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Insights of Concentrated Solar Power Utilization – Possible Deployment in Jordan

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ABSTRACT

Concentrated solar power (CSP) is a promising form of renewable energy that harnesses the immense power of the sun to generate electricity. It employs various mechanisms to concentrate sunlight onto a receiver, thereby producing high-temperature heat. This heat can be stored and converted into electricity through conventional steam turbines or for other heating applications. One of CSP's key advantages is its ability to store thermal energy for use during cloudy periods or at night, enhancing the reliability and dispatchability of solar power. This review article offers a comprehensive introduction to CSP including its principles, technological advancements, comparison analysis, and its potential to play a crucial role in the transition to a sustainable toward carbon neutral energy future. Various statistical charts on the operational CSP plants around the world have been presented in this review and showed that there is a notable interest in the MENA region for considering this technology in their energy mix. Jordan is part of the MENA region, therefore, possible deployment of this technology in the kingdom of Jordan has been assessed as well by studying the solar radiation measurements in the southern location of the country. Analysis has concluded that Ma'an governorate has the highest solar irradiance characteristics in the country and has the lowest values of diffuse irradiance. The annual average daily global irradiance is between 3.7 kWh/m² in January to 8.5 kWh/m² in June, equivalent to annual global radiation of more than 2200 kWh/m². The results have been validated using Global Solar Atlas and ener MENA high precision meteorological station installed in Ma'an. The costs and current challenges faced by this technology will also be discussed.

Keywords: concentrated solar power, direct solar irradiance, solar thermal generation, Jordan, Ma'an.

INTRODUCTION

Access to dependable and secure electricity is essential for the socioeconomic development of any nation. It encourages innovation and investment in new business ventures, acting as a catalyst for job creation, economic growth, and the general welfare of society. Wind energy and photovoltaics are two proven renewable resources that will play key roles in achieving the goals and will rise to unprecedented high shares. However, both wind power and photovoltaic power are intermittent, thus they have inherent variability and uncertainty of productivity (He et al. 2020). CSP with thermal energy storage (TES) can generate electricity and store excess thermal energy for use during cloudy conditions or at night, enhancing the reliability and dispatchability of solar power. Solar thermal technologies possess attributes such as their ability to generate amounts of power and their adaptability, across various plant sizes ranging from a few kilowatts to hundreds of megawatts (Szczygiellski & Wagner 2009).

Most of the solar systems in the market today can be categorized into two main categories: direct (or beam) and indirect solar power. Direct solar power refers to a system that directly converts the solar radiation into electricity using a photovoltaic (PV) cell. Indirect solar power on the other hand involves concentrating sunlight to generate heat first. This heat is then used to produce steam and operate a conventional turbine, as in the case of CSP (As'ad & Halawani 2020). Essentially a CSP plant functions like a steam power plant offering flexibility, adaptability, and reliability. To ensure power supply during periods without sunshine, CSP plant can be bridged by TES or auxiliary fossil fuels, enabling the plant to deliver power on demand at any time (Trieb et al. 2014). It is worth mentioning that the ability to integrate TES is a vital component of CSP systems and one of the key advantages of this technology. In fact, it plays a crucial role in ensuring the stability and reliability of power generation by allowing for the efficient storage and later use of thermal energy produced by the solar field.

BACKGROUND AND MOTIVATION

In principle, CSP plants use mirrors or lenses to collect and concentrate direct solar irradiance (DNI) onto a receiver. The concentrated sunlight is used to heat a fluid in the receiver at temperatures, the heat is then utilized to generate thermal energy and produce electricity using a conventional steam turbine or heat engine. The thermal energy produced by concentrated solar power plants can be stored whenever it is needed, day or night. Since CSP concept is based on the use of DNI, the reflector must be outfitted with a tracking mechanism so that it can follow the movement of the sun throughout the day. Figure 1 illustrates the basic block diagrams of a CSP plant.

The oil supply disruptions of the early 1970s were a driving force behind the development of alternative sources of energy and a rise in the amount of investment in energy conservation (Timilsina & Shah 2022). Accordingly, conventional CSP technologies have been mainly developed during the 1980s with some notable projects and advancements during that period. The first deployment of commercial solar energy generating systems in California plant, also known as SEGS I, began operation in 1984, and subsequent eight plants (SEGS II – SEGS IX) were built and operated in the following years. These nine SEGS power plants built between 1985 and 1991 rely on an identical concept with an overall integrated power capacity of 354 MWe (Flamant 2022).

However, from 1991 through 2005, the CSP was limited to the SEGS plants running and it is continued to evolve and improve by researchers under academic laboratories only (Py et al. 2013). As a result, there was no commercial CSP plant built at that time due to low fossil fuel prices. According to the author's point of view, this was a blackspot in CSP technology. The year 2006 marks the beginning of a new era in CSP since another plant was constructed in Spain and the technology continued to be developed and refined in the subsequent decades. Modern CSP systems have seen advancements in materials, receiver designs, thermal storage, and overall efficiency, making them more economically viable and environmentally friendly.

MAIN CSP TECHNOLOGIES AND CHARACTERISTICS

At present, there are four available CSP technologies, parabolic trough collectors (PTC), linear fresnel reflectors (LFR), solar power tower (SPT) and parabolic dish system (PDS) as illustrated in Figure 2. The systems are categorized according to their geometry of focus, either line-focus concentrators (PTC and LFR) or point-focus concentrators (SPT and PDS).

