Ouarzazate (Noor) Power Station – A Critical Examination of Concentrated Solar Power as a Means of Power Generation

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***Abstract-* Noor Power Station is the largest concentrated solar power (CSP) plant in the world. In this report, the main types of CSP in use at Noor were studied, namely parabolic trough and solar tower installations. The photovoltaic (PV) power station at Noor was also examined. A combination of simulation tools and qualitative study was used to compare the performance of each technology. It was found that solar tower technology outperforms parabolic trough both technically and economically. Considering whether CSP can compete with PV, both technologies will likely co-exist in the future. Hybrid PV-CSP plants are likely to become more popular.**

I BACKGROUND

It has been estimated that based on a European's average energy consumption, the world's total energy needs could be met by two 1000km by 1000km squares of concentrated solar power (CSP) in the desert [1]. DESERTEC is an organisation established to promote the concept of increased renewable infrastructure in the desert. They envision a future where solar power stations in the Mediterranean region generate and deliver clean power to northern consumption centres via HVDC links [1].

In order to examine the potential of CSP technology in the future energy landscape, this report will examine Ouarzazate (Noor) Solar Power Station. In 2011, the Moroccan government's new legislative agenda put a focus on the development of more green energy installations [2]. Out of this new initiative the Ouarzazate Solar Power Station was conceived. The main goal of the station was to "initiate the development of Concentrated Solar Power". The development was also in line with the government's 2009 energy policy which aimed to decrease reliance on foreign oil and improve "energy security" [2]. Before the construction of Noor Power Station, 97% of Moroccan energy came from imports. The project was commissioned as a Public Private Partnership (PPP). The main parties involved were: the private development company ACWA Power, the Spanish consortium TSK-Acciona-Sener and, MASEN (the Moroccan Agency for Solar Energy) [3].

The Solar Power Station was developed in several phases. Phase 1 saw the construction of Noor I CSP, a 160MW parabolic trough (PT) type of installation which was commissioned in 2016 [4]. Phase 2 saw the development of Noor II CSP and Noor III CSP. Noor II is a second PT installation with a generation capacity of 200MW. Noor III utilises the competing solar power tower (SPT) concept and has a generation capacity of 150MW. Both Noor II and III were commissioned in 2018 [5, 6]. All the CSP installations use molten "eutectic" salts for thermal storage. The third phase of the project saw the development of Noor IV, a conventional photovoltaic (PV) power station with 72MW of generation. This was commissioned in late 2018 [7]. This totals a full capacity of 582MW for the plant.

The study of this scheme presents a unique opportunity to compare the efficiencies of all major types of solar generation. This report will examine and compare the two main types of CSP employed at Noor: the parabolic trough and solar power tower. Conventional PV technology will also be examined as it is utilised at Noor IV. A detailed explanation of how the technologies operate will be given. Due to a lack of reliable and detailed power output data, simulation tools such as the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) will be used [8]. With SAM, the estimated power output and efficiency of the various plant technologies can be simulated and used to critically compare them. Weather data for Ouarzazate can be imported to SAM. Impacts of the project will also be assessed including a detailed look at the economic, social, and environmental implications. Finally, with the price of PV panels for conventional solar stations falling in recent years [9], the future value of CSP is being brought into question. This report will draw some conclusions on whether CSP technology is viable in the future solar power landscape when compared to PV and if so, what type of CSP is best suited to be utilised.

II TECHNICAL ANALYSIS

II.I Overview of CSP Technology

CSP uses a system of mirrors to reflect and concentrate sunlight onto receivers to create heat. The main source of energy for this process is direct normal irradiance (DNI). For optimum concentration of the sunlight to be achieved, the mirrors track the movement of the sun. Commercial CSP schemes consist of four main types: the parabolic trough, the solar power tower, the linear Fresnel reflector, and the parabolic dish [10]. A heat transfer fluid (HTF) is circulated through the receivers and is heated by the concentrated sunlight. The HTF is pumped to a steam generator where it converts water to a gaseous state. This drives a turbine and generator. The fluid is then condensed from its gaseous state using wet or dry cooling. Popular HTF options include synthetic oil and molten salt [10]. CSP plants can also include thermal energy storage (TES). During periods of excess generation, heat is stored in a secondary substance, usually molten salt.

