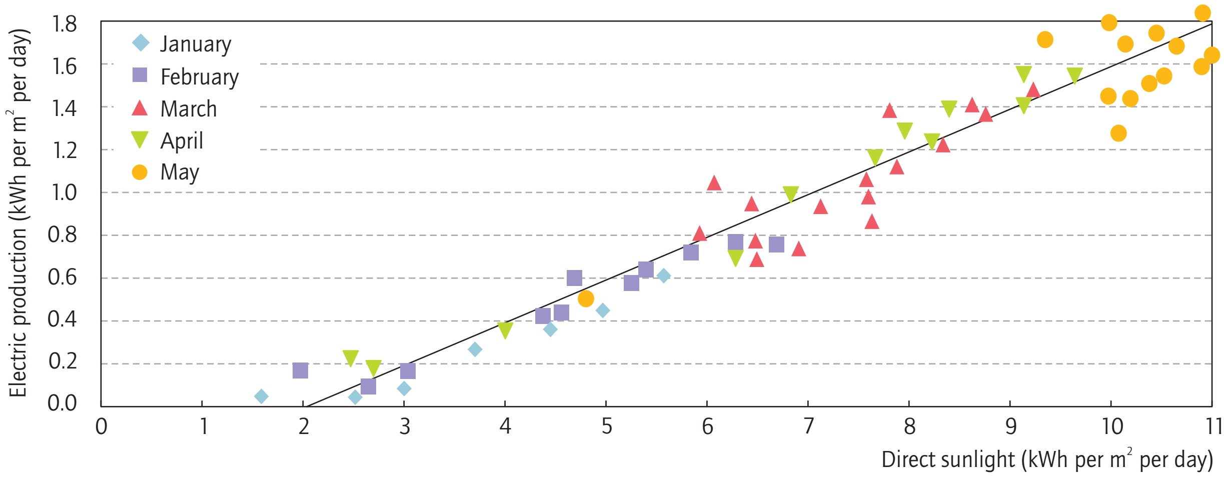
The sunlight hits the Earth's surface both directly and indirectly, through numerous reflections and deviations in the atmosphere. On clear days, direct irradiance represents 80% to 90% of the solar energy reaching the Earth's surface. On a cloudy or foggy day, the direct component is essentially zero. 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.

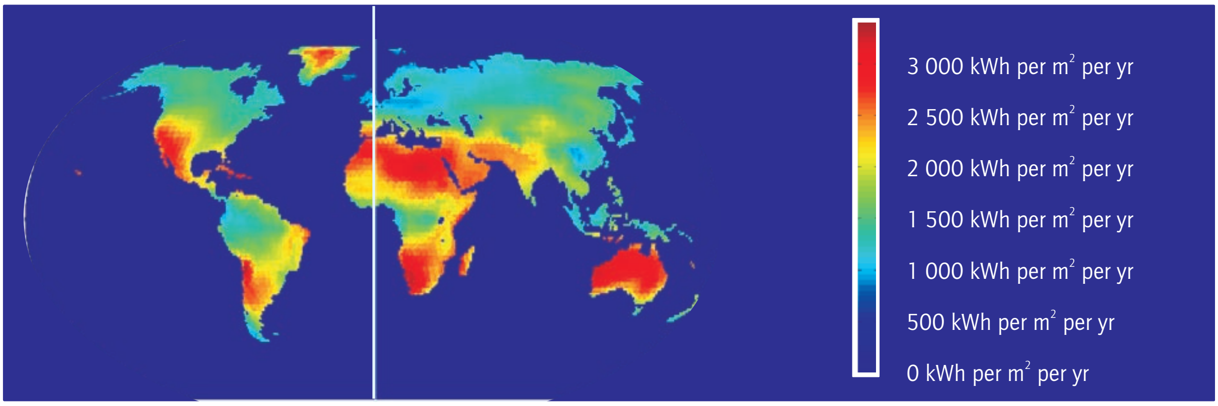
Several studies have assessed in detail the potential of key regions (notably the United States and North Africa), giving special consideration to land availability: without storage, CSP plants require around 2 hectares per MWe, depending on the DNI and the technology.

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/m²/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).

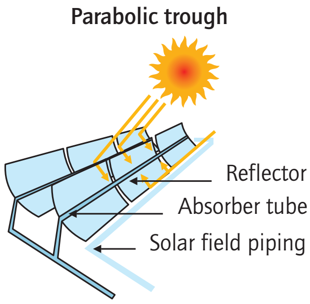
This creates opportunities for CSP plant operators to supply a larger range of consumers. However, the cost of constructing major transmission and distribution lines must be taken into account.

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.



