Concentrating solar power (CSP) - Technologies, costs, and potentials

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Introduction

Solar is a bountiful renewable source of energy. The energy in the sunlight which reaches the earth in one hour exceeds the energy consumed by all of humanity in one year. The phrase "solar energy conversion" includes both, photovoltaic cells (PV), which directly produce electricity, and concentrating solar power (CSP) technologies, which use thermal heat concentrated by solar radiation. The first CSP prototypes were built as early as the late 19th century. A prototype of a solar heat plant was constructed in 1901 in California.[1] A parabolic trough plant was installed in 1913 near Cairo (Egypt) and powered with its heat a 45 kW steam engine, which was used for driving pumps for irrigation purposes.[2]

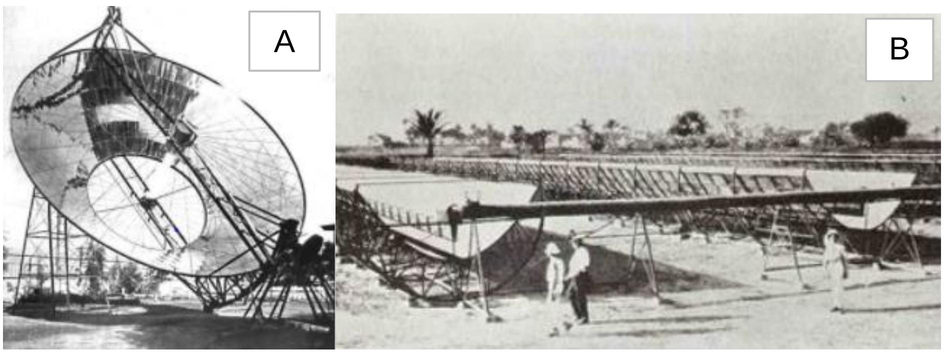

Figure 1: Historic CSP projects. (A) Solar heat plant in Los Angeles in 1901 (B) Solar trough collectors in Meadi (Egypt) 1913, near the Nile River. [1;3]

The first modern utility-scale CSP plants were built in the 1980s. For the following two decades CSP saw little expansion, but in recent years the use of CSP technologies has experienced an unprecedented growth as shown in Figure 2.[4]

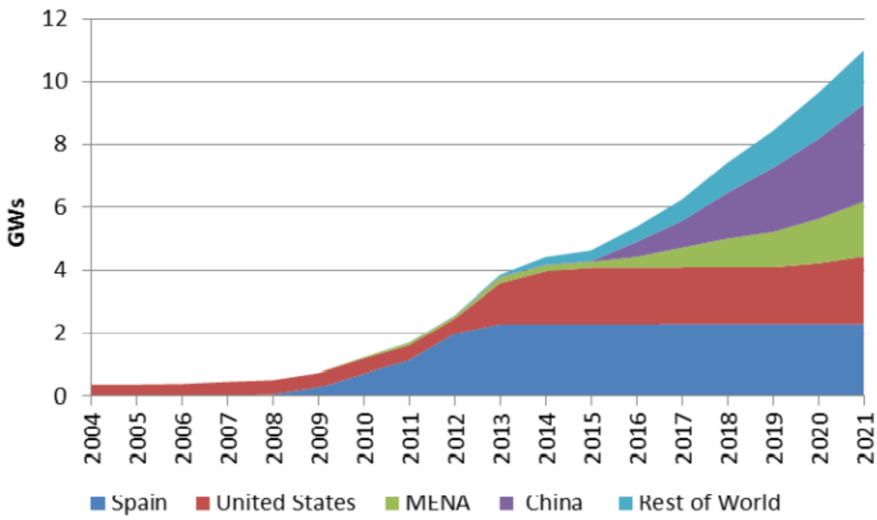

Figure 2: Actual installed (until 2015) and projected (2016 – 2021) global cumulative growth of CSP capacity.[5]

Photovoltaic cell plants currently have the largest deployment among solar electricity technologies, with the Levelized Cost of Electricity (LCOE) from PVs quickly dropping over the past decade.[6] There are some differences between the CSP and PV technologies that make CSP worth pursuing even if the costs of PVs are currently lower. Many of the practical differences arise from the fact that CSP plants use well-established turbine technologies to generate electricity. Turbines have very different scaling properties compared with PV systems because they become more efficient and cost effective with increasing size. Therefore, CSP can excel economically only in large installations (Figure 3) and limits CSP for small power plants and effectively excludes it from residential scale installations. CPS works best in areas with high year-round solar irradiance a condition found in the so called “global sunbelt” (Figure 4).

The most significant practical advantage of CSP over PV is the potential for thermal energy storage, which arises from its intermediary use of heat in the power production process. If equipped with sufficient Thermal Energy Storage (TES) capacity, CSP is able to completely decouple the solar-thermal and thermal-electricity conversion and can achieve continuous power production. It also allows the control of electric power output depending on the grid demand, regardless of the weather conditions. This dramatically increases the value of CSP plants for maintaining electric grid stability. Consequently, the relative value of a CSP plant can be up to twice as high as a PV plant (which has an inherently intermittent power output) for any electricity provider.[4;5]

In this article we will discuss current CSP technologies and its potential of economic improvement by reducing the LCOE. We will also provide a comparison of the LCOE for several CSP technologies as well as for fossil fuels and non-CSP renewable sources of power. However, before doing so, we will describe the typical daily and seasonal load variations of the grid’s electricity demands and the measures to cope with them.

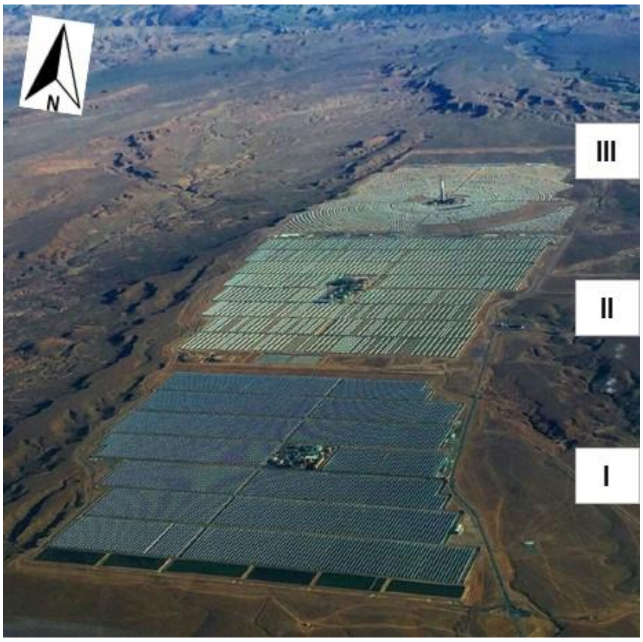

Figure 3: Aerial photo of the Noor I – III CSP-TES complex near Quarzazate (Morocco). Noor 1 (I): a 450 ha parabolic through plant with 150 MW capacity, Noor 2 (II) a 680 ha parabolic through plant with 200 MW capacity and Noor 3 (III) a 530 ha power tower plant with 530 MW capacity. Noor 4 (not shown) is a PV solar power plant.[7; 8]

The term “global sunbelt” refers to the regions between 35th degrees of northern and southern latitude. In this region the annual global solar irradiance at the land and ocean surfaces is highest on earth. These regions have the highest potential for solar power plants.[9] Approximately 80% of the world’s population in 148 out of 201 countries lives partly or completely in this region. NATO-members with state territory partly or completely in the “global sunbelt” are Greece, Italy, Portugal, Spain, Turkey and the United States of America, while for example, Malta is a Euro-Atlantic Partnership Council (EAPC) member. NATO partners in the “global sunbelt” are Australia, Colombia, Iraq, Japan, the Republic of Korea and Pakistan.