II.II Parabolic Trough Installations (Noor I and II)

Amongst CSP installations, the parabolic trough (PT) is the most in use today. It is estimated that 82% of CSP schemes utilise the PT [11]. Three main components make up a PT installation: the solar field, the TES system, and the power block.

The Solar Field and Parabolic Collectors

The solar field consists of many curved mirrors called parabolic trough collectors (PTC). They are arranged in a series configuration known as loops [11]. The models of collectors used are shown in Table 1. The collectors consist of a concentrator, receiver tube and tracking system. The concentrator focuses the light from the sun onto a central focal point where the receiver tube is placed. PTC receiver tubes consist of an inner and outer pipe (Appendix B, Figure 6). The inner tube contains the HTF. For Noor I and II it is a synthetic oil (maximum temperature 390C). The outer tube is made from low-iron borosilicate glass which improves the level of solar absorption. These receivers support a maximum temperature that ranges from $400-550C$ [13]. The PTCs have single axis tracking systems.

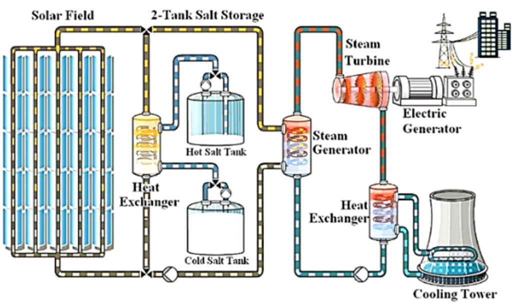

Figure 1: Parabolic Trough Installation Schematic [12]

The Thermal Energy Storage System

For the TES systems at Noor I and II, two molten-salt storage tanks are installed (Figure 1). Noor I and II use synthetic oil as the HTF. Charging of the storage system occurs when molten salt is pumped from the cold tank to the hot tank, passing through a heat exchanger where it is heated by the thermal energy of the oil. Discharging occurs when the system reverses. Noor I and II have storage capacities of 3 and 7 hours respectfully [4, 5].

The Power Block and Cooling Systems

The power block consists of the steam generator, turbine, and electrical generator. Thermal energy from the HTF heats water to steam which drives the turbine, generating electrical power. There are two primary types of cooling system for CSP: wet and dry. In the case of a water cooling condenser (WCC), the steam is condensed by means of a heat exchanger (Figure 1). The waste heat generated from condensing the steam is pumped to a cooling tower where it is ejected to the air by evaporation. In the case of a direct air cooling condenser (ACC), the steam is pumped directly through a series of "fin tubes". These are cooled by ambient air which is circulated around the tubes using fans [14]. Noor I and II use wet and dry cooling respectfully.

II.III Solar Tower Installation (Noor III)

Solar power towers (SPT) or central receiver systems are a novel form of CSP technology. Only 13% of CSP schemes currently in operation are solar towers [11]. The SPT is made up of the solar field, solar tower, TES system and the power block.

The Solar Field and Solar Tower

The solar field at Noor III consists of 7400 mirrors called "heliostats" [16]. These are used to reflect sunlight onto the central receiver system at the top of the solar tower (Figure 2). The heliostat model in use at Noor III is the HE54 with an effective area of 178.5m^2 (Table 1). These heliostats have two axis adjustment. The solar field accounts for up to 70% of the overall CAPEX costs of the project. The solar tower is where the central receiver is housed and is 247m tall. There are two main types of receiver, cavity and external [17]. Noor III uses an external tubular receiver with a ceramic exterior. The HTF in use at Noor III is molten salt. The HTF is pumped through the receiver at a low temperature of around 290C and is heated as high as 550C [6]. The heated salt is then pumped to the steam generator.

The Thermal Energy Storage System

The TES system of the SPT at Noor III is similar to the storage solution in use at Noor I and II. Molten salt is stored in a system of two tanks, one hot and one cold. The main difference is that since the HTF and thermal storage fluid are the same for the SPT, there is no requirement for a heat exchanger to transfer heat between synthetic oil and eutectic salts. Instead it is a "direct system". Salt is heated to 550C at the receiver and stored in the hot storage tank [17]. When demand is high it can be pumped to the steam generator. Once it has been cooled back to 290C it is pumped back to the cold storage tank completing the cycle (Figure 2).