Parabolic trough collectors – this is the most mature CSP technology, in this system, a group of parabolic mirrors is used to focus sunlight onto a focal line receiver facing the mirrors. The curved mirrors are reflectors that follow the sun on a

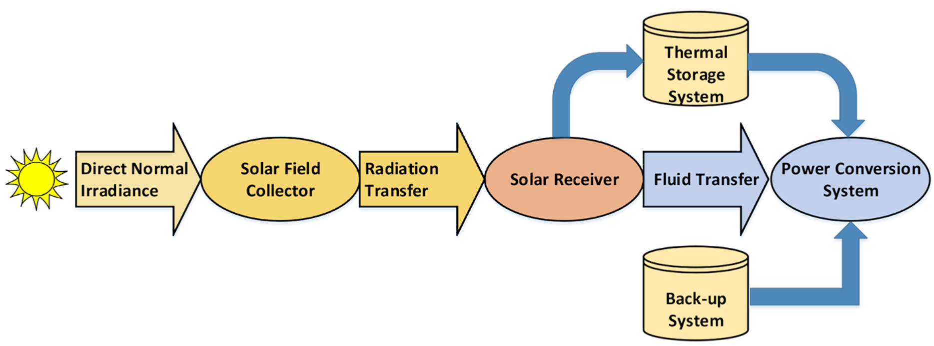

Figure 1. Block diagrams of a CSP plant (Mehta et al. 2014)

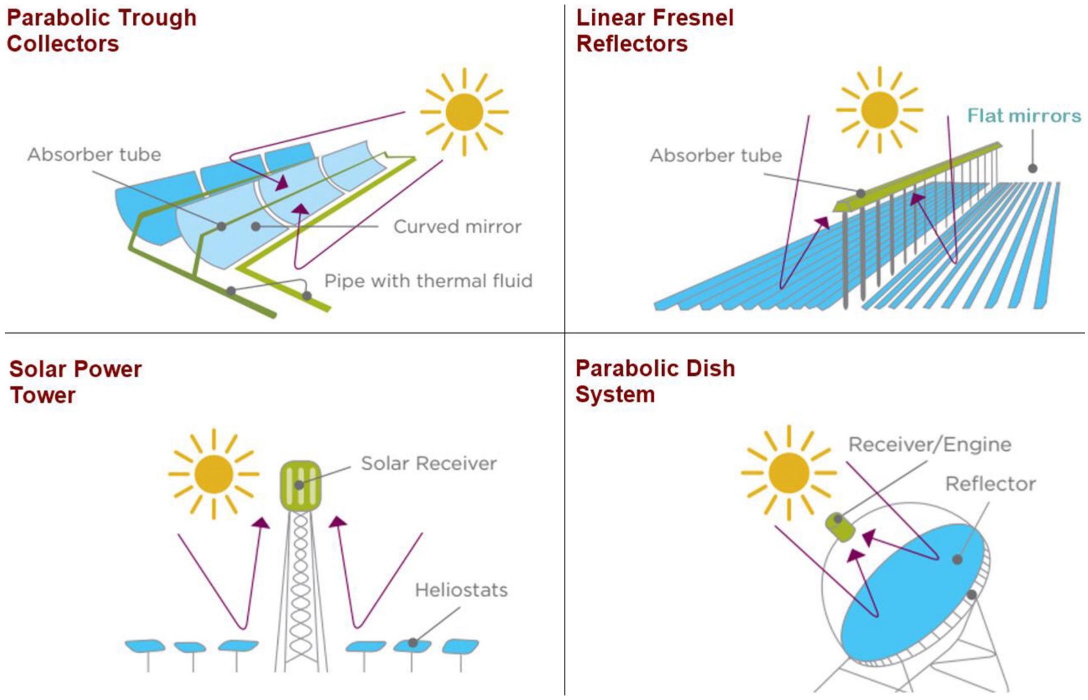

Figure 2. Main CSP technologies (Qader & Stückrad 2016 - based on Deutsches Zentrum für Luft- und Raumfahrt (DLR))

single axis mechanism. The receiver containing a heat transfer fluid (HTF), for instance, water or synthetic oil used to transmit heat from the sun to steam, which is then utilized to power a turbine to generate electricity. Linear Fresnel Reflectors: this type of CSP employs long rows of flat mirrors to reflect the sunrays onto a stationary linear receiver mounted over a tower above and along the linear reflectors. A single-axis mechanism permits the mirrors to track the sun (Zhang et al. 2013). The main advantage of LFR systems is the design simplicity of structure compared to PTC. In addition, this setup is more cost-effective since the receiver is shared by several mirrors. However, the mirrors can cause a solar shading effect for the adjacent ones if they are not mounted at a reasonable distance from each other.

Solar power tower – this system comprises a field of sun tracking flat reflectors, called heliostats, that individually track the sun in a two-axis mechanism and focus the sunrays onto a central receiver placed onto the top of a fixed tower. This heat is absorbed by the HTF, which is used to produce superheated steam. Then the super-heated steam is utilized in the Rankine cycle to drive conventional turbine (IEA 2013). The concept achieves very high temperatures, thereby improving the efficiency of the heat-to-electricity conversion process (Müller & Trieb 2004, OECD/IEA 2010).

Parabolic dish system – this system uses a parabolic dish-shaped reflector to track the sun in a two-axis and focus the sunrays onto a cavity receiver placed at the focal point of the dish. The concentrated light is then absorbed and transferred to a heat Stirling engine that generates electrical power directly (Pheng et al. 2014). The conversion of solar sunlight into mechanical power in a direct manner has the effect of decreasing both the cost and complexity associated with the primary driving mechanism which leads to high efficiency. It is worth mentioning that this type of CSP is less studied and in the process of being researched and developed.

