CONCENTRATING SOLAR POWER

CLEAN POWER ON DEMAND 24/7

THE WORLD BANK
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International Renewable Energy Agency

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CLIMATE INVESTMENT FUNDS

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The World Bank 1818 H Street NW | Washington DC 20433 | USA

202-473-1000 | www.worldbank.org

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World Bank. 2021. Concentrating Solar Power: Clean Power on Demand 24/7. Washington, DC: World Bank.

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ACKNOWLEDGEMENTS

This report provides an overview of the development of Concentrating Solar Power and its potential contribution in furthering cleaner and more robust energy systems in regions with high levels of direct normal irradiation (DNI). This work has been carried out under the Middle East and North Africa Concentrating Solar Power Knowledge and Innovation Program (MENA CSP KIP) with funding from the Clean Technology Fund of the Climate Investment Funds. Preparation of this report was managed by a World Bank team led by Jonathan Edwards Sinton and Elena Cuadros.

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ACRONYMS AND ABBREVIATIONS

CO_2	carbon dioxide
CSP	concentrating solar power
CTF	Clean Technology Fund
DEWA	Dubai Electricity and Water Authority
DSCC	decoupled solar combined cycle
DNI	direct normal irradiation
EPC	engineering, procurement, and construction
GHG	greenhouse gas
GW	gigawatt
HTF	heat transfer fluid
IFI	international financial institution
IPP	independent power producer
ISCC	integrated solar combined cycle
kWh	kilowatt-hour
kWh/m^2	kilowatt-hour per square meter
LCOE	levelized cost of electricity
m^2	square meter
MASEN	Moroccan Agency for Solar Energy
MENA	Middle East and North Africa
MW	megawatt
MWe	megawatt electric
OECD	Organisation for Economic Co-operation and Development
OPEX	operational expenditure
O&M	operations and maintenance
PPA	power purchase agreement
PPP	public-private partnership
PV	photovoltaic
REFIT	renewable energy feed-in tariff
UAE	United Arab Emirates

EXECUTIVE SUMMARY

Concentrating solar power (CSP) with thermal energy storage can provide flexible, renewable energy, 24/7, in regions with excellent direct solar resources

CSP with thermal energy storage is capable of storing energy in the form of heat, at utility scale, for days with minimal losses. Stored heat can then be converted into electricity and dispatched as required by demand, even at night or during cloudy periods of the day. CSP plants can be designed to work as baseload power generation assets, providing renewable power 24/7. CSP is also flexible, meaning that it can quickly ramp up or down as required by the grid. When ramping down, the output is not wasted; instead, it can be stored as heat in molten salt tanks and deployed hours or even days later.

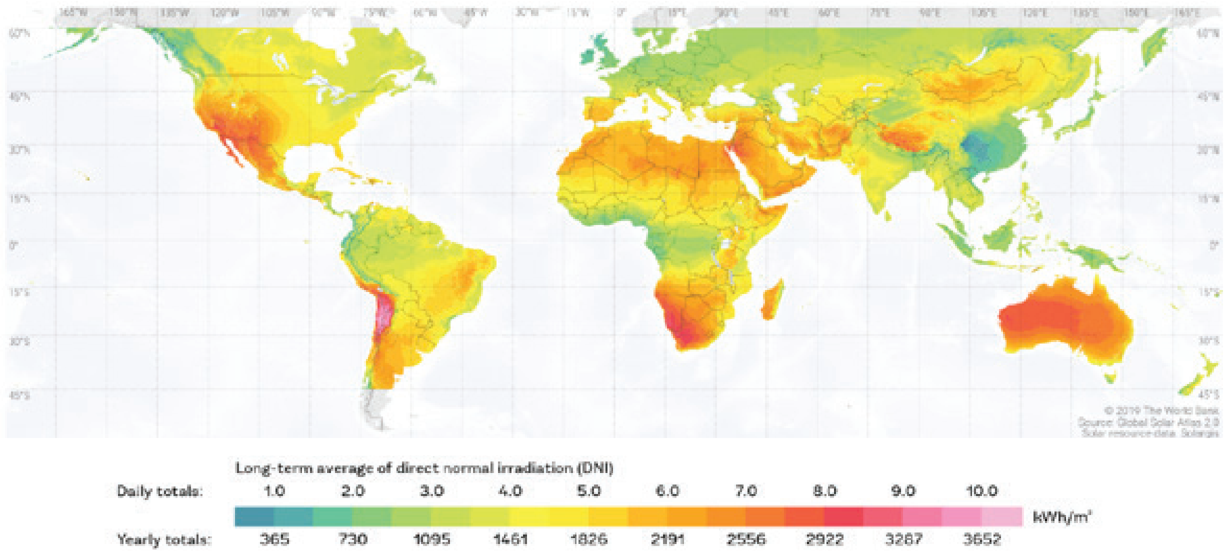
CSP with thermal energy storage can lower the cost of rapidly expanding renewable energy

In places with high levels of direct normal irradiation (DNI), which abound in the Middle East, northern and southern Africa, and several other regions around the world (figure ES.1), CSP with thermal energy storage can enable the lowest-cost energy mix at the country level by allowing the grid to absorb larger amounts of energy from cheap variable renewables, such as solar photovoltaic (PV). Recent bids for large-scale PV projects in the Middle East and North Africa (MENA) region have shown that prices between $0.02 and $0.03 per kilowatt-hour (kWh) are achievable in a wide range of contexts, suggesting that PV is the cheapest way to generate electricity in this part of the world.

However, using inexpensive PV to achieve the lowest-cost energy mix requires flexible generation assets or low-cost storage to meet electricity demand 24 hours a day. One way to achieve this flexibility via renewables is to combine CSP with thermal energy storage and/or hydropower, depending on availability. To simply add wind or PV capacity without mitigating variability is likely to lead to high levels of marginal curtailment, making each additional unit of PV or wind effectively more expensive because less and less additional output can be used. A study that modelled grid conditions in California estimates that deploying CSP with thermal energy storage can drastically reduce PV curtailment and therefore reduce overall system costs (Denholm, Clark, and O'Connell 2016).

CSP's capacity to reduce curtailment is important because it enables grid systems to realize the full value of PV and wind investments and to replace

FIGURE ES.1 **World map of direct normal irradiation (DNI)**



Source: Global Solar Atlas (ESMAP 2019).
Note: kWh/m2 = kilowatt-hour per square meter.

a larger share of fossil fuels in the energy mix. Power generation systems can be made more robust, resilient, and affordable by deploying these complementary renewable power generation technologies. Depending on resource availability, such a portfolio may include large amounts of variable renewables such as PV and wind, storage technologies such as batteries and pumped hydro, demand response measures, and dispatchable renewable energy sources such as CSP with thermal energy storage and hydropower dams.

CSP costs have fallen significantly over the past 10 years

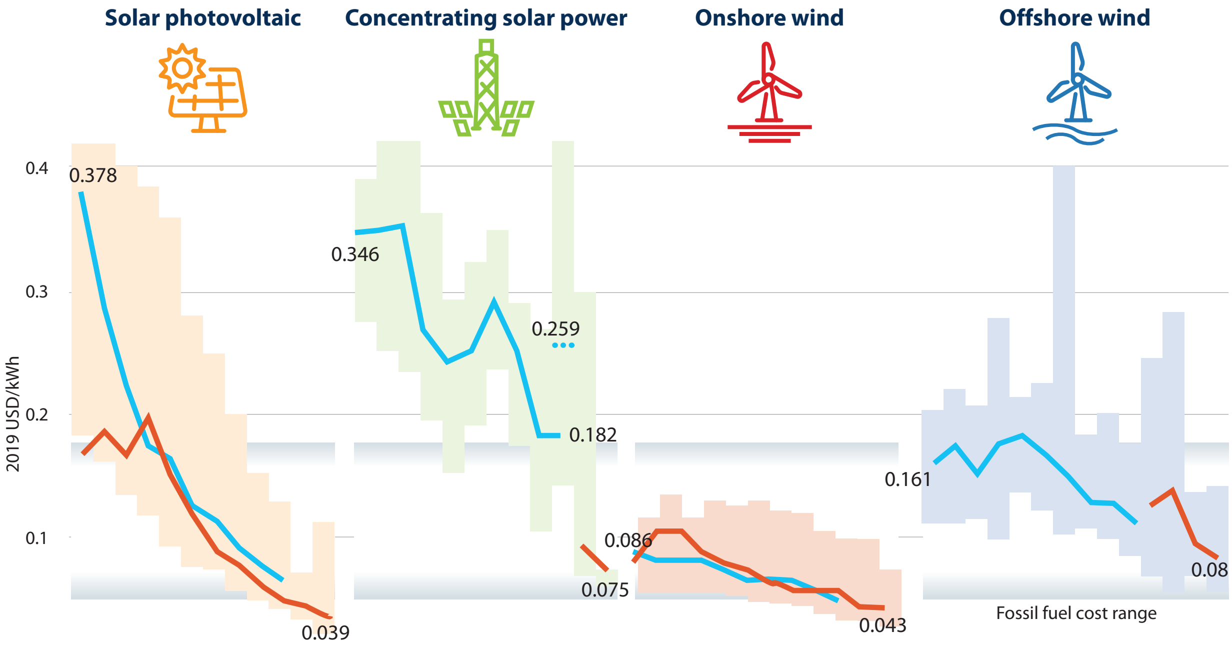
Electricity prices awarded to new CSP plants under power purchase agreements (PPAs) have declined significantly in the past decade (figure ES.2). For the Nevada Solar One plant in the United States, the power purchase price was around $0.30/kWh when the plant was first commissioned in 2007. Plants built in Spain between 2008 and 2012 received a feed-in tariff (FiT) of around $0.40/kWh. By contrast, the electricity price for Noor Ouarzazate III, awarded in 2015, was $0.16/kWh. More recently, a 950 MW CSP-PV hybrid plant by the Dubai Electricity and Water Authority (DEWA) in the United Arab Emirates was awarded a price of $0.073/kWh[1].

Given the trends observed since 2007, it is expected that PPA prices will continue to decline in the coming years if deployments continue to scale. Further deployments will incorporate technological improvements, improve economies of scale and unlock efficiencies in both the construction and operation of CSP plants.

Concessional financing plays a key role in reducing financial risks and lowering the cost of CSP

Despite promising developments in the overall cost of CSP technologies, their relatively high up-

FIGURE ES.2 Global weighted average LCOE and auction/PPA prices for CSP, onshore and offshore wind, and solar



Source: IRENA 2020.

Note: The thick lines are the global weighted average LCOE, or auction values, by year. The gray bands, which vary by year, are the cost/price range for the 5th and 95th percentiles of projects. For the LCOE data, the real weighted average cost of capital is 7.5% for China and members of the Organisation for Economic Co-operation and Development, and 10% for the rest of the world. The band that crosses the entire chart represents the fossil-fuel-fired power generation cost range. For CSP, the dashed blue bar in 2019 shows the weighted average value including projects in Israel.

CSP = concentrating solar power; LCOE = levelized cost of electricity; PPA = power purchase agreement; USD/kWh = US dollars per kilowatt-hour.

[1] These prices are quoted in nominal terms.

front investment costs remain a barrier to their deployment. But international financial institutions (IFIs) and multilateral development institutions, as well as national governments, can play an important role in addressing this barrier. By supplying longer-duration, lower-interest financing to CSP plant developers, these entities can help to lower the costs of initial market development. This will, in turn, foster more diverse and competitive supply chain for CSP and continue to drive down costs. Reducing perceived financing risks is particularly important when no entities, whether public or private, are willing to shoulder the full costs of a project on their own. Meanwhile, international financial institutions can provide capacity building and knowledge transfer to local and international stakeholders in the project.

One of the largest individual financial contributors to global CSP developments is the Clean Technology Fund (CTF), which has supported numerous projects, including:

- **Noor Ouarzazate I, II, and III (510 megawatts [MW] CSP), Morocco**. Along with various international financial institutions, the fund provided low-cost debt that decreased project costs by 25 percent, thereby decreasing the subsidy needed from the government of Morocco from $60 million to $20 million annually. Also, $435 million was awarded by the CTF.
- **Noor Midelt (800 MW CSP-PV hybrid), Morocco**. In 2017, a loan of $25 million was announced for this solar project, which combines solar thermal and PV.
- **Cerro Dominador (110 MW CSP), Chile**. Fund support was critical to the launch of bidding for South America's first CSP plant. Through the Inter-American Development Bank, the fund attracted the interest of other donors, including the European Union and KfW. This allowed an incentives package comprising grants and soft loans to be put together, closing the gap between CSP and other alternatives.

Most of the world's newest CSP plants have been built in Chile, China, Morocco, and the United Arab Emirates. There are around 6 gigawatts (GW) of operating CSP plants worldwide, which are concentrated in Spain (2.3 GW), the United States (1.6 GW), Morocco (0.5 GW), China (0.5 GW), and South Africa (0.5 GW). The MENA region is at the forefront of the most recent wave of construction projects, with Morocco and the United Arab Emirates being the most active markets in the region.

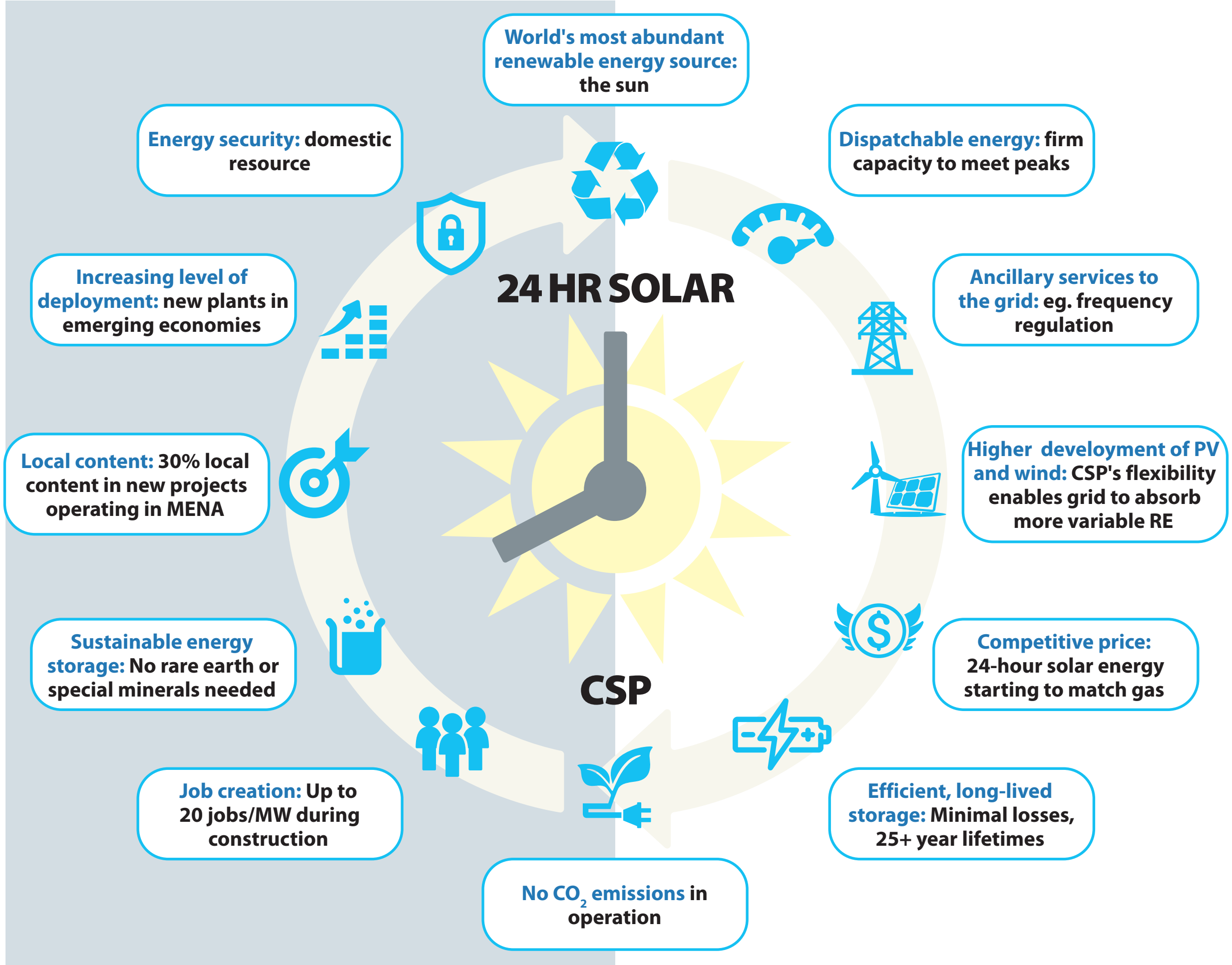
Recently, the lowest PPA for a CSP project was granted in Dubai (United Arab Emirates) at $0.073/kWh for the DEWA 950 MW CSP-PV hybrid project. The CSP part of this complex comprises three parabolic trough plants (200 MW each with 12.5 hours storage) and one tower plant (100 MW, 15 hours storage). The project is designed to provide electricity during the evening and is being built alongside a 250 MW PV plant; this hybrid design allows it to combine the strengths of both technologies to provide clean power 24/7.

Morocco is home to the largest operating CSP complex in the world: Noor Ouarzazate, which comprises 510 MW of CSP and a 72 MW PV plant. Subsequently, the Noor Midelt 1 project (800 MW, CSP-PV hybrid) was awarded, and stands as the first project in which output from both PV and CSP will be stored as heat in molten salt tanks (Kramer 2020). The Midelt solar complex will have further phases, so it is possible that there will be additional CSP plants in Morocco.

Other countries in the region that are actively considering the deployment of CSP include Jordan, Lebanon, and Tunisia. Outside MENA, the country to watch is China, where 500 MW of CSP have already being deployed, 414 MW are being developed, and 100 MW are under construction. Most of this activity is happening under a government-sponsored set of initial CSP pilot projects.

Some of the key benefits of CSP—which, combined with thermal energy storage, can be used to generate electricity 24 hours a day—are presented in figure ES.3.

FIGURE ES.3 Key benefits of CSP technology



Note: CO_2 = carbon dioxide; CSP = concentrating solar power; h = hour; MENA = Middle East and North Africa; MW = megawatt; PV = photovoltaic; RE = renewable energy.

1 WHY CONCENTRATING SOLAR POWER?

1.1 CSP explained

Concentrating solar power (CSP) is a renewable energy technology that uses mirrors to focus direct solar radiation on a fluid-filled receiver, typically thermal oil or molten salts. This fluid, commonly referred to as heat transfer fluid (HTF), then conducts heat that is used to generate electricity via a steam turbine generator similar to that used in conventional thermal power plants. By contrast, solar photovoltaic (PV) technology converts the energy of photons from the sun directly to electricity with a silicon-based semiconductor.

There are four CSP technologies: parabolic trough, solar tower, linear Fresnel, and parabolic dish (figure 1.1). With an 81 percent market share, the parabolic trough (figure 1.2, left) is the predominant technology of CSP plants deployed to date. Most of the remaining plants are solar towers (figure 1.2, right), while Fresnel and parabolic dish systems

Figure 1.1 Four types of concentrating solar power technologies

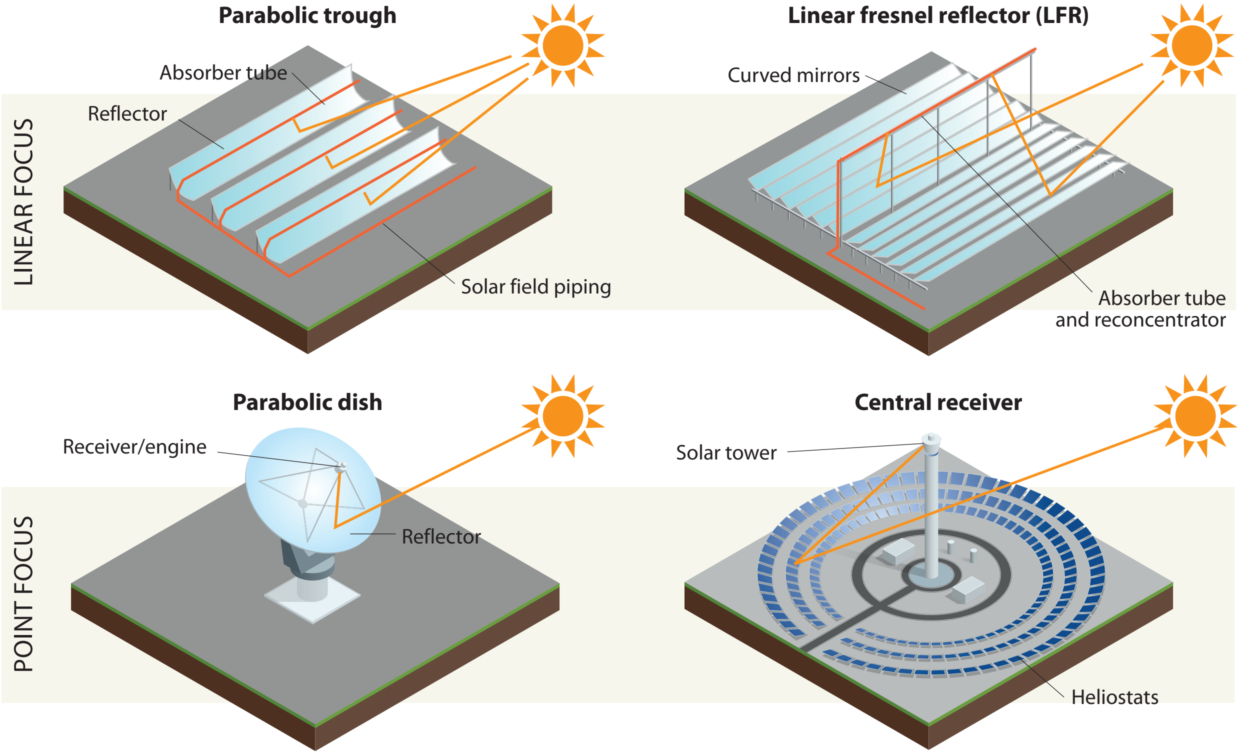
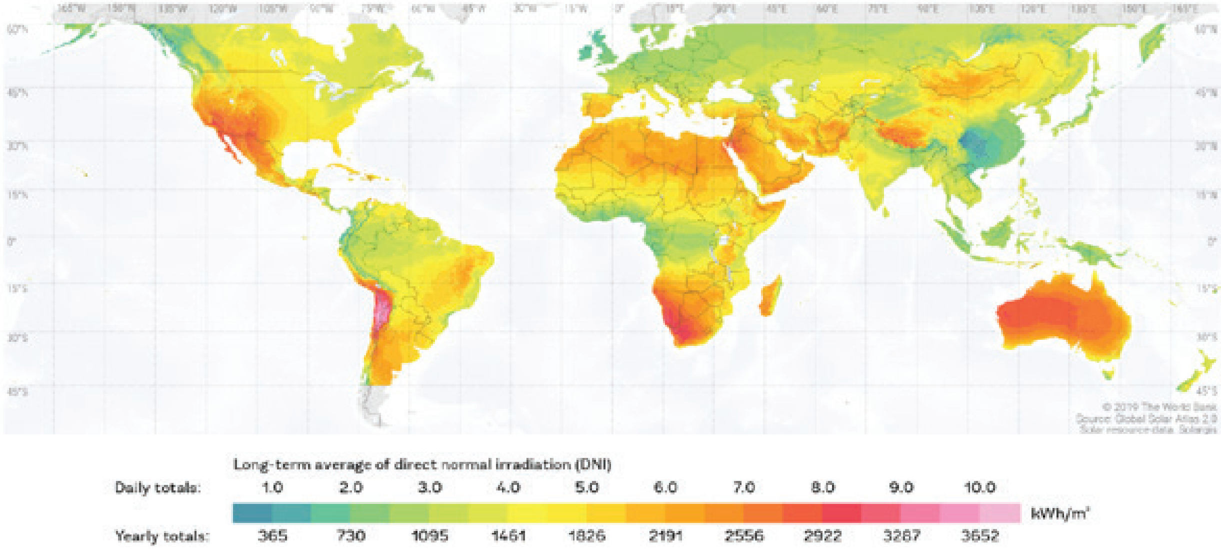


Figure 1.2 Parabolic trough collectors (left) and CSP tower (right)

Sources: Cuadros Fernández 2017; ACWA Power 2018.
Note: CSP = concentrating solar power.

FIGURE 1.3 **World map of direct normal irradiation (DNI)**



Source: Global Solar Atlas (ESMAP 2019).
Note: kWh/m^2 = kilowatt-hour per square meter.

represent a very small fraction of current installed capacity. (See Annex C. CSP Plants in Operation and Under Construction).

The primary driver of a CSP plant's performance is the level of direct normal irradiance (DNI), or direct sunlight, available at a given site. To be economic, developers typically require an annual DNI threshold of between 1,900 and 2,100 kilowatt-hours per square meter (kWh/m2).