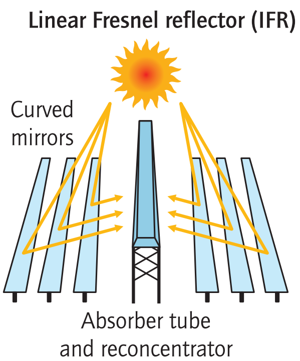
All parabolic trough plants currently in commercial operation rely on synthetic oil as the fluid that transfers heat (the heat transfer fluid) from collector pipes to heat exchangers, where water is preheated, evaporated and then superheated. The superheated steam runs a turbine, which drives a generator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

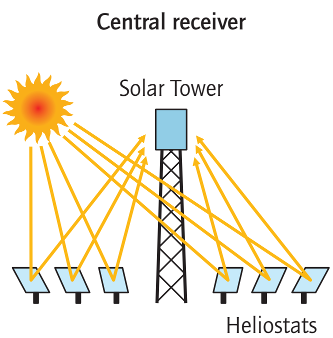
Linear Fresnel reflectors (line focus, fixed receiver)



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.

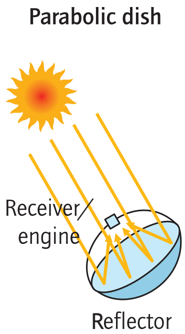
Solar towers (point focus, fixed receiver)



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

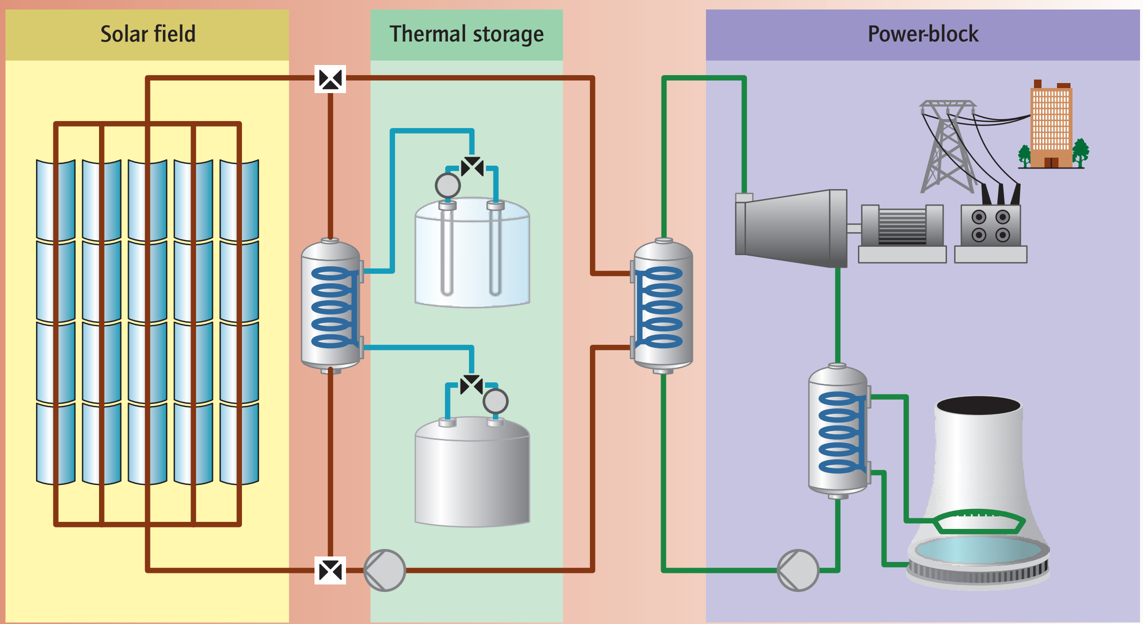
In arid and semi-arid areas suitable for CSP production, sunlight usually exhibits a good match with electricity demand and its peaks, driven by air-conditioning loads. However, the available sunlight varies somewhat even in the sunniest places. Furthermore, human activity and thermal inertia of buildings 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.

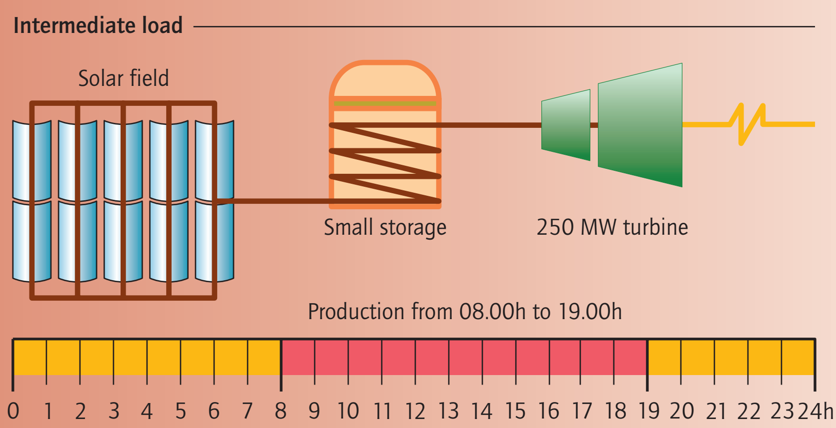
Studies show that, in locations with good sunlight (high DNI), extending electricity production to match this demand requires a storage capacity of two to four hours. In slightly less sunny areas, storage could be larger, as it also helps compensate for the somewhat less predictable resource. The solar 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 MW_e) 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.