The ability to capture heat efficiently is a key feature of CSP power production. The concentration ratio is a crucial factor to consider when planning a CSP power plant. The greater the concentration ratio, the more possible it is to achieve a higher temperature. The concentration ratio is the ratio of mean radiation flux density that gathers on the surface of the receiver's aperture to the solar DNI that enters the aperture of the concentration field. It is the same as the ratio of the area of the receiver to the total area of the reflectors. The CSP plant's annual efficiency is determined by the thermal collection efficiency and the efficiency of the thermal stream turbine (Wang

2019). Table 1 presents a comparison summary between various CSP technologies.

DIRECT NORMAL IRRADIANCE

DNI is a measured term, in the fields of energy and meteorology. It refers to the amount of radiation that a surface, positioned perpendicular to the sun's rays receiver. DNI specifically represents the sunlight that directly falls onto a surface without any obstructions or shading. DNI is typically measured in watts per square meter (W/m^2). Holds significant importance in various solar energy applications like CSP and solar tracking systems. Unlike global horizontal irradiance (GHI) which accounts for radiation received on a horizontal plane regardless of the suns angle, DNI focuses solely on the solar radiation that directly reaches a surface facing towards it. This characteristic makes DNI an essential metric for evaluating solar energy generation potential and optimizing the efficiency of energy systems in CSP technologies.

Figure 3 presents a map of the global distribution of direct normal irradiation. It represents the average daily/yearly sum of DNI covering the period from 1994/1999/2005/2007/2018 (depending on the geographical region) to 2022. The underlying solar resource database is calculated by the Solargis model from atmospheric and satellite data, indicating potential locations for CSP plants [Solargis 2023]. To ensure the optimal functioning of CSP plants in an effective manner, DNI needs to record sufficient values higher than 1800 $kWh/m^2/y$ (De & Cavalcante 2017). The regions that have the most potential for CSP resources are located in the south-western United States, northern Mexico, Chile, Peru, Australia, north-western India, the Middle East, southern Africa, and the western parts of China. Other relevant areas such as southern areas of Europe, Turkey, the central area of Asia, Brazil, and Argentina, are included (Răboacă et al. 2019).

STATISTICAL ANALYSIS ON THE GLOBAL CSP PLANTS

Several CSP projects have been deployed in different parts of the world. As of the writing of this research, there are more than 144 projects worldwide, of which 114 are in operation, 10 are no longer operational, 10 are decommissioned, and 10 are under construction (Alami et al. 2023). Spain and the United States are the leading countries in the construction and the operation of CSP plants. The continuous increase in the efficiency

Table 1. Characteristic data for various CSP technologies

Characteristic	PTC	LFR	SPT	PDS
Type of focus	Line	Line	Point	Point
Shape of reflectors	Curved	Flat	Paraboloid	Curved
Tracking mechanism	Single axis	Single axis	Two-axes	Two-axes
Maturity	High	Medium	Medium	Low
Commercialization	High	Low	High	Under development
HTF	Oil/ molten salt/ water	Water/ molten salt/ oil (limited)	Molten salt/ water/ air (limited)	Helium gas (stirling engine)
Receiver	Moving with the reflector	Stationary	Stationary	Moving with the reflector
Concentration ratio (Alam et al. 2023)	30–80	30–80	200–1000	1000–3000
Operating temperature (°C) (Chen et al. 2020)	200–400	50–300	300–1000	120–1500
Annual efficiency (solar to electric) %	14-22	13–18	15–23	18–25
Thermal storage capabilities	Suitable	Suitable	Highly Suitable	Difficult
Land occupancy	Large	Medium	Medium	Small
Operational typical capacity	50-600 (MW)	1–150 (MW)	10-400 (MW)	tens of kW (Zayed et al. 2021)
Cost	Medium to High	Medium	High	Low-Medium

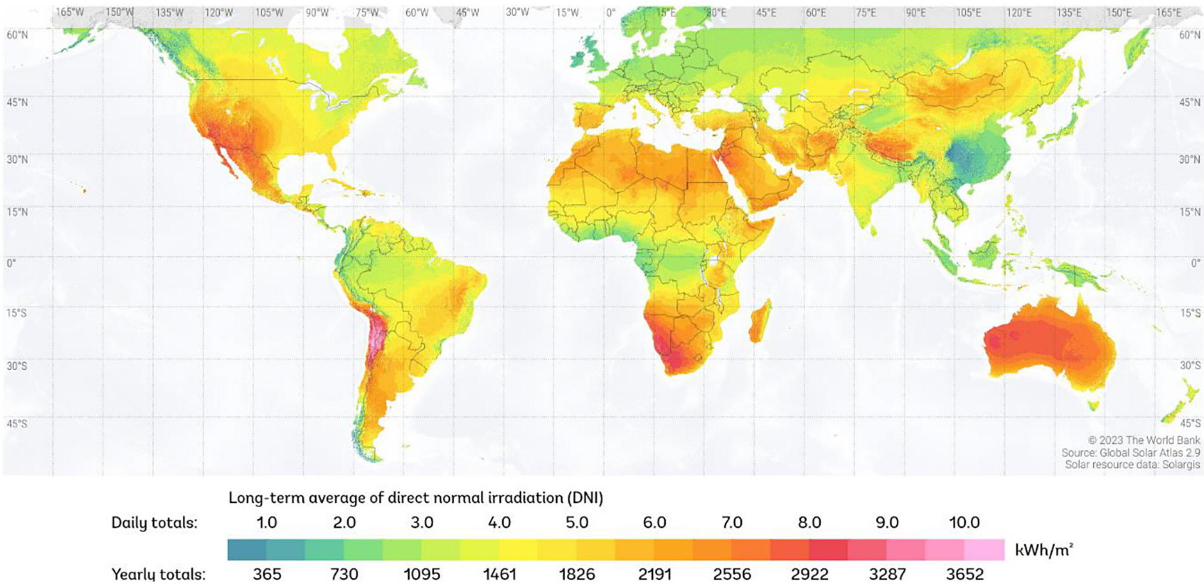

Figure 3. World map of long-term average of direct normal solar irradiance (SolarGIS 2023)