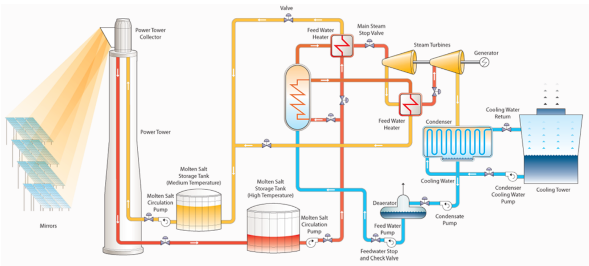

Figure 2: SPT Installation Schematic [15]

The Power Block and Cooling Systems

The power block is the same as the PT installations. The same wet and dry cooling options available for PT installations are available for SPT systems. Noor III utilises dry (AAC) cooling [6]. Table 1 below shows the technical specifications of all CSP installations at Noor.

II.IV Photovoltaic (PV) Power Station (Noor IV)

PV technology in use at Noor IV must be compared against CSP. A PV power station is made up of two main components: the PV arrays and the power converters (inverters) [18]. Noor IV does not have any battery storage installed. PV arrays are composed of a number of panels connected in series and parallel. Noor IV makes use of polycrystalline PV panels [19]. PV panels operate based on the PV effect. A PV cell consists of a p-type and n-type semiconductor joined together. When sun shines on the panel, the energy of the photons is transferred to the semiconductor material. This gives the electrons in the p-n junction of the cell enough energy to move to the conduction band and creates holes in the valence band. This movement of electrons and holes generates a current flow [20]. The PV arrays at Noor IV have single-axis

Table 1: Technical Specifications for CSP Installations at Noor I, II and III [4, 5, 6]

Technical Specification	**Noor I**	**Noor II**	**Noor III**
Type	Parabolic Trough	Parabolic Trough	Solar Tower
Solar Field			
Aperture Area (m^2)	1308000	1779900	1312000
Collector/ Heliostat Model	SenerTrough1	SenerTrough2	Sener HE54
Receiver Fluid (HTF)	Synthetic Oil	Synthetic Oil	Molten Salt
Inlet Temperature (C)	293	293	293
Outlet Temperature (C)	393	393	550
Receiver Model	Schott PTR70	Rioglass	External Tubular (Sener)
Thermal Energy Storage			
Storage Type	2-tank indirect Molten Salt	2-tank indirect Molten Salt	2-tank direct Molten Salt
Capacity (Hours)	3	7	7
Power Block			
Capacity (MW)	160	200	150
Power Cycle (PC)	Rankin	Rankin	Rankin
Cooling Type	Wet	Dry	Dry

tracking and fill an area of $137ha$ or $1370000m^2$. PV systems employ maximum power point tracking (MPPT), which identifies the optimum voltage and current for the PV arrays to achieve maximum power. Medium to large PV systems, such as Noor IV ($72MW$ capacity), make use of a central inverter to convert from DC to AC [18]. In the next section, simulations will be used to compare the performance of the Noor power installations.

II.V Simulation of Noor Power Station with SAM

Due to a lack of reliable data for the Noor installations, the SAM simulation tool by the NREL was used to compare the stations [8]. For detailed explanations of how SAM models the different CSP stations and calculates results, refer to the technical guides on the NREL website [21]. For modelling of the PV power station a tool within SAM called PVWatts is used which has its own manual [22]. We must simulate the weather in the region. Inputting the coordinates of Ouarzazate into SAM ($30.93°N$, $6.93°E$) we can plot the average DNI in the region for each month (Appendix B, Figure 8).

Simulation of CSP Installations (Noor I, II and III)

Parameters for Noor I and II are configured in SAM using data from Table 1 which shows the specifications of the plants. The only difference is that the collector model in SAM is set to Luz LS-3 as the SenerTrough1 is not available. Using the resulting data from this simulation, a number of graphs can be plotted to illustrate the performance of each installation. Figure 3 shows the power generation of Noor I in kW at different times during the day throughout the entire year. The early and late months of the year have less sunlight during the day resulting in lower power generation. This plant has 3 hours of storage capacity which allows it to generate power during dark hours. For Noor II, the power generation for different hours of the day throughout the year is plotted in Figure 4. Generation for Noor II occurs much later in the night compared to Noor I. This is due to the extra hours of energy storage and shows the benefit of large capacity TES. Now we model Noor III. Apart from the information given in Table 1, we require some extra data. The number of heliostats is set to 7400 and the area of the heliostat is set to $178.5m^2$. The tower height is set to $247m$. The plot for power generation at Noor III is shown in Appendix B, Figure 10. It is similar in distribution to Noor II due to the identical TES capacity of 7 hours.

