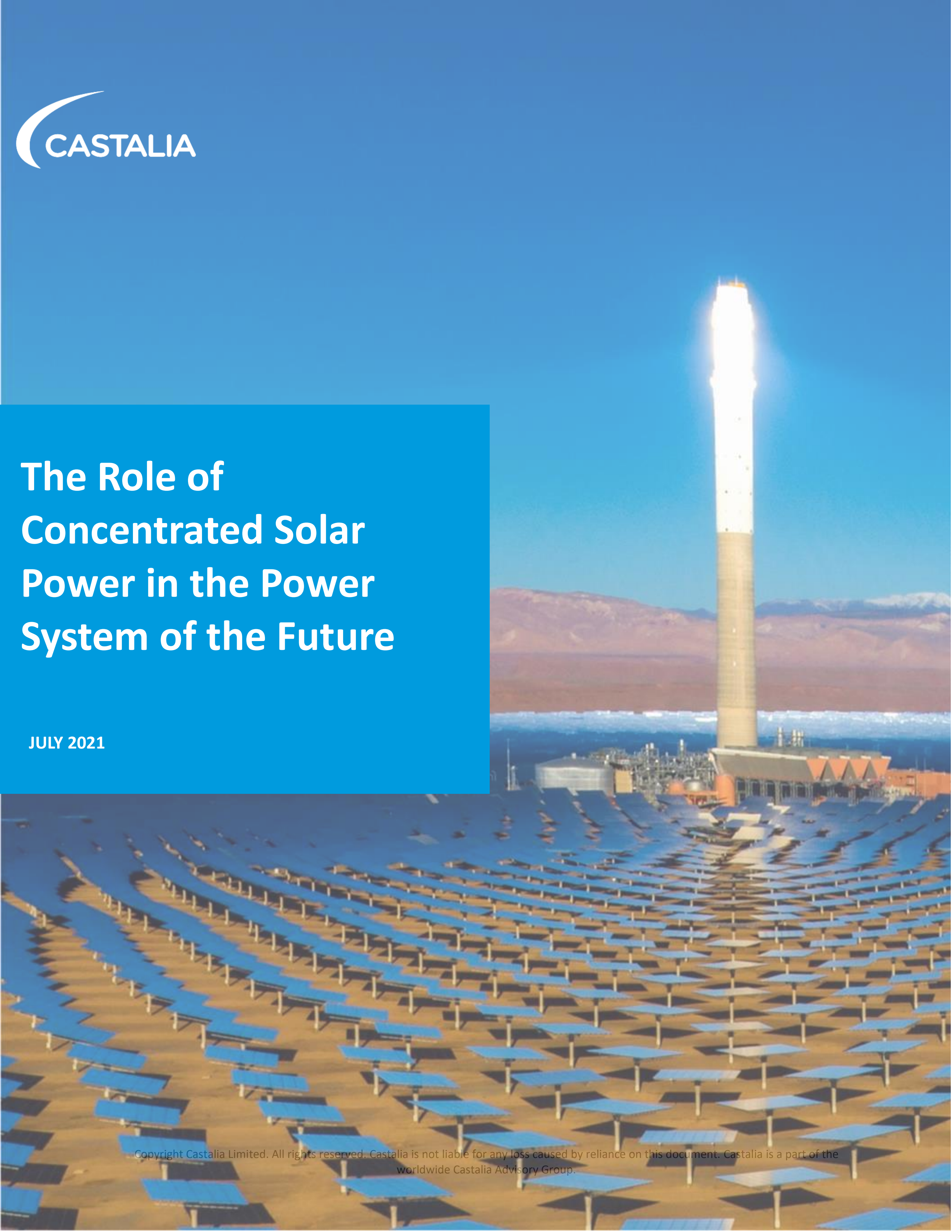


# The Role of Concentrated Solar Power in the Power System of the Future

**JULY 2021**

# Introduction

This White Paper discusses the role of Concentrated Solar Power (CSP) in the power system of the future. Given significant decreases in costs and ability to provide flexible power, CSP is expected to play a key role as local and renewable source of power to cope with increasing amounts of variable renewable energy (vRE) in power systems. Section 1 briefly explains how CSP works and describes the two leading CSP technologies. Section 2 details the two types of flexibility provided by CSP: providing power at night with thermal storage, and the ability to quickly start generating or increase power output during the day, to complement solar photovoltaic (PV).