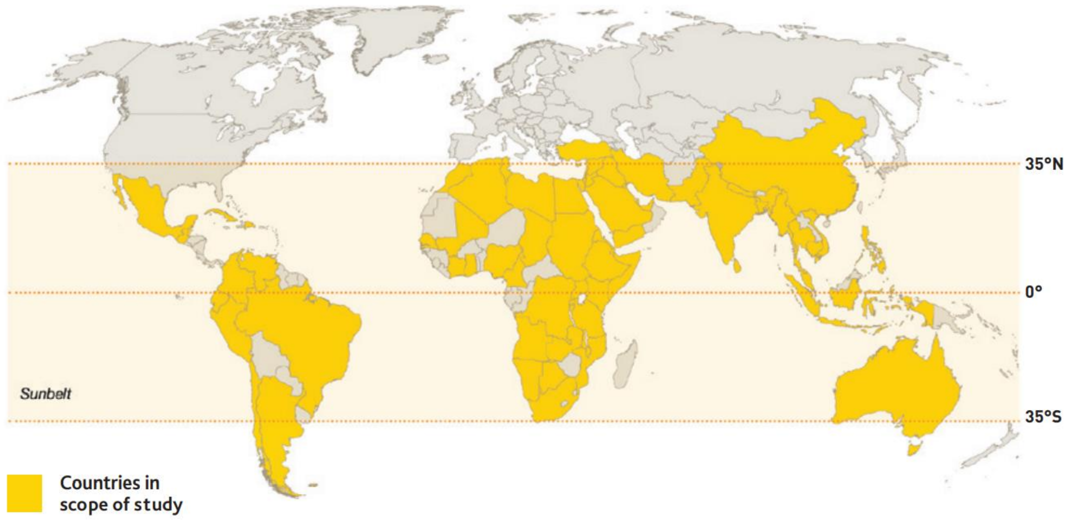

Figure 4: The region between 35 degrees of northern and southern latitude is referred to as the “global sunbelt”. Countries marked in yellow are included into a detailed study of the European Photovoltaic Industry Association.[9]

Diurnal and seasonal electricity demand and its coverage

Electrical load profiles in electric power grids vary on a daily as well as on a yearly basis. The variation is mainly driven by the composition of business and private consumers as well as by the season. The profile of private and business consumers mostly defines the patterns of the base load and the intermediate load, as well as the variations between weekdays and weekends. As the seasons influence the length of days and the daily temperature, it also influences the load profile as shown in Figure 5. The more pronounced the summer and winter seasons, the higher the weekly variation in electricity demand during the year. Therefore, the load management of power providers shows specific tasks depending on the environmental conditions.[10]

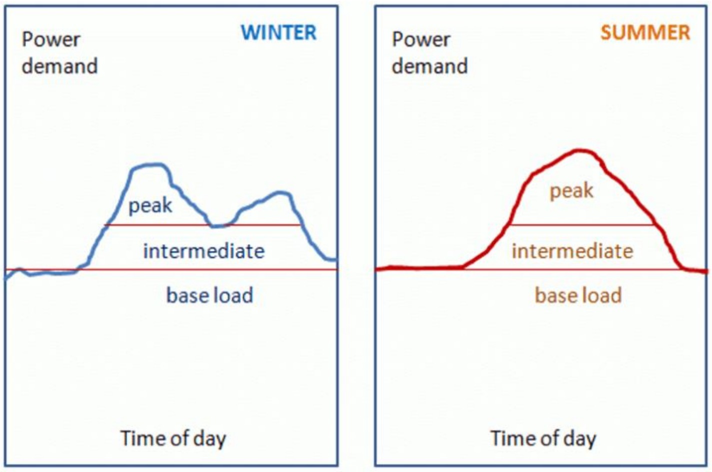

Figure 5: Daily electrical load profile on the same workday in winter and in summer in a subtropical climate. In winter two distinct peak load phases occur, related to sunrise and sunset. At noon sunlight is sufficient for living and working without electrical light. In summer the peak load phase is determined by the usage of air condition systems.[10]

Before the introduction of renewable power plants, power load management was optimised based on the properties of nuclear and fossil fuel power stations with respect to minimizing the LCOE. In this framework three categories of power plants exist: 1) baseload sources which operate day and night for most of the year with relatively high ramp up times (several hours) i.e., nuclear and coal-powered plants. The constant and efficient use of large turbines and generators reduced the cost of energy production. 2) Intermediate peaking sources that increase and decrease their power output during day and night, roughly matching the rise and fall of the electricity grid demand with medium ramp up times (several minutes), i. e. natural gas-powered plants with combined gas and steam cycles. These plants use its equipment for fewer hours than baseload facilities and therefore at a higher LCOE. 3) Fast peaking sources with very low ramp up times (seconds) i.e., natural gas power plants with gas powered turbines. These plants achieve the lowest working hours and consequently show the highest LCOE. The properties of the different plant types are shown in Table 1.[10; 11]

Energy source and heat engine technology	**Control properties**	**Energy Storage**	**Load profile**	**Flexibility profile**
Nuclear, steam	Not intended	No	Base load	--
Lignite/Coal, steam	Not intended	No	Base load	--
Natural gas, combined cycle	Yes	No	Middle load	+
Natural gas, gas turbine	Yes	No	Peak load	+
Biogas	Yes	Yes	Peak load	++
Running waterpower station*	No	No	Base load	--

Hydro dam*	Yes	Yes	Peak load	++
Pumped hydro dam*	Yes	Yes	Peak load	++
Geothermal, steam	Not intended	No	Base load	--
PV without battery storage*	No	No	Base load	--
PV with battery storage*	No	Yes	Base load	+
CSP, steam	No	No	Base load	--
CSP-TES, steam	No	Yes	Middle load	+
Wind*	No	No	Base load	--

Table 1: Load and flexibility profile of common electricity plants. Energy source and heat engine technology: Steam = Rankine cycle. Combined cycle = Brayton-Rankine cycle. Gas turbine = Brayton cycle. * = no heat engine in power production involved. Control properties: yes = delivering on demand. No = not delivering on demand. Not intended = controllable, but not done in practise. Energy Storage: energy storage in the standard realisation included. Load profile: properties in terms of ramp up time. Flexibility profile: ++ = controllable and storage, + = controllable or storage, -- not controllable and no storage.[11; 10]

Since renewable power plants enter power production in ever greater numbers, the concept of load profile optimising must gradually change into a concept of flexibility optimising over the coming years and decades. In this concept, inflexible power sources, which can only generate energy at certain times (wind, PV) will contribute all of its electricity production, while flexible power plants, which can generate or store energy on demand (CSP-TES, hydro and pumped hydro dams), will cover the gap between the inflexible sources and the actual demand.[11] Generally speaking, the inflexible sources show the lowest LCOE (PV, wind and geothermal) while the flexible ones show the highest LCOE (natural gas and biogas) (Table 5).

Electrical load management has become a demanding task in recent years and the demands will rise until sufficient storage capacity from renewable power plants is established. Because of its ability to provide low cost integrated energy storage and its flexibility with respect to the turbine technology used and the fast ramp-up rate, the combined CSP-TES technology offers considerable benefits to regional grids by supporting system operators and load-serving entities.[5]

CSP-TES plants consist of several interconnected compartments, which can be combined more or less freely. The most important functional components and the most common technical combinations are explained in the following sections.

Principles of energy conversion in combined Concentrating Solar Power - Thermal Energy Storage (CSP-TES) plants

The thermal heat energy produced and stored by CSP-TES plants is typically used to drive heat engines for driving generators. Heat engines convert heat or thermal energy to mechanical energy, which can be used to do physical work (e.g., drive electrical generators). In the process, a heat source transfers its thermal energy to a dedicated working substance (such as water) and brings it to a higher temperature state. The working substance passing through the working body of the engine, transfers the thermal energy into mechanical energy (for example, rotation) while the thermal state of the working substance drops to a colder sink where it reaches a lower temperature state. During this process some of the thermal energy is converted into mechanical work. The working substance usually is a fluid (gas or a liquid) with a non-zero heat capacity. Some heat is normally lost to the surroundings due to friction, drag and other irreversible processes and is therefore not converted to mechanical work and further to electricity. Most forms of energy can easily be transformed into thermal energy (e.g., through the absorption of light in CSP or exothermic combustion reactions of fuels). The working substance can be processed in an open cycle with internal heating, as in gas and steam turbines, also known as the air-Brayton or Joule cycle. The working substance can also be processed in a closed cycle with external heating as in Rankine or Stirling cycles.[12;14]