Sites with suitable DNI for CSP are found in arid and semi-arid areas with reliably clear skies and low aerosol optical depths, typically at subtropical latitudes 15° to 40° north or south (figure 1.3). Sites with these characteristics can be found in:

- Australia
- Chile and Peru
- Middle East and North Africa (MENA)
- Northwestern India
- Southern Africa
- Southwestern United States and northern Mexico
- Western China

CSP plants today are typically coupled with thermal energy storage, as this reduces the cost of electricity and provides increased generation flexibility. Storage is achieved by using thermal oil or molten salt heated by the solar field and stored in tanks for hours or even days. If the solar field and storage capacity are sufficiently large, operators may dispatch electricity generated by the plant up to 24 hours per day.

More details on CSP technology are presented in annex A.

1.2 The value of CSP

CSP offers a diverse array of services and benefits that complement other generation options to meet growing demand for affordable, secure, and clean power while offering opportunities for domestic industrial and social development.

As a renewable energy technology, CSP is also an essential component of the transition to an energy system that is less damaging to the environment and health of the population, and that provides greater energy security. Generating electricity with CSP uses a local, free energy source: the sun. In addition, using sunlight instead of depending on purchased fuel can significantly reduce the fiscal pressures on countries that rely on imported fossil fuels, while improving their balance of payments. This can help to improve access to financing and reduce the overall system costs of all locally generated power, by reducing the uncertainty of future generation costs. CSP with thermal energy storage can increase the security of an energy system by operating flexibly and for longer load hours than solar photovoltaics. Dry-cooled CSP plants also use relatively little water, especially compared with wet-cooled nuclear, coal, and natural gas facilities (NREL 2015), reducing water-stress in arid areas.

The following sections elaborate on the key characteristics of CSP.

CSP is a flexible source of renewable power that enhances grid reliability

CSP with energy storage is a flexible renewable resource that can quickly ramp up and down in response to demand and the needs of the grid operator.

The rise of wind and solar PV has highlighted the need for renewable assets that can assist the flexible operation of power systems to ensure the reliability of electricity supply and the value premium these flexible assets can command. This is because wind and solar PV are variable, which means that their output fluctuates depending on the availability of sunshine and wind, respectively. PV output, for example, tends to peak at around midday, when solar radiation reaches its highest point, and then falls steadily over the course of the day until it reaches zero at nightfall. Additionally, as the share of variable renewable energy rises the need to balance hourly fluctuations in their output also becomes more important.

The fluctuations in output from variable renewables require careful management and, at a high rate of penetration, could compromise grid reliability, if not properly planned for, potentially leading to brownouts and blackouts.

CSP with thermal energy storage offers a solution by allowing plant operators to store solar power and then, upon receiving instructions from the grid operator, dispatch electricity at short notice to complement fluctuations in output from variable renewables. The most evident example of this is when PV output falls in the late afternoon and CSP with thermal energy storage deploys stored energy to meet demand. But CSP can also do the opposite. As PV output peaks, CSP can stop evacuating electricity while storing the energy in the form of heat, which can then be deployed whenever it is needed, even at night. In this respect, CSP and solar PV are complementary.

Countries seeking affordable clean energy to replace fossil fuels would benefit from deploying a combination of low-cost variable renewable sources, such as wind and solar PV, alongside dispatchable clean energy sources, such as CSP, biomass, and hydro, and flexible auxiliary assets like electrochemical storage (batteries) and demand-side management.

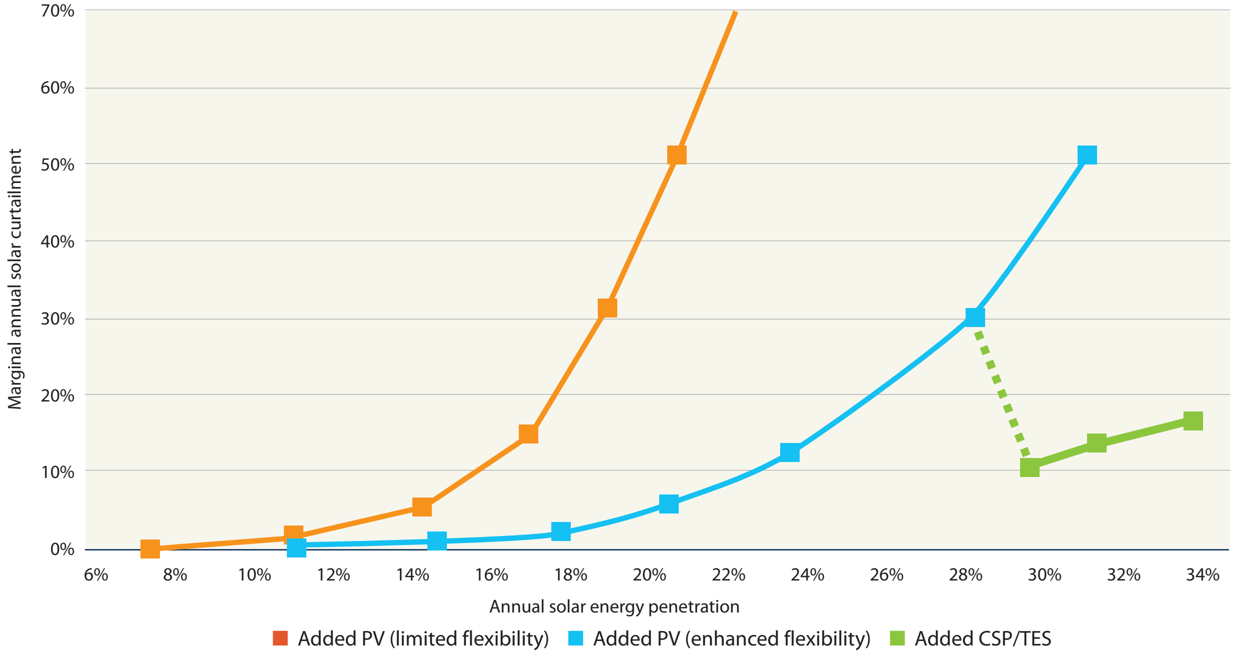
CSP enables grids to incorporate a larger share of variable renewable energy and reduces curtailment

Where the penetration of variable renewables is high, and in the absence of flexible generation assets or energy storage systems, a lot of variable renewable energy output could go to waste. This is known as curtailment. CSP with thermal energy storage helps reduce the curtailment of variable renewables and, in doing so, enables the grid to incorporate more renewables.

Reducing curtailment is particularly important for the delivery of affordable clean energy in the MENA region. Recent bids for large-scale PV projects in MENA have shown that prices between and $0.02/kWh and $0.03/kWh are achievable in a wide range of contexts in the coming years, suggesting that PV is the cheapest way to generate electricity in this part of the world. However, simply adding more PV without taking any other measures would, eventually, lead to high levels of curtailment.

As shown by a study carried out in California (Denholm, Clark, and O'Connell 2016), simply adding PV capacity without mitigating variability leads to high levels of marginal curtailment, making each additional unit of PV effectively more expensive because less and less additional output can be used. The same study shows that adding CSP with thermal energy storage to the generation mix enables greater utilization of PV by reducing curtailment. Figure 1.4 shows the level of solar PV production that would need to be curtailed under three conditions of system flexibility, as solar energy penetration increases.

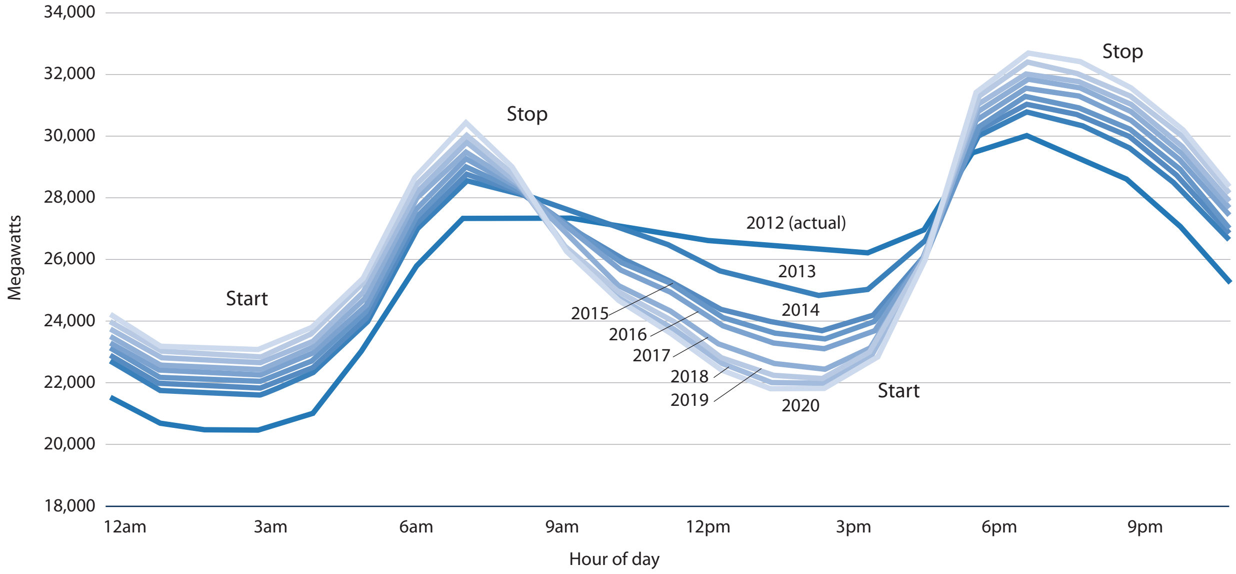
FIGURE 1.4 **Marginal curtailment in California due to overgeneration as the penetration of solar photovoltaics increases**



Source: Denholm, Clark, and O'Connell 2016.
Note: CSP = concentrating solar power; PV = photovoltaic; TES = thermal energy storage.

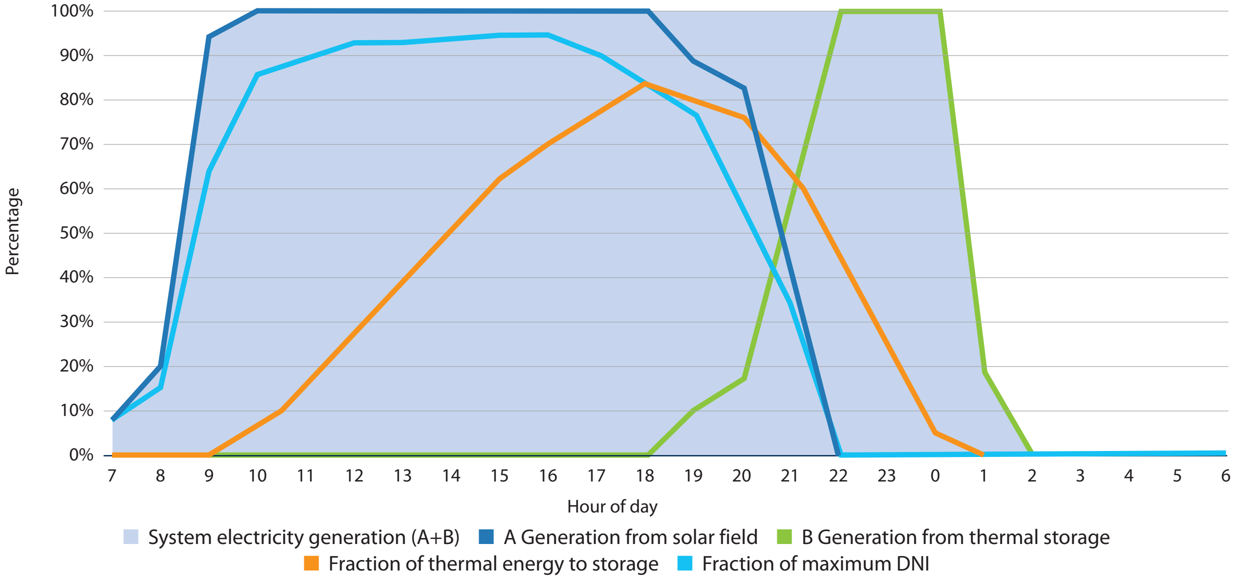
Where solar PV penetration reaches around 20 percent, almost 50 percent of marginal solar PV generation needs to be curtailed in an inflexible power system. Enhancing system flexibility with a variety of measures enables the grid to absorb much more PV generation, keeping marginal PV curtailment below 10 percent at a PV penetration of 20 percent (see the red line in figure 1.4). Even with enhanced measures, when PV meets 28.4 percent of total demand, marginal curtailment rises to 30 percent. In these circumstances, deploying one CSP unit, with six hours of thermal energy storage and enough capacity to supply 1 percent of additional solar generation, would reduce marginal curtailment from 30 percent to 10 percent (Denholm, Clark, and O'Connell 2016).

FIGURE 1.5 **Peak times of daily net electricity load (after solar PV): California's "duck curve"**



Source: CAISO 2016.

FIGURE 1.6 **The energy flows underpinning sustained solar electricity generation throughout the day**



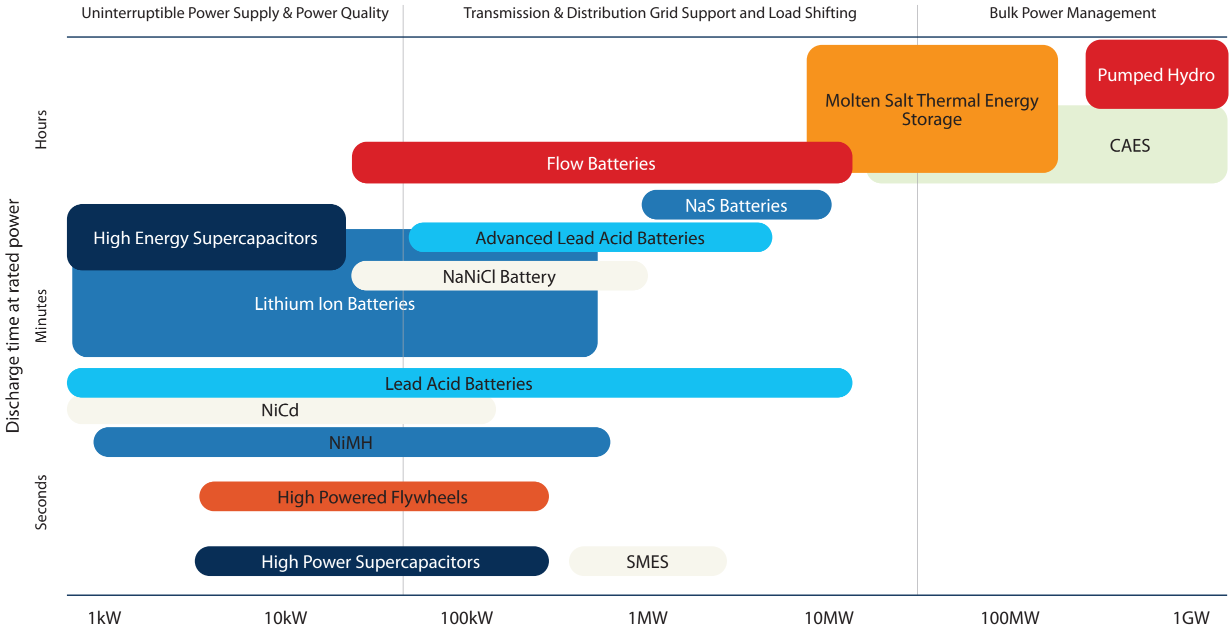
Source: Based on Protermosolar (2018). Note: DNI = Direct normal irradiation.

This combination of solar PV and CSP with thermal energy storage also reduces the consumption of fossil fuels such as natural gas in peaking plants by providing a comparable, but renewable, dispatchable power source over the same hourly peaks. Thus, CSP can reduce the need for support from fossil-fuel generation and enable the further deployment of solar PV.

CSP helps systems adapt to changing electricity demand profiles

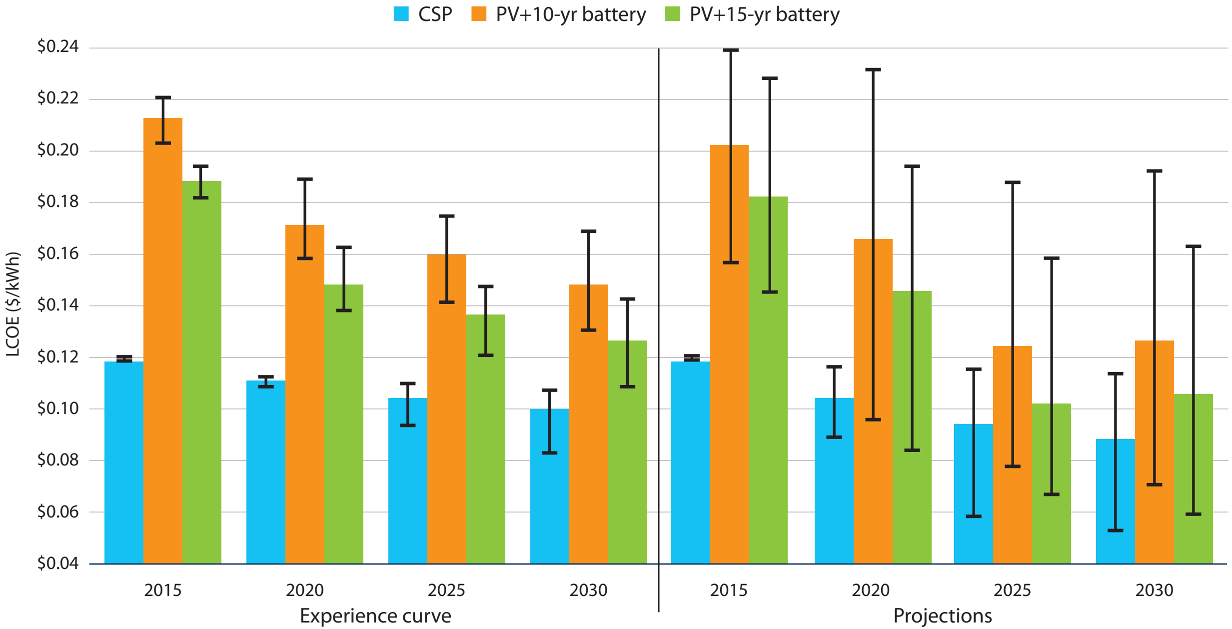
In most parts of the world, electricity load profiles are changing, especially as demand for electricity continues to increase. This change is most prominent in the evening hours, when peaks are becoming sharper. This means that as solar PV production starts to decline in the early evening, new capacity

FIGURE 1.7 **Key characteristics of available energy storage technologies**



Source: Adapted from DOE/EPRI (2013).
Note: CAES = compressed air energy storage; GW = gigawatt; kW = kilowatt; MW = megawatt; NaNiCl = sodium nickel chloride; NaS = sodium sulfur; NiMH = nickel metal hydride; NiCd = nickel cadmium; SMES = superconducting magnetic energy storage.

FIGURE 1.8 **A comparison of the levelized cost of electricity: CSP versus PV (both with nine hours of storage), 2015–30**



Source: NREL and US DOE 2016.
Note: $/kWh = US dollars per kilowatt-hour; CSP = concentrating solar power; LCOE = levelized cost of electricity; PV = photovoltaic.
Whilst it is true that cost reduction for solar PV has been steeper than anticipated in this study, the broad conclusion, that CSP retains a cost advantage for long duration storage, remains valid.

needs to be brought online to compensate for lower solar PV output. The well-known case of California is shown in figure 1.5: the projected midday load on the grid is falling over time, in part owing to the deployment of rooftop PV, while morning and evening peaks are rising.

Sharper morning and evening peaks leave progressively shorter ramping times for generation to meet demand. This strains the grid and can lead to significant additional costs. In this situation, CSP with thermal storage is particularly valuable, as it can ramp quickly, shifting generation from the hours when the sun is shining to the hours when it is most needed, covering early morning and evening peaks in demand, and supporting higher shares of solar energy in the grid (figure 1.6).

1.2.1 CSP with thermal energy storage compared with batteries and other storage technologies

Thermal energy storage is not the only storage technology available today (figure 1.7). All available options are expected to contribute in adding flexibility to the energy system and enabling a larger share of renewable energy into the grid at the lowest possible cost.

Thermal energy storage is best suited to storing energy in bulk, from tens to hundreds of megawatts, and for many hours, even days. Other technologies, such as the popular lithium-ion batteries, are best deployed to store relatively less energy and for shorter periods of time.

Simulations of a 100 MW CSP plant with nine hours of thermal energy storage compared to a 100 MW PV plant with a Li-ion battery energy storage system (BESS) with equivalent storage capacity, show that at this scale CSP is more cost competitive under most conditions and would remain so until 2030 (figure 1.8).

CSP can contribute to the integration of regional electricity markets

Integrating regional electricity markets offers multiple benefits for grid operators and utilities. Coupling electricity markets provides efficiency gains to both consumers and suppliers, since it reduces the need for additional generation capacity with low utilization rates. CSP with thermal energy storage, as a source of flexibility, can reduce overall electricity costs while allowing burden-sharing to manage fluctuations in power output levels and demand spikes. This is especially useful for grids that are

BOX 1.1

Country plans to reduce greenhouse gas emissions

Under the United Nations Framework Convention on Climate Change (UNFCCC) to reduce greenhouse gas (GHG emissions, signatory countries of the Paris Agreement agreed to publish their "intended nationally determined contributions" in the leadup to the United Nations Climate Change Conference held in Paris, France, in December 2015.

According to Article 4 paragraph 2 of the agreement:

"Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions."

Major emitters include China, which targeted a 60–65 percent reduction in GHG emissions per unit of gross domestic product by 2030; the United States, which targeted a 26–28 percent reduction by 2025; and the European Union, which targeted a 40 percent reduction of 1990 levels by 2030. India committed to a target of 33–35 percent per unit of gross domestic product as long as developed countries make financing available for this purpose.

seeing rising penetration rates of variable renewable energy generation.

CSP's grid services can make an important contribution to the integration of regional electricity markets. This has already been recognized internationally, in the Roadmap for Sustainable Electricity Trade that was signed by the governments of France, Germany, Morocco, Portugal, and Spain during the 22nd Conference of Parties in Marrakesh, Morocco, convened in 2016. The roadmap aims to analyze the benefits of increased renewable electricity exchanges resulting from electricity market integration; identify investments, processes, and procedures to enable sustainable electricity trade between the five signatories; and formulate an implementation pathway. With high utilization rates of capacity, and the technical possibility of shifting output to meet changing load profiles and cut down on curtailment, CSP offers significant opportunities for market integration.

CSP can offer similar benefits in the MENA region by complementing grid supply in different interconnected countries in the region and beyond. In the future, with even greater interconnection, CSP from the MENA region could provide electricity for Europe.

CSP supports the achievement of environmental goals

As a renewable energy technology, CSP can bring multiple environmental benefits. Fossil fuels provided around 73% of total global electricity generation in 2019 (REN21, 2020), with coal representing the largest share, followed by gas and, finally, oil. The extraction and combustion of fossil fuels release various types of air pollutants, with local impacts such as damage to the health of the population and to the flora and fauna. While the use of coal for electricity generation in the MENA region is not as high as in the rest of the world, oil and gas usage is significant. Oil-fired electricity generation is especially damaging, as it releases significant air pollutants into the environment that could be reduced by using renewable energy technologies such as CSP instead.

An increase in the use of CSP technologies can help countries not only reduce local air pollution from the use of fossil fuels, but also contribute toward realizing their goals for reducing GHG emissions (box 1.1). The recent pledges made by some MENA countries are especially important because the region has some of the highest per capita emissions rates in the world, and demand for electricity is growing fast. Prompt action is required to stop the exponential growth of negative impacts. However, to reap the full benefits of CSP in the region, efforts should focus on reducing costs and ensuring that grids are sufficiently modern to accommodate the full stack of grid services that CSP can offer, including flexible power output, peak shifting, and energy storage.

CSP supports domestic industrial and socioeconomic development

According to the latest statistics from the International Renewable Energy Agency (IRENA 2018b), around 34,000 people are employed in the CSP sector globally. A study on jobs supported

FIGURE 1.9 **La Africana parabolic trough plant in Córdoba, Spain**

Source: Cuadros Fernández 2018.

by CSP projects during the construction phase, estimates that these projects create up to 18 job-years per MW installed (Meyer et al, 2014).

The arrival of a large electricity infrastructure project can bring significant benefits to local labor markets. This is especially notable in the case of CSP. The scale and complexity of a CSP project—along with variables related to local economic development, labor market conditions, governance structures, and social norms—will influence how much local labor can be employed, as well as any spillover effects. Typically, short-term demand for local labor for construction, management, and coordination increases. Additionally, the ongoing operations and maintenance activities of a CSP plant will support local jobs and businesses directly and indirectly over the life of the project.

Indirectly, increased demand for services associated with a CSP project may generate jobs for new or existing firms as well as self-employed individuals. In cases where connectivity to communities outside the project-affected area expands, new job opportunities may benefit workers from either the project-affected area or those from other towns and areas, depending on what specific skills are required.

2 GLOBAL MARKET AND OUTLOOK FOR CONCENTRATING SOLAR POWER

2.1 A brief history of CSP

Although the first modern commercial CSP plants were built in the 1980s, CSP has a long history going back to the late 1800s, when it was used to power the first solar steam engine. Given the excellent solar resources in the Middle East and North Africa (MENA) region, it is not surprising to learn that the first parabolic trough systems were installed there in 1912, near Cairo, Egypt. The system was designed to generate steam for a pump, delivering 2,000 cubic meters per hour (m3/h) of water for irrigation. Notably, even in 1912 CSP plant technology was regionally competitive with coal-fired installations for generating steam (Müller-Steinhagen and Trieb 2004).