of parabolic trough technology in SEGS power plants in United States has encouraged many countries especially Spain to utilize this technology for generating clean and reliable energy through investing and constructing large scale CSP plants (Baharoon et al. 2015). In terms of the CSP market in 2021, there are 114 operational CSP plants in the world, 51 plants in Spain, China and United States followed by 14 and 10 plants respectively. Figure 4 presents the number of operational CSP plants per country. It is important to highlight that there is a notable trend towards developing countries and regions with high DNI that are now in the process of constructing several large plants. Consequently, there are currently ten CSP plants under construction, three in UAE, three in China, two in Italy and one each in Saudi Arabia and South Africa. Figure 5 illustrates the global cumulative growth of CSP capacity in MWp. (The consolidated sheet of all CSP project profiles around the world was obtained from National Renewable Energy Laboratory (NREL, 2023). The global cumulative CSP capacity has been growing rapidly in recent years and has reached 6,800 MWe by 2021 (was 3,425 MWe in 2013). Spain recorded the highest installed CSP capacity in the world, with 2,310 MW. This accounts for 35% of the global cumulative capacity. It is worth noting that Spain has not seen any CSP plant entering operation since 2013. The United States ranked second with 1,501 MW. In addition, there is a notable interest in China, India, South Africa, and the MENA region. Figure 6 shows the operational installed capacity per country. With respect to CSP technology, Figure 7 shows the overall installed capacity of CSP per technology.

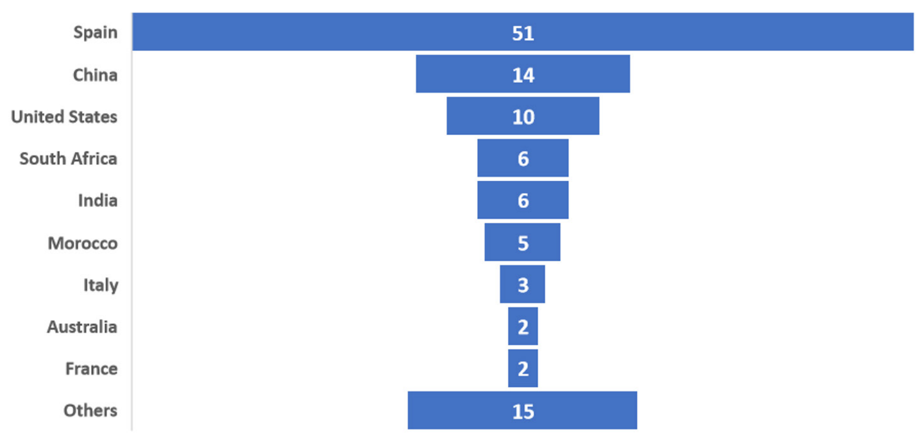

Figure 4. Number of operational CSP plants per country (extracted from NREL)

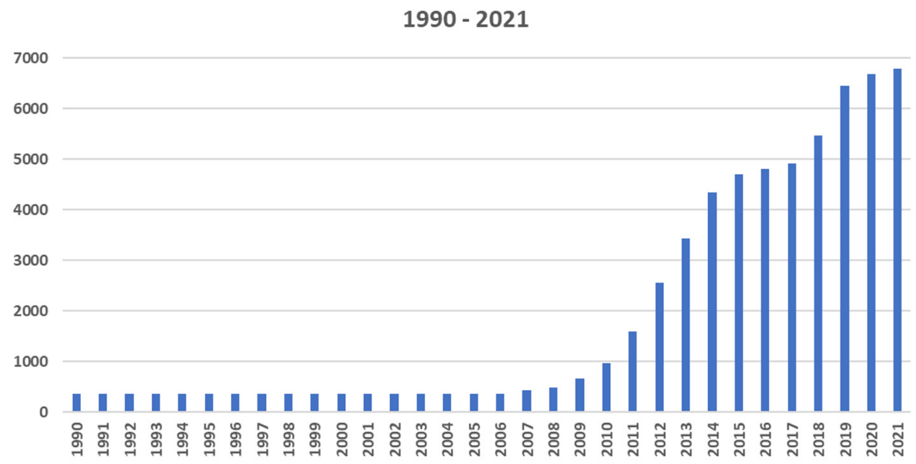

Figure 5. Global cumulative growth of CSP capacity (extracted from NREL)

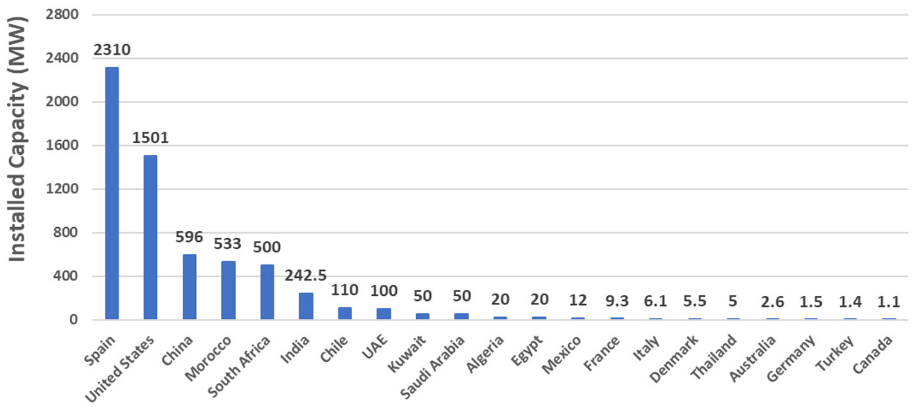

Figure 6. Global installed CSP capacity (MW) per country (extracted from NREL)

