A techno-economic assessment of electricity generation using Concentrated Solar Power (CSP)

This report focuses on the economic implications of using solar thermal power to produce electricity. Different types of CSP technology were analyzed and contrasted to find the most cost-effective solution. We found that point-focusing systems have generally higher thermal production efficiency due to the high concentration factor. Also, the Levelized Cost of Electricity (LCOE) is much higher for CSP plants mainly due to the vast land and Thermal Energy Storage (TES) requirements as compared to other energy sources. In a nutshell, the best CSP system does not exist, the total investment cost and LCOE will depend on the location.

1. Introduction

1.1. Why new energy sources?

The answer to this question depends on whether the responder tracks the depletion of conventional energy resources like coal, fossil fuels and natural gas. If that is the case, the, we do not need alternative energy sources. As a matter of fact, long-standing sources of highly concentrated energy include coal, oil, and gas [1]. It is estimated that the world's coal reserves can last for as long as 112 years [2]. The real issue is greenhouse gas emissions caused by burning fossil fuels.

Global fossil fuel combustion is reaching a new peak every year as climate impacts grew more severe. With a combined share of 81% in the world's primary energy supply, coal, oil, and natural gas continue to be the top three energy sources. With over 75% of all greenhouse gas emissions and almost 90% of all carbon dioxide emissions, these fuels are by far the biggest cause of climate change in the world [1]. Figure 1 shows the top polluting sectors in terms of CO_2 in the U.S. recorded in 2012. 38.4% accounts for electricity generation only. The most used energy sources to produce electricity are coal and natural gas, having a contribution of 37.5% and 30.4% respectively [3].

1.2. Increasing energy demands

Approximately 11.2 billion people will inhabit the planet by the year 2100 according to the United Nations [4]. Assuming that the energy use per person stays the same, there will be around 30% more people on Earth in the not-too-distant future, which will result in a significant rise in energy use [5].

The demand for electricity increased significantly in 2021, reaching 24,700 TWh, a 6% rise from the year before and the largest yearly growth since 2010. About half of the rise worldwide, or as much as all of today's electricity demand in Africa, is attributed to China alone. We should also note that the 3 biggest consumers of energy are China, the United States, and Europe, which together account for more than 60% of the world's electrical demand. [6].

This is why any energy transition that aims for net zero by 2050 must be built around renewable energy sources.

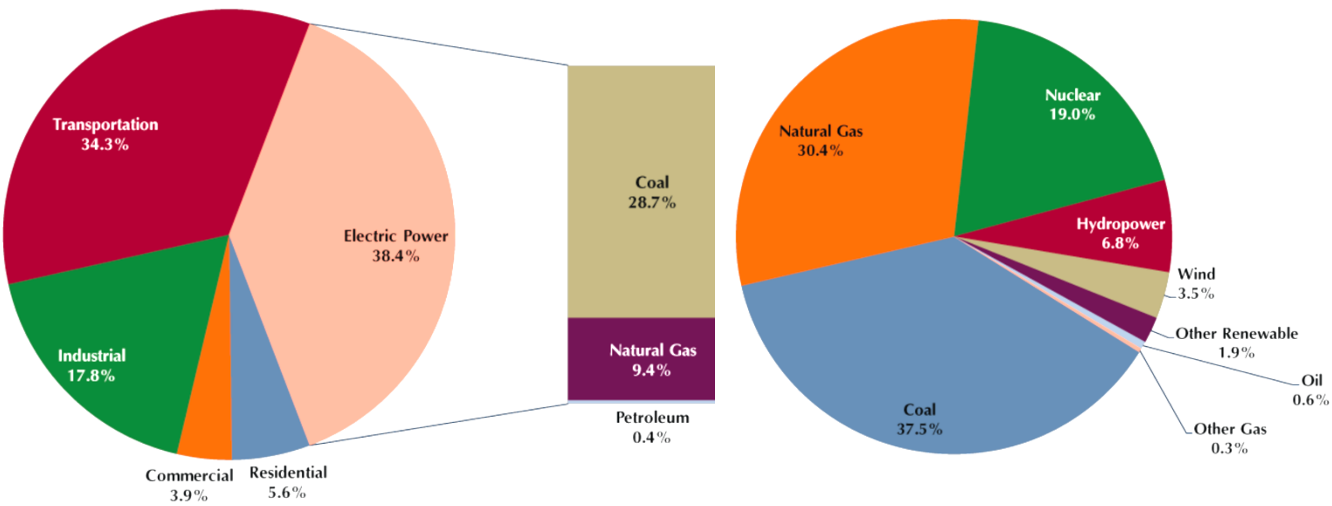

Figure 1 -The top polluting sectors in terms of CO_2 emissions in the U.S. in 2012 [3].