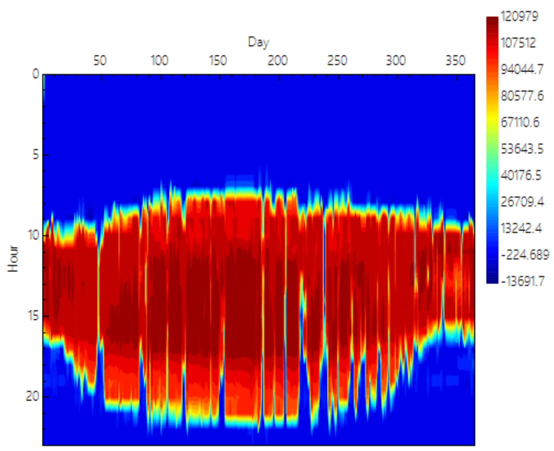

Figure 3: SAM Plot showing Power Generation in kW of Noor I at different Hours of the Day

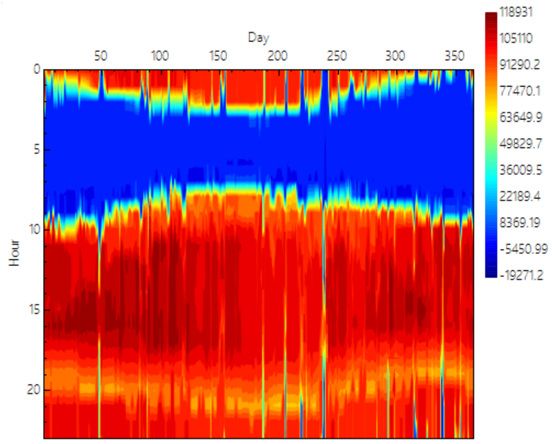

Figure 4: SAM Plot showing Power Generation in kW of Noor II at different Hours of the Day

Simulation of PV Power Station (Noor IV)

The PV Station is simulated using the PVWatts model. The capacity is set to $72MW$ and single axis tracking is selected. The plot showing power generation across different hours of the day is shown in Appendix B, Figure 12. It is similar to Noor I due to there being no battery storage implemented for this PV station. Table 2 shows the results of all the simulations. We can use these results to compare the technologies in use at Noor Power Station.

II.VI Critical Technical Analysis

Parabolic Trough vs. Solar Power Tower

The SPT at Noor III outperforms the similarly sized PT installation at Noor I. The SPT has a higher energy output per unit of land used with a performance increase of 21.04%. The SPT instal-

Table 2: Results of Technical Simulations in SAM for Noor I, II, III and IV

Simulation Results	Noor I	Noor II	Noor III	Noor IV
Expected Annual Energy Generation (GWh)	350	600	500	-
Simulated Annual Energy Generation (GWh)	398.425	515.810	483.772	156.323
Annual Energy Generation per m^2 of Aperture Area (MWh/m^2)	0.3046	0.2898	0.3687	0.1141
Capacity Factor (%)	45.5	58.9	53.4	24.8
Mean efficiency of the plant (η)	0.1739	0.2343	0.2185	-
Mean efficiency of the plant not considering darkness hours (η)	0.3895	0.3766	0.406	-
Annual Water Consumption (m^3)	1348362	132065	94109	-
Annual Water Consumption per m^2 of Aperture Area (m^3/m^2)	1.031	0.074	0.072	-

lation also has a higher CF. This is supported by relevant literature which suggests SPT installations can be up to 30% more efficient and their energy per unit of land use is $20-30\%$ higher [23]. Therefore, SPT is shown to be technically superior.

Dry vs. Wet Cooling Technology

For the PT installations, switching from wet cooling to dry cooling results in a 92.82% reduction in the amount of water used. However, in terms of technical performance, changing from wet to dry cooling reduces the efficiency by 3.3%. This drop is in line with literature on the topic which suggests a decrease of $4-5\%$ due to underperformance of dry cooling at high temperatures [14].

Concentrated Solar Power vs. PV Solar Power

From our data table its clear that in terms of land use, the SPT CSP installation is up to 323% more efficient than the PV installation and the CSP plants have a higher CF. However, the global market share of PV power stations is much higher than CSP stations. The main reason for this will be explored in the following section.