Despite its origins in the MENA region, present-day CSP technology can be traced to research in the United States conducted under the Nixon administration. When the United States became a net energy importer in 1971, President Richard M. Nixon established 16 research panels to examine the potential for new energy technologies to return the United States to a situation of energy surplus. In 1972 the Federal Council for Science and Technology concluded that solar thermal energy generation technologies could provide 20 percent of the country's energy needs by 2020. Given the prohibitively high costs of solar photovoltaic (PV) technology at the time, it was assumed that all solar energy would be thermal.

The US federal research budget for CSP tripled after the 1973 oil crisis. It was this research—combined with reforms connected with the Public Utility Regulatory Policies Act (PURPA) and a series of incentives offered by policy makers in the state of California—that led to the construction of the first commercial CSP plant. But as oil prices declined in the 1980s and Reagan-era budget cuts reduced CSP research and development (R&D), the sector stagnated until the early 2000s. At this time, a second generation of commercial CSP plants was built, predominantly in the United States and Spain. In the United States, renewed interest was driven by a combination of the Investment Tax Credit (ITC), PURPA reforms, and Renewable Portfolio Standards (RPS). In Spain, a generous government-backed feed-in tariff encouraged developers to start CSP projects, eventually making Spain the global leader in deployed CSP capacity. New CSP deployments stalled, however, when Spain scaled back and amended the tariff.

2.2 Status of markets

There are around 6 gigawatts (GW) of operating CSP plants worldwide, which are concentrated in Spain (2.3 GW), the United States (1.6 GW), Morocco (0.53 GW), China (0.5 GW), and South Africa (0.5 GW). The following subsections provide an overview of the markets where CSP projects are being planned or built.

CSP in Middle Eastern and North African countries

In the MENA region, countries such as Morocco and the United Arab Emirates have embraced large-scale CSP, and many others are actively considering adding CSP with thermal energy storage to their grids.

Public-private partnerships (PPPs) have been the model of choice for MENA, where many governments have shown that they consider CSP with thermal energy storage as an integral part of their long-term generation capacity. PPPs combine the efficiencies of the private sector with the lower capital costs of the public sector, making the economics of CSP plants more attractive. In this region, support from multilateral institutions has been key in the development of new plant capacity.

With many suitable sites with direct normal irradiation (DNI) values between 2,000 and 3,000 kilowatt-hours per square meter (kWh/m2) a year, the MENA region has one of the highest levels of DNI in the world. Northwestern Saudi Arabia and the Sahara report the highest DNI levels within the region.

The region could benefit in various ways from further CSP deployments. The MENA region is marked by stark differences in fossil fuel resources Only a few of the region's countries have the fossil-fuel resources needed to meet demand for more energy, with most relying on imports. However, the region is, almost universally, rich in solar resources and CSP can make a country's energy supply more secure and play a crucial role in integrating variable renewable technologies—such as solar PV and wind—into national or even regional power grids.

Table 2.1 provides an overview of the CSP plants operating in the MENA region, which have a total installed capacity of 770 megawatts (MW). Most plants involve parabolic trough technology; since

TABLE 2.1 CSP plants operating in MENA

Title	Country	Developers	Engineering, procurement, and construction	Gross capacity (MW)	Technology	Storage hours	Year operations started	Tariff type	Rate
Hassi-R'mel ISCC	Algeria	Abener	Abener	20 (155 CC)	Parabolic trough	0	2011	PPA	N/A
Kuraymat ISCC	Egypt	New and Renewable Energy Authority	Orascom	20 (140 CC)	Parabolic trough	0	2011	N/A	N/A
Ain-Beni-Mathar ISCC	Morocco	Airlight Energy	Abener	20 (470 CC)	Parabolic trough	0	2011	PPA (25 years)	N/A
Noor I	Morocco	ACWA Power Aries TSK	Acciona Sener TSK	160	Parabolic trough	3	December 2015	PPA (25 years) Tariff date: November 19, 2012	$0.19/kWh
Noor II	Morocco	ACWA Power	Sener–SEPCOIII	200	Parabolic trough	7	2018	PPA (25 years)	$0.15/kWh
Noor III	Morocco	ACWA Power	Sener–SEPCO III	150	Tower	8	2019	PPA	$0.16/kWh
Waad Al Shamal Power Plant ISCC	Saudi Arabia	Saudi Electricity Company	General Electric	50 (1,390 CC)	Parabolic trough	0	2019	N/A	N/A
Shagaya	Kuwait	Kuwait Institute for Scientific Research (KISR)	TSK	50	Parabolic trough	9	2019	N/A	$0.16/kWh
Shams 1	United Arab Emirates	Masdar Total Abengoa Solar	Abener Teyma	100	Parabolic trough	0	2013	PPA	N/A

Source: NREL Solar PACES, 2019.
Note: CC = combined cycle; CSP = concentrating solar power; ISCC = integrated solar combined cycle; MENA = Middle East and North Africa; MW = megawatt; N/A = not applicable; PPA = power purchase agreement; $/kWh = US dollars per kilowatt-hour.

TABLE 2.2 Pipeline of CSP projects in MENA

Title	Country	Developers	Engineering, procurement, and construction	Gross capacity (MW)	Technology	Storage hours	Year of planned operational start	Tariff type
DEWA CSP Trough Project	United Arab Emirates	ACWA Power	Shanghai Electric	600	Parabolic trough	12.5	2021	PPA (35 years)
DEWA CSP Tower Project	United Arab Emirates	ACWA Power	Shanghai Electric	100	Tower	15	2021	PPA (35 years)
Duba 1 ISCC	Saudi Arabia	Saudi Electricity Company	Initec Energia	43 (605)	Parabolic trough	0	N/A	N/A
Midelt (PV+CSP)	Morocco	EDF Renewables	Not disclosed	200 (800) *	Not disclosed	Not disclosed	Not disclosed	PPA

Source: NREL SolarPACES 2019.
Note: CSP = concentrating solar power; ISCC = integrated solar combined cycle; MENA = Middle East and North Africa; MW = megawatt; N/A = not applicable; PPA = power purchase agreement; PV = photovoltaic; $/kWh = US dollars per kilowatt-hour.
* The exact share of CSP and PV in the Midelt project is still undisclosed

2011, the main business model for installed capacity has been power purchase agreements (PPAs). Table 2.2 provides the list of plants in the pipeline for the region, with total capacity of around 550 MW.

In the MENA region, two countries stand out for being home to large-scale CSP projects, Morocco and the United Arab Emirates.

Morocco

Morocco has been one of the most active CSP markets in the last five years and is, arguably, the North African country that has pursued its renewable energy targets with the most energy and success. Morocco is on track to meet its target of producing 42 percent of electricity from renewables by 2020 and is continuing to develop capacity to meet its 2030 targets of producing 52 percent of its electricity from renewable sources, with an additional capacity of 6 GW (MASEN 2020).

Morocco is home to the largest operating CSP complex in the world: Noor Ouarzazate, which comprises 510 MW of CSP and a 72 MW PV plant. Subsequently, the Noor Midelt 1 project (800 MW, CSP-PV hybrid) was awarded, and will be the first project in which output from both PV and CSP will be stored as heat in molten salt tanks (Kramer 2020). The Midelt solar complex will have further phases, so it is possible that there will be additional CSP plants in Morocco.

United Arab Emirates

The United Arab Emirates has set itself a target to deploy 2.7 GW of clean energy by 2021 as part of its commitment to global efforts to combat climate

BOX 2.1

The DEWA IV 950 MW CSP/PV solar hybrid project

The Dubai Electricity and Water Authority (DEWA) IV 950 megawatt (MW) hybrid project consists of 700 MW of concentrating solar power (CSP) and 250 MW of photovoltaic (PV). The CSP component comprises four plants: a 100 MW tower plant with 15 hours of thermal energy storage and three 200 MW parabolic trough plants with 12.5 hours of thermal energy storage each.

This project holds the record for the lowest-priced CSP plant at $0.073 per kilowatt-hour (kWh) under a 35-year power purchase agreement (PPA), showing how far CSP costs have come down. In contrast, the 50 MW Bokpoort project came online in South Africa in 2016 at $0.21/kWh. Even though these projects are very different, and despite the United Arab Emirates' excellent financing conditions, the cost difference reflects many trends seen in the CSP industry at large. First, it shows that developers have applied the knowledge garnered in the development and construction of previous projects. Second, it demonstrates that larger projects bring economies of scale into play. Third, it highlights the importance of long-duration thermal energy storage, hybridization, and longer PPAs in reducing costs per kilowatt-hour.

This project is designed to provide clean energy 24/7. The 250 MW PV plant caters to demand during the daylight hours whereas the CSP with thermal energy storage plants serve demand during the evening and night. This suits the United Arab Emirates' load profile, which has a pronounced evening peak.

The DEWA IV 950 CSP/PV hybrid is the largest renewable energy project in terms of investment, at $4.3 billion, and will be the largest CSP complex in the world in terms of capacity.

Official name	Noor Energy 1—DEWA 700 MW CSP and 250 MW PV Hybrid IPP Phase IV
Location	Mohammed Bin Rashid Al Maktoum Solar Park, Dubai
Total capacity	950 megawatts electric (MWe)
Breakdown	Parabolic trough 3 x 200 MW; 12.5 hours thermal energy storage Tower 1 x 100 MW; 15 hours thermal energy storage PV 1 x 250 MWac
Cooling type	Air-cooled condensers
Plant commercial operations date (COD)	December 22, 2022
PPA duration	35 years from plant COD
PPA ($/kWh)	$0.073
Total investment costs	$4.3 billion
Lenders	Agricultural Bank of China Bank of China China Everbright Bank China Minsheng Banking Corporation Commercial Bank International Commercial Bank of Dubai Industrial and Commercial Bank of China Natixis Bank Standard Chartered Bank Union National Bank
Ownership	DEWA (51%); ACWA Power (24.99%); Silk Road Fund (24.01%)
Scope	Develop, build, own, operate (BOO)
Developer	ACWA
EPC contractor	Shanghai Electric
O&M contractor	Nomac
Off-taker	Dubai Electricity and Water Authority (DEWA)

Source: DEWA 2017.

change. It currently generates 127 terawatt-hours (TWh) of electricity per year, 99 percent of which is produced using natural gas. The United Arab Emirates' per capita carbon dioxide (CO_2) emissions are nearly identical to those of member countries of the Organisation for Economic Co-operation and Development.

The drive, therefore, to use a range of clean energy technologies—including solar, wind, and waste-to-energy technologies—will assist the United Arab Emirates in its endeavors. Further, the country will benefit from the added CSP capacity, which will displace CO_2-emitting sources and save natural gas for other uses.

The Mohammed bin Rashid Al Maktoum Solar Park (phase 4) was awarded by the Dubai Electricity and Water Authority (DEWA) to ACWA Power and Shanghai Electric to build a 950 MW CSP-PV hybrid complex that will supply electricity at $0.073/kWh—the lowest price awarded to a CSP plant to date (box 2.1).

Other countries in the MENA region

Other MENA countries that have expressed an interest in CSP include the following:

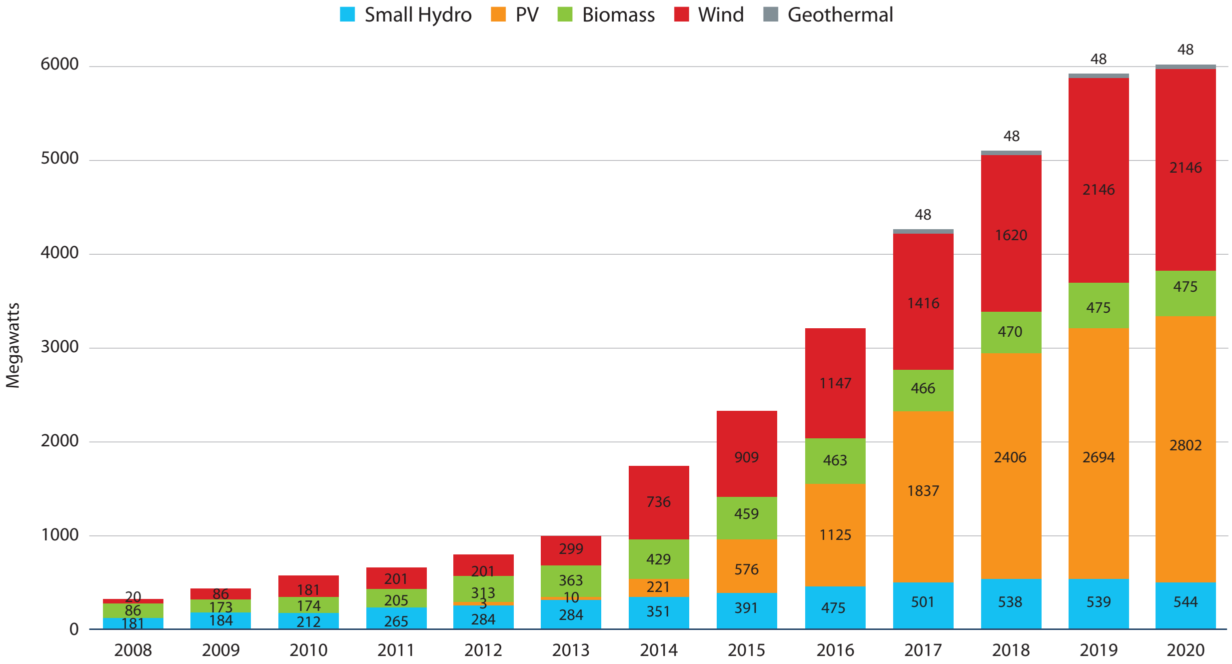
- Jordan has been working with the World Bank to establish the suitability of a site for a CSP plant, and to outline the optimal levelized cost of electricity (LCOE) and basic engineering of the plant.
- Lebanon launched a tender for consultancy services for developing a CSP plant of at least 50 MW in Hermel.
- In Kuwait, at least 200 MW are expected to be tendered for Phase 3 of the Shagaya Renewable Energy complex.
- The government of Saudi Arabia has set a target of 2.7 GW of CSP by 2030 as part of a 60 GW renewable energy build-up.
- Tunisia has been working with the World Bank to identify suitable sites and incorporate CSP with thermal energy storage for added grid flexibility and robustness.

CSP in select countries outside MENA

Chile

Chile is poised to be one of the most active CSP markets given its ambitious renewable energy targets, fast deployment of PV and wind (figure 2.1), and high levels of DNI in the Atacama region.
The Chilean government has set a number of ambitious targets. First, Chile intends to supply 70

Figure 2.1 Cumulative renewable energy capacity in Chile between January 2008 and February 2020



Source: ACERA 2020.
Note: PV = photovoltaic.

percent of electricity consumption from renewable sources by 2050. Second, the government has announced a complete phase-out of all coal plants by 2040, which is no mean feat given that coal capacity stands at 4.8 GW and comprises 20 percent of the generation fleet. Finally, the government has set a carbon neutrality target by 2050, or in other words, in 30 years Chile wants to be able to absorb as much CO_2 as it generates.

Observers are keenly observing the Cerro Dominador Project, Chile's first large-scale CSP project that includes a 110 MW CSP tower with 17.5 hours of thermal storage and a 100 MW PV plant. In April 2020, the project was 90 percent built, according to Cerro Dominador's CEO (Chamberlain 2020).

There are at least six additional Chilean projects, which add up to 610 MW, that have obtained the requisite permits to start construction (Revista Electricidad 2019).

China

The National Energy Administration kick-started the Chinese CSP market in 2016 by launching the first batch of CSP pilot projects, in which 20 CSP projects with a total capacity of 1.3 GW were selected to obtain a tariff of ¥1.15 ($0.17) per kilowatt-hour should they succeed in connecting to the grid by the end of 2018.

As of May 2020, seven of these projects, accounting for 450 MW, were operating (four tower, 250 MW;, two parabolic trough, 150 MW; and one Fresnel, 50 MW). Additionally, a 50 MW tower project that is not part of the first batch is also operational (CSP Focus 2020).

A further eight CSP projects (564 MW) are in progress, albeit at different rates. Finally, four projects (335 MW) have been cancelled.

The aim of the first batch of CSP pilot projects in China is to foster local know-how and operational experience as well as innovation (table 2.3). Many expect a second phase, even more focused on innovation, to be announced after the 14th Five Year Plan sets China's strategy in relation to energy policy. This crucial policy document is expected in early 2021 (Zhe 2019).

South Africa

In October 2019, South Africa published the Integrated Resource Plan 2019 (IRP 2019), a document that sets out government plans for energy infrastructure. According to this plan, 6,000 MW of

TABLE 2.3 CSP projects in China

Project name	Technology	Capacity (MWe)	Storage hours	Status
Luneng Haixi	Tower	50	12	Operational
Beijing Shouhang IHW Dunhuang	Tower	100	11	Operational
CPECC Hami Tower	Tower	50	8	Operational
Power China Gonghe	Tower	50	6	Operational
Qinghai SUPCON Solar Delingha	Tower	50	6	Operational
Lanzhou Dacheng Dunhuang Molten Salt Fresnel	Fresnel	50	13	Operational
CGN Solar Delingha PT	Trough	50	9	Operational
CSNP Royal Tech Urat	Trough	100	10	Operational
Royal Tech Yumendongzhen	Trough	50	9	Under Construction
Yumen Xinneng	Tower	50	6	Under Construction
CECIC Gansu Wuwei Solar Power Gulang	Trough	100	7	Development
China Three Gorges New Energy Jinta	Tower	100	8	Development
Dahua Shangyi	Tower	50	15	Development
Rayspower Yumen	Trough	50	7	Development
Shenzhen Jinfan Akesai	Trough	50	15	Development
Zhongyang Zhangjiakou	Trough	64	16	Development

Source: CSP Focus 2020.
Note: CSP = concentrating solar power; MWe = megawatts electric.

new PV and 14,400 MW of new wind capacity will be commissioned by 2030.

Regarding CSP, the plan contemplates that there will be up to 600 MW of CSP by 2030 (table 2.4).

There are currently 500 MW of CSP in operation in South Africa (table 2.5). The Redstone CSP project (100 MW) is still under construction; its expected commercial operation date is set for Q1 2022.

Spain

Spain has the largest fleet of operating CSP plants in the world (2.3 GW), and a recent government plan has announced 5,000 MW of additional CSP capacity by 2030, as part of a plan to expand renewable energy to cover 74 percent of electricity demand by 2030 (Miteco 2020a). For this plan to become a reality, it still has to be approved by a legislative process that started on May 19, 2020 (Miteco 2020b).

Initially, a feed-in tariff scheme under Royal Decree 436/2004 and Royal Decree 661/2007 drove the Spanish market for CSP, setting a target of 500 MW by 2010 (Frisari and Feás 2014). The Royal Decree 661/2007 then limited the size of all renewable plants to 50 MW to promote geographic dispersion and to provide opportunities for more companies to enter the market. In 2009, Royal Decree 6/2009 set up a preregistry for CSP power plants that fulfilled certain criteria, resulting in the installation of 2.3 GW. But in 2014, Royal Decree 413/2014 modified the feed-in tariff system, lowering incentives for existing CSP plants; the retroactive nature of the decree caused controversy in the sector and discouraged new projects. Although the feed-in tariff model facilitated the rapid deployment of CSP plants, aiding Spain's development and industry, the level it was set at to achieve this rapid growth did not produce cost reductions or encourage the development of new technologies.

With Spain being one of the worst hit countries in Europe, the Covid-19 crisis has cast a shadow on government plans to expand renewable energy. It remains to be seen whether renewable energy investments could be leveraged to kick-start economic recovery.

United States

In the United States, policy support at the state and federal levels has driven CSP growth since the 1980s. State-driven renewable portfolio standards, combined with a federal investment tax credit of 30 percent plus federal loan guarantees, allowed developers to kick-start the construction of CSP plants throughout the country's southwestern region (Gallego and others 2012).

TABLE 2.4 Summary of South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP)

	Bidding window 1	Bidding window 2	Bidding window 3	Bidding window 3.5	Bidding window 4	Expedited
Number of preferred bidders	28	19	17	2	26	Bid November 2015
Allocated capacity (MW)	1,425	1,040	1,456	200	2,205	1,800 MW available
CSP capacity (MW)	150	50	200	200	0	450

Source: CSP Focus 2020.
Note: CSP = concentrating solar power; MWe = megawatts electric.

TABLE 2.5 CSP projects in South Africa

Project name	Technology	Capacity (MW)	Storage hours	Status	REIPPP bidding window
KaXu Solar One	Trough	100	2.50	Operational	1
Khi Solar One	Tower	50	2.00	Operational	1
Bokpoort	Trough	50	9.30	Operational	2
Redstone CSP Project	Tower	100	12.00	Under construction	3
Ilanga CSP 1	Trough	100	5.00	Operational	3
Kathu CSP	Trough	100	4.50	Operational	3
Xina Solar One	Trough	100	5.00	Operational	3

Note: CSP = concentrating solar power; MW = megawatt; REIPPP = Renewable Energy Independent Power Producer Procurement Programme.

One of the most noteworthy CSP plants is the Ivanpah 392 MW tower project. The largest operational CSP project in the world when it came online in 2014, this project has been operating well since then. In 2019, Ivanpah provided a total of 772,213 megawatt-hours (MWh) (net) for the state of California.

Other large-scale projects include Abengoa's Solana (280 MW) and Mojave Solar One (280 MW) parabolic trough plants and Next Era's Genesis (250 MW) parabolic trough plant (CEC 2020).

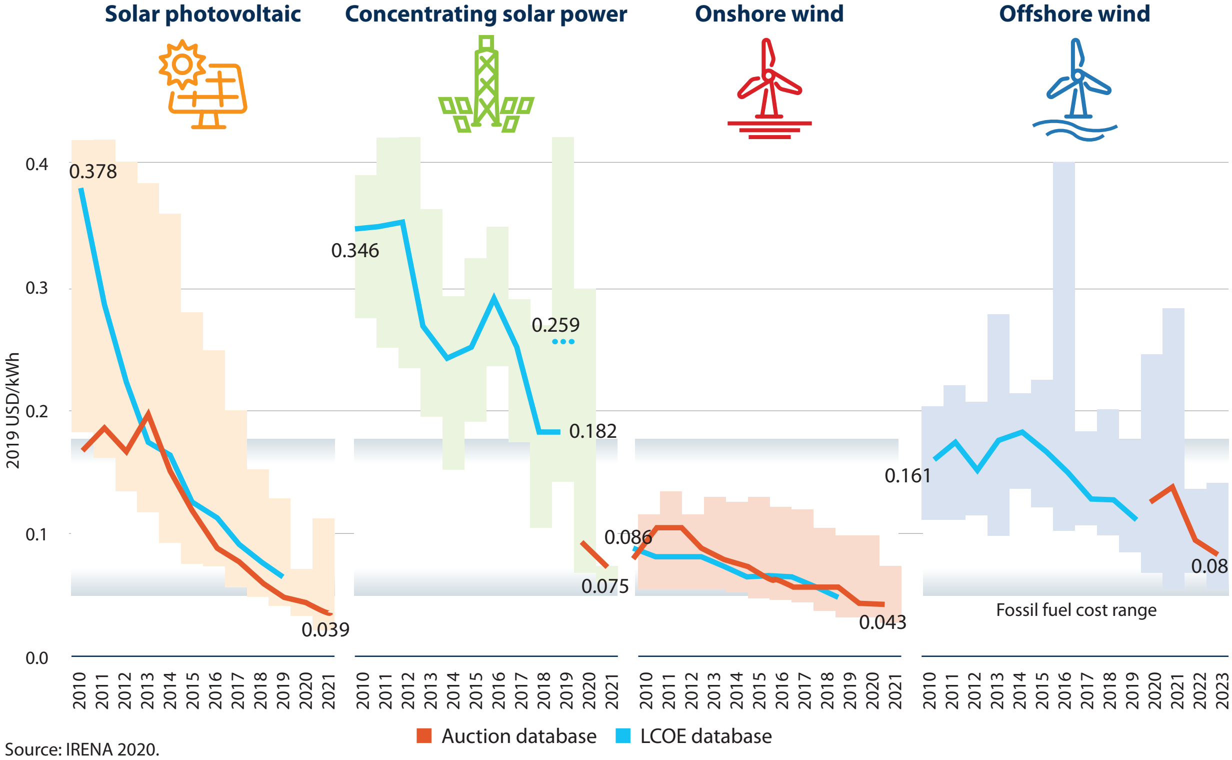
The United States saw robust deployments of CSP from 2012 to 2015, and then things ground to a halt due to a combination of factors including: plummeting PV and natural gas prices, uncertainty over the status of investment tax credits, underperformance of some CSP projects, and challenges in securing all requisite permits for construction. However, states such as Arizona, California, Nevada, and New Mexico have announced ambitious targets for deploying renewable energy and reducing GHG emissions. As more PV and wind are added to their grids, these states will need the kind of dispatchability that CSP with thermal energy storage provides.