The air-Brayton or Joule cycle is working at a constant pressure with air as the working fluid and is used in gas turbines and "air breathing" jet engines. Atmospheric air is drawn into a compressor, where its pressure increases. The compressed output airstream enters a combustion chamber, where energy is added by injecting and igniting fuel. Inside the combustion chamber, a high-temperature flow is generated. The heated working fluid and combustion products enter the turbine and expand, driving the turbine (or series of turbines) where the energy transition is taking place and mechanical energy becomes available. The hot exhaust gases are released into the environment. The cooling of the working fluid is omitted, as gas turbines are open systems that do not reuse the working fluid. However, a surplus on temperature, pressure or velocity within the working fluid might be used in a secondary cycle or sub-cycle. [13] A more advanced option for heat engines operating at temperatures from 500 – 800 °C is the use of supercritical carbon dioxide (s-CO_2) as working fluid in the s-CO_2 Brayton (closed) cycle with the potential to be used in nuclear or CSP plants. The primary advantage of s-CO_2 engines relates to the higher efficiency (potentially > 50 %) and small turbine size (possible due to the specific physical properties of CO_2).[5; 15]

The Rankine or Stirling cycle uses water as working fluid and is used in typical steam turbines. Heat energy is supplied to the system usually via a boiler. In the example shown in Figure 6 the heat is supplied by a heat exchanger using hot waste gas. The working fluid is converted to a high-pressure gaseous state (steam) to turn a turbine. After passing over the turbine the fluid is allowed to condense back into a liquid state - as waste heat energy is dumped into the environment - before being returned to the heating device, completing the cycle.[14]

The Rankine and the Brayton cycles run at different temperature optimums. Waste heat from the Brayton process can be used by the Rankine process. A combined gas and steam process improves the overall efficiency and therefore reduces fuel costs and CO_2 emissions. After leaving the open cycle gas turbine ("topping cycle"), the working fluid – in this case the waste gas – is still hot enough that a second subsequent heat engine – a closed cycle external heated steam Rankine - cycle – can extract energy from the heat in the exhaust ("bottoming cycle"). The two heat engines therefore use two different work fluids.[16] The combined cycle shown in Figure 6 used in a CSP plant uses natural gas in the Brayton cycle and, therefore, releases CO_2 into the atmosphere[17].

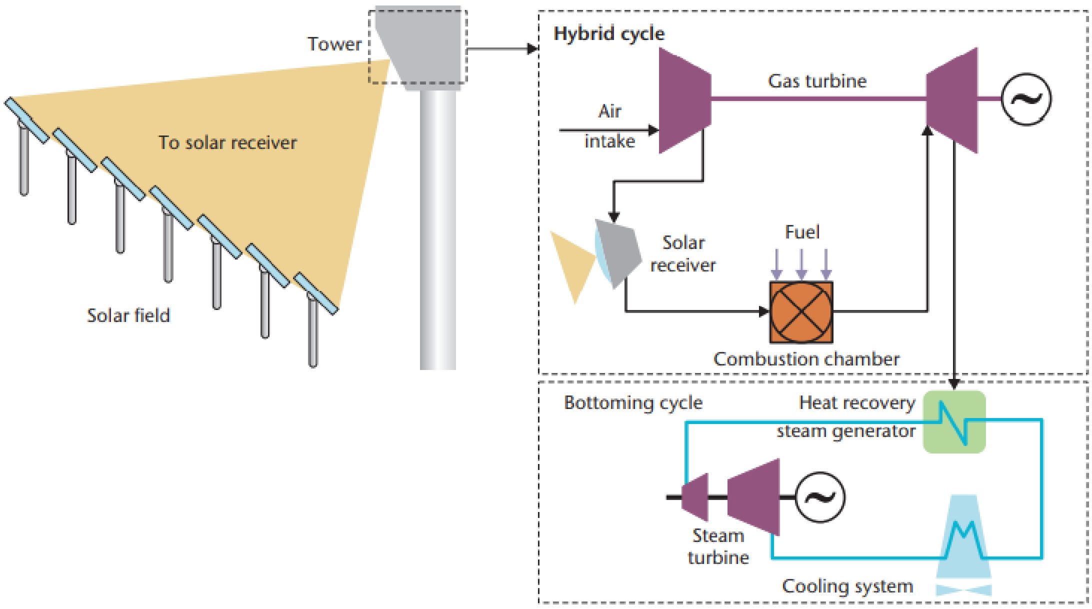

Figure 6: Working principle of a combined gas and steam power generation in a CSP plant. The upper box shows the "topping" gas turbine (Brayton cycle). The lower box shows the "bottoming" steam generator (Rankine cycle).[17]

Current CSP plants typically use Rankine cycles since they are efficient within the appropriate operating temperature range. Research and development work is being done on new engines and working fluids, which operate without any decomposition and disintegration at higher temperatures and require new concentrators/receiver/heat transfer fluid configurations (see discussion below).[4]

Current technologies for plants which concentrate solar power and store thermal energy

Conventional CSP technologies for power production use a five-step process (Figure 7): The incoming sunlight is 1) concentrated on large concentrators and redirected via focusing optics to a much smaller receiver. In the 2) receiver the sunlight is absorbed and converted into heat by the absorber. The heat is transferred and carried away by a 3) heat transfer fluid (HTF). The thermal energy can be stored in 4) tanks for later use or directly used in 5) heat engines, for electricity generation. The transfer process 3) is not strictly necessary for CSP systems as the absorber can be directly coupled with the heat engine. However, most current operating utility-scale CSP plants use heat transfer fluids. Also, storage 4) is optional for CSP systems. However, it is one of the primary advantages compared to other renewable electricity technologies, and as such is an important step.[4] All components mentioned above will be described below in more detail.

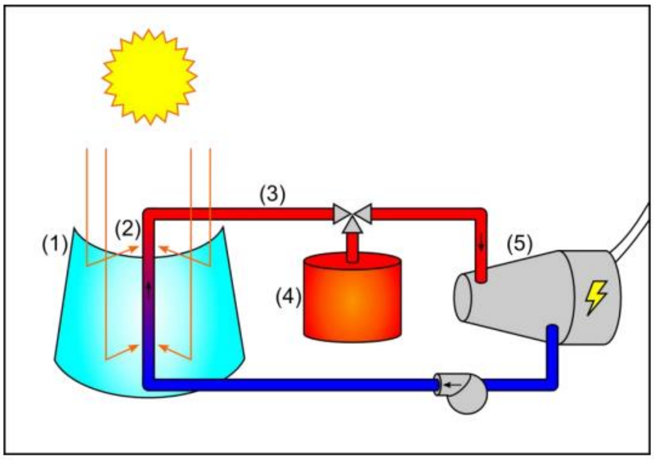

Figure 7: Components of a conventional concentrating solar power system (CSP): 1) Solar concentrator, 2) receiver, 3) heat transfer fluid, 4) thermal energy storage and 5) heat engine driving an electric generator.[4] Red: high temperature liquid. Blue: low temperature liquid.

Concentration of solar energy

Concentrators (number 1 in Figure 7) are used in CSP systems because very high operating temperatures are required for efficient power production (c.f. the Carnot-Limit of heat engines which will be discussed further below). The most cost-efficient ones have large surface areas of inexpensive concentrators, which direct the sunlight to a much smaller surface area of expensive receiver materials. The concentrators typically account for the largest amount of capital investment among all subsystems of a CSP plant.

The level of concentration can be characterized by the concentration ratio, which refers to the concentrator aperture area (the large mirror area intercepting sunlight) to the receiver aperture area (the small receiver area where the sunlight is redirected). Because concentration is required, CSP can only use the direct portion of the sunlight. Therefore, diffuse sunlight (found on a cloudy day) cannot be concentrated efficiently. This limits the ideal locations for CPS plants to areas with high and direct solar irradiation. Due to solar progression across the sky (daily in the east-west direction and seasonally in north-south direction) two axis tracking is required to maintain exposure of each concentrator towards the sun. With two axis tracking, sunlight can be focused towards a point (point-focus). While the sun has both east-west and north-south movement, most of its daily movement is in the east-west direction. If one only tracks a concentrator in the east-west direction, sunlight can be focused to a line (line-focus). Both line-focus and point-focus concentrators can be found in commercial use. Point-focus systems can achieve higher concentration ratios (> 500x), but the required two-axis solar tracking is more complex and more expensive to implement. Line-focus systems have lower concentration ratios (< 100x) but use simpler and less expensive single-axis solar tracking.[4]