III ECONOMIC ANALYSIS

Table 3 below compares the costs of the Noor installations in USD adjusted for inflation to 2020. CSP is much more expensive than PV on a per kW basis. PV panel prices have fallen $30-40\%$ in recent years which has further contributed to this disparity [9]. As more adoption and R&D occurs in the space of CSP we can expect to see prices fall. However, PV's large cost advantage accounts for its much greater share of the renewable market today. This cost data also shows little to no price increase between developing the PT installation at Noor II and the SPT installation at Noor III. This is a surprising result. The economic parity of choosing SPT over parabolic trough, combined with the technical benefits of SPT listed above makes it a very attractive option. However, just 13% of CSP installations are SPT. The lack of widespread adoption of SPT can be explained by two key factors. Firstly, SPT is a newer technology. Secondly, the necessary software to properly optimise heliostat placement is complex and only a small number of companies have access to these tools which has slowed the pace of development [23]. The final economic consideration is the levelised cost of Energy (LCOE). The LCOE value is less than or equal to the remuneration value for each plant which calls into question the profitability of the scheme. According to project documentation, the Noor installations are set to make an absolute loss over the 25 year operational period [2, 25]. The projects were made economically viable as the state agreed to finance the gap between the price MASEN pays to the developers of the project (LCOE/kWh) and the price that MASEN sells energy to the grid at.

Table 3: Economic Analysis of Noor Installations [4, 5, 6, 19]

Economic Analysis	Noor I	Noor II	Noor III	Noor IV
Total Construction Cost USD (2020)	1214.26 million	1119.2 million	877.05 million	80.92 million
Cost/kW USD (2020)	7589	5596	5847	112
LCOE/kWh USD (2020)	0.28	0.16	0.15	-
Remuneration USD/kWh (2020)	0.18	0.14	0.15	-

IV IMPACTS

IV.I Economic Impacts on all Stakeholders

The relevant parties here are the Moroccan government, ONEE, MASEN, the development companies such as ACWA power, device manufacturers such as Rioglass, and the financiers of the project including the World Bank and the EU. The economic schemes in place for both Phase 1 (Noor I) and Phase 2 (Noor II and III) of the development are the same so will be examined jointly. Firstly, considering the state and MASEN. The development of Phase 1 and 2 yields a net deficit over the 25 year operational period. The benefits for the state of Morocco therefore are at the macroeconomic level. The project improves the kingdom's trade balance of, reducing the amount of coal and fuel oil imports. Other economic benefits include the value of greenhouse gas emissions and the fact that energy will be generated and sold on the local market [2, 25].

For private firms involved in the construction of the project such as ACWA power the project has generated an attractive return on a per kWh basis due to the PPP deal signed between the state and the private developers [25]. Device manufacturers also benefit economically as large purchase orders were made for Sener and Rioglass PTR receivers. Finally, considering the financiers of the project including the World Bank and the EU. These bodies are incentivised to fund green infrastructure projects such as this in order to meet carbon neutral targets such as those pledged at the COP 21 Paris agreement. It also furthers the World Bank's 2013 energy strategy of integrating Euro-Mediterranean electricity markets, as electricity from the Noor installations in the desert could eventually be exported to Europe [26].

IV.II Environmental Impacts

Environmental impacts vary between the different installations at Noor power station. A comparison matrix has been created in Table 4 to examine the impacts in detail with a particular focus on the CSP installations. An environmental and social management plan (ESMP) was drawn up for each station in order to mitigate the risk of landslides, water pollution, and damage to wildlife.

IV.III Social Impacts

Social impacts are those that effect the local community surrounding the infrastructure project. These can be subdivided into a number of key areas. Employment benefits from the project are substantial. During the construction phase roughly

Table 4: Environmental Impacts of Noor Power Station Development [24]