# 1 Basics of Concentrated Solar Power

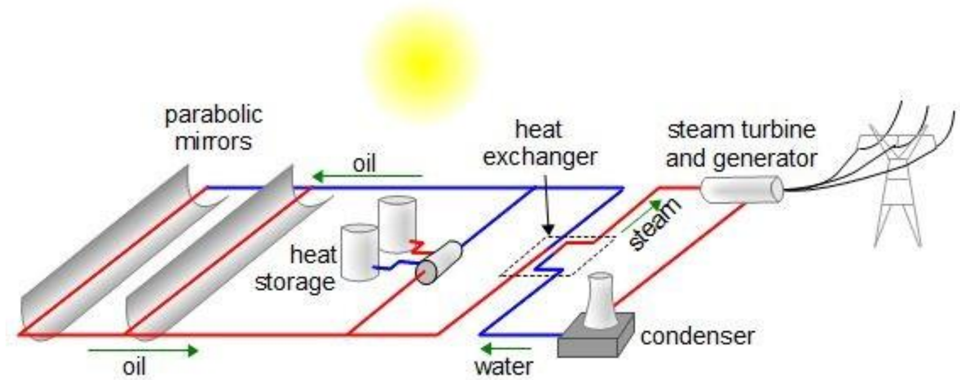
*Parabolic-trough collectors in the Nevada Solar One power plant*
*Source: Taylan and Berberoglu, Fuel Production Using Concentrated Solar Energy, accessed on April 22nd, 2021*

CSP plants are thermal power systems that capture direct solar irradiation, concentrate it, and transform it into heat and eventually into electricity. CSP plants are similar to conventional thermal power plants, the only difference being the heat source which is solar irradiation instead of combustive fossil fuels. Mirrors concentrate solar irradiation, which heats up a heat transfer fluid (HTF). The HTF is then used to generate steam by passing through a heat exchanger. The steam in turns generates electricity with a steam turbine. Heat can also be stored via a HTF called molten salt, which is kept in storage tanks. Molten salts are in liquid state at high temperatures (300°C to 500°C).

*Note: aerial view of the Germasolar plant in Spain,*
*Source: Castalia, Report to the World Bank, 2020, CSP Technology Review and Preliminary Assessment*

There are two front-runner CSP technologies:

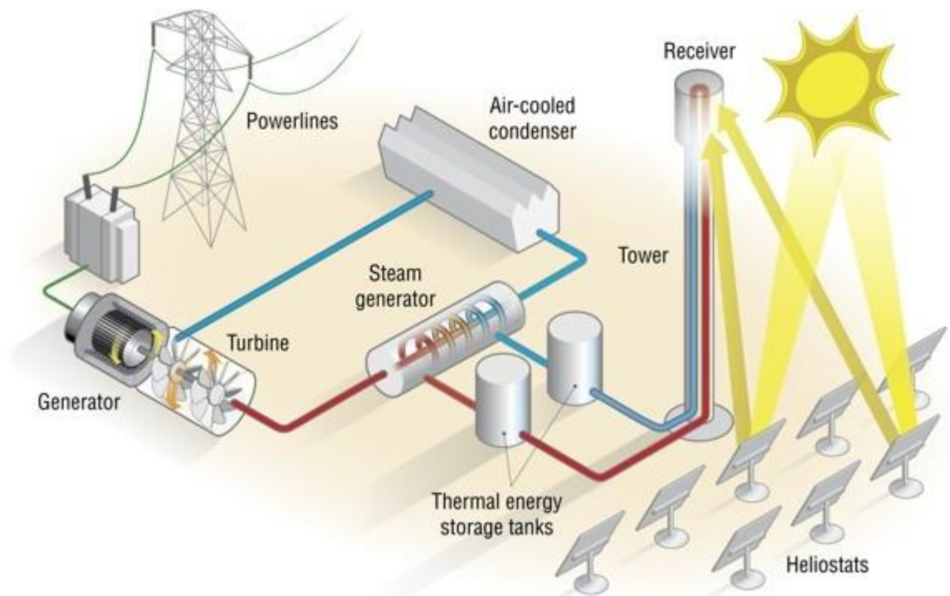
- **Parabolic Trough Collectors (PTC)** where the solar irradiation is concentrated at the center of parabolic mirrors. In PTC there are two HTFs. The first HTF is a synthetic oil. It flows at the center of each parabolic mirror and is directly heated by the solar irradiation.