Another distinction between different types of concentrators is whether the collecting (reflecting) surface is continuously bend or made up of discrete flat mirrors (facets). Concentrators with continuous surfaces can achieve higher concentration ratios as there is no sunlight lost between the facets and tracking is simpler since only one surface needs to be adjusted. When using a continuous surface, the focal axis should always intersect both the receiver and the sun. Therefore, the receiver is typically mounted with the reflector in a single assembly, limiting the receiver size. Concentrators with discrete facets can cover a greater area since the receivers can be stationary as they do not need to be tracked with the reflecting surfaces. Additionally, wind loading is typically a smaller concern for discrete facets since they can be kept closer to the ground. The stationary receivers in this case are still elevated so wind loading should be considered, but they are less susceptible to damage than reflector elements.[4]

The combinations of these systems result in four primary concentrators for CSP systems: linear Fresnel reflectors (LFR), heliostat fields, parabolic dish reflectors and parabolic trough collectors (PTC) which are shown in Figure 8. In a linear Fresnel reflector, long mirrors are tracking the sun from east to west and reflect sunlight onto a fixed and raised receiver. In a heliostat field individual mirrors track the sun across the sky to reflect sunlight to a central and raised receiver. With a parabolic dish reflector, the sun is tracked on both axes across the sky and sunlight is focused on a receiver which moves with the dish in such a way that it is always on axis with the sun. In a parabolic trough collector a long, curved and trough-shaped mirror tracks the sun from east to west and concentrates sunlight on a pipe at the focus of the curved mirror, with the whole assembly rotating together.[4]

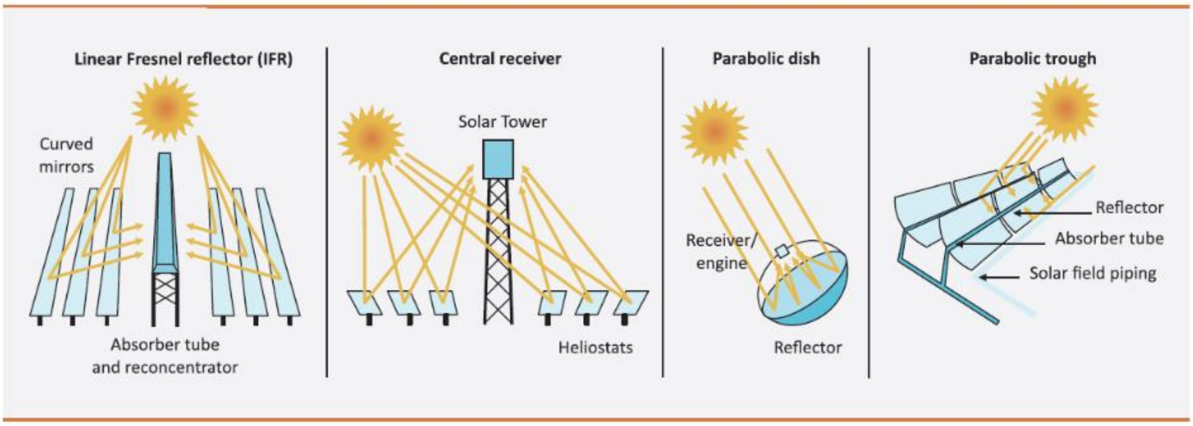

Figure 8: Main CSP technologies as combinations of point- or line-focus and continuous or facet surface. From left to right: Linear Fresnel reflector (LFR, facet surface and line-focus). Central receiver/heliostat field (facet surface and point-focus). Parabolic dish reflector (continuous surface and point-focus). Parabolic trough collector (PTC, continuous surface and line-focus).[17]

In practice the concentrator type determines many of the operating conditions of a CSP system. The concentrator type is paramount in determining the receiver concentration ratio and the overall plant size and performance. For example, parabolic dish plants are almost ubiquitously referred to as dish Stirling systems, because they are commonly paired with a Stirling engine to convert heat to electricity. Similarly, plants which use a heliostat field as the concentrator are often called power towers or central receiver systems, referring to the large towers where sunlight is focused at the centre of the field.[4]

The reflecting material of the mirrors is often silver, although aluminium and organic polymers are also used. While in principle lenses can also be used as the concentrating element in a solar concentrator, there has been limited deployment in CSP primarily due to higher cost per area compared with reflector systems. On top of that, it is more difficult to make precise lenses at the large scales required for CSP systems.[4]

Receiver, absorption of solar energy

The receiver is the portion of a CSP system where the concentrated sunlight from the concentrator is focused (number 2 in Figure *7*). The receiver always has an absorber where the sunlight is as efficiently as possible converted to heat and often contains piping, which carries a heat transfer fluid (HTF) to deliver the heat either to storage or directly to a heat engine.[4]

A high efficiency receiver has the following properties: high transmittance, absorption and concentration of the incoming sunlight, low emittance in the infrared (IR) spectrum and low convection of heat at the operating temperature. In practice, there is a trade-off between many of these technical factors, including their costs. Receiver efficiency decreases with increasing absorber temperature because thermal losses increase with higher temperatures. However, a high absorber temperature is desired because delivering the heat transfer fluid at higher temperature improves the heat to electricity conversion efficiency.[4]

Receiver designs and operating temperatures are very different for line-focus versus point-focus systems since the achievable concentration ratios differ largely. Established concentrator-receiver combinations for parabolic trough reflectors, linear Fresnel reflectors and heliostat fields are described below.

Vacuum tubes (see Figure 9) are the primary technology associated with line-focus CSP systems (concentrations ratios <500x) and are almost always used in parabolic trough reflectors. The evacuated enclosure suppresses the convective losses, but causes transmission losses through the enclosure walls (typically made from glass). The spectrally selective absorber shows a slightly lower absorptance than the optimal blackbody absorber, but has a low IR emittance. These systems are limited to around 500 °C for efficient operation – and in practise often lower due to insufficient HTF stability at high temperatures.[4]

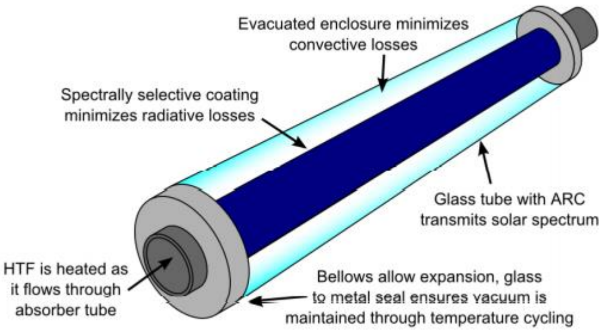

Figure 9: Diagram of a typical vacuum tube receiver. The receiver consists of a tube coated in a spectrally selective surface through which the heat transfer fluid (HTF) is flowing. The tube is in an evacuated enclosure which is maintained by a glass tube with an anti-reflecting coating. Metal bellows at the end of the tube accommodate expansion during daily temperature variation and a glass to metal seal with matched coefficients of thermal expansion ensures that the vacuum is maintained.[4]

Linear Fresnel reflectors are typically used with arrays of blackbody heat collections tubes in flat or trapezoidal receivers (Figure 10). These receivers operate in an air environment. The lack of vacuum makes convective losses substantial and limits the options for spectrally selective surfaces.[4]

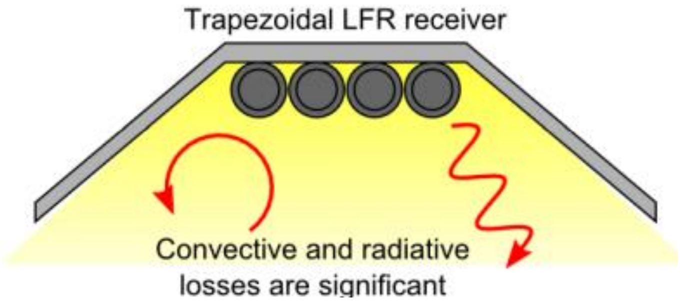

Figure 10: Diagram of a trapezoidal linear Fresnel reflector (LFR) receiver. This set up is open the atmosphere (at the bottom of the instalment) which results in energy losses due to convection and additionally limits the options for absorber materials.[4]

Central receivers are the technology associated with point-focus heliostat field CSP systems. These systems are often referred to as “power towers”, since the receiver typically sits atop a large tower toward the heliostats reflect the sunlight. Heliostat fields have large concentration ratios (>1000x). High absorptance is the primary concern for good receiver efficiency in central receivers. There are two primary designs for central receivers (Figure 11): in an external receiver the absorbing surface is on the outer surface of the receiver, which typically has a cylindrical shape, and the heliostat field surrounds the central receiver. In a cavity receiver sunlight is focused on an aperture leading to an internal cavity where the sunlight is absorbed. In this case, the heliostat field is located only on the side of the receiver aperture. The most common absorber coating for external receivers is a black silicone-based paint with high temperature stability.[4]