Environmental Impacts	Parabolic Trough (Noor I and II)	Solar Tower (Noor III)
CO2 Emissions	Reduction in CO2 emissions of 762000 tonnes annually over the lifetime of the scheme (Noor I, II and III)	
Natural Environment	Impact during construction. Pollution due to use of synthetic oil as HTF, leakage in pipes can effect streams (wadis), with high heritage value.	Impact to environment during construction, excavated earth.
Biological Environment	Disturbance to wildlife and animal life during the construction of the project.	Birdlife effected, reflections from heliostatic mirrors can blind birds.
Landscape	Viewable from the nearby roads (RP1511)	Project solar tower can be seen from town of Ouarzazate.
Air Quality	Fumes from vehicles during construction and shipment of materials to site. Fossil fuel usage by the plant will effect air quality.	
Water Consumption	For wet cooling at Noor I, an estimated 2.5 million m^3 is required annually. Dry cooling in use at Noor II.	Dry cooling in use at Noor III so low consumption.
Pollution	Fossil fuels needed for booster power supply. Gas oil has sulphur content 50ppm. Synthetic oil used for HTF. Eutectic salts kept at high temp. using fossil fuels	Fossil fuels needed for booster power supply. Eutectic salts kept at high temp. using fossil fuels.

2000 to 2500 direct jobs were generated [24]. During the operational phase the amount of jobs depends on the type of solar installation. For PV stations like Noor IV very little maintenance is required and less than 50 full time employees may be recruited. For CSP installations at Noor I, II and III regular maintenance is required and each station requires 500 employees. The plant also likely disturbed the local population. During the construction phase heavy goods vehicles may have caused traffic issues and noise pollution was likely generated by heavy machinery and on-site assembly. While the plant is running the turbine, generator and cooling system are very loud. The visual impact of the site may also effect local residents as the SPT is viewable from Ouarzazate [24].

Regarding the impact to the original owners of the land, the project site for Phase 1 and 2 consists of 2500*ha*. This land was owned by the Ait Oukrour Toundout ethnic group and was being used for grazing. This activity was easily moved to neighbouring land. MASEN followed appropriate land purchasing procedures and after attaining the relevant permissions the deal was finalised on 18 October 2010. The Ait Oukrour Toundout group approved the deal on 20 May 2010 [24]. Compensation was given in the form of Moroccan Dirhams. A price of DH 25000000 was set by a review board (DH 10000 per *ha*) which equates to 6.8 million USD (2010). Finally, considering impacts on the tourism industry, the construction of one of the largest CSP power plants in the world had a positive impact as it generated positive news coverage for the region on a national and international level.

V CONCLUSION

One of the primary goals of this report was to assess the viability of CSP technology when compared to PV technology. In terms of technical specifications, CSP has a superior TES system which uses molten salt storage tanks compared to the battery systems in use by PV technology which have lower efficiencies and capacities. Furthermore, the SPT installation at Noor III has been shown to be approximately 3 times as land use efficient as the PV panels at Noor IV. However, CSP is much more expensive than PV technology on a per *kW* basis. The PV power station at Noor IV cost \$112 per *kW* while the SPT installation at Noor III cost \$5847 per *kW*. This accounts for the large market share discrepancy between CSP and PV plants. In 2017 less than 2% of solar capacity worldwide utilised CSP technology [27]. With PV panel prices set to continue to drop over the next few years it is unlikely CSP can outpace this reduction in price, even with an increase in R&D spending. Therefore, it seems at first glance that CSP as a technology may struggle to compete with PV in the coming decades.

However, due to the advantages and disadvantages of both technologies which have been shown in this report, it seems misguided to treat these technologies as competitors. In fact, they are suited to working together as a hybrid solution just as in the case of Noor power station. The intermittent nature of PV technology can be supplemented by the TES systems of CSP plants, providing power day and night. Many other hybrid PV-CSP plants are now being developed around the world. The largest currently under construction is in the Mohammed Bin Rashid Al Maktoum Solar Park where a 950*MW* hybrid project is being developed [28]. Furthermore, many have suggested that CSP competes more with natural gas than PV [9]. They are both thermal based energy sources and like natural gas, CSP can release its generation when it is needed using TES. While natural gas is currently much more affordable than CSP, this is beginning to change. A recent PV-CSP installation in Chile was shown to have a lower LCOE than natural gas plants in the region [29].

Finally, this report also considered the optimal type of CSP technology. The SPT and PT installations at Noor power station have been compared in detail. It has been conclusively shown that SPT is superior both economically and technically. Due to its novel nature, it has not achieved the same level of market penetration as parabolic trough. However, this looks set to change in the coming years with many SPT projects under construction including Atacama-1 in Chile with a net capacity of 110MW and Ashalim Plot B in Israel with a net capacity of 121MW [30]. Therefore the market share of SPT installations should increase over the coming decades. Overall, the future looks extremely promising for CSP technology as a means of power generation as we move towards a greener more sustainable future.