*Source: Castalia, Report to the World Bank, 2020, CSP Technology Review and Preliminary Assessment*

Thermal energy from the synthetic oil may be used directly to produce electricity or may be stored through the second HTF, molten salt. PTC is the most mature and least risky technology. The first PTC plant (without thermal energy storage) dates back to 1985.

- **Central Receiver Tower (CRT) with molten salt**, where the solar irradiation is concentrated onto a single receiver at the top of a tower, where it heats molten salt (the HTF).




*Source: US Department of Energy, "CSP System Analysis", https://www.energy.gov/eere/solar/csp-systems-analysis, accessed on November 7th, 2020*
*Note: heliostats are the mirrors used to concentrate the solar irradiation*

In CRT, all the HTF is stored before passing through the heat exchange to generate steam and electricity. CRT is the most promising technology due to its high potential for increase in efficiency and cost reductions.

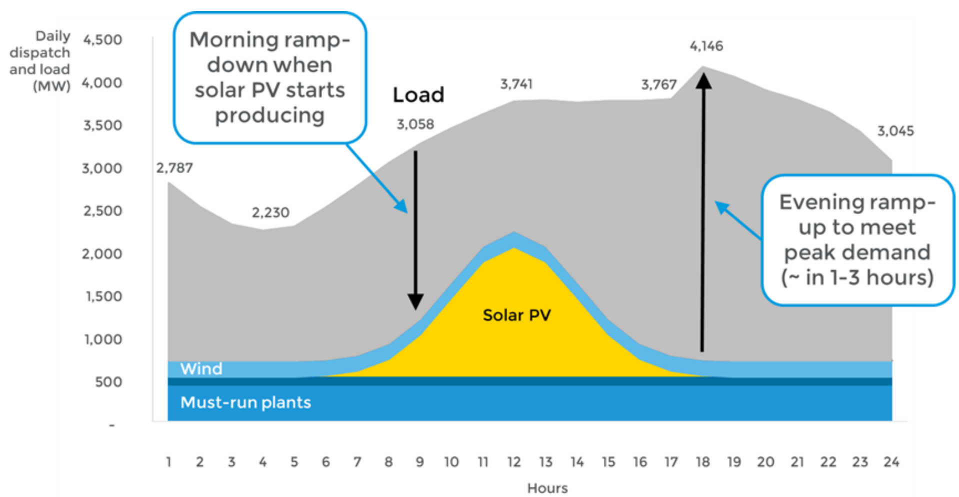
# 2 CSP with Thermal Storage Provides Flexible Renewable Power

This section first identifies the challenges posed by increasing amounts of variable renewable energy (vRE) in power systems and defines flexibility (Section 2.1). The section then describes the two types of flexibility that CSP can provide: flexibility to provide power at any time of the day, and especially at night (Section 2.2); and flexibility to quickly start generating power or increase power output in response to changes in demand and supply from other power plants (Section 2.3).

## 2.1 What does flexibility mean and why is it important?

Flexibility has become critical in power systems today, given the increasing penetration of vRE. Flexibility of a power system refers to the ability of a power system to cope with the following challenges posed by increasing vRE deployment:

- **Need for power at night**: solar PV alone, without storage, cannot meet demand at night. This means that power systems need other forms of supply for power at night (gas-fired power plants, or other thermal plans); or storage solutions for solar PV (e.g., pumped hydro storage or battery storage)
- **Need to ramp up and down power supply during the day**: with large uptakes of solar PV to meet demand during the day at low cost, power systems must be able to quickly ramp up supply in the evening, while solar PV output decreases at the same time as the evening peak demand materializes. This is illustrated in the stylized daily dispatch and load profile below.