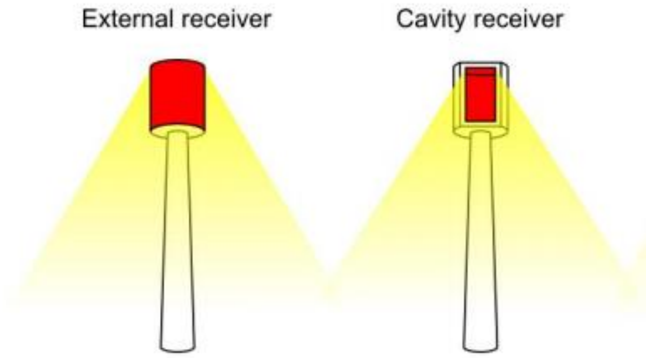

Figure 11: A diagram of central receiver configurations. Red colour indicates the absorbing surface. In an external receiver (left) sunlight from all around the receiver can be absorbed. In a cavity receiver (right) sunlight can only be absorbed from the side of the receiver which the cavity is facing.[4]

Heat transfer

The thermal energy harvested in the receiver is typically delivered to a heat transfer fluid (HTF) by convection. The heat is transported to a heat exchanger, connected to a power cycle for electricity generation or temporarily stored for subsequent use (see Figure *7*). The multi-functional HTF, therefore, needs to collect, transport and exchange heat obtained from solar radiation and is therefore an extremely important part of a CSP system.[4]

The heat transfer from receiver to HTF depends on the convective heat transfer characteristics of the HTF. This includes 1) a high thermal conductivity that enables efficient transfer of heat from the absorber to the power block, 2) a high density and specific heat capacity which enables high fluxed at reasonable mass flow rates and 3) low viscosity which minimizes the required pumping power. Currently four categories of HTF are in use: oils, molten salts, pressurized gases, and other liquids (molten metals, nanofluids and ionic liquids). This article will concentrate on the currently commercially used oils and molten salts.[4]

Since the outlet temperature of the solar collector is the "hot side" of the power cycle, it has a large effect on its efficiency (for more details see below). Higher efficiencies are possible at higher temperatures and, therefore, the HTF must remain stable at the maximum possible temperature. While the operating temperature of a solar thermal plant varies, it is commonly limited by the highest temperature where the HTF remains stable. Another important aspect regarding the temperature stability is its freezing point. The diurnal cycle of solar irradiation forces the HTF to operate between the CSP plant's peak operating temperature and the night-time temperature. The HTF could freeze during cold nights and safeguards must be built into the system to prevent the HTF from freezing in the plumbing, which can cause damage and accelerate deterioration.[4]

Heat Transfer Fluids

The most common types of HTFs are mineral (fossil) or synthetic oils. Synthetic oils have a higher thermal conductivity, a lower viscosity and are less flammable than mineral oils and are, therefore, generally preferred over mineral oils. Oils are important HTFs since they offer the best available combination of a low freezing point and a high upper temperature limit. They are liquid at ambient conditions and do not require external temperature control to maintain a reasonably low viscosity. Thermal stability is limited to a maximum of 400 °C, depending on the respective oil. Oils are normally used in line-focus CSP. Oils have lower densities and heat capacities compared to molten salts. Therefore, larger fluid volumes are required that demand larger storage space and result in higher costs. Oils are flammable and environmentally toxic, which complicates their handling.[4]

Molten salts can operate at much higher temperatures than oils. While the highest possible operating temperature (> 1 000 °C) is not yet reachable due to receiver material limitations, the higher operating temperatures that are achieved (today as high as 550 °C) result in a higher efficiency of the power cycle and lower LCOE. Additionally, molten salts can be directly used for thermal storage, which increases the hours of electricity production and further reduces the LCOE.[4]

Molten salts are typically mixtures of inorganic nitrates, chlorides, and fluorides. From a thermo-physical perspective, molten salts have a comparable viscosity, but much higher volumetric heat capacity and thermal conductivity than oil based HTFs at the respective operating temperatures. Molten salts do solidify well above ambient air temperature, making anti-freezing strategies unavoidable. Corrosion by common nitrate-bases salts is negligible while pipes and containers for chlorides and fluorides are recommended to be manufactured of stainless steel.[4]

Energy storage

To generate electricity on demand despite variations in solar irradiation, some form of energy storage must be implemented (See Figures 4 and 7). This makes CSP plants more reliable and amendable to integration in any electric grid. With storage options, electricity production can be adjusted to meet the demand and keep the power grid stable. The most appropriate storage mechanism for CSP is thermal energy storage (TES), as the heat is already present. TES is significant cheaper than most alternative energy storage technologies (e.g. batteries).[4]

There are two primary characteristics of a TES system: capacity and power. Capacity is a measure of how much thermal energy a TES system can store, while power is a measure of how much heat the system can deliver while discharging. Ideally a TES system has both, a high capacity and power at low cost. For commercial TES systems the primary concern is achieving low specific cost. System capacity and power are related to the thermal properties of the materials being used for the TES (gravimetric/volumetric storage capacity and thermal conductivity). The system typically has a specific range of operating temperatures which need to be compatible with the concentrator, the receiver, and the heat engine. The TES system also has a characteristic storage time which is most appropriate for responses in the order of hours to address weather changes and load shifting. At the long end of this response time range (>15 hour storage time) the use of TES for base load i.e. continuous power generation has also been considered.[4]

Although other methods are available, TES is most frequently performed by raising the temperature of the storage material. One well established method involves the use of a steam accumulator, which uses water as the TES material. In a steam accumulator, pressurized, saturated water (gaseous water which is dissolved in liquid water to the maximum amount possible) stores the thermal energy. To extract the thermal energy, steam is produced by lowering the pressure of the saturated water. Operating temperature and pressure in these systems are limited by the critical point of saturated water (374 °C and 221 bar). For its operational temperature range, a steam accumulator is a very cost effective and energy dense option for TES. A deployed example of a steam accumulator used in CSP is at the Plants Solar towers in Spain where it provides approximately 1 hour of thermal storage, operating at temperatures from 250 - 300 °C.[4]

For higher temperatures that cannot be achieved with a steam accumulator, molten salts are the best option. Salts have reasonably high storage densities and are inexpensive, making them an economical storage material. The operating temperature range is limited on the low end by the freezing temperature and on the high temperature end by increased corrosion. Freezing temperatures (i.e., when the liquid salt is crystallizing) of the salt solutions as low as 80 °C can be reached.[4]

Power generation

The heat engine (see Figure 7) coupled with a generator in a CSP plant converts the collected heat to electricity. In commercial plants this is typically achieved via a thermodynamic cycle converting the heat to mechanical energy, which is used to drive a generator and produce electricity. The thermodynamic cycle typically has four steps: The working fluid is: 1) compressed to high pressure, 2) heated to the temperature peak using the solar energy input,

3) expanded to low pressure (through a turbine), which produces actual mechanical work, and 4) cooled down and moved to the system's temperature sink.

Essential for the efficiency of a heat engine or a system of heat engines is the difference between the peak temperature and the sink temperature. The net power output of the heat engine is given by the power produced by the expansion step minus the power input required for the compression step. Current CSP plants typically use Rankine cycles with water/steam as a working fluid. The other commonly used cycle is a Brayton cycle, which uses a working fluid that does not undergo a phase transition during the whole thermodynamic cycle. Parabolic dish collectors usually use Stirling cycles and Stirling engines which share many components with fossil fuel fired power plants. Due to the long history of research into engines for use with fossil fuels technological improvements reached almost an optimum. Therefore, a great portion of the potential cost reduction in using steam-Rankine and air-Brayton heat engines for CSP nowadays comes from simple upscaling.[4]

Heat cycle	**Operating temperature range [°C]**	**Typical efficiency [%]**
Steam-Rankine	350 °C – 600 °C	40 %
Stirling	400 °C – 800 °C	45 %
Supercritical Steam-Rankine	600 °C – 760 °C	45 %
Supercritical CO_2 Brayton	500 °C – 800 °C	50 %
Combined s-CO_2-Brayton-Rankine cycle	> 800 °C	60 %

Table 2: Typical operating temperatures and efficiencies at maximal temperatures for heat engines compatible with SCP.[4]

As mentioned before, the concentration technology used defines many of the downstream technologies of a plant. For line-focusing technologies, oil is usually used as HTF, while point-focusing technologies use salt solutions. Parabolic dish reflectors usually use Stirling heat engines, while all other technologies use Rankine heat engines. Storages of various kinds are possible for all technologies except for parabolic dish reflectors. Typical setups with examples of operational commercial plants are listed in Table 3. Further information about heat engine efficiencies can be found in the appendix.