The United States has also been actively involved in R&D efforts to lower the cost and improve the performance of CSP. In 2016, the US Department of Energy's Solar Energy Technologies Office launched the Sunshot Initiative 2030 program with the aim of reducing the cost to $0.05 for baseload CSP plants and $0.10 for peaking plants, without subsidies (US DOE 2016).

2.3 CSP market trends: Falling costs, increasing scale

The biggest trends in the CSP industry include falling prices, increasing plant sizes, the ubiquity of thermal energy storage in new plants, and the emergence of Chile, China, Morocco, and the United Arab Emirates

FIGURE 2.2 Global weighted average LCOE and auction/PPA prices for CSP, onshore and offshore wind, and solar



Source: IRENA 2020.

Note: The thick lines are the global weighted average LCOE, or auction values, by year. The gray bands, which vary by year, are the cost/price range for the 5th and 95th percentiles of projects. For the LCOE data, the real weighted average cost of capital is 7.5% for China and members of the Organisation for Economic Co-operation and Development, and 10% for the rest of the world. The band that crosses the entire chart represents the fossil-fuel-fired power generation cost range. For CSP, the dashed blue bar in 2019 shows the weighted average value including projects in Israel.

CSP = concentrating solar power; LCOE = levelized cost of electricity; PPA = power purchase agreement; USD/kWh = US dollars per kilowatt-hour.

as the new centers of CSP growth. In this section, we will examine each of these trends in turn.

PPAs indicate that CSP costs have fallen significantly in the past 10 years

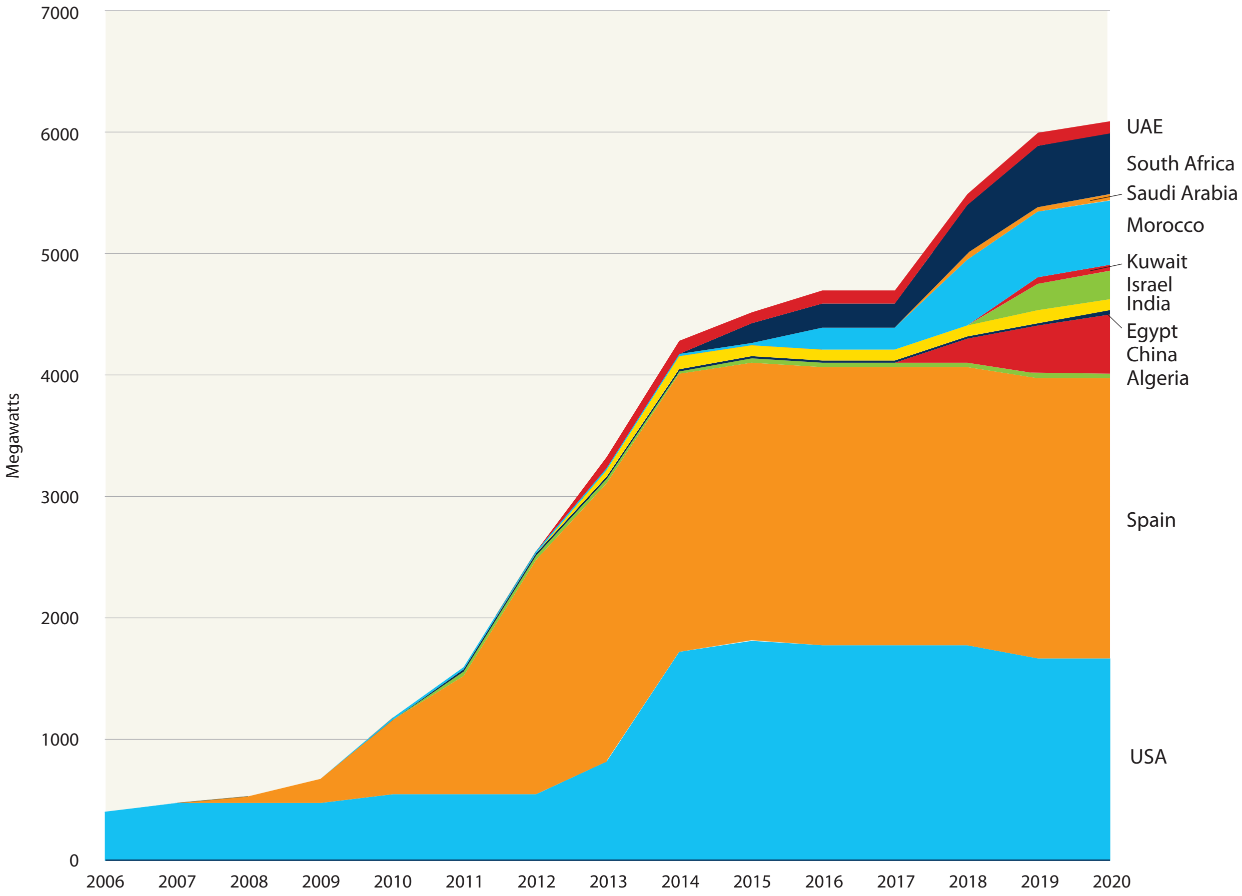
Electricity prices awarded to new CSP plants under power purchase agreements have declined significantly over the past decade. For the Nevada Solar One plant in the United States, the agreed-on power purchase price was around $0.30/kWh when it was first commissioned in 2007. Plants built in Spain between 2009 and 2012 received a feed-in-tariff of around $0.40/kWh[2]. By contrast, the PPA of Noor Ouarzazate III, which was awarded in 2015, was $0.16/kWh. More recently, the DEWA 950 MW CSP-PV hybrid complex plant in the United Arab Emirates was awarded a price, via PPA, of $0.073/kWh.

Given the trends observed since 2007, it is expected that the prices set in PPAs will continue to decline in the coming years, as further deployments improve economies of scale and enhance efficiencies in both the construction and operation of CSP plants (figure 2.2).

CSP plants are trending toward larger capacities

Commercial CSP plants are trending toward larger capacities. In Spain, plants built during the first wave of CSP projects between 2009 and 2012 were required by legislation to be 50 MW in size. By contrast, most recent CSP projects have been tendered as clusters of plants that are, individually, at least 100 MW in size. Such is the case with the Noor Ouarzazate Complex (510 MW CSP and 72 MW PV) in Morocco and DEWA 950 CSP-PV hybrid in Dubai (700 MW CSP). For CSP, larger sizes favor efficiency and are strongly linked to lower costs per unit of electricity.

Figure 2.3 Global cumulative installed CSP capacity, January 2006–May 2020



Source: NREL 2019.
Note: CSP = concentrating solar power; UAE = United Arab Emirates; USA = United States of America.

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[2] In Spain, CSP plants received a feed-in tariff of €0.27/kWh under the incentives scheme set out in Royal Decree 661/2007, issued on May 25, 2007. The conversion from euros to US dollars has been made using the average closing exchange rate in 2008 ($1.47 = €1) (Macrotrends 2020).

BOX 2.2

CSP project development and operational best practices

The National Renewable Energy Laboratory has compiled a report that analyzes the most common issues encountered in developing CSP projects and how they could be prevented. In more than 50 information gathering sessions, key industry players representing over 80 percent of the CSP plants operating worldwide shared their experiences.

Most interviewees mentioned project implementation issues that occurred before the start of plant operations. This highlights the importance of assembling an experienced team and hiring contractors with a proven track record of delivering CSP projects.

On the operations side, a significant number of issues related with the steam generation system were reported for both parabolic trough and tower plants. Molten salts-related systems (such as heat trace, valves, receiver, and storage) were reported by tower operators as one of the main sources of reliability issues.

Having said this, the findings of this extensive research project indicate that both parabolic trough and tower CSP plants can be built on time, within budget constraints, and perform as per their specification. The report contains detailed analysis of the challenges of building and operating a CSP project, as well as mitigating measures. The report may be accessed here: https://www.nrel.gov/docs/fy20osti/75763.pdf

Thermal energy storage is becoming ubiquitous in CSP plants

Since 2016, a large majority of utility-scale CSP projects have been built with thermal energy storage capacities ranging from 4 to 10 hours. This is true of the plants under the Chinese CSP demonstration program, the DEWA 950 MW CSP-PV complex in Dubai, and the Noor Ouarzazate and Noor Midelt complexes in Morocco. The incorporation of low-cost thermal energy storage is the norm because it allows a lower LCOE than those without, although the exact level of storage that is economic depends on the solar resource and the project-specific capital costs.

The addition of thermal energy storage is significant because it allows CSP to operate flexibly and deliver power when needed—unlike CSP without storage and PV, which can only deliver power when the sun is available. As explained in chapter 1, the added flexibility provided by CSP with thermal energy storage allows more variable renewables to be added to the grid.

More countries than ever deploy CSP with thermal energy storage

The recent shift of CSP deployments to Africa and Asia, and away from North America and Europe, has altered perceptions of CSP and the role it might play in a country’s generation mix (figure 2.3). In particular, this shift indicates that CSP is coming to be seen as the technology of choice to add flexibility to a grid with high levels of variable renewables, especially in developing countries with the requisite high direct irradiation levels.

Interest in CSP is evident in countries that rely on fossil-fuel imports to generate electricity as a complement to combined cycle power plants. This is because CSP can help to reduce fuel imports by preventing the need to deploy additional combined cycle gas turbines.

The early dominance of the US and Spanish markets reflects the high costs and low deployment levels first associated with new technologies. But the growth of global markets since 2012 demonstrates that CSP development has passed an inflection point. In line with the development of other renewable technologies, more CSP projects will likely be developed as costs continue to decline, but greater policy certainty to develop the scale of deployment needed to ensure the cost reductions from learning by doing would be welcome.

3 FRAMEWORKS FOR THE DEPLOYMENT OF CONCENTRATING SOLAR POWER

3.1 Overview

While concentrating solar power (CSP) can offer countries a significant variety of grid services to enable a transition away from fossil fuels and toward a clean energy future, developing an appropriate policy framework first is necessary. Broadly, an enabling policy framework for CSP will have a combination of market support mechanisms, alongside fiscal incentives to support the early development of CSP. This combination is important to help create a market that values the services that CSP provides, while also driving down costs and reducing the initial development risk for early developers; engineering, procurement, and construction contractors; and local manufacturing suppliers. This may need to be complemented by capacity-building policies to ensure the development of local supply chains and the achievement of local social and development goals.

While there are no set rules on the exact combination of support mechanisms needed to encourage CSP, an appropriate starting point is for policy makers to review the type of project ownership and development model that they wish to encourage. In some markets, it may be preferable for utilities to operate a CSP plant after it has been constructed by a private sector partner. In others, facilitating a market where independent power producers (IPPs) can construct and operate CSP plants may be the optimal option. Therefore, developing an understanding of which model is best suited to local needs is an important part of helping to design an optimal mix of policy support mechanisms (an extensive, but not exhaustive, list of project models can be seen in box 3.1).

3.2 Types of support mechanisms

There are three principal types of mechanisms that have been used to support CSP, either alone or in combination, including: (i) investment based, (ii) regulated quantities, and (iii) regulated prices.

Broadly speaking, investment-based mechanisms include:

- **Grants and soft loans.** These are provided by donors, such as a development bank, or by a government institution to help achieve investment. Soft loans at an advantageous interest rate or via climate bonds can be important where country risk levels are significant. A grant can cover part or all of a project's equity or debt, which reduces the impact on the weighted average cost of capital.
- **Partial risk guarantees.** Under this mechanism, the donor guarantees debt repayment to a commercial lender, which indirectly reduces the weighted average cost of capital by lessening the risk premium for the lender and the investor.
- **Tax exemptions and credits.** A tax exemption reduces the total amount of taxable income. A tax credit reduces the actual amount of tax owed by allowing the taxpayer to subtract a specified amount from the total owed. Sometimes, tax credits are granted to specific individuals or businesses based on location, classification, or industry.

An alternative approach is to regulate quantities; this includes the use of mechanisms such as competitive tenders and auctions. Tenders and auctions, when properly designed, are transparent procurement methods aimed at obtaining goods and services at the lowest price by stimulating competition and preventing favoritism. Typically, the government or competent authority invites bids from developers or contractors, either directly or through a public utility, by openly advertising the proposed contract's scope, specifications, terms, and conditions, as well as the criteria by which the bids will be evaluated. At a renewable energy auction, an offtaker buys a specified amount of energy from one or several suppliers under specific conditions, related to, among other things, the starting date, contract duration, delivery schedule, technology, and connection to grid. Suppliers are evaluated and selected based on technical and economic criteria.

A company that is awarded a contract resulting from a government tender or auction typically bears all of the project risk (although other models of risk-sharing are also possible) and must supply the energy according to the agreed-on conditions. Meanwhile, the offtaker is usually required to accept and/or pay for the energy procured, regardless of actual demand. An offtaker can be a private entity, often a large one, such as a mining company or a private utility company, or it can be a public entity—often a state-owned utility. During a typical bidding process, a specific project or group of potential projects is tendered with a total generation capacity in megawatts and/or gigawatt-hours. Projects can be technology specific or more general. Bidders submit their price offers, usually for one unit of electricity to be generated from the auctioned capacity. The criteria for qualifying as a bidder at an auction are generally clear. Bids can be designed in a variety of ways to determine the winner of a tender process, such as with a ceiling price or lowest bid, priced as bid or at the highest clearing price for multiple projects.

The last category of government support measures relies on regulated pricing; such mechanisms include feed-in tariffs and green energy credits.

A renewable energy feed-in tariff (REFIT) is designed to accelerate investment in renewable energy technologies by offering cost-based compensation to renewable energy producers. By providing a guaranteed purchase price, a REFIT provides price certainty to investors and can play a powerful role in helping a country to finance renewable energy investments when set at an appropriate level. These tariffs make investments more attractive by providing a guaranteed price and have low transaction costs, making them suitable for small-scale technologies. But their main drawback is that they may not exert as much pressure on developers to lower investment costs or to innovate as an auction or competitive tender. However, REFITs do reduce market risks by changing them to regulatory risks, thus making a project bankable as long as it uses proven technology. This also reduces the risk of developers providing unrealistic proposals to secure the rights to develop a CSP site, and subsequently finding themselves unable to deliver on their commitment.

A REFIT plan usually:

- **Provides for the priority dispatch of the energy produced.** Distribution or retail electric companies are obligated to prioritize the access of renewable energy to the grid and facilitate grid connections.
- **Offer cost-based compensation.** A price is set, per kilowatt-hour received by the renewable energy plant, to compensate for investment and generation costs; the set price is typically independent from the wholesale electricity market price, which makes it predictable. Although it is possible to link the feed-in-tariff to the wholesale price using different mechanisms, to a greater or lesser extent.

Feed-in tariff programs have often been used to stimulate market growth and drive down costs by including volume or time targets for "tariff digression," a mechanism by which the price (or tariff) awarded to new projects ratchets down over time.

Green certificates are tradable commodities to prove that electricity was generated using renewable energy sources. One certificate typically represents the generation of 1 megawatt-hour (MWh) of electricity. Certificates can be traded independently from the produced energy, and represent the environmental value of the generated renewable energy. However, they have no intrinsic value assigned to them, and their value can be determined in one of two ways:

(i) It can be spontaneously set according to consumers' willingness to pay an additional price for renewable energy, which minimizes government interference in the market but makes

BOX 3.1

CSP project structure models

There are a variety of ways in which the roles, responsibilities, and ownership of a CSP project can be structured. Several common models may be summarized as follows:

Build-operate-transfer (B-O-T). The concessionaire is licensed to design, construct, maintain, and operate the power plant for a specified period. The grantor of the concession indirectly guarantees the financing for the project by setting a predictable income source that allows the concessionaire to acquire structured financing. The concessionaire is entitled to retain all revenues generated by the project and is the legal owner of the plant until the concession expires, at which time ownership of the plant is transferred to the grantor of the concession at a previously agreed-on price, or often at no cost.

Under this structure, the owner receives the benefit of the concessionaire's expertise, and the concessionaire receives financing and makes a profit with limited risk.

Build-operate-train-transfer (B-O-T-T). This model is similar to build-operate-transfer but also includes a provision committing the concessionaire to public sector training for a smoother transfer of the ownership process.

Build-own-operate-transfer (B-O-O-T). This model is also similar to build-operate-transfer, except the concessionaire is responsible for securing project financing and is the plant's legal owner until the concession expires, at which time ownership is transferred to the grantor of the concession at a previously agreed-on price, often at no cost. The final price is usually higher, to compensate for the premium level of risk that is concentrated on the concessionaire under this structure, On the other hand, as the ownership is on the concessionaire side, this system can be combined with other incentive systems such as tax credits to compensate or even push down the final price obtained (as was done in the case of Morocco's Noor 1).

Build-own-operate (B-O-O). This model is similar to build-own-operate-transfer, except the plant ownership is not transferred when the concession ends. It is typically used when the concession period equals the expected useful life of the plant, leaving only residual value in the postconcession assets.

Build-lease-transfer (B-L-T). This model is also similar to build-own-operate-transfer, except that after construction, the concessionaire leases the plant to the government, which is then responsible for plant operation and maintenance. After the concession expires, plant ownership is transferred to the grantor of the concession at a previously agreed-on price. Under this structure, the concessionaire maintains property rights but avoids operational risk, which could be desirable in a country where a high level of risk is perceived.

Design-build-finance-operate (D-B-F-O). Similar to build-own-operate-transfer, the concessionaire in this model is responsible for securing project financing, but the grantor of the concession maintains ownership at all times. This model is extremely risky and financially stressful for the concessionaire and is therefore not typically used for renewable energy projects but rather for infrastructure projects for which the technology and operational risks are very low. When this model is applied to a project that does not generate income on its own (leaving cash flow to come from government rental payments for the facility), it is called **design-construct-manage-finance (D-C-M-F)**.

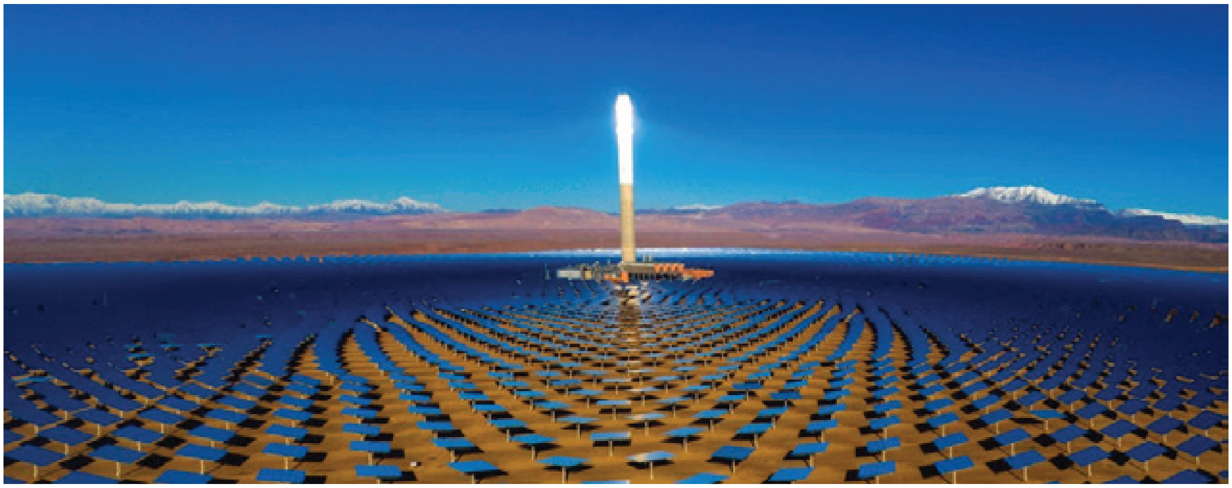
the certificate's value somewhat unpredictable.

(ii) It can be set by a market process which involves fixing, by policy, renewable quotas for electric companies and/or large consumers. The market can be a formal trading system, or indirect, where those required to purchase quotas also can directly contract for individual projects and their green certificates. Quotas must be carefully calculated and evolve to accommodate the reality of the country's energy mix, both actual and desired. A floor or cap can be set for the certificate's value through a penalty for missing the quota or a price cap on the traded value, which makes this approach more predictable.

3.3 Support mechanisms in practice

A wide range of fiscal support mechanisms have supported the deployment of CSP technologies globally. Investment subsidies, mostly in the form of grants and soft loans, have been utilized in numerous development projects, including Cerro Dominador in Chile (BNEF 2019), Delingha in China (ADB 2018); ISCC Ain Beni Mathar (World Bank 2014) and the Noor-Ouarzazate complex in Morocco (Climate Investment Funds 2014) (figures 3.1 and 3.2); ISCC Kuraymat in Egypt (World Bank 2007); Xina Solar One in South Africa (African Development Bank Group 2015); and PS10, Andasol I, and Gemasolar in Spain (EIB 2013).

FIGURE 3.1 **Solar tower at Noor III in Ouarzazate, Morocco**



Source: MASEN.

One of the largest individual financial contributors to global CSP developments has been the Clean Technology Fund (CTF), which has supported numerous projects, including:

- **Noor Ouarzazate I, II, and III (510 MW CSP), Morocco.** Along with several international financial institutions (IFIs), the fund provided low-cost debt, which decreased the required tariff by 25 percent, thereby decreasing the subsidy needed from the government of Morocco from $60 million to $20 million annually. Also, a $435 million loan was awarded from the CTF.
- **Noor Midelt (800 MW CSP-PV hybrid), Morocco.** In 2017, a $25 million loan was announced for the Noor Midelt solar project, which combines solar thermal and PV.
- **Cerro Dominador (110 MW CSP), Chile.** Fund support was critical to launch the bidding for South America's first CSP plant. Through the Inter-American Development Bank, the fund attracted the interest of other donors, including the European Union and KfW. This allowed an incentives package comprising grants and soft loans to be put together, closing the gap between CSP and other alternatives.

Globally, there has been a significant divergence in the types of fiscal incentives deployed to promote the use of CSP.

The United States has utilized tax exemptions and credit mechanisms extensively for capital-cost-intensive CSP plants, including depreciation tax breaks. As investments depreciate over several years, in terms of calculating profit for accounting and fiscal purposes, the depreciation decreases profits and thereby lowers the income tax. CSP plants in the United States also receive fiscal benefits, for example, by deducting a portion of their investment from their tax bill. The main advantage of tax credits is that they can be transferred to another company, generate sufficient profit to compensate investors, and thereby improve the plant's cash flow at early stages or decrease the original investors' equity. However, this practice is limited and severely regulated in most countries to prevent tax-avoidance schemes.

The United States has also provided loan guarantees to renewable energy projects. Through them, the government guarantees debt associated with energy production or manufacturing facilities relevant to renewable and other energy technologies. A government guarantee on the debt lowers the risk and required yield on the funds raised and makes more capital available to the industry. A $1.45 billion loan guarantee was issued to finance Solana in 2010, a 280 MW parabolic trough CSP plant with an innovative thermal energy storage system with molten salt as the energy storage media.

Outside the United States, fiscal subsidies based on feed-in tariffs have been applied in China and Spain, among others. They were the basic mechanisms for

FIGURE 3.2 **Noor Ouarzazate Solar Complex**

Source: ©SENER Engineering
Note: CSP = concentrating solar power.

the early-stage development of CSP in Spain, while in Morocco and South Africa, competitive auctions and bidding have been used as the preferred support policy for CSP. Auctions and bidding introduce competition among participants and ensure a competitive price for consumers, when well designed. Experience

TABLE 3.1 **Incentives and support mechanisms for the commercial development of CSP, by country**

Country	Investment-based incentives/support mechanisms	Generation-based incentives/support mechanisms
Chile	Direct subsidy and concessional loans	Green certificates: Atributo ERNC, moderately successful Renewable quota: Obligación ERNC; modified in 2013
China	Exemptions to corporate income tax Financial subsidies for renewable energy development Soft loans from Asian Development Bank	Competitive bidding, unsuccessful Feed-in tariff, 2016
Egypt	Global Environment Facility grant to develop integrated solar combined cycle, Kuraymat	
India	Tax holiday under the domestic income tax law Financing through the Indian Renewable Energy Development Agency Accelerated depreciation Custom and value-added tax reductions	Feed-in tariff, generation-based incentives, unsuccessful Reverse bidding, moderately successful Renewable quota, renewable purchase obligation
Morocco	Soft loans from the World Bank and other international financial institutions; concessional funds from the African Development Bank, the Climate Investment Fund, European financing institutions, and the World Bank	Public-private partnership: build-own-operate-transfer via competitive bidding, successful
South Africa	Certified emissions reduction value-added-tax exemption Tax incentive allowance and accelerated depreciation for research and development expenses Support from the Climate Investment Fund and International Financial Corporation	Feed-in tariff, 2009, unsuccessful Competitive bidding, including time-of-day tariff, 2011, successful
Spain	Tax incentives Reduction of income tax from certain intangible assets Corporate income tax credit for investments in assets to protect the environment Corporate income tax credits for research and development Capital duty exemption Allowances on local taxes	Feed-in tariff and premium, 2004, unsuccessful Priority grid connection and dispatch for renewable projects Feed-in tariff, 2007, successful Constrained, 2009 Retroactive cuts in 2012 and 2013 Modified scheme in 2014, change of feed-in tariff to fixed investment compensation
United Arab Emirates	—	Public-private partnership via competitive bidding
United States	Investment tax credit Tax credit bonds Manufacturing tax credit to expand manufacturing facilities Department of Energy loan guarantee program State-based incentives	Renewable Portfolio Standards

Sources: CIF 2014; CSE 2015; Chilean Ministry of Economy, Development and Tourism 2013; IFC 2012; NREL n.d.; OECD 2013; SARS 2006.

demonstrates that this is an appropriate model for commercially mature, large-scale technologies such as wind, PV, and more recently, even CSP. However, in the early stages of CSP deployment, auctions led to unrealistic energy prices for the Datang project in Erdos, China, and the Jawaharlal Nehru National Solar Mission Phase 1 in India. Historical experience therefore suggests that during the early stages of CSP deployment, adopting a feed-in tariff mechanism is more efficient. Once domestic expertise and supply chains are established, it is then possible to transition to well-designed auction systems to ensure the most competitive results for consumers.