In the Announced Pledges Case (APC), it is estimated that the amount of electricity produced worldwide would nearly double over the 30 years, going from 26,800 TWh in 2020 to over 50,000 TWh in 2050. The increase is attributed to a rise in the proportion of renewable energy sources used to generate power, which goes from 29% in 2020 to almost 70% in 2050. Solar PV and wind energy will account for about half of the world's electricity by 2050 [7].

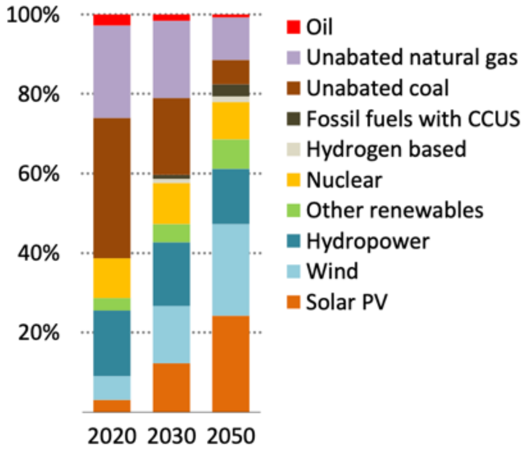

Figure 2 - The energy source used for electricity generation in the APC [7]

Figure 2 shows the energy source to be used for electricity generation in the APC for the year 2020, 2030 and 2050 [7].

2. Solar Thermal Power

Solar energy cannot be used directly; instead, it needs to be collected and transformed into more useful forms of energy, primarily electricity and heat as its average energy density is low (approximately 170 W/m^2 at Earth's surface). There are two ways of generating electricity from sunlight: Photovoltaic and Solar thermal power generation. In this report, only solar thermal power generating methods will be considered and analysed.

2.1. Why Solar energy?

The amount of solar energy travelling through one meter square of space perpendicular to the direction of the radiation at the average distance of Earth from the sun, is called the solar constant. It is used to indicate the amount of energy carried by solar radiation and is taken as 1367 W/m^2. When absorption and scattering at clouds are taken into account, the total solar flux that reaches Earth's surface is thought to be 1.08×10^8 GW each year. This is equivalent to 7000-8000 times the yearly energy consumption of the entire world. If only 0.1% of this energy was used to generate electricity, with an efficiency as low as 10%, it would still produce 4 times more capacity than the required worldwide total of 5000 GW, which is an astonishing potential [2].

2.2. An Overview on CSP

Solar thermal power, also referred as Concentrated Solar Power (CSP) entails using the sun merely as a heat source. This heat is collected, focused with the help of reflectors, and used to power a heat engine. The heat engine can be a standard steam turbine, where the heat will be used to produce steam, or it can be a closed cycle system that uses a thermodynamic fluid. There are 4 main technologies used in solar thermal power:

- Parabolic troughs
- Solar tower
- Solar dish
- Linear Fresnel

Figure 3 shows the how these applications are used to collect solar radiation. Parabolic troughs and Linear Fresnel reflectors can be considered as line focussing systems. Point focussing systems include Solar dish and Solar tower systems. It is important to note that point focussing systems are harder to handle but have a much larger concentration factor than line focussing systems, hence achieving much larger temperatures and thermal efficiencies [8].

A typical CSP plant hence comprises two main systems: One for capturing, converting, and storing solar energy, and another system for producing electricity using a thermodynamic cycle similar to those found in fossil fuel power plants. The only distinction is that solar energy, rather than combustion, provides the thermal input in the power plant.

2.3 Thermal Energy Storage in CSP

The component of solar radiation that directly hits the collectors (Direct Normal Irradiance, DNI) is the only type of normal irradiation that the CSP technology can utilise. In contrast, PV technology can use not just the DNI, but also the dispersed component caused by clouds, water vapour, and atmospheric particles as well as the reflected component as a result of the albedo effect [9]. However, CSP facilities enable thermal energy storage with cheaper costs and less environmental impact than storing electric energy produced by PV systems [10]