	Concentration type (Concentration ratio)	**HTF**	**Operating temp.** [°C]	**Heat engine type**	**Existing plant**
Linear Fresnel reflector (LFR)	Line-focus (30)	Oil	300 – 400	Rankine cycle	Puerto Errado (34.4 MW, Spain, 2009)
Heliostat/Power Tower	Point-focus (1 000)	Salt	400 – 600	Rankine cycle	Ivanpah (392 MW, USA, 2014)
Parabolic dish reflector	Point focus (1 500)	Oil	550 – 750	Stirling cycle	No large setups known
Parabolic trough collector (PTC)	Line-focus (80)	Oil	400	Rankine cycle	Solaben (200 MW, Spain, 2012)

Table 3: Frequent combinations of technical components in commercial CSP plants. Concentration type = line (east-west adjustment) or point (east-west and north-south adjustment) focus. Concentration ratio = solar irradiation on the mirrors in relation to the irradiation on the concentrator. HTF = Heat transfer fluid. Operating temperature = operating temperature of the heat transfers fluid. Heat engine type = cycle used. Existing plant =

example of an operational plant in a NATO member nation with name of the plant, maximum capacity, country and year of commission.[4; 5]

In conclusion, it can be stated that the technological efficiency limits of CSP technologies are not yet reached because higher peak working temperatures are feasible from a thermodynamic point of view. These higher temperatures require the development of new materials such as working fluids, plumbing, valves, and pumps.

The LCOE of CSP

LCOE is a measurement of the lifetime costs of a plant that is used to compare technologies either within a fuel category or for different fuels. Mean LCOE for CSP plants in 2015 as well as their efficiencies are shown in Table 4. LCOE of parabolic dish reflectors cannot be compared because no data is available. Peak efficiency refers to the highest instantaneous solar to electricity efficiency achieved typically during solar noon. While annual efficiency considers the effect of daily and seasonal variation on performance and is more relevant to LCOE than peak efficiency.[4]

The LCOE are in the same order of magnitude for all three technologies (parabolic dish systems not included here). The lowest LCOE are reported for the heliostat/power tower technology which corresponds with the highest annual efficiency, the possibility of upscaling the plants, the higher operating temperature and the possibility to use standard heat engine technology.[4] An IRENA report from 2018 states LCOE in the same order of magnitude[18]. Although the reported maximum LCOE were lower than in the 2015 report from Lee A. Weinstein, et al..[4]

	LCOE [US$-ct$_{2015}$/kWh] ([€-ct$_{2015}$/kWh])	**Annual efficiency** [%]	**Peak efficiency** [%]
Linear Fresnel reflector (LFR)	14 – 45 (13 – 41)	13	18
Heliostat/Power Tower	13 – 30 (12 – 27)	16	22
Parabolic trough collector (PTC)	16 – 40 (14 – 36)	14	25
Parabolic dish reflector	No commercial plants	20	32

Table 4: Key performance parameters of typical SCP configurations. LCOE = levelized cost of electricity in US$-ct and €-ct in values of 2015. € were calculate with the mean exchange rate for 2015 (1 € = 1.11 US$).[19] Annual efficiency = mean efficiency in one year. Peak efficiency = maximum efficiency. Modified after Lee A. Weinstein, et al.[4]

Costs of power production follow the general economic laws of production: costs in companies are typically split into capital expenses (CAPEX) and operational expenses (OPEX). Typical CAPEXs are the funds needed for acquiring assets such as CSP plants. Typical OPEX are the costs of running the plant e.g., maintenance.

LCOE comparison of fossil and renewable electric power plants

Since 2018 the LCOE from renewable sources have been cheaper than from fossil sources (see Table 5).[18;20] The main advantage of fossil fuels over most renewable sources is their availability on demand. Although hydro and geothermal power can fulfil these criteria as well, in most cases their actual capacities are not sufficient to cover the demand.

Electricity source	LCOE 5^{th}-95^{th} percentile	
	[€-ct_{2018}/kWh]	[US$-$ct_{2018}$/kWh]
Renewables		
Solar CSP[18]	9.2 – 23.1	10.9 – 27.2
Solar PV (industrial parks)[20]	3.7 – 6.8	4.4 – 8.0
Wind, onshore[20]	4.0 – 8.2	4.7 – 9.7
Wind, offshore[20]	7.5 – 13.8	8.8 – 16.3
Biogas[20]	10.1 – 14.7	12.0 – 17.4
Bioenergy (direct combustion and gasification)[18]	4.1 – 20.6	4.8 – 24.3
Hydro[18]	2.5 – 14.1	3.0 – 16.6
Geothermal[18]	5.1 – 12.1	6.0 – 14.3
Fossil Fuels		
Lignite[20]	4.6 – 8.0	5.4 – 9.4
Coal[20]	6.3 – 10.0	7.4 – 11.8
Natural gas (gas turbine)[20]	11.0 – 22.0	13.0 – 25.9
Natural gas (combined gas and steam turbine)[20]	7.8 – 10.0	9.2 – 11.8

Table 5: The LCOE for renewable electricity producing plants commissioned in 2018 according to IRENA compared with fossil fuels. LCOE = in US$ and € in values of 2015 (€ calculated with the mean exchange rate for 2015: 1 € = 1.18 US$).[18; 19] The electricity source is given in the left column. The LCOE column shows the 5^{th}-95^{th} percentile of global average LCOE for plants commissioned in 2018 in € and US$ per kWh produced.[18; 20]

The intermediate storage of all excess power produced from PV and wind turbine plants is currently not possible. Battery storage is expensive and pumped hydro power stations depend on specific geological and topographic settings in water rich regions. CSP plants come with the advantage of an inherent thermal transfer process where energy losses can be minimized. CSP plants with significant storage capacity have been built already. The Andasol Parabolic Trough plant in Spain for example contains a thermal heat storage (salt-based) for 7.5 full capacity load hours of running its electric power generators.[21] Such plants with temporal storage capacity represent a high value with respect to maintaining grid stability.

Measures to reduce LCOE from CSP-TES power plants

To reduce the LCOE from solar sources, the U.S. Department of Energy launched the "SunShot Initiative" in 2011 with the goal of making PV and CSP solar electricity cost-competitive by 2020 compared with fossil generation technologies.[5] The goal was to achieve 6.0 US$-$ct_{2011}$/kWh which translates into 4.3 €-ct_{2011}/kWh (exchange rate 2011: 1 € = 1.39 US$[19]). Since 2011, many research and development projects, as well as test facilities, related to solar power production with many lines of possible improvements have been implemented.[5; 22; 15] This article will focus on CSP systems since these systems are currently the most advanced.

Redesigning CSP-systems works best by starting with the selection of the heat engine type. A promising option is a combination of a high temperature "topping" air- or alternatively s-CO_2-Brayton cycle and a lower temperature "bottoming" Rankine cycle. An air-Brayton engine is fuelled by natural gas, which means that the technology is not completely carbon-free. The more useful technology in terms of CO_2-emission reduction is an s-CO_2-Brayton cycle engine. Combined cycles are very efficient heat engines, with the potential to surpass the 60% heat to electricity conversion efficiency. Using combined cycles is currently challenging for CSP systems because the high temperature needed (>800 °C) cannot be reached due to restrictions in the durability of upstream components of the CSP plant. New HTF must be developed, as the maximal temperature for the typical solar-salt being used (60 per cent by weight $NaNO_3$ and 40 per cent by weight KNO_3) is 565 °C. Salt mixtures that include carbonates, fluorides and even s-CO_2 are currently explored as HTF. Especially CO_2 is interesting as a base material for HTF, because it is abundant, inexpensive and has an easily achievable critical point (i.e., the point from which on gas and liquid coexist with favourable physical properties for the desired technical process, 30.98 °C, 7.38 MPa). It also shows a good thermal stability up to 1500 °C and poses no freezing problems down to -55 °C. However, advances in the design of sub-components (e.g., multiple cycle separation with heat exchangers) and finding materials which are reliable and resistant to the corrosive nature of s-CO_2 are needed before significant commercial adoption of s-CO_2 engines and HTF systems will be possible.[5; 15]

Many of these approaches have been already tested an implemented. The reduction of LCOE for CSP plants in the coming years seems now very likely and presents CSP in combination with TES as an excellent alternative to power production from fossil or nuclear plants.