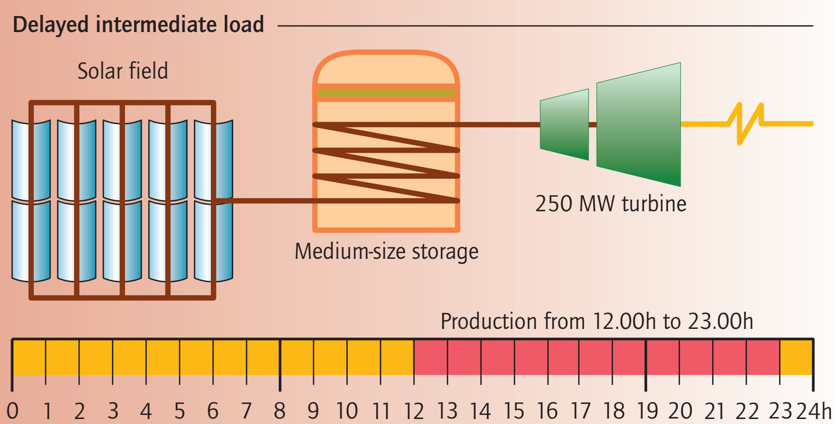
Tailoring storage to serve purpose

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.

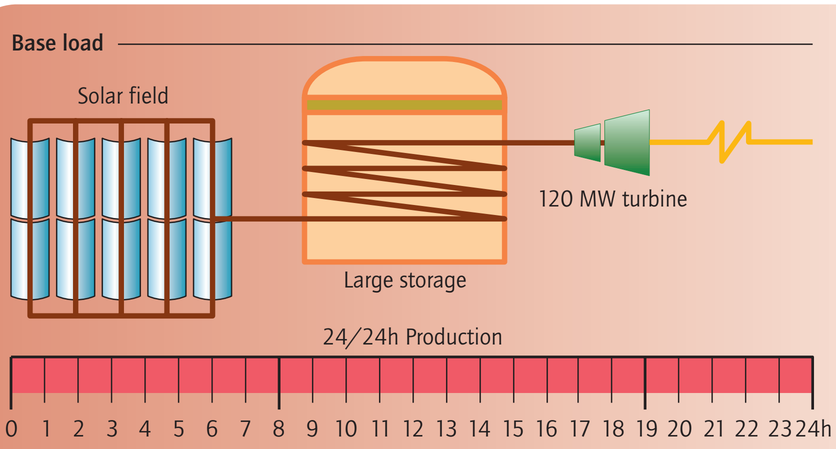
Figure 3: Four different configurations of CSP plants of a given solar field size



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.

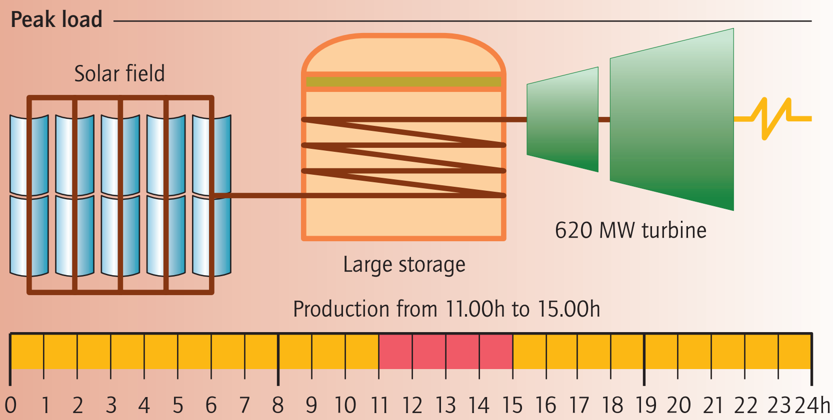


The delayed intermediate load design collects solar energy all day but produces electricity from noon on and after sunset, corresponding to peak and shoulder loads. It has the same size turbine as the intermediate load plant but requires a larger amount of storage.



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.