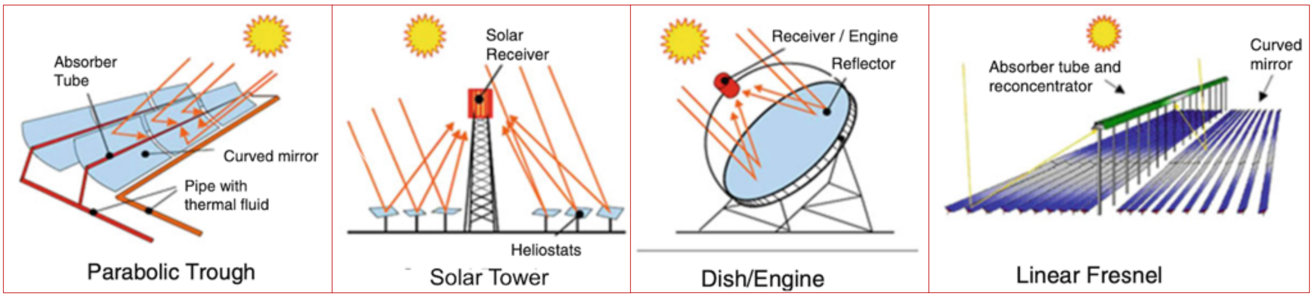

Figure 3 - Concentrated Solar Power technologies [14]

The main objectives of Thermal Energy Storage (TES) system in a CSP plant are primarily to reduce the effects of weather changes, to extend the time during which power is produced, and to avoid potential blackouts of the CSP power plant, which could not only affect the solar field's ability to produce energy but also in the case where molten salt is used as a heat storage medium, cause damage if it solidifies, which happens at 230 °C [8]. The most common molten salt used in plants is a mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3) [8].

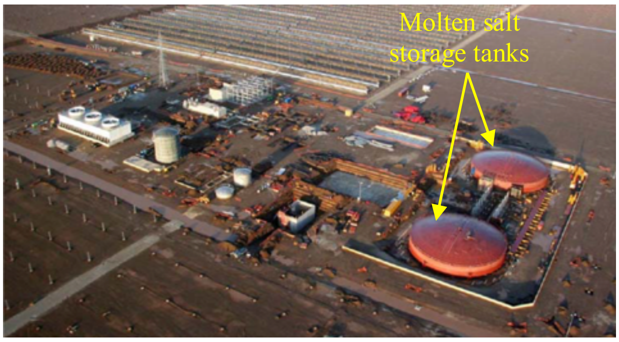

Figure 4 - Molten salt storage tanks in ANDASOL, Spain [8]

As shown in Figure 4, two tanks make up the storage system: one hot tank, where molten salt from the solar field is held at 550 °C, and one "cold" tank, where heat transfer fluid is kept at 260 °C [11]. The molten salt from the hot tank is transferred to the cold tank after being used to generate steam for electricity. This TES system is very efficient as it accounts for only 1-2% loss over 1 day of storage [8]. A CSP plant can increase its capacity factor from about 20–30% to 60% with a TES system [2].

3. Analysis of CSP technologies

3.1. Parabolic troughs

As mentioned in section 2, there is not enough energy present in the diffused form of sunlight when it hits Earth’s surface, even though can feel hot. Light coming from the sun must be captured from a wide area and concentrated

The parabola is the perfect form for a solar reflector because it concentrates all of the sunlight that strikes it at the focus point. A reflector with a parabolic cross section in the shape of a trough has shown to be more efficient for sunlight concentration across a broad surface area. A line that runs along the length of the trough, known as the focus line, is the point at which the incident sunlight is concentrated, and where the heat absorption system (the heat transfer fluid) is located [2].

Figure 5 - Parabolic trough in series [12]

The parabolic trough arrays, as shown in Figure 5, are given a tracking mechanism so they can follow the sun as it moves across the sky. Each trough's long axis is oriented north to south so that it can spin to follow the sun as it moves from east to west. Different countries use different set-ups for this orientation. A typical 50 MW parabolic trough CSP system can consist up to 600 individual troughs and a total reflector area of over 500,000 m^2 [2].

A parabolic reflector has the capacity to increase the temperature of the heat transfer fluid (HTF) to as much as 550 °C by concentrating sunlight between 60 and 100 times on the focus line. However, the HTF medium, typically synthetic oil, must be kept below 400°C to prevent it from degrading. For a conventional parabolic trough CSP plant, the HTF enters the solar field at 290 °C and exits at 390 °C [2]. Figure 6 shows a schematic process diagram for a two-system CSP plant using parabolic troughs in the solar field where thermal energy is transferred to the heat storage medium through heat exchangers.