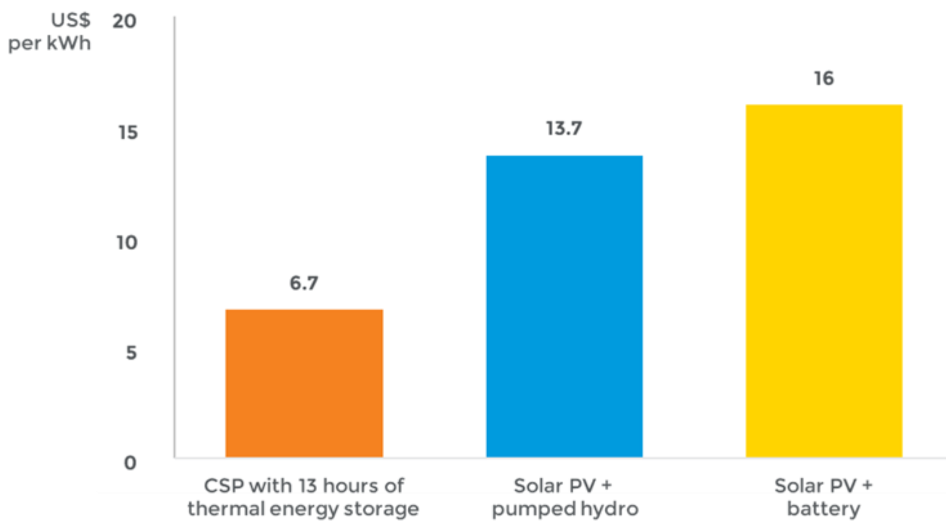



- **Need for rapid response**: output of solar PV and wind power plants is variable based on weather conditions: solar PV output decreases as clouds go by and wind power output varies according to windspeed. These frequent variations put pressure on the grid stability, which must at all times balance supply and demand. Power systems need supply sources that can provide rapid response and balance voltage and frequency variations (these are called ancillary services).

CSP with thermal energy provides a solution to the first two challenges of future power systems by providing renewable power at night (Section 2.2 ) and the ability to ramp up and down during the day (Section 2.3).

## 2.2 CSP with thermal storage provides nighttime power

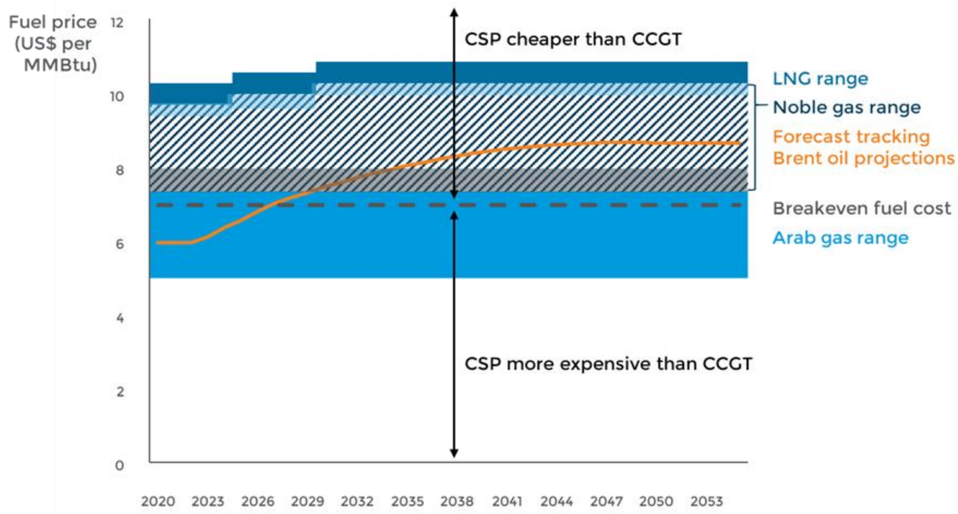
CSP with thermal energy storage provides least-cost renewable nighttime power. As illustrated in the figure below, CSP with TES (13 hours in the example below) is cheaper than solar PV with storage, be it with pumped hydro or with battery storage.




*Source: Castalia, Report to the World Bank, 2020, Feasibility Study for CPS in a Middle-Eastern country*
*Note: This is an estimate with a 150MW CSP plant and 13 hours of storage. This graph does not provide a complete apples-to-apples comparison since solar battery with storage technologies would provide different services than CSP (ancillary services and rapid response), but it gives an order of magnitude of levelized cost of electricity (LCOE) for a large amount of energy stored.*

Further, CSP is competitive with combined-cycle gas turbine (CCGT) plants, under most fuel forecasts, as illustrated in the figure below.[1] The breakeven gas price estimated for a 150MW CSP plant with 13 hours of storage is US$6.96 per MMBTU. Above the breakeven gas price, CSP is cheaper on an LCOE basis than CCGT.