PTC occupied 75%, since it demonstrates the highest level of maturity, most of these facilities are in Spain. SDF ranked second with 21%, and LFR with 4%. When it comes to the type of HTF utilized in the commercial CSP plants, thermal oil is being the commonest HTF compared to molten salt and water due to several essential advantages, such as no tendency for corrosion, no possibilities for frost damage, high efficiency, and the simplicity in installation and replacement. However, thermal oil is not suitable at elevated temperatures especially above 400 C, thus for safety reasons, it is absolutely forbidden in SDF technology. Figure 8 depicts the installed cumulative capacity by HTF category in the commercial plants of CSP. In regards of land occupation, another

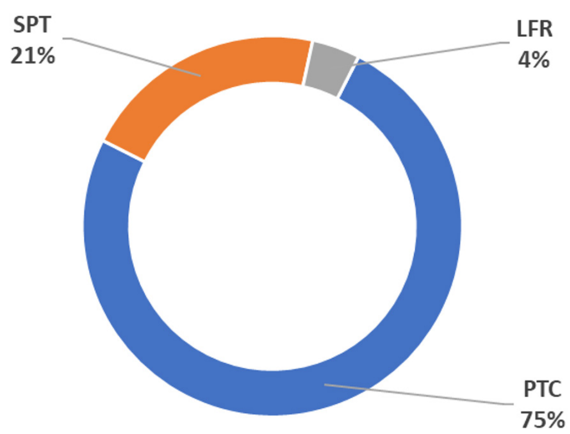

Figure 7. Global installed CSP capacity by technology (extracted from NREL)

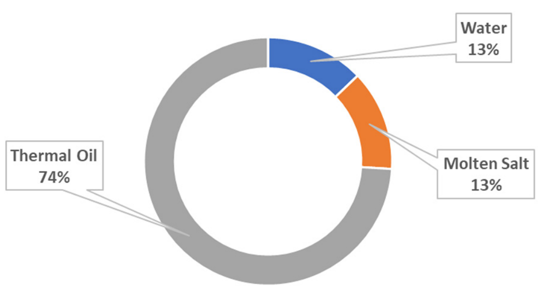

Figure 8. Global installed CSP capacity by HTF (extracted from NREL)

analysis was conducted on 94 plants to determine the average solar reflector area required in m^2 to generate 1 MW of capacity, the findings showed that the CSP with a parabolic trough needs around 8,612 m^2 for every 1 MW of capacity. Figure 9 presents the other technologies as well.

CURRENT CHALLENGES AND COST OF CSP

One of the main challenges facing CSP is its dependence on weather conditions. Without consistent and favorable weather patterns, the efficiency and reliability of CSP systems can be greatly affected. This can be particularly challenging in regions with unpredictable weather patterns or frequent cloud cover. While solar energy is a renewable source, its intermittent nature means that it cannot provide a constant and reliable power supply without efficient storage and backup fossil fuel systems. This is where CSP encounters another obstacle – the development of efficient and cost-effective energy storage systems. Given the fact of intermittent power generation, CSP plants require reliable storage systems in order to ensure a steady and dependable electricity supply. Without efficient and cost-effective TES, the full potential of CSP remains unrealized. Additionally, addressing the scalability of CSP technology poses another challenge. The installation of CSP stations requires large areas of land, making it difficult to scale up and meet the growing demands for energy. This issue is further complicated by acquiring land that is easily accessible while avoiding potential conflicts with other land uses. Another challenge to be addressed is related to the cost effectiveness of CSP. Although the costs of CSP technology have been decreasing over the years as presented before, it still remains relatively expensive compared to other forms of renewable energy, for instance PV and Wind. The primary reason for this is the high initial investment required for constructing CSP plants and infrastructure. Additionally, CSP can provide a viable solution in reducing greenhouse gas emissions, addressing climate change, and ensuring energy security. However, CSP faces certain challenges, such as high initial costs, land and water requirements, and intermittent operation due to weather conditions. Ongoing research and development are being dedicated to surpassing these limitations by exploring materials improving storage capabilities and integrating systems more efficiently. As the global demand for clean energy sources continues to grow, CSP stands as a renewable energy technology with immense promise, contributing to a cleaner and more sustainable world. In regards of the levelized cost of CSP, 2010-2020 saw a dramatic improvement in the competitiveness of CSP technologies, the cost of electricity from utility-scale CSP fell by 68%. Figure 10 illustrates the global weighted-average levelized cost of electricity (LCOE) for CSP

ASSESSMENT OF CSP SITES IN JORDAN

Jordan has encountered two significant energy crises over the last two decades; the interruption of Iraq's oil supply in 2003 and the disruptions of Egyptian natural gas exports in 2011, these