Potential of CSP combined with TES

TES is one of the main advantages of CSP because it is significantly cheaper than other energy storage technologies (e.g., battery storage). However, TES is not applicable to other intermittent renewable energy technologies such as PVs and wind turbines. For these applications other grid-level energy storage technologies are economically more competitive (e.g., pumped hydro or compressed air).[4; 5]

If equipped with sufficient TES capacity, CSP can completely decouple the thermal solar energy harvesting process from the thermal electricity conversion of power production. In this scenario a continuous power production and capacity regulation is possible.[5] As CSP-TES plants can be equipped with any given turbine technology, the electrical load demands of the respective grid can be met with a combination of base, intermediate and peak load plants. This can create a flexible electricity source which operates entirely on renewable energy.[5]

Discussion and conclusions

The energy of the sunlight which reaches the earth in one hour exceeds the energy consumed by all of humanity in one year. Therefore, at least theoretically, CO_2-neutral power production for all of humanity using solar irradiation alone appears entirely possible. Power production is most sensible in the "global sunbelt". It is home to approximately 80% of the world's population in mostly developing and emerging countries.[9]

A major obstacle for sunlight-related power generation technologies is the inevitable gap in electricity production during nighttime. In CSP plants these gaps can be addressed by TES, which can provide an efficient form of energy storage in CSP plants because no additional energy transformation is needed. Combined CSP-TES plants are of high value for grid managers because they can provide a constant power supply and can be equipped with a generator technology according to the specific demands of the local grids (i.e,. covering base, intermediate or peak loads).

Operational CSP plants without storage may be retrofitted with TES which can cover renewable energy production gaps. Currently such gaps are closed by flexible fossil fuel plants. Alternatively, carbon-neutral biogas plants near CSP plant may also fill these gaps. The produced methane can be stored and handled in the same manner as natural gas. CSP and biogas technologies require different skill sets. Currently, companies and operators with a broad range of expertise are rare. The biogas option also appears not very feasible because CSP plants are typically placed in arid or semiarid remote areas. The production of biogas from biomass waste or municipal sewage and waste is unlikely because of missing input material in these areas.

On the other hand, CSP plants can improve the performance of fossil fuel plants by using the same steam-Rankine engine setup. The variable power production from CSP can be used when available, while the fossil fuel plant is used as a default as soon as CSP is not producing. This combination is most promising for gas and oil powered plants. It would reduce CO_2-emissions and costs. The combination of the turbines and generators leads to higher working hours and results in reduced operational costs (OPEX) per kWh produced.[4]

CSP plants are often welcomed by the general public as they are frequently built in remote, unproductive, arid and semiarid areas that have very small populations (and few sources for income). Therefore, environmental and aesthetic reservations are either absent or easily solved. Nonetheless, the water demand of CSP plants is significant and the allocation of the available water between the plant and the local population may become a disputed issue. The demand for water cooling of the heat engines can be reduced by advanced technology as demonstrated in the Noor plants (Morocco). The CSP-TES plant commissioned first (Noor I) uses a water-cooled heat engine, while the Noor II and Noor III plants do not require water for cooling purposes.[8] Still, water demand for cleaning the mirrors remains and must be addressed. Going forward, water recycling technologies may solve this issue and reduce the issue of water scarcity.

Sites for future CSP-TES plants have therefore to be chosen carefully. The priority list of selection criteria includes: 1) solar irradiation, 2) water availability, 3) political stability of the host nation and 4) distance and security along the electric power transmission path to consumers, among many others. Of those criteria, solar irradiation and water availability can be easily evaluated.

Figure 12: Ivanpah solar electric generating system in the Mojave Desert in California (USA). The solar park consists of three prominent power towers with a maximum capacity of 392 MW. One power tower is shown in the setting of the desert landscape.[23]

The lifetime of a CSP-plant ranges between 30 to 50 years and during this period climatic changes may be experienced on the site of the plants. Therefore, current as well as future irradiation and precipitation patterns must be considered.

Solar irradiation is mainly influenced by clouds and aerosols. Both reduce the direct portion of the sunlight and increase its diffuse portion. As the diffuse portion cannot be concentrated this situation will lead to decreased yield or even intermittences in the power supply. Heat waves are also predicted to rise in the coming years but may not have detrimental effects on CSP plants. PV plants can use diffuse irradiation, although direct irradiation results in higher yields. PV plants are sensitive to heat, as the efficiency of the PV-modules decrease with increasing temperature. A combination of CSP-TES and PV plants may be favourable to cover-up the inherent weaknesses of both technologies.[24]

Water supply for CSP plants is often not influenced by local rainfall patterns as water may be supplied from far away regions. Future possible changes in the precipitation pattern in the originating hydrographic basins must be considered. Water conflicts with local communities as well as with neighbouring countries must be addressed not only in arid and semiarid regions. A steady and reliable supply of clean water is already a problem in many countries - even in temperate regions - with the potential of conflicts. A recent example is the filling of the Grand Renaissance Dam on the Blue Nile in Ethiopia, which led to fears of water shortages in Sudan and Egypt and severe tensions in the region.[25]

Electricity produced by CSP-TES has the potential to boost the economy of the hosting country by improving the access to power for the citizens as well as by increasing state revenues. In poorer countries the generated power in the near future will most likely be used by their own citizens. Only after complete electrification is reached and the local demand saturated, power – or downstream products such as alternative (e.g., synthetic) fuels - may be exported. These measures may also lead to improved living standards in these countries.

On the other hand, many current oil and gas producing states found within the Sunbelt may see their states revenues fall drastically in the coming years. This could give rise to fears of necessary cuts in their welfare systems and potential social unrests [26]. These countries may use their financial capital for re-investing in CSP-TES technologies for power and alternative fuel export purposes. In this context, methane is of special interest because in recent years many liquefied natural gas shipping terminals were built around the globe and existing infrastructure from natural gas exploitation could be reused.[27; 28]

The value of CSP plants in combination with TES and with respect to their CO_2-neutral power production and their potential for stabilizing power grids has become more obvious in the last years. Therefore, the U.S. government took the lead by starting the "SunShot" initiative — a generously funded research and development program with the aim to bring down LCOE of CSP-plants to the cost level of fossil fuel plants.[5] The benefits of this research program may be reaped in the coming years and profoundly increase power production from new CSP-TES plants. The expected technical improvements in future CSP-TES plants may also help substantially to facilitate the clean energy transition around the world and provide more social and political stability for countries within the "global sunbelt".

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References

[1] Stefanie Müller, „Eine kleine Geschichte der Energiewende, Teil 1 | Sunbeam", Sunbeam GmbH, Schönhauser Allee 52, 10437 Berlin, Germany, https://sunbeam-communications.com/eine-kleine-geschichte-der-energiewende-teil1/, Accessed May 20, 2021.

[2] H. Gernsback and H. W. Secor, "The Utilization of the Sun's Energy", *The Electrical experimenter*, No. 11, 35, 1916.

[3] Wikipedia, "Moteur solaire", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://fr.wikipedia.org/w/index.php?title=Moteur_solaire&oldid=180309719, Accessed June 1, 2021.

[4] Lee A. Weinstein, et al., "Concentrating Solar Power", *Chemical reviews*, No. 23, 115, 2015, 12797–12838.

[5] Mark Mehos, et al., "*Concentrating Solar Power Gen3 Demonstration Roadmap*", National Renewable Energy Laboratory, 2017, Accessed March 30, 2021.

[6] Max Roser and Hannah Ritchie, "Solar PV module prices vs. cumulative capacity", Global Change Data Lab, Registered Charity in England and Wales, Accessed April 6, 2021.

[7] HELIOSCSP, "Morocco largest Concentrated Solar Power complex NOOR 1,2,3", Solar Thermal Energy News, C/ Alberto Alcocer 5, 2º-B, Madrid, Spain, https://helioscsp.com/morocco-largest-concentrated-solar-power-complex-noor-123/, Accessed October 29, 2021.