[1] Based on gas prices in a Middle-Eastern country.




*Source: Castalia, Report to the World Bank, 2020, Feasibility Study for CSP in a Middle Eastern country*

## 2.3 CSP provides flexible power output during the day

CSP plants have the required flexibility to increase or decrease their load to complement solar PV. The typical metrics used to define the capabilities of a plant to start generating power or increase its power output are:

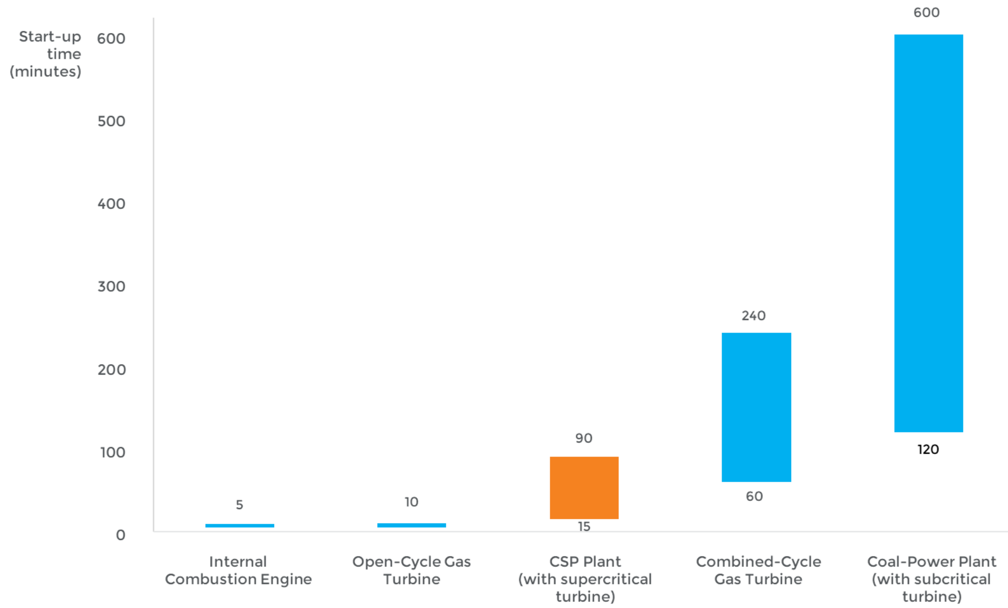
- **Start-up time** (in minutes or hours): the time that it takes for a plant to go from 0% to 100% load. Start-up time depends on the heat of the turbine, which in turn depends on how long the power plant has been turned off. Typically, start-up time is divided into three categories: cold, warm, and hot start.

| Type of start | Preceding Standstill Time (h) |
|---|---|
| **Cold Start** | >48 |
| **Warm Start** | >8 and ≤48 |
| **Hot Start** | ≤8 |

*Source: Gonzalez-Salazar et.al, 2017, [Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables]*

- **Minimum load** (in %): the minimum load is the minimum current or power that must be drawn from the power supply in order for the supply to meet its performance specifications
- **Ramp rate** (in MW/min or %/min or % per hour): the rate at which a plant can change its net power during operations
- **Uptime and downtime** (in minutes or hours): the time that the plant must keep running before shutdown and the time that it must remain closed after shutdown.

CSP with supercritical steam turbines are more flexible than the majority of installed coal-fired power plants and have flexibility levels similar to CCGT plants. Such CSP plants are well-placed to increase or decrease their load while solar PV ramps up or down at the start of the day or in the evening.




*Note: start-up times are lower for hot start than for cold start.*
*Sources:*

- *Conventional power plants:*
  *IRENA, 2019, Flexibility in Conventional Power Plants, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Flexibility_in_CPPs_2019.pdf?la=en&hash=AF60106EA083E492638D8FA9ADF7FD099259F5A1*
- *CSP:*
  - *NREL, 2014, Operation of Concentrating Solar Power Plants in the Western Wind and Solar Integration Phase 2 Study, https://www.hindawi.com/journals/ijp/2019/8796814/ https://www.nrel.gov/docs/fy14osti/61782.pdf This study assumes ability to ramp up to 100% load in an hour.*
  - *Price et.al (SolarPACES), 2017, Dispatchable Solar Power Plant, https://www.solarpaces.org/wp-content/uploads/Hank-Price-Dispatchable-Solar-Power-Plant-.pdf This study assumes ability to start up (warm start) and ramp to full load in 30 minutes*
  - *ATA, 2019, Middle East and North Africa CSP Knowledge and Innovation Program, Technology Evaluation Report. This study assumes the following: cold start: 60-90 minutes; warm start: 20-60 minutes; hot start: 15 minutes.*