A third option for fostering renewables has been to generate and sell green certificates. These support green electricity generation in a way that is more closely tied to the environmental goals being pursued, while using market mechanisms to discover the cost. This approach can sometimes be less bureaucratic than investment supports such as feed-in tariffs and energy auctions, but much depends on design. Such national trading schemes have been used to foster renewable energy in Belgium, Chile, Italy, Poland, Sweden, the United Kingdom, and some US states. Table 3.1 provides an overview of the incentives and support mechanisms used for the commercial deployment of CSP, by country.

3.4 Financing CSP projects

Despite promising developments regarding the cost of CSP technologies, the higher up-front investment costs of CSP remain among the main barriers to their deployment. But IFIs and multilateral development institutions, as well as national governments, can play an important role in addressing this barrier. By supplying longer-duration, lower-interest financing to CSP plant developers, these entities can help to lower the costs of initial market development. This will, in turn, foster a more diverse and competitive supply chain for CSP and continue to drive down costs. Reducing perceived financing risks is particularly important when no entities, whether public or private, are willing to shoulder the full costs of a project on their own.

Today, public investment accounts for around 25 percent of global investment in the financing of all renewable energy technologies (IEA 2018b). Public investments are roughly split between in-country financing and financing from international sources; typically, grants or concessional financing tools are used for the public financing of renewable energy investments. Concessional financing comprises loans with either interest rates below market value, long grace periods, or both. Increasing traditional public financing and expanding other innovative forms - such as guarantees, derivative instruments, and liquidity facilities - will be crucial to scaling up CSP capacity, especially in emerging economies with little or no experience in its deployment. This will also mitigate CSP-related risks and barriers that typically affect private sector investments (IRENA 2018a).

Nearly all capacity for CSP built before 2012 depended on financial support from public sources. In a study examining experiences of public support for CSP deployment in India, Morocco, and South Africa, lessons were offered to make national policies more effective. These included providing long-term and stable financial support to projects that otherwise would have been unviable. By reducing the financial risks, the cost of debt fell, which promoted the involvement of local actors. This involvement was further supported through developing long-term policy signals, making reliable solar irradiation data publicly available, making sure that financial support was in line with the actual cost of the technology, and reducing policy risk through the reduction of support costs by aligning the financial interests of public and private actors (Stadelmann, Frisari, and Rosenberg 2014).

IFIs have also played an essential role in scaling up CSP capacity in several countries, including Chile, India, Morocco, and South Africa. This experience suggests that, for IFIs to effectively invest in renewable energy capacity, they need to (i) either reduce costs for hedging foreign currency or eliminate currency risks for investors, (ii) adjust requirements according to the stage of technology development in the country, as well as other context-specific circumstances, and (iii) take a harmonized approach when more than one institution is providing funds to a project (Stadelmann, Frisari, and Rosenberg 2014).

Independent power producers

IPPs have participated in the development of most CSP plants worldwide, such as in Spain, United States, Chile, India and South Africa.

An IPP, or non-utility generator, is not a public utility. It is an entity, operating on a commercial basis, that owns facilities that generate electric power to sell to utilities and end users. These can be privately held facilities, corporations, cooperatives, or non-energy industrial concerns capable of feeding excess electricity into the system.

A typical CSP project promoted by an IPP is designed and constructed by one or more contractors selected by the promoter through a bidding process (similar to D-B [design-build] or D-B-B [design-bid-build]), but not necessarily open or publicized (see box 3.1 for other examples). Incentives can be offered to a project through structural features relating to procurement and pricing mechanisms, such as subsidies to investment, tax credits, REFITs, or green certificates. The standard financing sources for these projects are as follows.

- **Debt financing**, usually limited to a fraction of the total project cost (leverage), may take several forms:
  - Corporate debt: Commercial financial entities provide the capital, and the IPP's assets are used as collateral. The applied interest rate tends to be moderate because the tangible and liquid collateral favors a low-risk premium. This financing option is available only to large companies, and it affects their overall credit scores. As the development of the CSP project becomes integrated in the producer's usual business, tax credits can be used without requiring the participation of third parties.
  - Structured project financing: Commercial financial entities provide the capital, but the collateral is the project itself, including assets and future income structured into a separate company, called a special purpose vehicle, that is fully owned by the IPP or a consortium. The applied interest rate tends to be higher than for corporate debt due to the low liquidity of the collateral, which raises the risk premium. This financing option is available cheaply only when the CSP project's future income is predictable. It therefore likely requires the existence of a feed-in tariff, a guaranteed public-private partnership (PPP), a non-volatile green certificate market, or something similar.
  - Concessional financing: A portion of the debt capital could come from a soft loan, granted as part of an incentive system.
- **Equity financing** provides the portion of the project's cost not covered by the debt. The IPP can raise the required capital by issuing new shares (secondary equity offering) or reinvesting previous profits. Tax credits or other incentives can help attract equity investors.

Public-private partnerships

PPPs are important for supporting large-scale renewable energy capacity deployment because they bring the private sector into project development, sharing the risk between the public and private sectors. This partnership also offers a number of significant benefits to governments. The mechanism offers additional capital to developers, who in turn provide know-how regarding technology, installation, and operation. The experience of existing CSP projects also demonstrates that they can usually be executed much more quickly with private sector participation than without.

PPPs can take different forms—and there is no universally accepted definition of what exactly a PPP is (OECD 2014). For example, public and private sector actors can form a consortium to undertake a project; or a private sector actor can take on the responsibility of providing a service under a contractual agreement with the public sector. The arrangement can be for the entire development and operation of the project and the purchase of all or a share of the electricity generated at the plant. The Noor Ouarzazate Project in Morocco was developed through a PPP, as were several other projects in the MENA region (see box 3.2).

BOX 3.2

Morocco: The Noor Ouarzazate CSP Project

The Moroccan Agency for Solar Energy (MASEN) developed the Noor Ouarzazate project scheme as a public-private partnership, a special purpose vehicle with MASEN participating in a consortium of private developers. The 582-megawatt (MW) project (Noor I, II, III, and IV) is already online, making it one of the largest solar independent power producers in the world.

Project rationale

There is enormous unexploited potential for CSP in the MENA region. However, in Morocco, the competitive gap between CSP and carbon-intensive energy alternatives is evident.

The government of Morocco, World Bank, Asian Development Bank, Clean Technology Fund, and private sector sponsors developed the 160 MW Ouarzazate project—Noor 1. The plant uses parabolic trough technology and has a three-hour thermal storage system. Located 200 kilometers south of Marrakesh, the plant went online in 2015 and allows Morocco to avoid 240,000 tons of carbon dioxide emissions per year.

The project had two main objectives:

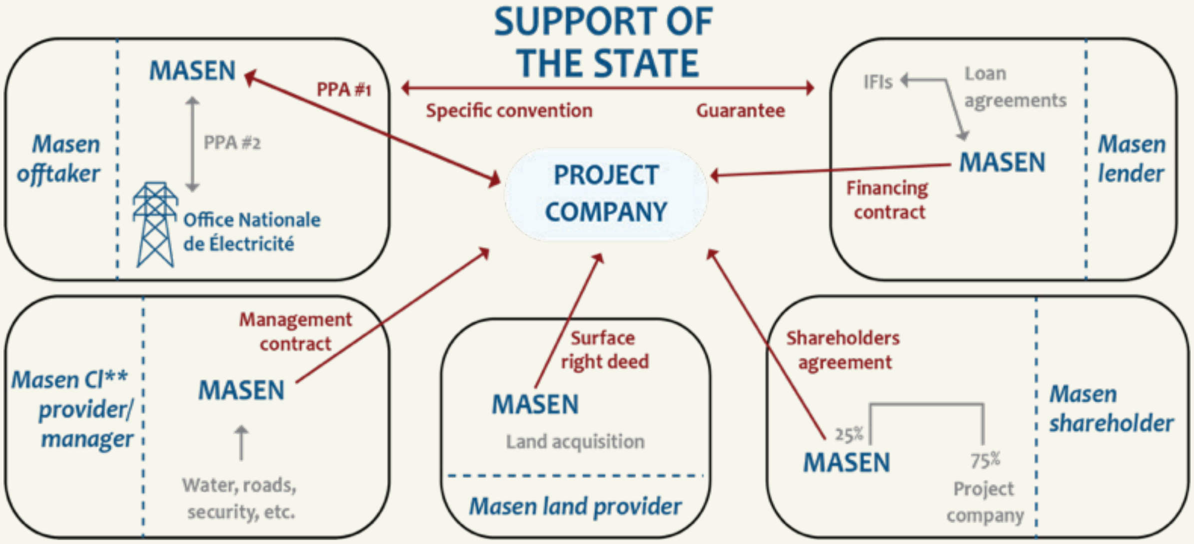
- To install CSP at a scale that demonstrates the storage technology component and generates cost reductions and economic benefits, such as local manufacturing, energy security and a shift away from fossil fuels.
- To test a business model through the public-private partnership formula that could increase private sector backing and increase the availability of capital and know-how.

Key stakeholders include:

- The government of Morocco and MASEN (figure B3.2.1), which together are expected to contribute $883 million over the life of the plant (mostly in the form of operational subsidies);
- International financial institutions and other donors that have committed over $1 billion for the construction of the facility; and
- A consortium of private developers that will contribute $190 million of equity capital and expertise for an estimated 14 percent after-tax rate of return. These developers include ACWA Power International (95 percent Saudi Arabia), Aries Ingenieria y Sistemas (Spain), and TSK (Spain).

The contract scheme for the greenfield project is build-own-operate-transfer, conducted through a 25-year public-private partnership.

FIGURE B3.2.1 How the Moroccan Agency for Solar Energy steered the development of CSP plants



Source: OECD 2014.
Note: CI = Common Infrastructure; IFIs = international financial institutions; MASEN = Moroccan Agency for Solar Energy; PPA = power purchase agreement.

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ANNEX A.
FURTHER REFLECTIONS ON CONCENTRATING SOLAR POWER TECHNOLOGY

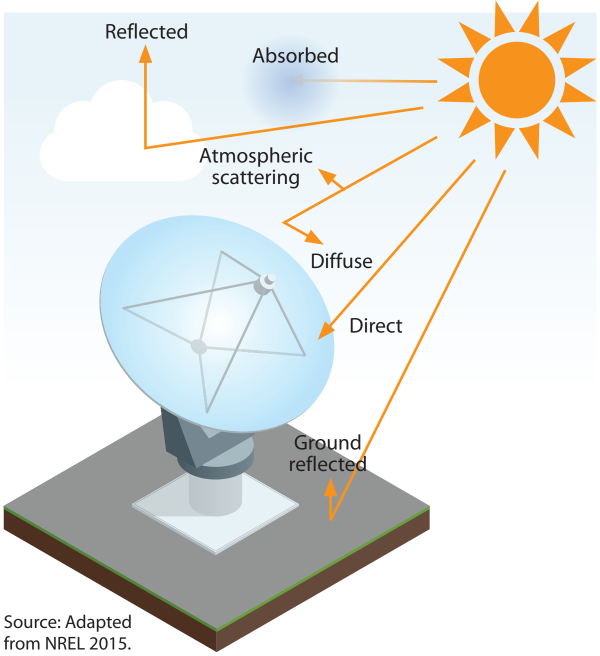
A.1 Solar resources

Concentrating solar power (CSP) is suited to countries with high levels of direct solar radiation, that is, solar rays that reach the surface of the earth in a straight line from the sun. This is important because non-directional radiation—though it can be processed into energy via solar photovoltaic (PV) technology—cannot be concentrated. CSP projects are most attractive where direct normal irradiation values are close to or exceed 2,000 kWh/m2 a year. Even though the technology can be developed in areas with lower values, the generated energy is generally too expensive to offset the costs.

CSP's global generating potential is an estimated 885,000,000 terawatt-hours (TWh) per year, considerably higher than global electricity consumption in 2018, at 23,400 TWh (IEA 2018a). Theoretically, a global CSP capacity of 300 gigawatts (GW) could supply over 5 percent of current global demand.

The technology is becoming more common as the development of new plants moves from traditionally dominant markets such as the United States and Spain, toward China and also countries in the Middle East and North Africa (MENA) region, such as the United Arab Emirates and Morocco. These markets are well positioned to take advantage of CSP, and if prices reach competitive levels, they could participate in cross-border electricity markets to export surplus production.

FIGURE A.1 Solar radiation components resulting from interactions with the atmosphere



Source: Adapted from NREL 2015.

A.2 Solar heat generation and utilization

CSP technology concentrates solar radiation onto a trapped heat transfer fluid, usually a synthetic oil mixture (e.g., a eutectic mixture of biphenyl and diphenyl oxide), that is used to heat water and produce steam. The steam then generates electricity using a conventional turbine generator, following the same process as conventional thermal power plants based on Rankine cycles. Most CSP plants, regardless of the exact technology used, have three main parts: a solar field, thermal storage, and a power block.

Broadly speaking there are two main approaches to CSP: a linear focus and a point focus. The first uses solar collectors to concentrate the solar irradiance along a focal line and the second has a single focal point, where solar irradiance is focused using a series of mirrors.

Reflector panels in the solar field concentrate the sun's rays onto a receiver, inside which a heat transfer fluid circulates. The temperature of the heat transfer fluid increases via solar radiation and then transports that heat to a steam generation system or to a thermal energy storage unit for later use. Sometimes, the heat transfer fluid also serves as the thermal storage medium.

As with conventional fossil-fuel-based thermal power plants, there is a rated efficiency of heat-to-electricity conversion, which is mainly due to energy losses that occur during the conversion of heat to mechanical energy. Accordingly, only some of the heat supplied by the heat transfer fluid to the steam cycle converts into electricity, while the rest of the heat dissipates into the atmosphere.

Direct systems use the heat transfer fluid for thermal storage. These systems can use water by evaporating and superheating it in the receiver and then storing it in a steam accumulator. Another approach is to heat molten salt in the receiver and then transfer it to thermal storage. Indirect systems use a heat transfer fluid to collect heat and heat exchangers to deliver it to the thermal energy storage unit.

A.3 Types of CSP power plants

The three technologies used to build commercial CSP plants are the parabolic trough, tower, and linear Fresnel.

Parabolic trough

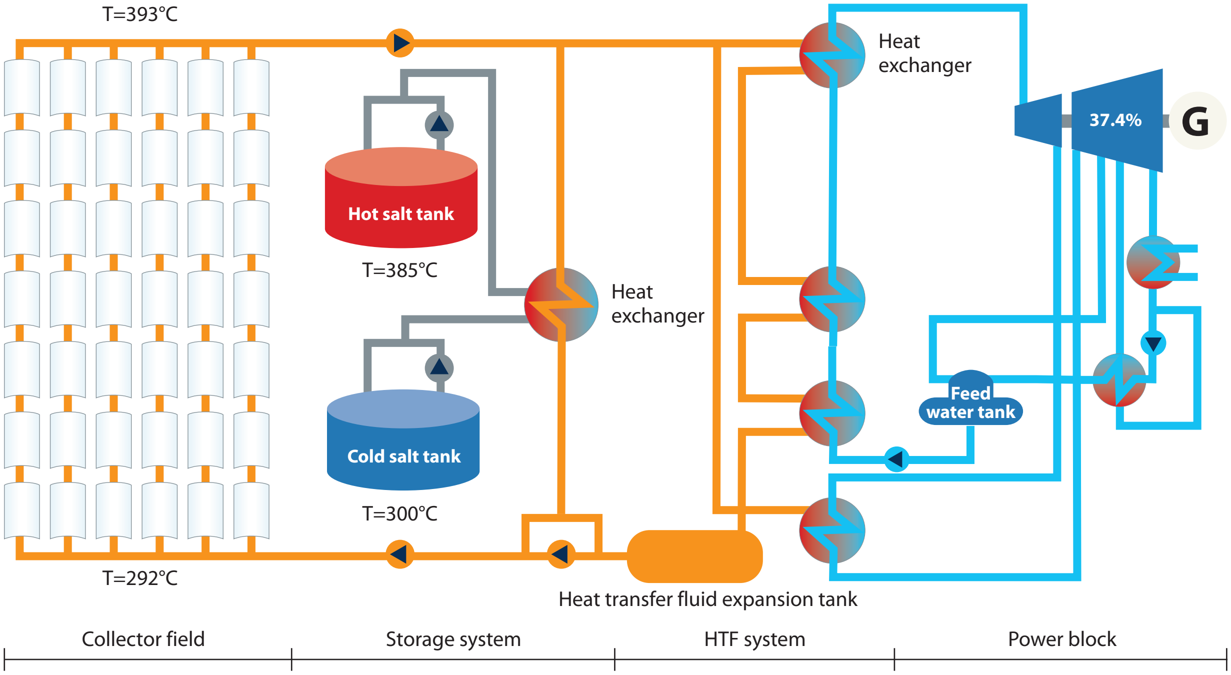
Trough systems use large parabolic reflectors or focusing mirrors that concentrate solar irradiance onto heat transfer fluid tubes that run through the center of the system or through a focal point. Mirrored reflectors are tilted toward the sun and focus sunlight on the tubes to heat the heat transfer fluid to temperatures as high as 390°C. To achieve the necessary stiffness and parabolic shape, mirrors are made with a thin, silver film set on a low-iron, highly transparent glass support.

Synthetic oil—again, usually a eutectic mixture of biphenyl and diphenyl oxide—serves as a heat transfer fluid in all operating commercial parabolic trough plants. The hot oil generates steam to be used by conventional steam turbine generators. Silicone-based fluids and molten salts are among several new fluid sources under development.

Receivers, or absorber tubes, consist of two concentric tubes. The inner tube is stainless steel with a highly absorptive, low-emission coating, which channels the flow of the heat transfer fluid. The outer tube is a highly transparent, low-iron glass with an antireflective coating. A vacuum is produced in the annular space between them. This configuration reduces heat losses and thereby improves the overall performance of the collector.

A solar tracking system positions the collector to follow the apparent position of the sun during the day, concentrating the solar radiation onto the receiver. The system consists of a hydraulic drive unit that rotates the collector around its axis and a local controller. The frame holds the tracker in place, maintaining the relative positions of the components, transmitting

FIGURE A.2 **Parabolic trough design**



Source: Adapted from IRENA (2016).
Note: The heat transfer fluid, shown in orange, is thermal oil; the storage medium, shown in gray, is molten salt. The water/steam circuit is in blue. HTF = heat transfer fluid. G = Generator.

the driving force from the tracker, and avoiding deformations caused by the components' own weight or external forces such as wind.

The power block at a parabolic trough plant resembles those used by conventional thermal plants, but instead of a combustion or nuclear process, the solar field collects the heat to generate superheated steam. There are two types of heat exchangers in the power block: (i) steam generators, which produce the high-pressure steam that drives the turbine; and (ii) preheaters, which increase the efficiency of the cycle. Thermal energy storage systems use molten salt as the heat storage medium, and exchangers use a heat transfer fluid to allow heat to enter and exit the system. A steam turbine generator expands input steam and transforms kinetic energy into electricity.

Exhaust steam from the turbine must be condensed before reentering the steam generator. This is accomplished by the condenser. The condenser's performance affects the plant's overall performance because it modifies the turbine's discharge pressure. Heat transfer fluid pumps keep the heat transfer fluid circulating through the solar field and steam generators. Fluid must flow continuously to collect heat during the day and to keep it from freezing at night. These commercial pumps are widely used in the petrochemical industry. Parabolic trough plants usually use a two-tank indirect thermal storage system.

FIGURE A.3 Physical principles of a parabolic trough collector

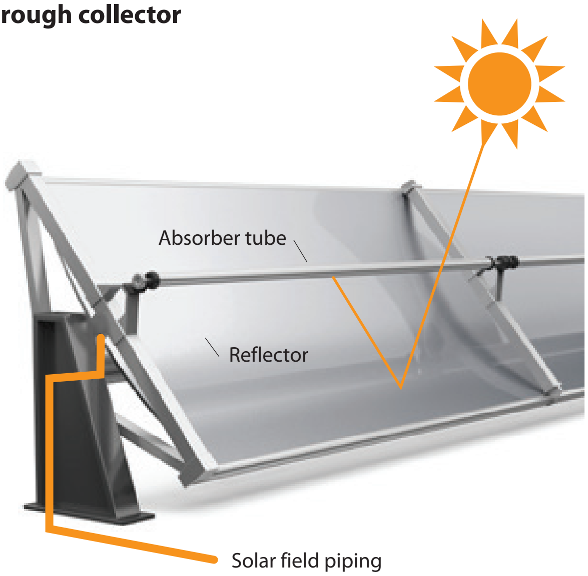


FIGURE A.4 Parabolic trough collectors at "La Africana" Spain

Source: Cuadros Fernández 2018; World Bank.

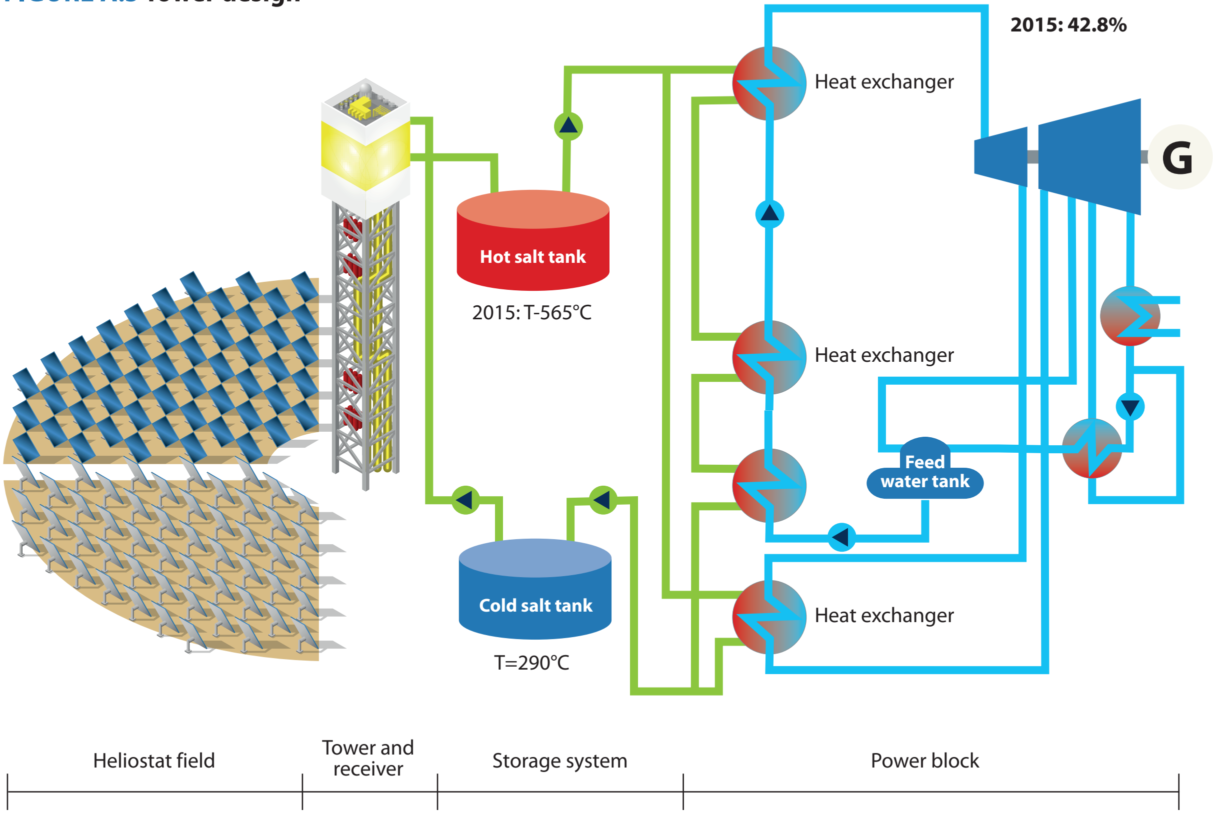
Tower

The design of tower plants is more complex than other CSP systems because they use hundreds of thousands of small reflectors (called heliostats) which track the sun along two axes and focus irradiance at a single point/receiver, placed atop a fixed tower (figure A.5). Conventional towers have a single solar receiver that is mounted on the top of a tower, and sunlight is concentrated by a field of heliostats. However, multitower systems are currently under development.