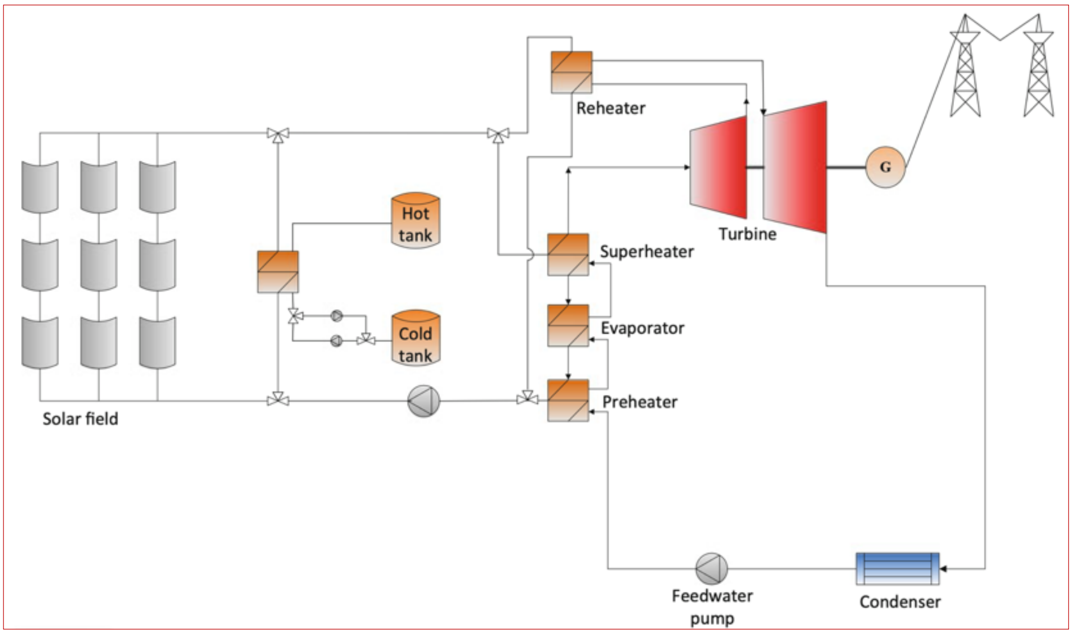

Figure 6 – Parabolic trough field transferring heat to a steam cycle using molten salt as heat storage medium [14].

3.2. Solar Tower

Compared to the line-focussing parabolic trough, the solar tower directs the heat from sunlight towards a single central facility which includes an energy receiver and heat collector located on top of a tower, as shown in Figure 7. This point focussing system comprises of several parabolic mirrors, also called heliostats, placed all around the tower. The heliostats are independently controlled of concentrate the radiation on the solar energy receiver.

The solar tower system provides greater thermodynamic efficiency as it has an operating temperature ranging from 800 °C 1000 °C thanks to a concentration factor of between 600 and 1000. Even though existing plants have only reached a factor of 600, this still results in a 20% improvement in the steam cycle's efficiency over a parabolic trough plant using thermal synthetic oil as HTF [2].

Figure 7 - Solar tower field with central receiver [13]

The size of a solar tower plant can be easily increased by varying the number of heliostats, but is however limited. The further away a heliostat is placed, the lower the efficiency. Larger plants may comprise of multiple solar fields to increase their capacity, as shown in Figure 8. Solar tower plants are usually cheaper to build that parabolic trough plants. This is because the reflectors used are almost flat and are much cheaper to manufacture than troughs. In addition, troughs required a flat surface over a large area of terrain, whereas a field of heliostats does not need to be built on a flat surface, as each of them are individually adjusted and pointed towards the receiver [2].

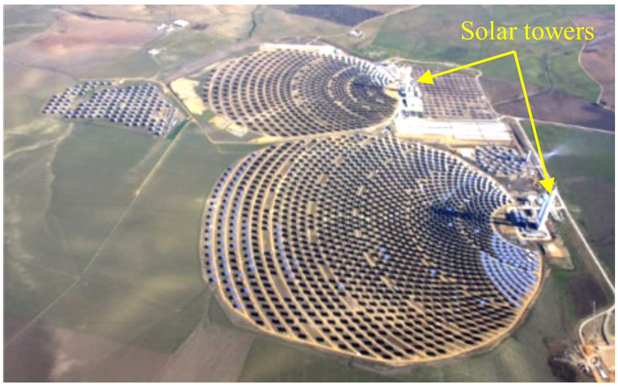

Figure 8 - Solar tower plant in with multiple solar fields in Spain (Abengoa Solar) [8]

The receiver can consist of tubes or be volumetric. HTF in solar tubular receivers can be water or steam, and molten salts, liquid sodium, or even air in the case of a volumetric receiver. The HTF then flows into a steam cycle to generate electricity, as shown in Figure 9.