[8] Wikipedia, "Ouarzazate Solar Power Station", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://en.wikipedia.org/w/index.php?title=Ouarzazate_Solar_Power_Station&oldid=1019552365, Accessed May 19, 2021.

[9] Jochen Hauff, et al., "Unlocking the Sunbelt Potential of PV, No. Second Edition, 2020.

[10] Symons Energy, "What Is Base Load Power", Symons Energy, https://www.symonsenergy.com.au/blog/batteries/what-is-base-load-power, Accessed April 20, 2021.

[11] ABC Science, "Busting the baseload power myth", ABC Science, https://www.abc.net.au/science/articles/2010/12/02/3081889.htm, Accessed April 20, 2021.

[12] Wikipedia, "Heat engine", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://en.wikipedia.org/wiki/Heat_engine, Accessed April 13, 2021.

[13] Wikipedia, "Brayton cycle", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://en.wikipedia.org/w/index.php?title=Brayton_cycle&oldid=993744786, Accessed April 14, 2021.

[14] Wikipedia, "Rankine cycle", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://en.wikipedia.org/wiki/Rankine_cycle, Accessed April 13, 2021.

[15] Pan Zhou, et al., "Dynamic modeling and transient analysis of a molten salt heated recompression supercritical CO2 Brayton cycle", *3rd European supercritical CO2 Conference, September 19-20, 2019, Paris, France*, No. DOI: 10.17185/duepublico/48879, 2019.

[16] Wikipedia, "Combined cycle power plant", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://en.wikipedia.org/w/index.php?title=Combined_cycle_power_plant&oldid=1012163744, Accessed April 14, 2021.

[17] IEA, "*Technology Roadmap Solar Thermal Electricity*", IEA, 2014, https://www.iea.org/reports/technology-roadmap-solar-thermal-electricity-2014, Accessed April 6, 2021.

[18] The International Renewable Energy Agency (IRENA), "*Renewable power generation costs in 2018*", IRENA Headquarters, Masdar City, P.O. Box 236, Abu Dhabi, United Arab Emirates, 2019, file:///C:/Users/jutta/AppData/Local/Packages/Microsoft.MicrosoftEdge_8wekyb3d8bbwe/Tem

pState/Downloads/IRENA_Renewable%20Power%20Generations%20Costs%20in%202018%20(1).pdf, Accessed May 28, 2020.

[19] Statista, „Durchschnittlicher Dollarkurs 1999-2019“, Statista GmbH, Johannes-Brahms-Platz 1, 20355 Hamburg, https://de.statista.com/statistik/daten/studie/200194/umfrage/wechselkurs-des-euro-gegenueber-dem-us-dollar-seit-2001/#:~:text=Im%20Jahr%202018%20erhielt%20man%20f%C3%BCr%20einen%20Euro,zu%20einer%20Ab-%20und%20Aufwertung%20des%20W%C3%A4hrungskurses%20kommen.

[20] Christoph Kost, et al., „Stromgestehungskosten erneuerbare Energien“, Fraunhofer-Institut für Solare Energiesysteme ISE; Heidenhofstraße 2; 79110 Freiburg, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2018_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf, Accessed June 1, 2020.

[21] Wikipedia, "Andasol – Wikipedia", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://de.wikipedia.org/wiki/Andasol, Accessed March 22, 2020.

[22] Elliott Bryner, et al., "*Optimizing the CSP Tower Air Brayton Cycle System to Meet the SunShot Objectives*", Southwestern Research Institute, Culebra Road, San Antonio, Texas 78238, 2016, https://www.osti.gov/servlets/purl/1369568/, Accessed April 14, 2021.

[23] Wikipedia, "Ivanpah Solar Power Facility", Wikipedia, 149 New Montgomery Street Floor 6, San Francisco, CA 94105, United States, https://en.wikipedia.org/w/index.php?title=Ivanpah_Solar_Power_Facility&oldid=1050470231, Accessed October 28, 2021.

[24] Sarah Feron, et al., "Climate change extremes and photovoltaic power output", *Nature Sustainability*, No. 3, 4, 2021, 270–276.

[25] Ros Atkins, "Nile dam dispute: Ethiopia, Egypt and Sudan agree to resume talks", BBC, Broadcasting House London, London, United Kingdom, https://www.bbc.com/news/world-africa-53494604, Accessed May 22, 2021.

[26] Andrew Walker, "Shift to green energy 'could cost oil states $13 trillion' by 2040", BBC, Broadcasting House London, London, United Kingdom, https://www.bbc.com/news/business-56017415, Accessed May 22, 2021.

[27] Jutta Lauf, "Replacing NATO F-34: Technologies and economic aspects of using secondary carbon sources for Power-to-Fuel production", *Energy Highlights*, No. 14, 2020, 30–51.

[28] Jutta Lauf, "Hydrogen: Production and costs with a closer look to highly regulates market situations", *Energy Highlights*, No. 14, 2020, 15–29.

Appendix: Efficiencies of heat engines

Efficiency of heat engines

While any heat engine should be reliable and ideally require low capital investment, the main performance metric of the heat engine is how efficiently it converts heat to electricity. Increases in efficiency are mostly driven by operating at higher temperatures. The highest achievable efficiency is the Carnot efficiency (η_C).

$$\eta_C = 1 - \frac{T_C}{T_H} \qquad (1)$$

In the ideal Carnot-engine T_C is the temperature of the cool side (sink) and T_H is the maximum achievable temperature of the engine. Heat is dissipated during the cooling step. Increasing the operating temperature will increase the maximum achievable efficiency if the cold side temperature can be held constant. The cold side temperature should be kept as low as possible, which is limited in practice by the ambient temperature the plant operates in as well as by the heat transfer to the ambient environment. The Carnot efficiency represents the theoretical maximum performance limit and cannot be reached by real heat engines. A lower efficiency, called the Chambadal-Novikov efficiency, can be derived for a heat engine with irreversible heat transfer processes operating at maximum power output. The Chambadal-Novikov efficiency η_{CN} is given by

$$\eta_{CN} = 1 - \sqrt{\frac{T_C}{T_H}} \qquad (2)$$

Both, the Chambadal-Novikov efficiency and the Carnot efficiency do increase with increasing operating temperatures. The efficiency of real heat engines matches the Chambadal-Novikov efficiency much better than the Carnot efficiency, and as such the Chambadal-Novikov efficiency is generally a reasonable estimate to use for calculating the heat engine performance in a system level analysis. The Carnot and Chambadal-Novikov efficiencies are shown in Figure for operating temperatures of current CSP systems (350 °C – 600 °C) and for temperatures that could be achieved with high concentrators and advanced receivers (up to 800°C). Table 2 lists typical operating temperatures and efficiencies for heat engines, which are or could be used with CSP systems.[1]

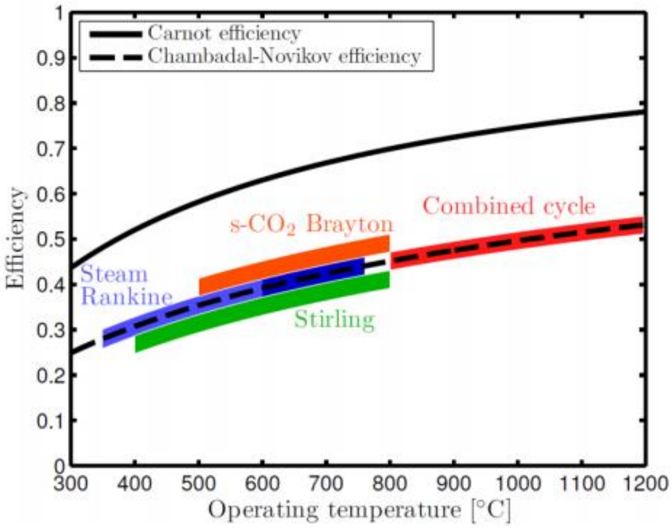

Figure 1: Carnot and Chambadal-Novikov efficiencies for typical CSP operating temperatures as well as approximate efficiencies of real cycles. Blue = water/steam Rankine cycle. Green = Stirling cycle. Orange = s-CO_2 Brayton cycle. Red = combined cycles.[1]

References

[1] Lee A. Weinstein, et al., "Concentrating Solar Power", *Chemical reviews*, No. 23, 115, 2015, 12797–12838.