The bottleneck in the flexibility of a CSP plant is the steam turbine, which is less flexible than a gas turbine or a combustion turbine. Steam turbines are also used in other conventional technologies, such as coal-fired power plants, and in CCGT plants (which combine steam and gas turbines). Most installed coal-fired power plants (80%) use subcritical steam engines that have low flexibility.[2] However, more flexible steam turbines, called supercritical steam turbines, are increasingly used in coal-fired power plants[3] and can also be used for CSP plants.[4]

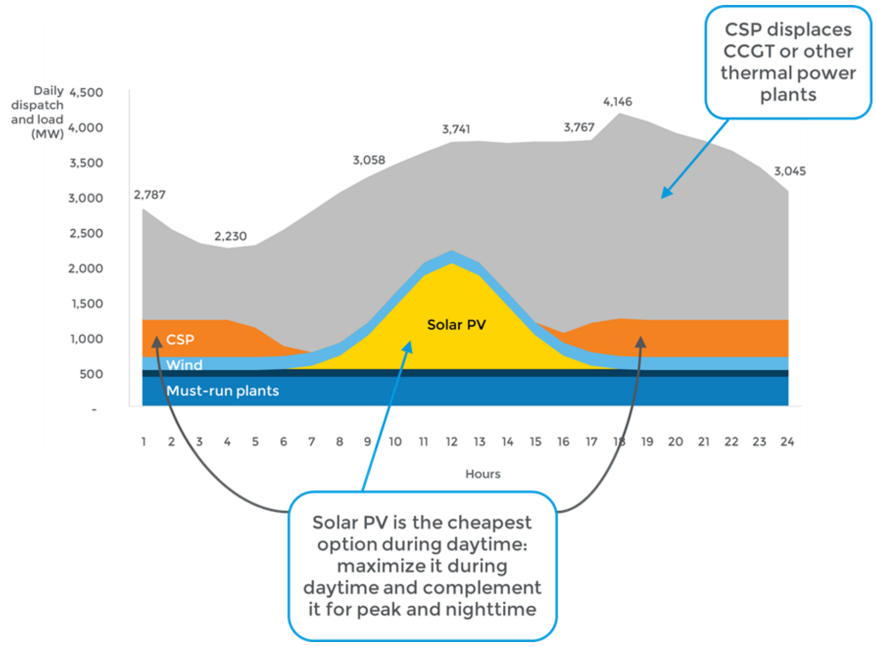
A comparison of start-up time between CSP with such turbines and conventional thermal power plants shows that CSP plants with supercritical steam engines are more flexible than the majority of the installed coal-fired power plant fleet, and have flexibility levels in the same order of magnitude as CCGT plants.

[2] Gonzalez-Salazar *et.al*, 2017, https://www.sciencedirect.com/science/article/pii/S1364032117309206

[3] About 15% of the fleet of coal-fired plants use supercritical steam turbines.
Source: Ibid.

[4] Sandia National Laboratories, 2013, Incorporating Supercritical Steam Turbines into Advanced Molten-Salt Power Tower plants: Feasibility and Performance, https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2013/131960.pdf

CSP with thermal energy storage is, therefore, well-placed to complement solar PV. It allows maximizing solar PV, which is the cheapest source of supply during the day, while providing power during peak and at night (as illustrated in this figure). CSP is cost-competitive and has the technical capabilities to play this role instead of CCGT and other thermal plants that are currently playing it.




# 3 Key Takeaways

| | |
|---|---|
| **Flexibility has become critical in power systems today, given the increasing penetration of variable renewable energy.** | **CSP is competitive with CCGT plants under most fuel forecasts.** |
| **CSP plants with supercritical steam engines are more flexible than the majority of the installed coal-fired power plant fleet and have flexibility levels in the same order of magnitude as CCGT plants.** | **CSP with thermal energy storage is well-placed to complement solar PV. It allows maximizing solar PV, which is the cheapest source of supply during the day, while providing power during peak and at night.** |

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