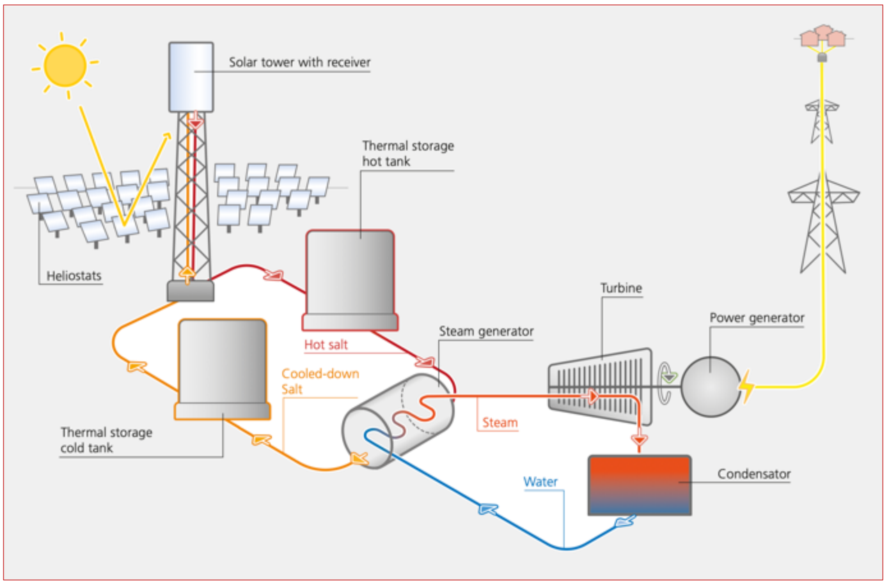

Figure 9 - Solar tower plant schematic drawing powering a steam turbine [19].

TES can be added to the system using molten salt or ceramic materials if the HTF used is gas or any phase change medium like water-steam. When integrated into gas cycles, these systems can be up to 50% more efficient [14]. This system has an estimated capacity factor of 65%, while its estimated overall efficiency is 15% [2].

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3.3. Solar Dish

The Solar dish consists of parabolic mirror with a heat/Stirling engine located at its focal point as shown in Figure 10. It is controlled to track the sun in two axes so that the focal point is always on the heat engine. Smaller dishes use polar tracking and match Earth rotating speed about a parallel axis. The majority of solar dish power units have a capacity of 25 kW or less. They can also be used in greater quantities to offer more generating capacity. Solar dishes' efficiency and simplicity are their key benefits. The energy conversion efficiency of a single solar dish with a Stirling engine may reach 31.25% and achievable up to 40%, which is substantially greater than that of any other CSP technology [2].

Figure 10 - Multiple solar dishes coupled with their respective heat engines [8].

The HTF in a solar dish can be hydrogen or helium in a Stirling engine. Some Solar dishes are coupled with a micro turbine in which air is used as HTF as they are cheaper to build. However has a lower relative efficiency of 30% [2]

Being a point focussing system like the solar tower, a solar dish alone can reach a concentration factor of 2000. This makes it possible to reach extremely high temperatures of up to 1000 °C which highly increases the efficiency of energy conversion. With a 10 m diameter dish and a direct solar insolation of 1000 W/m^2, the heat engine at the centre of the dish can generate about 25 kW of electrical power.

3.4. Linear Fresnel

Like the parabolic troughs, the Linear Fresnel system is a line focusing system where solar radiation is concentrated onto a tube in which the HTF flows and powers a steam cycle. However, this system is built with a simpler design architecture and shows some similarity with the solar tower. The Fresnel system consists of a fixed receiver tube located at the centre of the solar field. The mirrors are located close to the ground and arranged in a rectangular pattern below the receiver as shown in Figure 11. They are designed like almost flat reflectors and track the sun during the day [2].

The linear Fresnel system features a weight reduction per unit area of roughly 75% when compared to the parabolic trough. This not only shows a reduced cost, but also results in less pollution being released during the construction phase of the plant.

Figure 11 - Reflectors and receiver for a Linear Fresnel power station [8]

However, compared to a parabolic trough, the Fresnel system requires around 33–38% more mirror aperture area for the same amount of thermal energy production, mainly due to its basic optical design [8] [14]. The linear Fresnel system can operate HTF like synthetic oil and molten salt, or direct steam to increase the efficiency and reduce cost in some cases. Plants of this type coupled with a molten salt TES system operate similarly to a parabolic trough system.

As far as steam cycle overall efficiency is concerned, the Linear Fresnel is less efficient than a parabolic trough. The world has seen a significant number of implementations of this system mainly thanks to its low construction cost, low maintenance cost and far better land use efficiency compared to other types of CSP technology. A recent study conducted by Cau and Coco comparing the performance the parabolic trough to the Linear Fresnel system has led to the conclusion that Parabolic trough is, without doubt, a better option thanks to the better optical efficiency. However, this choice may vary in locations where land is not easily available [15].