Tower systems currently represent 18 percent of total installed CSP capacity, but this is expected to increase in the coming years. Plant unit sizes range from 10 to 150 MW and usually incorporate higher thermal energy storage capacity, making them suitable for dispatchable markets. Integration of towers into advanced thermodynamic cycles is also feasible.

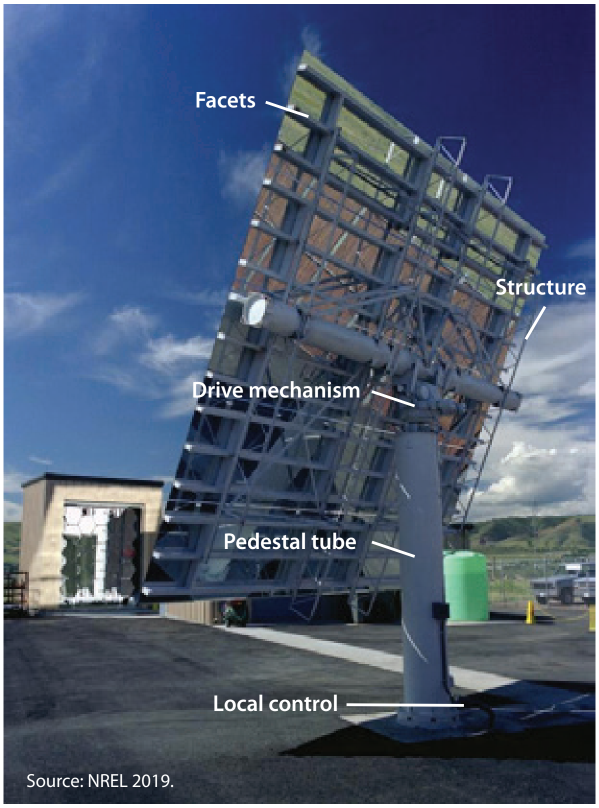
Sometimes referred to as "facets," tower mirrors reflect direct solar radiation, concentrating it onto the receiver. A mirror is made by depositing a thin, silver film on a low-iron, highly transparent glass that assures high reflectivity. A support frame provides the necessary stiffness. Although small heliostats can be made of flat glass, a slight curvature is necessary for larger units to accommodate the less-than-ideal optics because the sun is not a point of focus for the heliostats (rather the tower itself is). In a tower, the solar field comprises a variable number of heliostats that reflect the sunlight toward the receiver. The heat transfer fluid's maximum temperature is 565°C.

FIGURE A.5 Tower design



Source: Adapted from IRENA (2016).
Note: Molten salts, shown in green, serve as the heat transfer fluid and storage medium. The water/steam circuit is in blue. G = generator

FIGURE A.6 Components of a heliostat



Source: NREL 2019.

The solar tracking system changes the position of the mirrors on the heliostats, allowing them to follow the sun during the day and to concentrate solar radiation onto the receiver. Each heliostat performs two-axis tracking with a drive that rotates the mirrors, governed by a local control. The frame maintains the shape and relative position of the components, transmits the driving force from the tracker, and avoids deformations caused by the components' own weight or by other external forces, such as wind.

The solar field includes a central receiver that collects the radiation reflected by the heliostats and warms the heat transfer fluid. The central receiver is the core of a tower system and the most technically complex because it must absorb the incident radiation under demanding flux conditions and with minimal loss of heat. Receivers can be classified by their configuration, as either external or cavity systems, or by technology, as a tube, volumetric, panel/film, or direct absorption system. Because of the stringent stress and corrosion conditions, receivers are usually built from super alloys or ceramics.

The components of a tower's power block—that is, heat exchangers, steam turbine generator, pumps, and a condenser—are similar to those of a parabolic trough plant, but the steam generators are different, either salt water or direct steam generation in the receiver.

Tower systems can also integrate long-duration thermal storage solutions, to enhance their ability to continuously dispatch power long after the sun has set. Thermal storage systems include:

- **Direct molten salts.** Some plants use salt both as a heat transfer fluid and as a storage medium. Steam turbine generator operation is stable because it does not depend on instantaneous radiation.
- **Steam accumulators**. These provide towers with some buffering, but only for short periods of time.

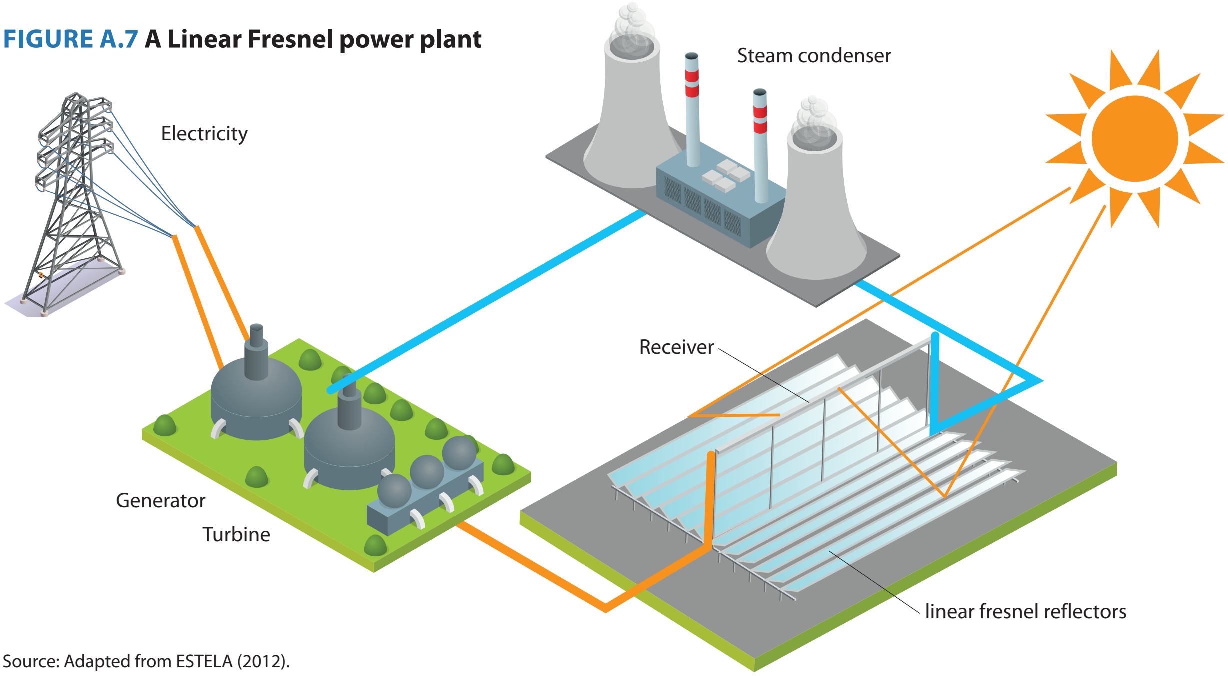
Towers are more diverse in their design than parabolic trough plants because designers can choose from a variety of different components, such as heliostats and receivers, as well as different site configurations. These configurations can include utilizing one or multiple towers, as well as choosing to either position heliostats around a tower (or towers) or only on north-facing fields. With regard to towers' storage configurations, direct molten salt systems are emerging as the preferred option, used by nearly all towers currently under construction or in development. This is due to the higher operating temperatures that can be obtained when molten salt, as opposed to thermal oil, is used as the heat transfer fluid. As greater temperatures lead to a higher power block and a greater overall plant efficiency, there is considerable current interest in developing this technology further, notably in China.

Linear Fresnel

Linear Fresnel systems are conceptually simple. They use compact optics (flat mirrors) that can produce saturated steam at 150–360°C with less than 1 hectare per megawatt of land use. Flat mirrors lie close to the ground and direct sunlight to a fixed absorber tube, making linear Fresnel collectors cheaper to produce and less vulnerable to wind damage than other technologies. However, because of lower concentration ratios and cosine factors before and after noon, they are less efficient than parabolic trough systems or towers, although the intraday energy outflow variations are higher than they are with parabolic trough systems (figure A.7).

A linear Fresnel solar field consists of connected, parallel solar loops, where each loop raises the temperature of the circulating heat transfer fluid. Commercial applications use water for the fluid in a direct generation configuration to produce

FIGURE A.7 A Linear Fresnel power plant



Source: Adapted from ESTELA (2012).

saturated steam or molten salt as the heat transfer fluid and storage medium. The main components of a linear Fresnel solar field are mirrors, a receiver, and a tracking system. Mirrors made from a thin, silver or aluminum film deposited on a low-iron, highly transparent glass support reflect direct solar radiation and concentrate it onto a receiver placed in the focal line of the Fresnel collector. Receivers, or absorber tubes, made of steel coated with a highly absorptive and low-emission material, channel the flow of the heat transfer fluid. There is a tube placed inside a secondary reflector with a flat cover made of low-iron, highly transparent glass that has an antireflective coating. A solar tracking system positions the mirrors to track the position of the sun during the day, allowing solar radiation to concentrate onto the receiver.

The power block of a linear Fresnel CSP plant resembles that of a conventional thermal power plant. Its main components are a condenser analogous to the one described for parabolic trough plants; a steam turbine generator, also analogous to the equipment described for parabolic trough plants, but often designed for low-temperature configurations with saturated steam; and heat exchangers, with most commercial applications using water as the heat transfer fluid in a direct steam generation configuration, eliminating the need for steam generators. Nevertheless, reheaters remain necessary to increase the overall efficiency of the cycle.

A.4 Summary of CSP plant technologies

Most existing CSP capacity involves parabolic troughs, but towers appear to be increasing their share of the market. Their higher working temperatures allow for greater efficiencies and lower storage costs, and these advantages seem to be shifting preferences among developers.

Site conditions and the ratio of capital expenditure to performance largely determine the technology used. Until now, towers posed a greater risk because of their lower installed capacity. But this has changed since major tower projects have become operational and the financial sector has gained confidence in them. Competing technologies could yet evolve to produce new innovations and benefits.

Table A.1 summarizes the features of the three main technologies in use today. Each one has its strengths and weaknesses, and deciding which to use necessitates a careful evaluation of the desired application and the existing constraints. Choosing the appropriate configuration for a certain function at a specific location involves the careful balancing of optimal performance and reasonable cost.

A.5 Thermal energy storage

CSP is best viewed as a dispatchable renewable energy technology that is capable of harnessing and storing

TABLE A.1 Comparison of concentrating solar power technologies

	Parabolic trough	Towers	Linear Fresnel
Application	• Utility-scale generation • Daytime generation, extended into the evening in most cases	• Utility-scale generation • Daytime generation and/or peaking	• Utility-scale generation • Daytime generation
Advantages	• Well proven with 5 gigawatts (GW) in operation • Stable operation under semi-cloudy conditions because of built-in 30–45 minutes of inertia provided by the heat transfer fluid system • Short focal distance allows use in higher-humidity and low-visibility environments • Can support storage	• Stable and flexible operation because of extended storage; effective decoupling of solar field and power block operation • Towers are more efficient and, due to higher operating temperatures, have a greater thermal storage capacity per kilogram of molten salt than both parabolic trough and Fresnel CSP • Simpler direct storage configuration • Can be built on hilly terrain	• Tight configuration with minimal footprint • Simple systems with good local manufacturing potential • Good for solar augmentation of existing thermal cycles • Good for low-cost heat supply
Disadvantages	• Poor yield from line-focusing systems in winter months in relatively high latitudes • Requires flat sites to deploy the solar field, which means that the ground must sometimes be flattened • Environmental risk posed by oil-based heat transfer fluid • Fire risk caused by heat transfer fluid in the solar field and in the pumps • Steam cycle efficiency lower due to the 400°C limit	• Long focal distance poses an issue in sites with dust, aerosols, or humidity in the atmosphere • Performance can be poor in semi-cloudy conditions because of refocusing protocols • Harm to avian population has been reported	• Less efficient than parabolic trough or towers • Poor yield from line-focusing systems in winter months, at relatively high latitudes

Source: Solar Technology Advisors.

energy from solar radiation, an intermittent and renewable resource. Thermal energy storage is key to this process because it evens out the intermittent patterns of solar radiation. While transporting heat is more expensive and complicated than transporting electricity, the opposite is true for storing heat.

Several storage technologies are available, including two-tank indirect and indirect systems, single-tank thermocline, and steam accumulators.

In a two-tank direct system, which are most commonly employed in tower plants with molten salt, the fluid used to collect the primary thermal energy also stores it. Two tanks (or two groups of tanks) store the fluid, one at a high temperature and the other at a low temperature. A pump sends fluid from the cold tank to the solar collector or receiver, where solar energy heats it. The pump then sends the hot fluid to the hot tank for storage, from where it is pumped through a steam generator, where it produces steam that is used to generate electricity. The fluid exits the steam generator at a low temperature and returns to the cold tank (figure A.8). The most common medium for the fluid is molten salt, a eutectic mixture usually 60 percent sodium nitrate ($NaNO_3$) and 40 percent potassium nitrate (KNO_3).

With a two-tank indirect system, which is the most often deployed in commercial parabolic trough plants, a heat transfer fluid circulates through the receiver and collects heat from solar radiation. Two tanks hold the storage fluid, one hot and the other cold. In loading mode, a pump sends storage fluid from the cold tank to a heat exchanger where heat from the fluid transfers to the storage medium that flows to the hot tank for storage. In unloading mode, the fluid from the hot tank flows through another heat exchanger where it transfers its heat back to the fluid. This fluid moves to the steam generator, where it generates steam to produce electricity. The storage fluid exits the heat exchanger at a low temperature and returns to the cold tank (figure A.9). Indirect systems are less efficient than direct systems due to efficiency losses in the heat exchange process.

Single-tank thermocline systems (figure A.10) store thermal energy in a single tank. During operation, the temperature of the upper portion of the medium is high, and the temperature of the lower portion is low. A temperature gradient, or thermocline, keeps the hot and cold regions separate.

FIGURE A.8 **Two-tank direct storage system**

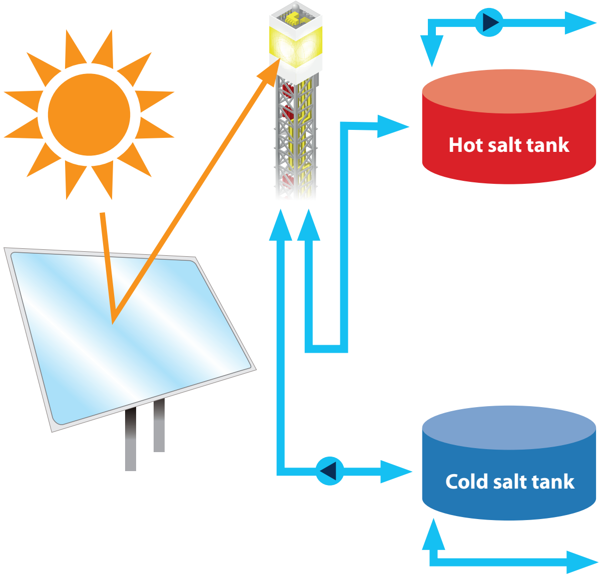
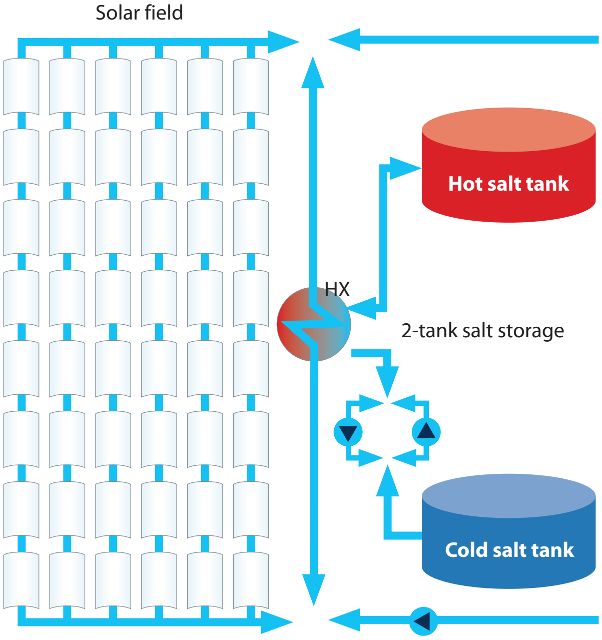


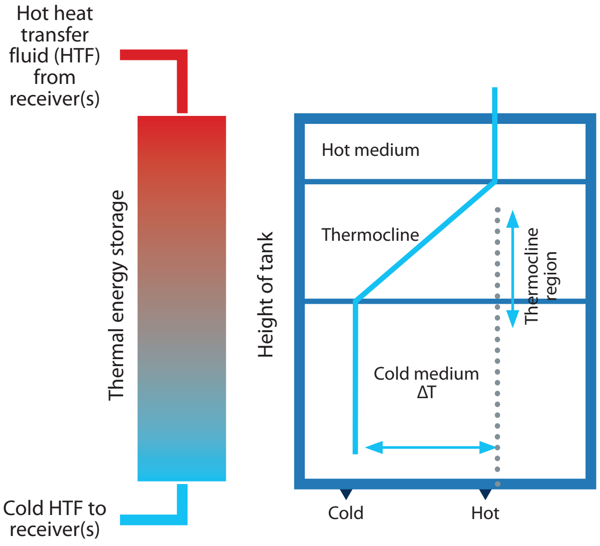
FIGURE A.9 **Two-tank indirect storage system**



Note: HX = heat exchanger.

The hot transfer fluid flows to the top of the thermocline, leaving the temperatures at the bottom low. This process moves the thermocline down and adds thermal energy to the system for storage. By inverting the flow, the thermocline moves up, and the system's recovered thermal energy generates

FIGURE A.10 **Single-tank thermocline storage system**



Source: Solar Technology Advisors.

steam and electricity. The flotation effects create a thermal stratification of the fluid inside the tank, which helps to stabilize and maintain the thermocline. In theory, the solid storage medium in a single tank makes this system less costly than two-tank systems. However, the system is complicated, and two-tank systems are currently the norm.

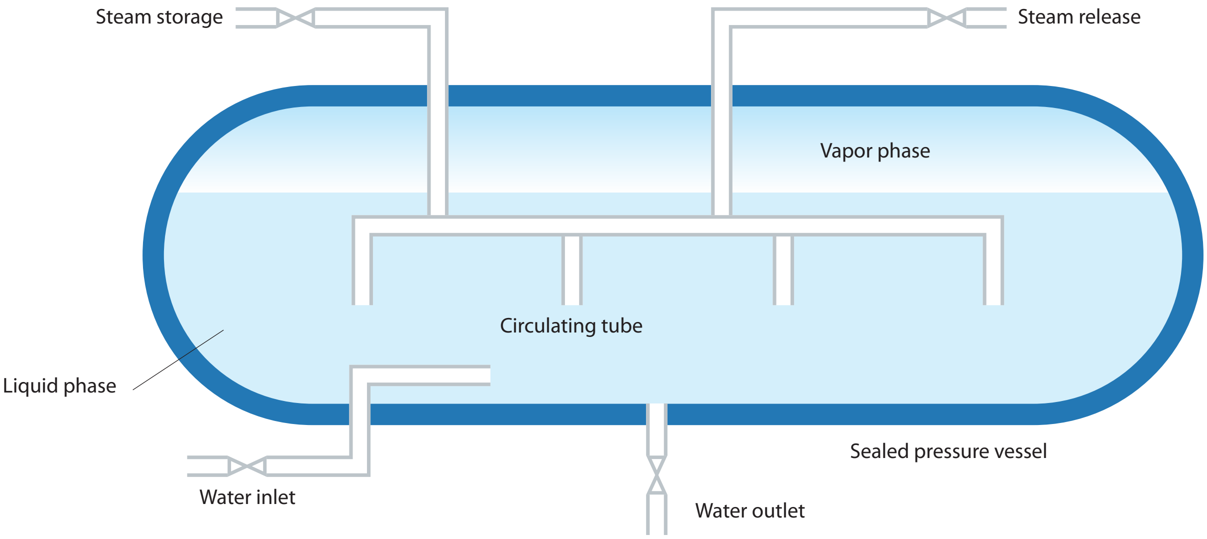
Some tower plants use a direct steam accumulator (figure A.11); however, it is not cost competitive compared to two-tank storage systems. When demand is lower than solar output, steam charges into the accumulator through injectors. A portion of this steam condenses and heats the water; the rest remains as steam, filling the space above the water. When demand is greater than solar output, steam discharges from the accumulator. The pressure drops depending on the amount discharged.

Beyond these systems, a few CSP initiatives under development involve sensible heat, latent heat, and thermo-chemical systems. The sensible heat option involves a thermocline system with a concrete or compact bed or sand exchange system. Latent heat systems include molten salt and mechanical alloys. Thermo-chemical systems include metal oxide, ammonia decomposition, and cycles with sulfur. Some have demonstrated potential to significantly reduce costs and will likely be installed in demonstration projects. The driver behind these initiatives is the need for cheaper thermal storage systems with lower operational costs.

A.6 Technical challenges and trends to overcome them

Table A.2 presents an overview of the current challenges and issues facing various CSP system components—and the shifts needed to overcome them—as well as general trends in research and development (R&D). All these technologies will contribute to reducing the cost and increasing the performance of CSP power plants, with current R&D efforts focusing on issues critical to

FIGURE A.11 **Steam accumulator**



Source: Sun, Hong, and Wang 2016.

TABLE A.2 Concentrating solar power: Technical challenges and efforts to overcome them

	Power block	Heat transfer fluid	Mirrors	Frames, supports, and trackers	Receiver	Thermal energy storage system	Hybrid systems
Challenges/ issues	• Thermal to electric technologies are inefficient • Small steam turbines reduce efficiency • Daily start-up and shutdown processes shorten the life span • Excessive water consumption	• Fluid is toxic, flammable, and inefficient; ambient air temperature and degradation pose issues • All central receiver tower's circuit elements are subject to freezing and corrosion	• Glass thickness must be optimized • Transition piece between back of mirror and structure needs improvement • Mirror prices can be prohibitive • The reflecting layer, collector frames, and glue used on mounting pads degrade over time	• Trade-offs between rigidity and cost • Long-term durability due to corrosion • Costly assembly by hand For parabolic troughs: • Wider apertures • Simplified installation For tower plants: • Larger heliostats with cheaper actuators • Smaller heliostats, possibly preassembled • Autonomous heliostats • Automated assembly and/or installation	• Central receiver towers are not standardized • Excessive concentration on a single element is a risk • Corrosion due to use of molten salts is possible • Hydrogen can permeate parabolic trough units due to degradation of heat transfer fluid • Corrosion of steel tubes • Need for more absorptive receivers to the visible spectrum of solar light; low thermal emittance • Able to work at higher temperatures to improve efficiencies	• Substantial backup energy required because molten salt cannot remain frozen • Need for more reliable, corrosion-resistant, longer-lived systems • Concerns regarding parasitic use and costs of antifreeze fuel • Expensive molten salts used as storage media	
System that the challenge applies to	• Steam generators • Steam turbines	• Heat transfer materials • Corrosion-resistant materials	• Parabolic mirrors • Heliostat mirrors • Flat/Fresnel mirrors	• Collector frames • Drives • Control systems • Materials	• Receiver materials • Receiver design • Absorptive coatings	• Heat storage media • Thermodynamic cycle design	• Heat transfer fluids • Thermal storage
Technology shift proposed	• For Rankine, develop new materials able to work at 415 bar and 700°C • Switch from Rankine to Brayton or other cycles • Switch to alternative working fluids such as carbon dioxide (CO_2)	Switch to: • CO_2 • New salt mixes • Sulfur	• Thin glass • Polymeric films • First face mirrors • Mirror-cleaning techniques	• Greater integration of collector components • Self-supporting structures for mirrors • Integrated drives, possibly without hydraulics	• Corrosion-resistant receivers • Improved designs, less subject to thermal stress • Improved absorption	• Non-corrosive media • Phase-change systems • Encapsulated salts	• Decoupling of solar and conventional cycles
General trends of research and development in technology	• Running cycles at supercritical temperatures • Supercritical cycles using CO_2 and air-Brayton cycles at around 1,200°C for tower systems • Combined cycles that work with high temperature and utilization of heat waste • Dry cooling	• Fluids that work at higher boiling points, lower melting points, high thermal stability, low vapor pressure at high temperatures, low corrosion, low viscosity, high thermal conductivity, and heat capacity for energy storage • New and less aggressive salt mixtures featuring containment materials that work at higher temperatures and have a lower freezing point and higher energy density	• Composite materials that can replace glass to provide accuracy, strength, and support • Thinner glass, to improve reflectivity or reduce the cost • Polymeric films with metallized surfaces • First-surface (or front-surface) mirrors • New mirror-cleaning techniques and antisoiling coatings to reduce water consumption during cleaning process	• In tower plants, trends influencing heliostat design are larger heliostats that reduce the number of units or smaller heliostats that require more units but for which mass production would bring substantial savings • Autonomous heliostats that do not require trenches to supply them with power and control • Automated assembly and installation • New collectors for parabolic trough that feature structures with wider apertures, requiring fewer drives, foundations, controllers, and receiver tubes	• Multiple towers and modular approaches for tower plants • Higher working temperatures • Quartz windows for cavity receivers • Compact receiver designs to enlarge the available heat-transfer area • Solar selective coatings for parabolic trough • Receivers working at higher temperatures and with different heat transfer fluids • Large diameter tubes • Longer life spans and new absorbent coatings	• Thermochemical reactions to store energy	• New concepts such as: decoupled solar combined cycle; photovoltaics plus CSP; coal plus CSP; thermal energy storage systems that can be fed by both CSP and PV

Source: Solar Technology Advisors.

the cost of electricity and improved construction and manufacturing.