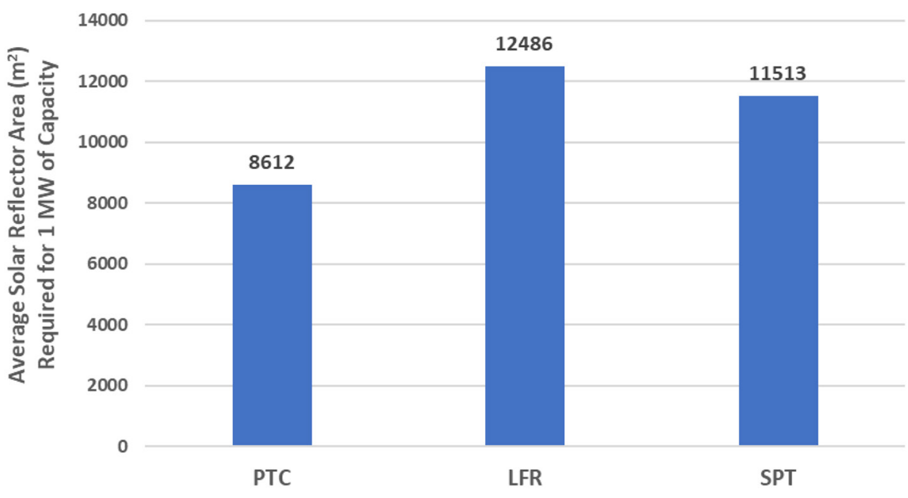

Figure 9. Average solar reflector area (m^2) required to generate 1 MW of capacity (calculated from NREL)

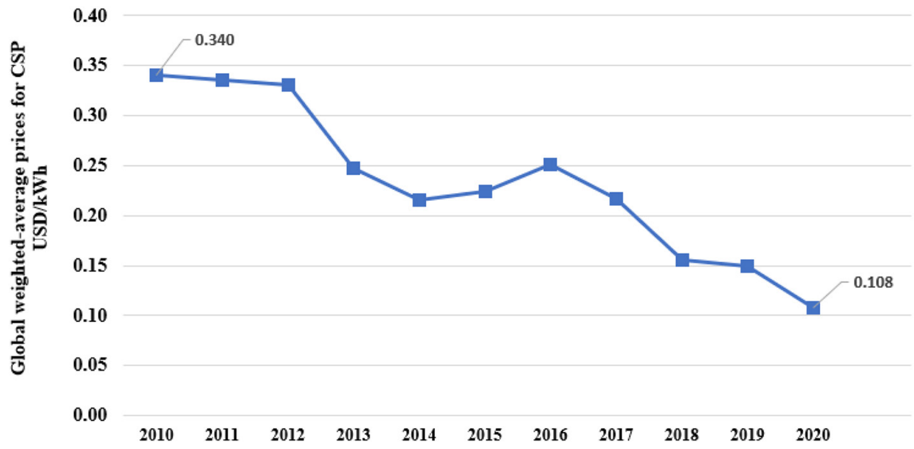

Figure 10. The global weighted-average LCOE prices for CSP, 2010–2020 (World Energy Transitions Outlook, 2022)

incidents led to energy shortages and increased costs for Jordan, including electricity generation and transportation. (Kiwan & Al-Gharibeh 2020). Jordan has a limited supply of fossil fuel resources, which are the primary energy source that is used today for electricity generation.

The Jordan National Energy Strategy 2020–2030 focuses on promoting energy security through improving energy efficiency, energy mix diversification, reducing carbon emissions, bringing down energy cost, and increasing renewable energy share of the entire electricity generation by installing more PV systems, wind turbines farms and CSP plants. Jordan is indeed located within the solar belt of the world, which means it receives a high amount of solar radiation

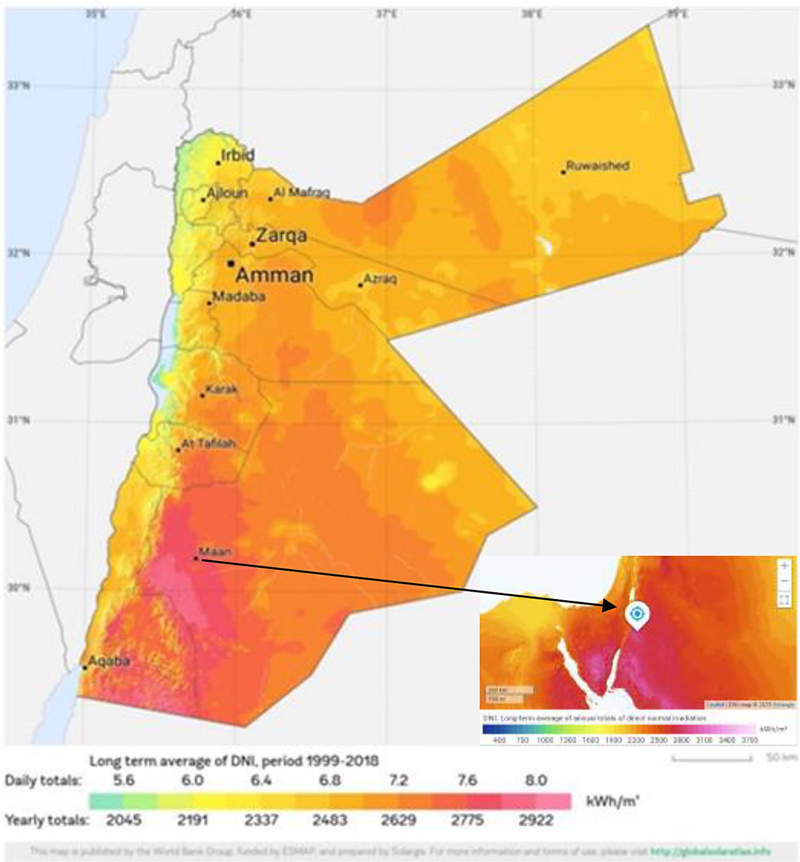

Figure 11. DNI for Jordan in (kWh/m^2) (Global Solar Atlas 2023)