Table 2 compiles the characteristics, performance, advantages and disadvantages of all four CSP technologies discussed in this section. Point focusing systems tend to have better overall efficiency thanks to a much higher concentration factor and operating temperature.

4. Economic Analysis of CSP technologies.

It is not straightforward to estimate the true cost of a project of this nature because the running costs of solar thermal power plants vary greatly. This is partially due to the fact that many of them are either demonstration projects or early commercial initiatives, meaning that expenses will be both greater and more variable than for plants that have been operating for commercial purposes.

For comparison purposes, the cost of different power generation technologies can be evaluated using the Levelized Cost of Electricity (LCOE) variable. This model is used to estimate the average cost of electricity produced that is needed for the plant to recover its life-cycle cost of the power generation facility [16]. It is important to note that comparing LCOE is a simple “rule of thumb” and does not consider other details contributing to the net life-cycle cost of a plant. Factors like the cost of work-force for construction, operation and maintenance, and the location of a plant in question may affect its specific LCOE and should be taken into consideration. For example, the network transmission costs will eventually increase when a plant of built far away from a region of high demand.

Table 1 consists of estimated cost for the production of electricity using solar thermal power reported in the US.

CSP Technology	Capital Cost ($/kW)	LCOE ($/MWh)
Parabolic trough	4500–5800	150–272
Solar tower	4800–6300	130–260
Solar dish	3300–10,000	n/a

Table 1 - Estimated cost for electricity production using CSP technology [2]

Since 2008, the cost of solar CSP power generation in the EU nations has decreased by 44%, and have an approximate LCOE of 155 $/MWh. And a 15% reduction was reported in the G20 countries, where 75% of them were estimated to have a LCOE below 136 $/MWh. India and China have the lowest LCOE due to very low CAPEX (Capital Expenditure or Investment cost), estimated at 3,100 $/kW and 1,300 $/kW, respectively, compared to levels seen in South Africa and the US, which are roughly 7,600 $/kW and 7,200 $/kW, respectively [17].

Characteristic	Line focussing system		Point focussing system	
Solar field type	Parabolic Trough	Linear Fresnel	Solar Tower	Solar dish
Typical capacity (MW)	10-250	5-200	10-100	0.1-1
Operating temperature (°C)	350-550	270-550	550-1000	750-900
Plant peak efficiency (%)	21	15	<20	31.25
Net Annual efficiency (%)	10-16	8-12	10-16	16-29
Collector concentration factor	60-100	35-170	600-1000	up to 3000
Thermal storage medium	Molten salts, concrete, phase-change material	Molten salts, concrete, phase-change material	Molten salts, concrete, ceramics, phase-change material	No storage available
Thermodynamic power cycle	Superheated Rankine steam cycle	Saturated Rankine steam cycle	Superheated Rankine steam cycle	Stirling
Cost of the solar field (€/m^2)	300-350	200-250	300-400	>350
Integration into the environment	Demanding	Simple	Moderate	Moderate
Operation requirements	Demanding	Simple	Demanding	Simple
Land requirements	High	Low	High	Moderate
Advantages	1. Long-term proven reliability and durability 2. Storage options for oil-cooled trough available	1. Simple structure and easy field construction 2. Tolerance for slight slopes 3. Direct steam generation proven	1. High temperature allows high efficiency of power cycle 2. Tolerates non-flat sites 3. Possibility of powering gas turbines and combined cycles 4. High maintenance	1. High temperature allows High efficiency of power cycle 2. Independent from land slope 3. High modularity
Disadvantages	1. Limited temperature of heat transfer fluid compromising efficiency and effectiveness 2. Complex structure, high precision required during field construction 3. Requires flat land area	1. Storage for direct steam generation (Phase Change Material) in very early stage	1. High maintenance and equipment costs	1. Not commercially proven 2. High complexity compared to stand-alone PV 3. No storage available

Table 2 - Summary of CSP technologies characteristics, performance, advantages and disadvantages [8] [14]

Figure 13 and Figure 14 illustrates the cost breakdown for a 100 MW parabolic trough plant with 13.4 hours of TES, and a 100 MW solar tower plant with 15 hours of TES respectively [9].