The US Department of Energy (DOE) launched the SunShot Initiative in 2011 to reduce the total costs of solar energy by 75 percent by 2020, making it cost competitive at a large scale with other forms of energy without subsidies by the end of the decade. This target was achieved by 2017, when the industry reached $0.06 for utility-scale PV plants. Building up on its original aim of reducing costs, the US DOE launched the Sunshot Initiative 2030, setting a new target of $0.03 for utility-scale PV, $0.05 for baseload CSP (12 hours of storage or more), and $0.10 for peaking CSP (6 hours or less of storage) (US DOE 2016).

At a global level, R&D is ongoing on several key components:

- **Power blocks.** High-temperature power cycles are the focus of current research, including supercritical CO_2, solid-state power conversion techniques, hybrid power systems, and cooling-related water consumption.
- **Heat transfer fluid.** Improved measures are being studied for working temperatures, corrosion, melting points, costs, and environmental impacts.
- **Collectors (mirror, frame, support, and tracker).** Whether for trough, tower, linear Fresnel, or dish systems, collectors represent up to 40 percent of capital costs for CSP. Current R&D focuses on improvements in optical accuracy, structural weight, material usage, and methodologies for mass manufacturing.
- **Receiver.** Current R&D on the design of receivers focuses on improved (i.e., higher) operating temperatures and more durable selective coatings; corrosion and heat transfer fluids are also receiving attention.
- **Thermal storage.** Current research concentrates on sensible, latent, and thermochemical energy storage systems that improve heat transfer, lower storage costs, and reduce material degradation caused by corrosion. Current projects are investigating thermal fluids that are stable at high temperatures and possess superior thermophysical properties; novel storage methods are also being studied.
- **Hybrid systems.** As an intermediate step toward full-solar plants, current research focuses on improving hybridization with natural gas, photovoltaics, or even coal; projects are aiming for optimal integration to achieve better capacity and lower investment costs.

A.7 Power block

Power blocks have three key elements: a steam turbine, a steam generation system, and a condenser. All are technologies inherited from conventional applications with a few modifications. Power blocks remain largely unchanged since the first power plants, while other aspects of the technology have certainly advanced.

The power block must be carefully operated during rapid startup and shutdown operations in order to maintain steam turbine integrity and performance during its entire lifetime.

Water is required for cooling CSP plants using a wet-cooling condenser. Since CSP plants generally operate in arid locations, most of them operate with air-cooled condensers. Air cooling greatly reduces water consumption but comes at the expense of reducing the cycle efficiency and increasing auxiliary electrical consumption.

Researchers and developers seeking to address the limitations of Rankine cycles are looking at cycles running at supercritical temperatures. They are considering supercritical cycles that use CO_2 for tower systems (Cheang, Hedderwick, and McGregor 2015). Air-Brayton cycles running at around 1,200ºC are under study for tower systems through the development of volumetric receivers. Hybridization with a gas turbine is another interesting option (Quero et al. 2014). "Concentrating Solar Power Gen3 Demonstration Roadmap," a technical report from the National Renewable Energy Laboratory, provides a description of these two product lines (Mehos et al. 2017).

Other innovations include combined cycles that work with a high-temperature Air-Brayton cycle and a steam Rankine cycle that uses waste heat at a lower working temperature. Dry cooling is also getting a lot of attention. EU-funded WASCOP and MinWaterCSP are both seeking to further develop dry cooling technologies. In the United States, ARPA-E's ARID (Advanced Research in Dry Cooling) has funded several dry-cooling projects.

A.8 Heat transfer fluid

Parabolic trough

As currently formulated, the heat transfer fluid (HTF) is a synthetic thermal oil—a eutectic mixture of biphenyl and diphenyl oxide. HTF systems use expansion and overflow tanks, pumps and piping, backup heaters, and oil treatment systems (filters, ullage, and reclamation systems).

Issues of concern around the use of heat transfer fluid include:

- **Toxicity.** In the event of a spill, it is environmentally harmful.
- **Flammability.** Solar field leaks and damaged seals in the pumps can ignite.
- **Low thermodynamic cycle efficiency.** It requires periodic filtering and replenishment. HTF degradation increases exponentially at temperatures above 400°C.
- **Ambient temperature requirements.** Thermal oil freezes at 12°C. To prevent thermal oil from freezing it must circulate continuously and, depending on the season and plant location, sometimes it must be heated by gas burners or electrical heaters, both of which incur in parasitic consumption of fuel and electricity.
- **Low vapor pressure.** To maintain the thermal oil in liquid phase, it must remain over 10 bar at 400°C. This requirement, among many other things, make two-tank direct systems economically unviable.

Anticipated trends

Researchers are mainly concentrating on fluids that work at higher boiling points. At higher temperatures, these can feed better-quality steam into the turbine and increase overall system efficiency. Other desired characteristics for the heat transfer fluid include a low melting point, high thermal stability, low vapor pressure (<1 bar) at high temperatures, low corrosion (metal alloys able to contain the heat transfer fluid), low viscosity, high thermal conductivity, heat capacity for energy storage, and low cost (Vignarooban et al. 2015).

Alternatives to synthetic thermal oil which are under consideration include:

- **Molten salts (maximum temperature of 565°C).** By using the same fluid in the solar field and thermal energy storage system, systems can omit the heat exchanger, thereby reducing thermal losses and capital cost. But because the mixtures are solid at ambient temperatures, they can freeze and cause serious damage, and the higher working temperatures can corrode circuit elements, pipes, tanks, valve seats, pumps, and the receiver. While oil might freeze at about 12°C, molten salts freeze at over 230°C and are really fluid at 260°C or more. Hence, the risk of freezing and the parasitic consumption involved to avoid it are much greater with molten salts than oil.
- **Water steam (direct steam generation technology).** This technology would simplify the power block, obviating the need for a heat exchanger between thermal oil and water. But a two-phase water/steam flow in the receiver system complicates things. One issue is the control over the outlet steam parameters. Additionally, the system must be designed to withstand much higher pressures and temperatures, which drastically increases costs. This technology still lacks suitable thermal energy storage systems (Eck and Hirsch 2007).
- **New silicone-based synthetic oil formulations.** These new thermal oil forms have lower melting and boiling points, producing fewer gaseous compounds at 425°C compared with currently applied heat transfer fluids at only 400°C. The lower replacement rate reduces the levelized cost of energy by 5 percent (Jung et al. 2015).

Central receiver tower

Some commercial tower projects rely on direct steam generation, but the most recent projects use direct molten salt systems.

Anticipated trends include new, less corrosive salt mixtures featuring containment materials that will work at higher temperatures (Myers and Goswami 2016) and have a lower freezing point and higher energy density (EERE 2018a).

A.9 Mirrors

Both parabolic trough and tower CSP plants use mirrors. The typical configuration of parabolic mirrors uses pieces that are slightly curved to obtain the parabolic shape needed to concentrate sunlight on the receiver. The low-iron glass is 2–4 millimeters thick, depending on the strength required (heliostats and loops, placed along the perimeter of the plant, that endure greater wind stress and use thicker glass). A layer of silver, protected by several polymeric coatings, reflects the solar irradiation. Lead-free mirrors are standard in highly regulated developed countries, although their use presents durability challenges (Sutter et al. 2015).

Optimizing the thickness of the glass requires trade-offs between reflection loss, cost, and durability. The transition piece between the back of the mirror and the structure needs improvements to balance the differing coefficients in thermal expansion that cause mirrors to buckle over time. Mirrors are composed of glass and a supporting metallic structure in addition to adhesives and layers of polymer and silver. Current issues with mirror technology include the following:

- Their cost is linked to the amount of materials used in their fabrication.
- They rely on glass to hold their shape, and the amount of glass used dictates their thickness and reflectivity.
- Their reflecting layer degrades over time.
- The collector frame that holds the mirrors in position can degrade over time (Ren et al. 2014).
- The chemical bond that affixes pads to the back weakens over time, posing a medium-term risk.
- They require on-site mounting.
- Cleaning requires demineralized water.

One anticipated development is that composite materials will replace glass, providing accuracy, strength, and support at a lower cost. Other expected innovations include:

- Thinner glass, to improve reflectivity or reduce cost.
- Polymeric films with metallized surfaces (García-Segura et al. 2016).
- First-surface (or front-surface) mirrors.
- New mirror-cleaning techniques and anti-soiling coatings to reduce water consumption (Bouaddi, Ihlal, and Fernández-García 2017; Truong Ba et al. 2017).

A.10 Frames, supports, and trackers

Towers and parabolic troughs direct solar irradiation onto the receiver with conceptually similar but technically distinct structures and trackers.

Heliostats have evolved from around 40 square meters (m^2) (Solar One) to nearly 178 m^2 (Noor III), with demonstration plants in the range of 150–200 m^2 (Böer 2012). The increased area per unit improves the economics by requiring fewer drives, pedestals, and foundations. However, wind stress can reduce optical performance, increasing deformations. Additionally, making the structure more rigid tends to make it more expensive (Arancibia-Bulnes et al. 2017). Not all technology suppliers agree that the benefits of increasing heliostat size outweigh the disadvantages; the tower plant in the DEWA IV 950 MW CSP-PV hybrid project will deploy heliostats of 25 m^2.

In addition to the lack of integration between components—supports, frames, and mirrors—there are concerns about long-term durability due to corrosion. Further, most parabolic trough collectors require costly assembly by hand. In central receiver tower plants, two contrary trends are influencing heliostat design (Pfahl et al. 2017). Larger heliostats reduce the number of units, but the structure must bear the stress without buckling. Smaller heliostats mean more units, but the requisite mass production would bring substantial savings.

If heliostats were autonomous in terms of power supply requirements and were designed with a wireless control system, they would not need trenches to supply them with power and control. This could result in cost savings. Also, assembly and installation could be automated. New parabolic trough collectors would feature structures with wider apertures that would mean fewer drives, foundations, controllers, and receiver tubes (Jebasingh and Herbert 2016).

A.11 Receiver

Central receiver tower

Several concepts have been tested for central receiver towers (CRTs), but no standards have yet been set for this component. Some concepts which are going through the R&D stage use air as the heat transfer fluid, others use water/steam, and still others utilize molten salts. Each of the three are priced completely out of line with their production costs—probably a reflection of their quasi-experimental status.

So, in addition to a lack of standardization, CRTs run the risk of excessive concentration on a single element. The coordination between the focusing process of the heliostat field and the circulation of molten salt trough the receiver must be well defined and performed.

CRTs could improve heliostat field performance by moving to multiple towers and modular approaches (Schramek and Mills 2003). Working temperatures will likely increase. Several lines of research are being pursued (Mehos et al. 2017), including liquid metal, silicon carbide, and particle receivers; quartz windows for cavity receivers; and compact receiver designs that would enlarge the available heat-transfer area, such as multicavity or microchannel concepts (Ávila-Marín 2011; Ho 2017; Ho and Iverson 2014).

Parabolic trough: Issues and trends

The heat transfer fluid degrades over time, and when this happens to a parabolic trough, hydrogen can permeate the unit and break the vacuum (Moens and Blake 2010; Li et al. 2012). In some cases, corrosion of the steel tubes can warrant their replacement, which is costly.

Developers are working on solar-selective coatings for parabolic trough systems. Receivers should be highly absorptive of the visible solar light spectrum and have low thermal emittance. They should be able to operate at high temperatures in an oxidizing environment with large, possibly sudden thermal gradients (EERE 2018b).

New receivers under development may be able to operate at higher temperatures and with different heat transfer fluids, such as water/steam, gas, or molten salts (EERE 2018c). Wider collectors will necessitate larger-diameter tubes. Longer life spans and new absorbent coatings will create greater resistance to oxidization and help prevent hydrogen permeation. New materials will also address internal corrosion.

A.12 Thermal storage system

Both central receiver tower and parabolic trough systems use molten salts in two storage arrays, one hot and the other cold. Storage capacity is approximately proportional to the temperature difference between the two. Because they must not freeze, thermal storage systems require substantial backup fuel and electricity.

Storage systems are more cost-effective in central receiver towers than in parabolic trough plants because they work at a higher temperature gradient and their capacity factor is typically higher, leading to a higher energy yield and accelerating capital recovery, other things being equal.

There is a need for more reliable, corrosion-resistant, and longer-lived storage systems. Parasitic use of fuel and electricity, along with the costs of antifreeze and circulation pumping, are concerns as well.

New product lines could bring down the cost of thermal storage by an order of magnitude. Thermochemical reactions may offer a way to store energy. As storage media, molten salts are relatively expensive (table A.3). Other options include sulfur storage; solid-state sensible storage; phase-change materials; and systems using solid particles, such as sand, alumina, or sintered bauxite (Baumann and Zunft 2015).

Sulfur storage, in particular, could reach a price of $2 per kilowatt-hour thermal (kWh-t) (GA-DLR 2013), and this could entirely reshape plant design, bringing CSP plants' capacity close to that of conventional gas cycles.

TABLE A.3 Material costs of thermal storage media

Media	Energy density (KJ/kg)	Cost of materials ($/kWh-t)
Gasoline	45,000	0.108
Sulfur	12,500	0.018
Molten salt (phase change)	230	7.56
Molten salt (sensible)	155	11.22
Elevated water dam (100 meters)	1	-

Source: GA-DLR 2013.
Note: KJ/kg = kilojoules per kilogram; kWh-t = kilowatt-hour thermal.

Solid-state sensible storage systems are low-cost options able to operate at higher temperatures than current, state-of-the-art systems. The main challenge is to achieve efficient heat-transferring cycles into and out of a solid (Li 2016; Tiskatine et al. 2017).

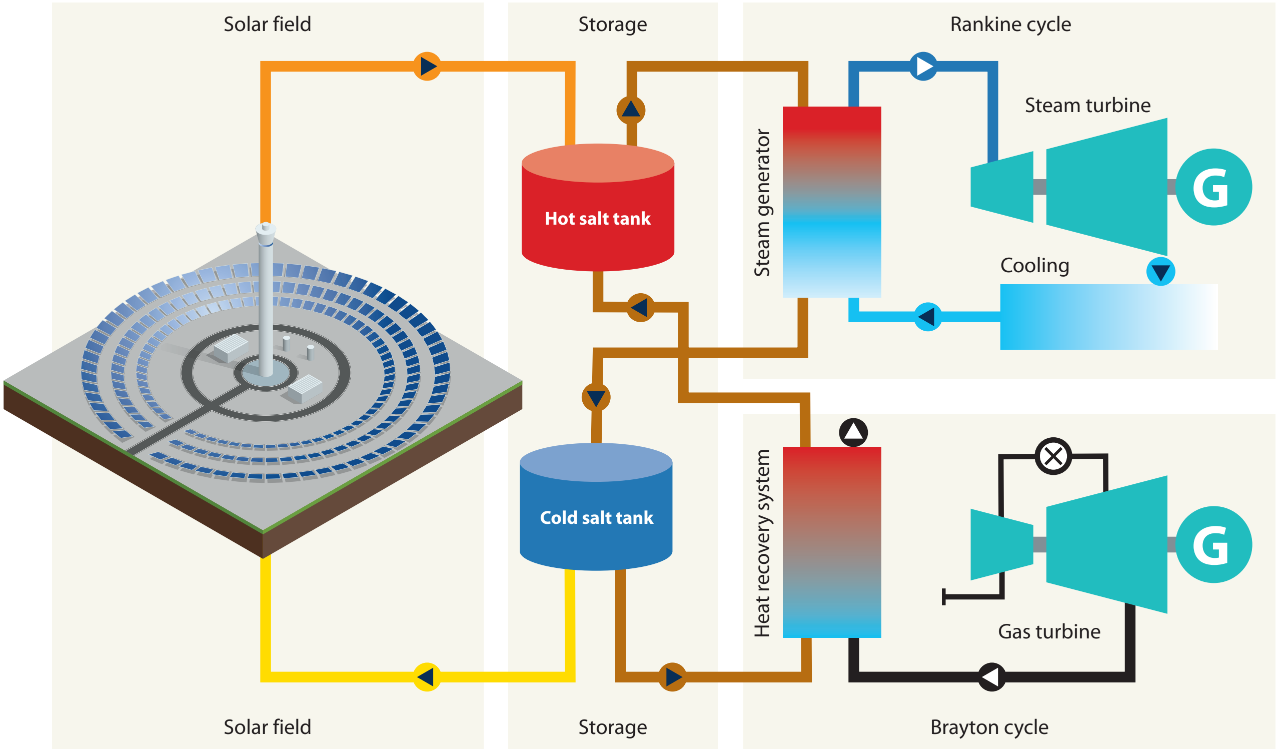
The latent heat of the phase change materials allows for the storage of energy at high densities, but the isothermal process results in exegetic losses. Phase change is under consideration for single-thermocline tanks, which would reduce investment in thermal energy storage systems (Galione et al. 2015; Zhao et al. 2016).

A.13 Hybrid systems

Hybrid systems provide the following general advantages:

- **Firm generation, independent of solar radiation.** The integration of thermal power generation into a CSP power plant compensates for long periods of solar scarcity.
- **Shared infrastructure, which reduces the cost of the power plant.** The common electrical infrastructure used to export the electricity to the grid can be shared among different technologies, reducing total installation costs.
- **Reduced number of power plants.** Hybrid power plants can behave like combined cycle power plants, adapting their operation to the grid operator´s demand.
- **Reduced cost of generation.** The capacity to operate 24 hours a day, 7 days a week reduces energy costs.
- **Load-tracking operation.** Performance is not penalized at partial loads due to decoupling. The solar field can keep outputting heat to the thermal energy storage at 100 percent load with no primary energy loss.

FIGURE A.12 Decoupled solar combined cycle system using central tower receiver



Source: Servert et al. 2015.

BOX A.1

Increasing generation flexibility: Thermal energy storage in decoupled solar combined cycle configurations

Decoupled solar combined cycle (DSCC) technology draws on various heat sources to load thermal energy—either pure, from a solar field, or cogenerated exhaust from a gas turbine. Components work independently at optimal efficiency with thermal energy storage, and the DSCC offers a competitive advantage when working as a load-tracking power plant.

The DSCC approach overcomes the performance penalties associated with other hybrid configurations, such as integrated solar combined cycle and coal + concentrating solar power. DSCC performance values are akin to combined cycle gas turbines but with poorer performance due to the heat exchanger, although the performance penalty is less than 10 percent. At partial loads, performance of combined cycle gas turbine suffers penalties of more than 50 percent due to inefficiencies in the gas and steam turbines. Some studies (Osterman-Burgess, Goswami, and Stefanakos 2015) have shown that there are benefits to including thermal energy storage in combined cycle gas turbines.

Energy-mix scenarios forecast high shares of variable renewable energy (photovoltaics and wind power). Flexible backup energy power plants should be operated at partial load conditions, where DSCC technology has a competitive advantage.

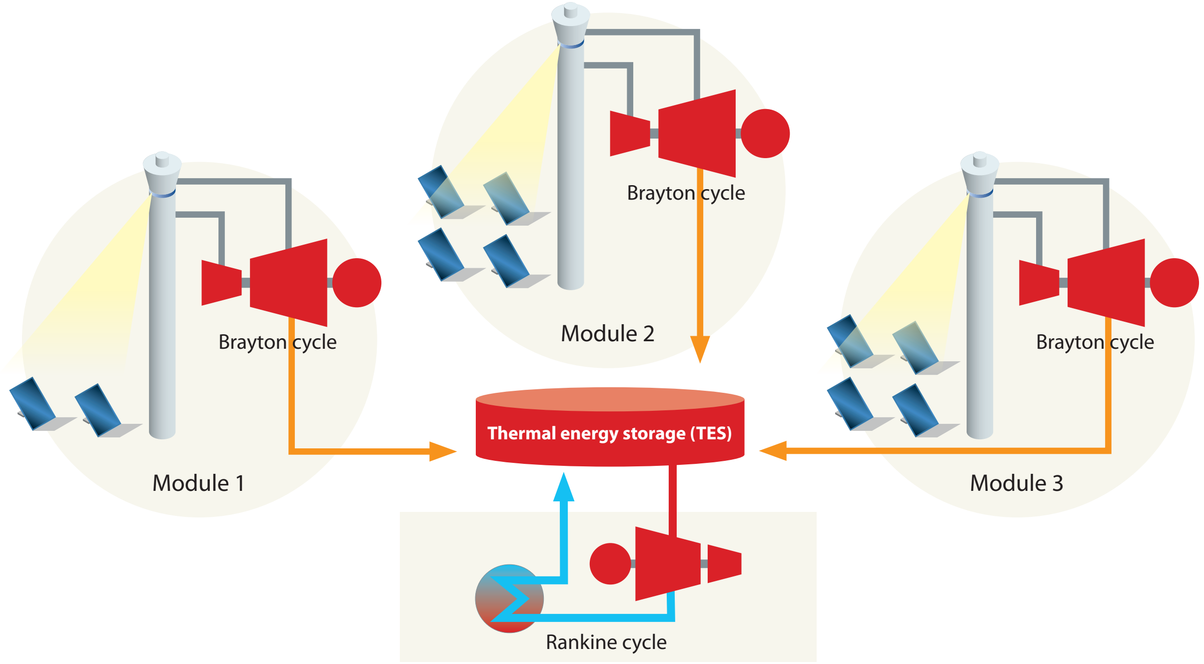
These characteristics suggest that the DSCC technology could substitute coal + combined cycle gas turbine power plants in future energy markets.

An integrated solar combined cycle system is a traditional hybrid technology with only a 5–10 percent solar share of the percentage of energy contributed by the solar field. Above these levels, efficiency losses exceed the solar energy being injected as turbines are optimized to work at a nearly full load. If they must throttle down to accept the solar field's contribution, they burn gas less efficiently. Solar steam is also cooler than heat-recovery steam, making the turbine steam generator less efficient. Therefore, direct hybridization can accept only minimal solar contributions (Zhu et al. 2015).

New concepts are under development to address these limitations, such as the decoupled solar combined cycle system (figure A.12 and box A.1).

Multiple configurations can be derived from this

FIGURE A.13 Schematic of CAPTure power plant



Source: CAPTure Consortium n.d.

concept as long as they contribute heat to the thermal energy storage, including gas turbines, tower systems, parabolic trough solar fields, exhaust from Brayton turbines, and biomass boilers. Figure A.13 presents a concept where solar tower driving Brayton turbines cogenerate electricity by driving a steam turbine generator through a thermal energy storage.

From an economic point of view, decoupled solar combined cycle technologies have obvious advantages: all the components share the same thermal energy storage and the steam turbine generator, making capital recovery costs for these two items nearly optimal. The consequence is that the levelized cost of energy for the decoupled solar combined cycle technology can be on a par with that of a standard combined cycle plant, but with lower CO_2 emissions and fuel consumption.

At their best, other hybrid concepts, such as photovoltaics + CSP, reach a capacity factor of 50 percent; decoupled hybrid solutions can reach up to 80 percent (Ju et al. 2017; Petrollese and Cocco 2016).

A coal + CSP plant is another thermal hybrid solution that can provide firm power (Siros et al. 2012) . At current gas and coal prices, these require 75 percent less capital expenditure than the decoupled solar combined cycle to output the same amount of energy, but the solar share is under 5 percent in most cases, and CO_2 emissions are mostly unchanged.

ANNEX B.
DEVELOPMENT PHASES, COMPONENT SUPPLIERS, AND SERVICE PROVIDERS INVOLVED IN CSP PROJECTS

TABLE B.1 **Companies involved in the construction of CSP plants, by type and project phase**

Type of company	Description
Developer	The project developer handles all project development activities from initial site location, feasibility studies, financial models, contracts, permits, installation, and construction management to ongoing maintenance and operations contracts. The company manages all parties within the transaction and is responsible for successful completion of the solar project. Examples: ACWA Power, Masdar, Engie, EDF NE, Cerro Dominador
Engineering, procurement, and construction (EPC) company	Usually a large construction company that subcontracts specific parts of the engineering and construction of the project and that carries out the procurement. Often has an equity investment in a concentrating solar power (CSP) project so it shares in the performance risk. Examples: TSK, Sener, SEPCO III, Acciona Construcción, Grupo Cobra, Shanghai Electric
Solar field equipment suppliers	Parabolic trough • Solar collectors - Mirrors - Receiver tubes - Collector structure - Tracker - Ball joints/flexible hose • Heat transfer system - Thermal oil - Heat transfer fluid piping - Heat transfer fluid circulation pumps - Expansion system Tower • Heliostats - Mirror - Structure - Tracker • Central receiver • Heat transfer fluid: molten salt Examples: Rioglass, Royal Tech, Sener, Abengoa, Aalborg, DOW, Therminol, BASF, SQM, Yara, Haiga, TSK Flagsol, John Cockerill (CMI)
Power block equipment suppliers	Supply equipment such as: • Steam turbine and electrical generator • Solar steam generator (heat exchange system) • Cooling system (dry: air-cooled condenser; wet: condenser + cooling tower) • Preheaters • Feed-water pump Examples: Siemens, Alstom, MAN, GE, Lointek, Foster Wheeler, SPX, GEA, Shanghai Electric
Balance of plant equipment suppliers	Supply equipment such as: • Electric system (step-up transformer, pump motors, and variable frequency drivers) • Instrumentation and control system (transmitters, cables) Examples: ABB, Siemens, GE, Schneider, Isotrol, Emerson
• Thermal energy storage system providers	Parabolic trough • Storage tanks • Heat exchanger system (molten salt to thermal oil) • Molten salts • Molten salt pumps (hot and cold pumps) Tower • Storage tanks • Molten salts • Molten salt pumps (hot and cold pumps) Examples: Siemens, Alstom, MAN, GE, Lointek, Aalborg CSP, Foster Wheeler, SPX, and GEA,
• Technical service providers	Supply services such as: • Environmental impact assessment • Solar resource assessment • Engineering design • Lenders' advisory and technical due diligence • Operation and maintenance service providers Examples: ATA Renewables, Worley Parsons, EA, Sener, Abengoa, TSK Flagsol
• Construction service providers	Services provided include land levelling and solar field assembly
• Investment and financing	Commercial banks and financial institutions that provide financing for CSP projects. Examples: Santander, BBVA, Standard Chartered Bank, the Silk Road Fund, Industrial and Commercial Bank of China (ICBC), Bank of China, Agricultural Bank of China, China Minsheng Bank

Source: ATA Insights.
Note: The companies listed in this table are for illustration only. Their inclusion does not constitute endorsement by the World Bank. Some of these companies might no longer be operating in the CSP space.