throughout the year. This makes the solar energy potential in Jordan enormous and positions the country as a favorable location for solar power generation [Owhaib et al. 2022, ZAFAR 2014). Jordan is part of the MENA region and based on the DNI distribution for the kingdom of Jordan presented in Figure 11, it was found that Jordan has an outstanding potential for CSP, especially in the southern locations of the country (Al-Soud & Hrayshat 2009), Ma'an Governorate in particular. The Ma'an development area located 30.1927° N, 35.7249, it enjoys about 320 days of sunshine a year since the climate in Ma'an is mostly desert climate. Ma'an has the highest solar irradiance characteristics in the country and has the lowest values of diffuse irradiance (Alrwashdeh et al. 2019). The annual average daily global irradiance is between 3.7 kWh/m² in January to 8.5 kWh/m² in June, equivalent to annual global radiation of more than 2200 kWh/m². Figure 12 shows the sun paths chart for Ma'an which was generated from PVsyst software based on Meteonorm 7.2. In terms of DNI distribution in Ma'an, Figure 13 shows the monthly averages of DNI throughout the year. Figure 14 presents the DNI in regards of the average hourly profiles per month (imported from Global-Solar-Atlas for Ma'an)

Figure 15 displays real measurement data of DNI collected by high precision enerMENA Meteorological station in Ma'an for July month. The average values for each day are shown in the graph with a time resolution of 1 minute between each point. A Comparison between global-solar-atlas and enerMENA station (10 minutes resolution) for the month of July in Ma'an has been conducted and illustrated in Figure 16. Although

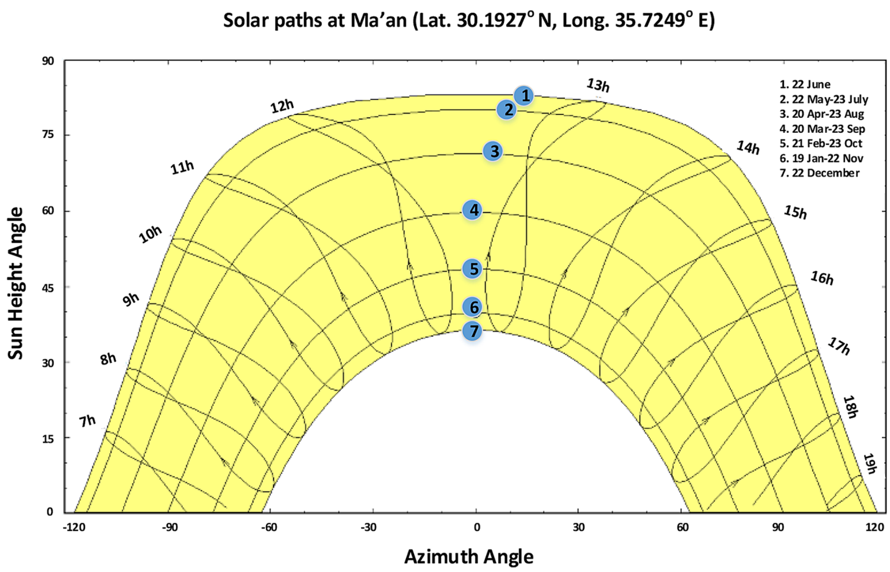

Figure 12. Sun paths chart for Ma'an (created by PVsyst for Ma'an governorate)

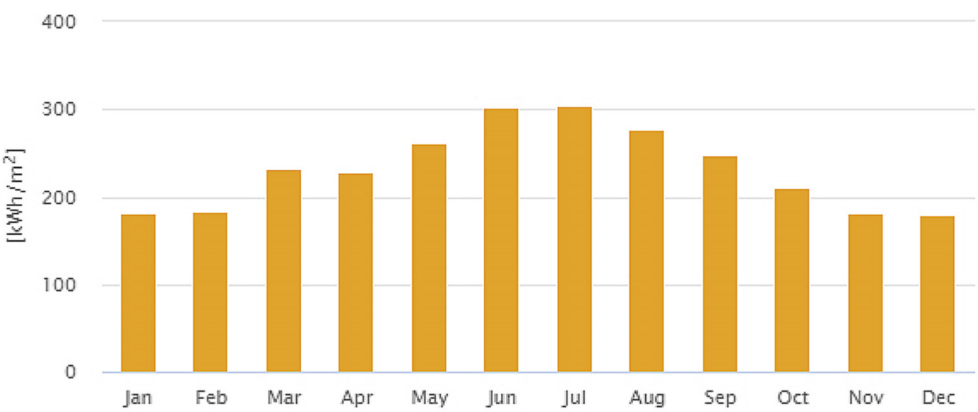

Figure 13. Monthly averages of DNI in Ma'an (extracted from Global Solar Atlas for Ma'an governorate – Jordan)