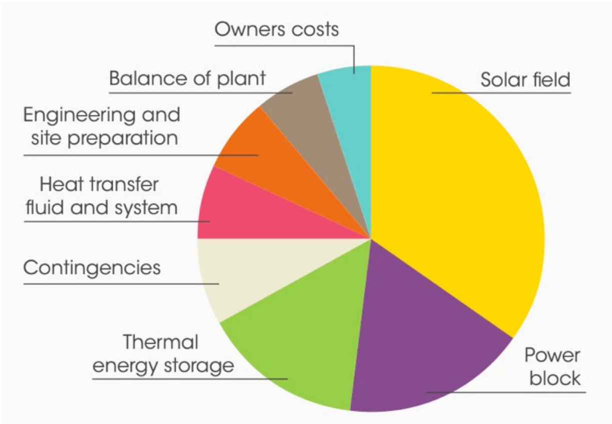

Figure 13 - Cost breakdown for a 100MW parabolic trough plant with 13.4 hours of TES in South Africa [9].

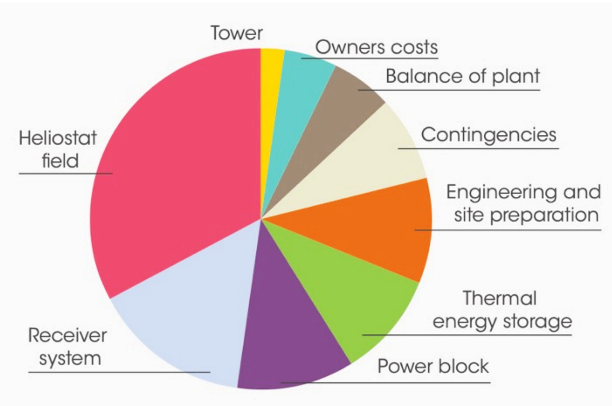

Figure 14 - Cost breakdown for a 100MW Solar tower plant with 15 hours of TES in South Africa [9]

The solar field equipment accounts for around 38% of the entire cost of a Parabolic trough or Solar Tower CSP plant, making it the most capital-intensive component. The cost of the metal support structure (10.7% of the overall plant cost), the receiver (7.1%), the mirrors (6.4%), the heat transfer system (5.4%), and the heat transfer fluid (2.1%) mostly determine the cost of a solar collector. The salt and the storage tanks are the main expenses for the thermal energy storage system, which accounts for 10% of overall costs.

5. Discussion

CSP technology remains the most expensive method of power generation. Figure 12 compares CSP technologies with other power generation processes. Wind, geothermal and hydro power are the least expensive applications and this justifies their superior number of realisations. In contrast to power plants powered by fossil fuels, the initial investment cost, which makes up about four-fifths of the entire cost, dominates the LCOE of CSP units. The remaining sum represents the cost of plant operation, maintenance, and insurance [9].

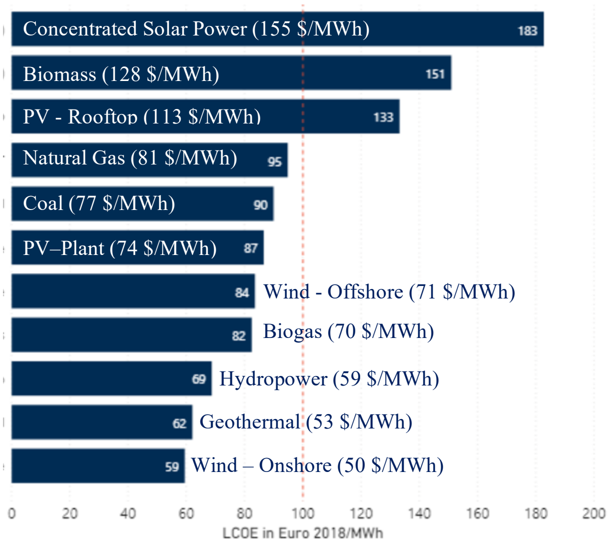

Figure 12 - LCOE for different energy source [17]

Although they are typically much more expensive, CSP facilities with thermal energy storage enable larger capacity factors. Despite having higher particular investment costs ($/kW) because of the storage system and the wider solar field, they will often have lower electricity generation costs as a result of their increased electricity generation. Therefore, special consideration should be given to energy storage, as it has the potential to lower the cost of electricity produced by the CSP plant and enhance power production.

PV technology has seen a drastic reduction in CAPEX due to a large number of solar panels being mass-produced in China. Likewise, another way of reducing the cost of CSP technologies can be the use of cheaper components followed by mass production. Reflectors made of thin aluminium sheets may be used and mass produces. These are significantly lighter and cheaper; thus, a less complex supporting structure and smaller concrete foundation will be required. Also, further experiments can be carried out on reflector surfaces to increase optical efficiency and reduce soiling which heavily affects optical performance.