TABLE B.2 CSP component suppliers and service providers

Technology	Cost group	Solar industry	Supplier	Country	Project references
Parabolic trough or tower	Power block	Condenser	GEA	Germany	• Shams 1: 100 MW • PS20: 20 MW
			GEA Ibérica	Spain	• Andasol 1: 50 MW • Extresol 1: 50 MW
			MAN SE	Germany	• TSE 1—Parabolic Trough: 5 MW • Enerstar Villena: 50 MW
			SPX Corporation	United States	• Khi Solar One: 50 MW • Ivanpah SEGS: 392 MW
Parabolic trough or tower	Power block	Electric generator	ABB	Switzerland	• SEGS VIII: 80 MW
			Alstom	France	• Crescent Dunes: 110 MW
			GE Power	United States	• Mojave Solar: 280 MW • Palma del Rio I: 50 MW
			Siemens	Germany	• Ivanpah SEGS: 392 MW
Parabolic trough or tower	Power block	Steam generation system	Aalborg CSP	Denmark	• Godawari Green Energy: 50 MW; • Gujarat Solar One: 25 MW • DEWA Phase IV (200 MW x 3 PT SGS)
			Alstom	France	• Ashalim CSP plant 1–2: 110 MW and 121 MW respectively
			Foster Wheeler	Switzerland	• Andasol 1–2: 50 MW each • Samcasol 1–2: 50 MW each
			Lointek	Spain	• Manchasol 1–2: 50 MW each; Palma del Río I: 50 MW • DEWA Phase IV (100 MW x 1 CT SGS)
				United States	• Ivanpah SEGS: 392 MW
Parabolic trough or tower	Power block	Heat exchangers	Alfa Laval	Sweden	• Solana: 280 MW • Khi Solar One: 50 MW
			Lointek	Spain	• Manchasol 1–2: 50 MW each
			Talleres MAC	Spain	• Samcasol 1–2: 50 MW each • Termosol 1–2: 50 MW each
Parabolic trough	Power block	Heat transfer fluid pumps	Flowserve	United States	• Crescent Dunes: 110 MW • Mojave Solar: 280 MW
			KSB	Germany	• Solnova I: 50 MW
			GE Oil and Gas	United States	• Green Duba: 50 MW
			Sulzer	Switzerland	• Godawari Green Energy: 50 MW
Parabolic trough or tower	Power block	Steam turbine	Alstom	France	• Crescent Dunes: 110 MW • Ashalim CSP plant 1–2: 120 MW each
			GE Power	United States	• Mojave Solar: 280 MW • Palma del Rio I: 50 MW
			MAN Turbo	Germany	• Shams 1: 100 MW • Andasol 3: 50 MW • TSE1—parabolic trough: 5 MW • Enerstar Villena: 50 MW
			Siemens	Germany	• Nevada Solar One, Boulder City, Nevada, United States—parabolic trough (oil): 64 MW steam turbine: Siemens SST-700; power output: up to 74 MWe • Andasol 1 + 2, Granada, Spain—2 x parabolic trough (oil) plants: 50 MWe; 2 x Siemens SST-700 steam turbines; power output: 2 x 50 MWe • Solar tower (air): 1.5 MWe located in the city of Jülich, northwest Germany; steam turbine: Siemens SST-110, power output: 1.6 MW • Ivanpah Solar Power Complex, California, United States—3 x solar tower (water/direct steam) plants: 392 MWe (total); • BrightSource Energy—steam turbine: 3 x Siemens SST-900, power output: 123 MWe each • Puerto Errado 1 (PE1), Calasparra, Spain—linear Fresnel (water/direct steam): 1.4 MWe; steam turbine: Siemens SST-120, power output: 1.4 MW • Kuraymat, Egypt—ISCC plant: 126 MWe; steam turbine: Siemens SST-900; power output: 77 MW • Lebrija 1, Lebrija, Spain—parabolic trough (oil): 49.9 MWe, located in southern Spain in the province of Seville, Andalusia; steam turbine: Siemens SST-700; power output: up to 52 MW • Gemasolar, Fuentes de Andalucía, Spain—solar tower (molten salt): 17 MWe; steam turbine: Siemens SST-600; power output: up to 19 MW

Technology	Cost group	Solar industry	Supplier	Country	Project references
Parabolic trough or tower	Power block	Storage tanks	Caldwell Tanks	United States	• Solana
			Monesa	Spain	• Samca 1–2 • Arcosol 50 (Valle 1) • Termesol 50 (Valle 2)
			Flagsol	Spain	• Arenales
			Imasa	Spain	• Termesol 50 (Valle 2) • Arcosol 50 (Valle 1)
Parabolic trough or tower	Power block	Pumps	Ensival Moret	France	• Gemasolar • Extresol 3 • Termosol 1 • Termosol 2 • Extresol 1 • Extresol 2 • Andasol 1 • Andasol 2 • Casablanca • Manchasol 1 • Manchasol 2 • Arenales • Termesol 50 (Valle 2) • Arcosol 50 (Valle 1) • La Florida (Samcasol 1) • La Dehesa (Samcasol 2)
			Sulzer		• Andasol 1 • Andasol 2 • Solnova • Solnova 3 • Solnova 4 • Gemasolar • SEGS I • SEGS II • SEGS VIII • Godawari Green Energy • PS10 • PS20
			Flowserve	United States	• Gemasolar • Crescent Dunes
			GE Power	United States	
			KSB	Germany	
			Ruhrpumpen	Germany	
Parabolic trough	Solar field	Heat transfer fluid (thermal oil)	Dow Chemical	United States	• Solnova 1 • Solnova 4 • Extresol 1 • Extresol 2 • Extresol 3 • Aste 1A • Aste 1B • Andasol 1 • Andasol 2 • Thermosolar Borges • Ibersol Puertollano • Majadas • Martin Next Generation Solar Energy Center • Guzman (Termosolar Soluz Guzman)
			Therminol		• Helios 1 • LEBRIJA 1 • Has'i R'mel ISCC • Kuraymat ISCC • Solana • Abhijeet • Solnova 3
			Radco		• Saguaro • Holaniku at Keahole Point
			Solutia (Monsanto)	United States	• Godawari Green Energy • Kuraymat ISCC • Abhijeet • Aïn Beni Mathar ISCC • Helios 1 • Shams 1

Technology	Cost group	Solar industry	Supplier	Country	Project references
Parabolic trough or tower	Solar field	Mirror	Flabeg GmbH	Germany	• Saguaro • Caceres • La Africana • Extresol 1 • Extresol 2 • Extresol 3 • Manchasol 1 • Manchasol 2 • Genesis solar • Palma del Rio I • Termosol 1 • Andasol 1 • Andasol 2 • Avarado 1 (La Risca) • SEGS I • SEGS II • SEGS III • SEGS IV • SEGS V • SEGS VI • SEGS VII • SEGS VIII • Kuraymat ISCC • Enerstar Villena • Shams 1 • Aste 1a • Aste 1b • Nevada Solar One • Guzman (Termosolar Soluz Guzman) • Crescent Dunes • Sierra SunTower
			Guardian	United States	• Gemasolar • Ivanpah SEGS
			Siemens	Germany	• Lebrija 1
			Rioglass Solar	Spain	• Solana • La Florida (Samcasol 1) • La Dehesa (Samcasol 2) • Hassi R'mel ISCC • Mojave Solar • Helioenergy 1 • Helios 1 • Helios 2 • Palen SEGS • Agua Prieta II ISCC • Noor Ouarazate II and III • Ibersol Puertollano
			Saint-Gobain	France	• Extresol 1
Parabolic trough	Solar field	Receiver tube	Solel		• Manchasol 1 • Manchasol 2 • Caceres • Nevada Solar One • Andasol 1 • Andasol 2 • Extresol 2 • Martin Next Generation Solar Energy Center • Ibersol Puertollano • Manchasol 1
			Schott Solar AG	Germany	• Ibersol Puertollano • Solana • Manchasol 1 • Manchasol 2 • Kraymat ISCC • Extresol 1 • Extresol 3 • Has'i R'mel ISCC • La Florida (Samcasol 1) • La Dehesa (Samcasol 2) • La Africana • Archetype SW550 • Shams 1 • Majadas • Enerstar Villena • Andasol 1 • Andasol 2 • Andasol 3 • Helios 1 • Nevada Solar One
			Siemens	Germany	• Megha Engineering • Abhijeet
			Archimede	Italy	• Campu Giiavesu • Flumini Mannu • Archimede–Chiyoda Molten Salt Test Loop • Gonnosfanadiga • Archimede

Technology	Cost group	Solar industry	Supplier	Country	Project references
Tower (molten salts)	Solar field	Central receiver	Sener	Spain	• Gemasolar (Seville, Spain), 20 MWe (operational) • Noor III (Morocco), 150 MWe (operational)
			SolarReserve Rocketdyne	United States	• Crescent Dunes (Tonopah, Nevada), 110 MWe (operational) • Crossroads solar energy project (Gila Bend, Arizona, United States), 150 MWe (planned) • Saguache solar energy project (United States), 200 MWe (planned) • Quartzsite (United States), 100 MWe (planned)
Tower (steam)	Solar field		CMI Energy	Belgium	• Planta Solar Cerro Dominador (Atacama 1), Chile, 110 MWe (under construction) • DEWA Phase IV, 100 MWe Tower, Dubai, (under construction) • Planta Solar Cerro Dominador (Atacama 2), Chile, 110 MWe (under construction) • Khi Solar One (South Africa), 50 MWe (operational)
			Abengoa	Spain	• Planta Solar Cerro Dominador (Atacama 2), Chile, 110 MWe (under construction) • Planta Solar Cerro Dominador (Atacama 2), Chile, 110 MWe (under construction) • Khi Solar One (South Africa), 50 MWe (under construction) • PS10 (Spain), 11 MWe (operational) • PS20 (Spain), 20 MWe (operational) • Solugas (Spain), 4.6 MWe (operational) • Eureka (Spain), 2 MWe (operational)
			Aalborg CSP	Denmark	• Integrated energy system for Sundrop Farms, Australia, 2016 (operational) • Molten salt receiver tower, South America, 2012 • Solar tower receiver (superheated steam, 20 MWe), Spain, 2008 • Solar tower receiver (saturated and superheated steam, 3 MW-t), Turkey, 2010
Parabolic trough or tower	Solar field	Structure—tracker	Gossamer	United States	• Large aperture trough—LAT (Nevada Solar One, 50 MW), Martin Next Generation Solar Energy Center (75 MW), La Risca (Spain, 50 MW), Majadas (Spain, 50 MW), Palma del Rio (Spain, 50 MW)
			SBP	Germany	• EuroTrough (Andasol I–III: Spain, Egypt, India, and United States) • UltimateTrough (Duba, Saudi Arabia) • Stellio (PSA, Spain) • Stirling engine 3–50 kW (Spain, France, Germany, Italy, and India)
			SENER	Spain	• Heliocost project (Gemasolar, Seville, Spain, 20 MWe) • SENERtrough®
Parabolic trough or tower	Storage system	Solar salt	SQM	Chile	• Kaxu Solar (2014—22600 MT) • Xina Solar One (2016—48,400 MT) • Ilanga 1 (2017—37,290 MT) • Bokpoort (2015—38,214 MT)
			Haifa	Israel	• Shams 1

Technology	Cost group	Solar industry	Supplier	Country	Project references
Parabolic trough or tower	Engineering, procurement, and construction contract	Engineering, procurement, and construction contractor	Abengoa	Spain	• Mojave Solar: parabolic trough, United States, 280 MWe (operational) • Shams 1: parabolic trough, United Arab Emirates, 100 MWe (operational) • DEWA Phase IV, 200 MWe Parabolic Trough, Dubai, (under construction) • Khi Solar One: central receiver, South Africa, 50 MWe (operational) • Kaxu Solar One: parabolic trough, South Africa, 100 MWe (operational)
				Spain	• Ilanga CSP 1: parabolic trough, South Africa,100 MWe (operational) • Casablanca: parabolic trough, Spain, 50 MWe (operational) • Manchasol 1: parabolic trough, Spain, 50 MWe (operational) • Crescent Dunes: central receiver, United States, 110 MWe (operational) • Gemasolar: central receiver, Spain, 20 MWe (operational) • Andasol 1: parabolic trough, Spain, 50 MWe (operational) • Andasol 2: parabolic trough, Spain, 50 MWe (operational) • Arcosol 50: parabolic trough, Spain, 50 MWe (operational) • Termesol 50: parabolic trough, Spain, 50 MWe (operational) • Extresol 2: parabolic trough, Spain, 50 MWe (operational) • Kathu Solar Park: parabolic trough, South Africa, 100 MWe (under construction) • Duba 1: parabolic trough solar field for 43 MW ISCC plant, Saudi Arabia
				United States	• Extresol 2: parabolic trough, Spain, 50 MWe (operational)
				Saudi Arabia	
			Acciona	Spain	• Palma del Rio II: parabolic trough, Spain, 50 MWe (operational) • Majadas: parabolic trough, Spain, 50 MWe (operational) • Alvarado 1—La Risca: parabolic trough, Spain, 50 MWe (operational) • Olivenza 1: parabolic trough, Spain, 50 MWe (operational) • Noor I: parabolic trough, Morocco, 160 MWe (operational) • Bokpoort: parabolic trough, South Africa, 50 MWe (operational) • Redstone CSP project: central receiver, South Africa, 100 MWe (under development)
				Spain	
				Spain	• La Florida–Samcasol 1: power block of parabolic trough, Spain, 50 MWe (operational) • La Dehesa–Samcasol 2: power block of parabolic trough, Spain, 50 MWe (operational) • Extresol 1: parabolic trough, Spain, 50 MWe (operational) • Noor I: parabolic trough, Morocco, 160 MWe • Bokpoort: parabolic trough, South Africa, 50 MWe • Shagaya CSP project: parabolic trough, Kuwait, 50 MWe (operational)

Source: Solar Technology Advisors
Note: CSP = concentrating solar power; ISCC = integrated solar combined cycle; kW = kilowatt; MW = megawatt; MWe = megawatt electric; MT = metric tons; MW-t = megawatt thermal; SEGS = solar energy generating system.
Some of these companies might no longer be operating in the CSP space.

TABLE B.3 New potential suppliers emerging from the Chinese CSP demonstration program

Technology	Cost group	Solar industry	Supplier
Parabolic trough or tower	Power block	Steam turbine	• Shanghai Electric Turbine • Dongfang Turbine • Harbin Turbine • Hangzhou Turbine
Parabolic trough or tower	Power block	Condenser	• Shanghai Boiler Turbine • Dongfang Turbine • Harbin Turbine • Hangzhou Turbine
Parabolic trough or tower	Power block	Electric generator	• Shanghai Electric Turbine • Dongfang Turbine • Harbin Turbine • Hangzhou Turbine
Parabolic trough or tower	Power block	Heat exchangers	• Jiangsu Sunhome • Hangzhou Boilers • Dongfang Boilers • Shanghai Electric Station • Harbin Turbines
Parabolic trough or tower	Storage system	Storage tanks	• Jiangsu Sunhome • Shenzhen Enesoon • Dongfang Boiler • Harbin Turbine Company • Shandong Sunway
Parabolic trough or tower	Storage system	Molten salt pumps	• Guilin Guanghui • Jiangsu Jinlin Chemicals • Dailian Deep Blue • Suzhou Sulzer Pumps (Sulzer)
Parabolic trough or tower	Storage system	Solar salt	• Shenzhen Enesoon • Zhajiang United Chemical • Xinjiang Nitrate Potash • Wentong Potash • Baijirui (TianJin) New Energy
Parabolic trough	Heat transfer fluid system	Heat transfer fluid thermal oil	• Suzhou Therminol • Jiangsu Manto • Shenzhen Enesoon • Jiangsu Zhongneng Chemical
Parabolic trough	Heat transfer fluid system	Heat transfer fluid pumps	• Daian (Hermetric) • Dalian Deep blue pump • Suzhou (Sulzer)
Parabolic trough	Solar field	Structure—Tracker	• Rayspower Energy Group • Suncan CSP • Changzhou Royal Tech • Chengdu Broad Youth
Solar tower	Solar field	Central receiver	• Hangzhou Boiler • Dongfang Electric Group Boiler • Shouhang • Supcon Solar • Shanghai Boiler
Parabolic trough or tower	Solar field	Mirror	• Sundhy Chengdu • Wuhan S&P • Taiwan Yueda • Zhejiang Daming
Parabolic trough	Solar field	Receiver tube	• Beijing TRX CSP • Changzhou Royal Tech Solar Thermal • Lanzhou Dacheng • Weihai Huiyin Group

Source: Solar Technology Advisors.
Note: CSP = concentrating solar power. Some of these companies might no longer be operating in the CSP space

ANNEX C.
CSP PLANTS IN OPERATION AND UNDER CONSTRUCTION

Country	Project name	Technology	Capacity (MWe)	Storage Hours	Status
Chile	Cerro Dominador 1	Tower	110	17.5	Under Construction
China	Luneng Haixi	Tower	50	12	Operational
China	Beijing Shouhang IHW Dunhuang	Tower	100	11	Operational
China	CPECC Hami Tower	Tower	50	8	Operational
China	Power China Gonghe	Tower	50	6	Operational
China	Qinghai SUPCON Solar Delingha	Tower	50	6	Operational
China	Lanzhou Dacheng Dunhuang Molten Salt Fresnel	Fresnel	50	13	Operational
China	CGN Solar Delingha PT	Trough	50	9	Operational
China	CSNP Royal Tech Urat	Trough	100	10	Operational
China	Royal Tech Yumendongzhen	Trough	50	9	Under Construction
China	Yumen Xinneng	Tower	50	6	Under Construction
Egypt	Kuraymat ISCC	Parabolic Trough	20	0	Operational
India	Godawari Green Energy	Parabolic Trough	50	0	Operational
India	Megha	Parabolic Trough	50	8	Operational
Israel	Ashalim Plot A (Negev Energy)	Parabolic Trough	110	4.5	Operational
Israel	Ashalim Plot B (Megalim Solar Power)	Tower	121	0	Operational
Kuwait	Shagaya CSP Project - Phase One	Parabolic Trough	50	10	Operational
Morocco	Noor Midelt I*	Trough	200	5	Under Construction
Morocco	Noor Ouarzazate I	Parabolic Trough	160	3	Operational
Morocco	Noor Ouarzazate II	Parabolic Trough	200	6	Operational
Morocco	Noor Ouarzazate III	Tower	150	7.5	Operational
Saudi Arabia	Waad Al Shamal ISCC Plant	Parabolic Trough	50	0	Operational
South Africa	Ilanga CSP 1 (Karoshoek Solar One)	Parabolic Trough	100	5	Operational
South Africa	KaXu Solar One	Parabolic Trough	100	2.5	Operational
South Africa	Kathu CSP	Parabolic Trough	100	4.5	Operational
South Africa	Xina Solar One	Parabolic Trough	100	5	Operational
South Africa	Bokpoort	Parabolic Trough	50	9.3	Operational
South Africa	Khi Solar One	Tower	50	2	Operational
Spain	Andasol 1	Parabolic Trough	50	7.5	Operational
Spain	Andasol 2	Parabolic Trough	50	7.5	Operational
Spain	Andasol 3	Parabolic Trough	50	7.5	Operational
Spain	Arenales PS	Parabolic Trough	50	7	Operational
Spain	La Africana	Parabolic Trough	50	7.5	Operational
Spain	ASTE - 1A	Parabolic Trough	50	8	Operational
Spain	ASTE - 1B	Parabolic Trough	50	8	Operational
Spain	Astexol-2	Parabolic Trough	50	7.5	Operational
Spain	Enerstar Villena	Parabolic Trough	50	0	Operational
Spain	Casablanca	Parabolic Trough	50	7.5	Operational
Spain	La Dehesa	Parabolic Trough	50	7.5	Operational
Spain	La Florida	Parabolic Trough	50	7.5	Operational
Spain	Extresol 1	Parabolic Trough	50	7.5	Operational
Spain	Extresol 2	Parabolic Trough	50	7.5	Operational
Spain	Extresol 3	Parabolic Trough	50	7.5	Operational

Country	Project name	Technology	Capacity (MWe)	Storage Hours	Status
Spain	HelioEnergy 1	Parabolic Trough	50	0	Operational
Spain	HelioEnergy 2	Parabolic Trough	50	0	Operational
Spain	Helios 1	Parabolic Trough	50	0	Operational
Spain	Helios 2	Parabolic Trough	50	0	Operational
Spain	La Risca	Parabolic Trough	50	0	Operational
Spain	Lebrija 1	Parabolic Trough	50	0	Operational
Spain	Manchasol 1	Parabolic Trough	50	7.5	Operational
Spain	Manchasol 2	Parabolic Trough	50	7.5	Operational
Spain	Consol Orellana	Parabolic Trough	50	0	Operational
Spain	Palma del Rio I	Parabolic Trough	50	0	Operational
Spain	Palma del Rio II	Parabolic Trough	50	0	Operational
Spain	Morón	Parabolic Trough	50	0	Operational
Spain	Olivenza I	Parabolic Trough	50	0	Operational
Spain	Puertollano Ibersol	Parabolic Trough	50	0	Operational
Spain	Solaben 6	Parabolic Trough	50	0	Operational
Spain	Solaben I	Parabolic Trough	50	0	Operational
Spain	Solaben II	Parabolic Trough	50	0	Operational
Spain	Solaben III	Parabolic Trough	50	0	Operational
Spain	Solacor 1	Parabolic Trough	50	0	Operational
Spain	Solacor 2	Parabolic Trough	50	0	Operational
Spain	Solnova 1	Parabolic Trough	50	0	Operational
Spain	Solnova 3	Parabolic Trough	50	0	Operational
Spain	Solnova 4	Parabolic Trough	50	0	Operational
Spain	Soluz Guzman	Parabolic Trough	50	0	Operational
Spain	Majadas	Parabolic Trough	50	0	Operational
Spain	Termosol 1	Parabolic Trough	50	9	Operational
Spain	Termosol 2	Parabolic Trough	50	9	Operational
Spain	Valle 1	Parabolic Trough	50	7.5	Operational
Spain	Valle 2	Parabolic Trough	50	7.5	Operational
UAE	Noor Energy 1 CSP Project - Unit 1	Tower	100	15	Under Construction
UAE	Noor Energy 1 CSP Project - Unit 2	Parabolic Trough	200	12	Under Construction
UAE	Noor Energy 1 CSP Project - Unit 3	Parabolic Trough	200	15	Under Construction
UAE	Noor Energy 1 CSP Project - Unit 4	Parabolic Trough	200	15	Under Construction
UAE	Shams 1	Parabolic Trough	100	0	Operational
USA	Genesis Solar 1	Parabolic Trough	125	0	Operational
USA	Genesis Solar 2	Parabolic Trough	125	0	Operational
USA	Mojave Solar Project	Parabolic Trough	280	0	Operational
USA	Solana	Parabolic Trough	280	6	Operational
USA	Nevada Solar One	Parabolic Trough	64	0.5	Operational
USA	Martin Next Generation Solar Energy Center	Parabolic Trough	75	0	Operational
USA	SEGS VIII	Parabolic Trough	89	0	Operational
USA	SEGS IX	Parabolic Trough	89	0	Operational
USA	Ivanpah Solar Electric Generating Station I	Tower	126	0	Operational
USA	Ivanpah Solar Electric Generating Station II	Tower	133	0	Operational
USA	Ivanpah Solar Electric Generating Station III	Tower	133	0	Operational

Source: ATA Insights, CSP Today Global Tracker and NREL SolarPACES. * The exact share of CSP and PV in the Midelt project is still undisclosed