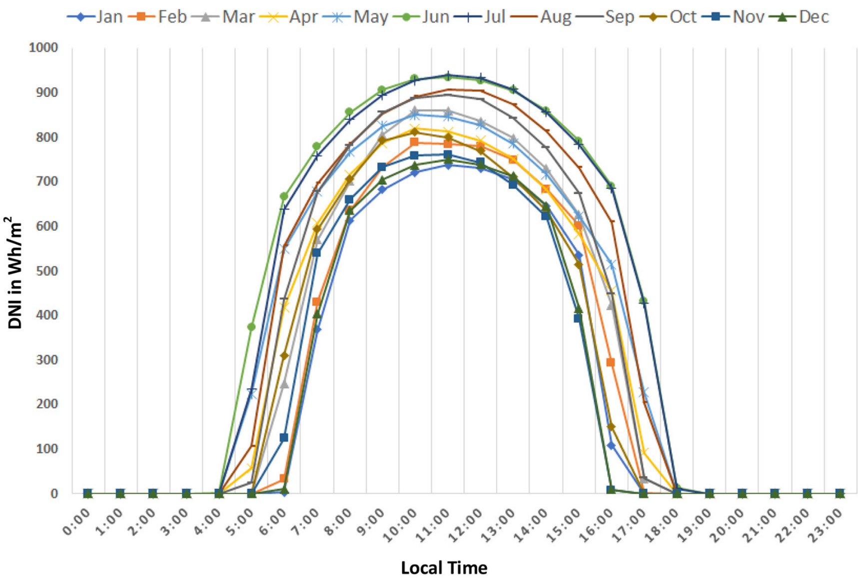

Figure 14. Average hourly profiles of DNI per month (imported from Global Solar Atlas for Ma'an)

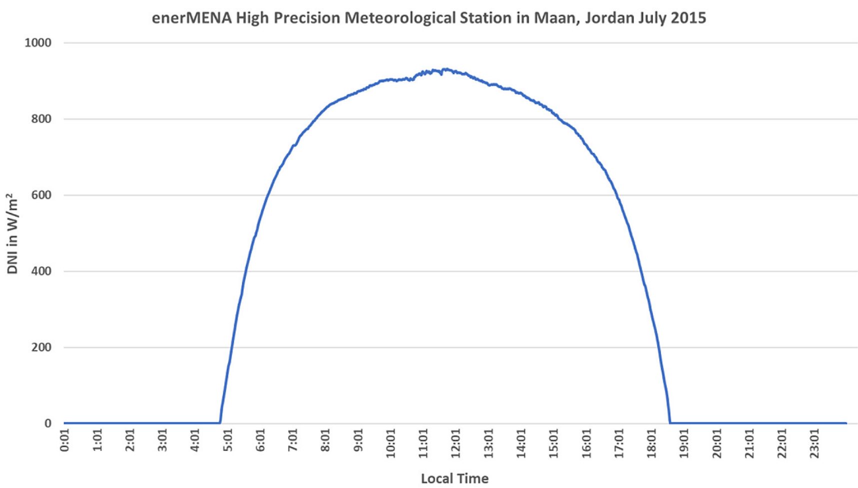

Figure 15. Real measurement data of DNI in Ma'an for the month of July (imported from enerMENA station located in Ma'an)

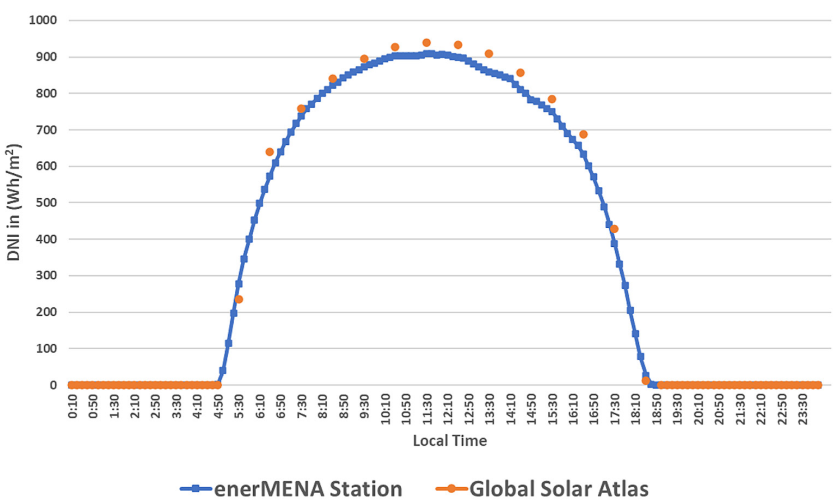

Figure 16. Comparison between global Solar Atlas and enerMENA station for July month

Ma'an Governorate has the largest area of the 12 governorates that constitute the Kingdom of Jordan, it has the lowest population density (less than 4 persons per square km) which mean that the land is available and accessible there. Based on the DNI data provided by Global Solar Atlas and enerMENA station in Ma'an, it was found that Ma'an has an outstanding potential for CSP, with the added benefit of being able to sell excess electricity to Syria, Iraq, Egypt and Palestine, whose electric grids are connected to Jordan. This Synergy makes Ma'an a prime location for realizing Jordan's National Energy Strategy vision of producing half the country's electricity from domestic sources by 2030.

CONCLUSIONS

The significance of energy generated from renewable sources is growing globally in view of the urgent need to tackle climate change. CSP shows a great promise as a renewable energy source. It offers a sustainable and clean solution for generating dispatchable electricity. It is worth mentioning that during the past decade, the global cumulative installed capacity of concentrated solar power has doubled, and there is a notable trend towards developing countries and regions with high DNI that are now in the process of constructing several large plants of CSP. Jordan has a limited supply of fossil fuel resources, which are the primary energy source that is used today for electricity generation. Jordan is indeed located within the solar belt of the world, which means it receives a high amount of solar radiation throughout the year. Based on the DNI distribution for the kingdom of Jordan, it was found that Jordan has an outstanding potential for CSP, especially in Ma'an Governorate since it has the highest solar irradiance characteristics in the country and has the lowest values of diffuse irradiance. The annual average daily global irradiance in Ma'an is between 3.7 kWh/m² in January to 8.5 kWh/m² in June, equivalent to annual global radiation of more than 2200 kWh/m². The analysis is performed using Global-Solar-Atlas, SolarGIS, and sunchart generated from PVsyst, then the data is validated by real measurements of DNI extracted from a high precision enerMENA Meteorological station in Ma'an.

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