A two-tank molten salt TES system is the state-of-the-art TES option for CSP systems. Innovative studies can be conducted to optimise the conventional designs as a way of reducing the LCOE. For example, two configurations were suggested in a recent study by Cascetta et al. to offer an alternative to the two-tank TES system: a one-tank TES system utilising silica as solid storage media and another one similar to that using molten salt as a phase change material. In comparison to the two-tank TES system, this would provide a 45% reduction in investment costs and a 48% decrease in levelized storage costs [18].

Operation and maintenance expenses can be reduced by implementing more automation in a power plant. For example, automatic washing systems for soiling can reduce workforce and thus the LCOE. Also, broken mirrors reportedly contribute to one-fifth of outages [9]. This mainly is caused by the effect of wind loads. Reinforcing the reflector is another way of reducing the LCOE.

6. Conclusion

The electricity production using fossil fuels is one of the biggest polluting sectors the world is witnessing. The excessive emission of CO_2 and greenhouse gasses is what makes it inevitable for this sector to converge towards renewable energy sources. Solar energy has proven to be of great potential in countries where Direct Normal Irradiance is concentrated.

If the cost is relatively high for CSP plants to produce electricity, it is mainly because of vast area of solar fields required for a maximum production capacity as seen in section 4. The TES system also contributes to the high cost of this technology. However, TES is important in solar thermal power to cater for weather changes or extend production time. Further studies need to be conducted on how to reduce Levelized Cost of Electricity (LCOE) for CSP applications. This may be achieved by reducing the cost of materials or optimising the conventional design of CSP systems. Investing in R&D will improve performance at all levels in the process, i.e., from the solar fields to the steam turbines.

Choosing the best CSP technology is not straightforward. Eventually for a project to realise, nations have to cater for profit making as well. Factors like workforce, land availability or intensity of solar radiation vary for different nations and in these cases, individual Multi Objective Optimisation can be helpful.

7. References

[1] SEI; IISD; ODI; Climate Analytics; CICERO; UNEP, “The Production Gap: The discrepancy between countries’ planned fossil fuel production and global production levels consistent with limiting warming to 1.5°C or 2°C,” 2019.

[2] P. Breeze, Power Generation technologies, Elsevier Ltd, 2014.

[3] R. E. Arafy, “Air Pollution Control Technology for CO2 Reductions,” The university of Alabama at Birmingham, 2014.

[4] UN, “World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100,” 2017. [Online]. Available: https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100. [Accessed 26 November 2022].

[5] Mackay and M. E., Solar Energy - An Introduction, Oxford University Press, 2015.

[6] IEA, “World Energy Outlook 2022,” International Energy Agency, 2022.

[7] IEA, “Net Zero by 2050 - A Roadmap for the Global Energy Sector,” International Energy Agency, 2021.

[8] Fichtner, “Regional Water Outlook part 2 - Desalination Using Renewable Energy,” 2011.

[9] IRENA, “Renewable energy technologies: Cost analysis series (Concentrating Solar Power),” International Renewable Energy Agency, 2012.

[10] Cavallaro and Fausto, “Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems,” *Applied Energy,* vol. 87, no. 2, pp. 496-503, 2010.

[11] U. Desideri and P. E. Campana, “Analysis and comparison between a concentrating solar and a photovoltaic power plant,” *Applied Energy,* vol. 113, pp. 422-433, 2014.

[12] Modelon, “Modelon,” 2017. [Online]. Available: https://modelon.com/dynamic-modeling-of-a-parabolic-trough-solar-thermal-power-plant-with-thermal-storage-using-modelons-thermal-power-library/. [Accessed 29 November 2022].

[13] Wang and Zhifeng, Design of Solar Thermal Power Plants, Academic Press, 2019.

[14] P. Palenzuela, Concentrating Solar Power and Desalination Plants, Springer International Publishing, 2015.

[15] G. Cau and D. Cocco, “Comparison of medium-size concentrating solar power plants based on parabolic trough and linear Fresnel collectors,” *Energy Procedia,* vol. 45, pp. 101-110, 2014.

[16] EIA, “Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022,” U.S. Energy Information Administration, 2022.

[17] Trinomics, “Final Report – LCOE & LCOH: Energy costs, taxes and the impact of government interventions on investments,” Trinomics, Rotterdam, 2020.

[18] M. Cascetta, M. Petrollese, J. Oyekale and G. Cau, “Thermocline vs. two-tank direct thermal storage system for concentrating solar power plants: A comparative techno-economic assessment,” *International journal of energy research,* vol. 45, no. 12, pp. 17721-17737, 2021.

[19] DLR, “Solar thermal power plants - Heat, electricity and fuels from concentrated solar power,” DLR, Germany.