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A NOMENCLATURE

Abbreviations

ACC Air Cooling Condenser

CAPEX Capital Expenditure

CF Capacity Factor

COP Conference of the Parties

CSP Concentrated Solar Power

DH Moroccan Dirhams

DNI Direct Normal Irradiance

ESMP Environmental and Social Management Plan

HTF Heat Transfer Fluid

HVDC High Voltage Direct Current

LCOE Levelised Cost of Energy

MASEN Moroccan Agency for Solar Energy

MPPT Maximum Power Point Tracking

ONEE Office of Electricty and Drinking Water

PC Power Cycle

PPP Public Private Partnership

PT Parabolic Trough

PTC Parabolic Trough Collector

PV Photovoltaic

SAM System Advisor Model

SPT Solar Power Towers

TES Thermal Energy Storage

WCC Water Cooling Condenser

B SUPPLEMENTARY FIGURES

Figure 5: Map showing CSP Required to supply the World's Energy Consumption

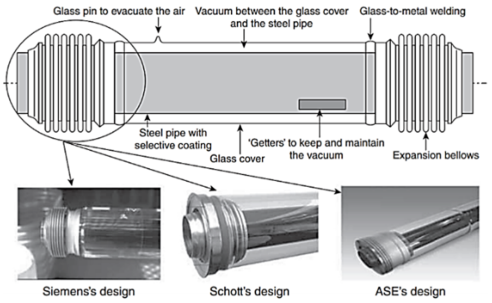

Figure 6: Receiver Designs for Parabolic Trough CSP

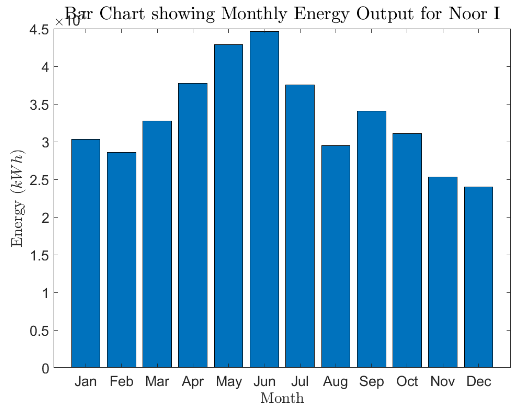

Figure 9: SAM Plot Showing Monthly Energy of Noor I

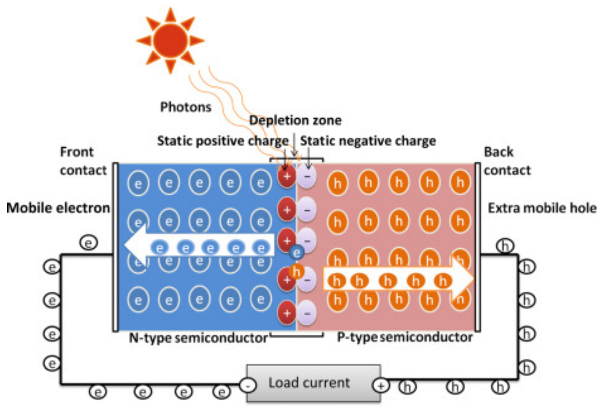

Figure 7: Schematic illustrating operation of PV cell

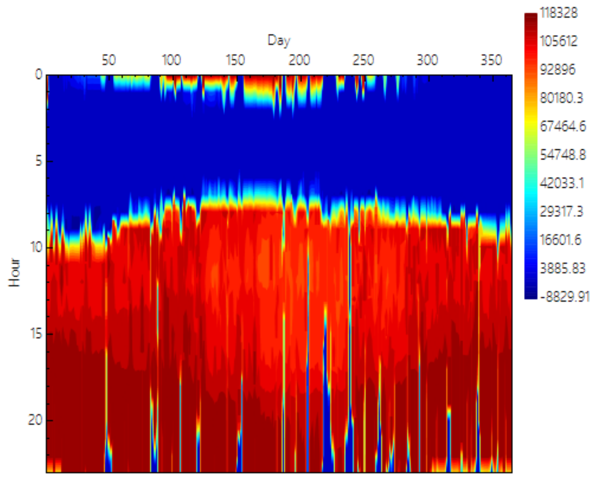

Figure 10: SAM Plot showing Power Generation in kW of Noor III at different Hours of the Day

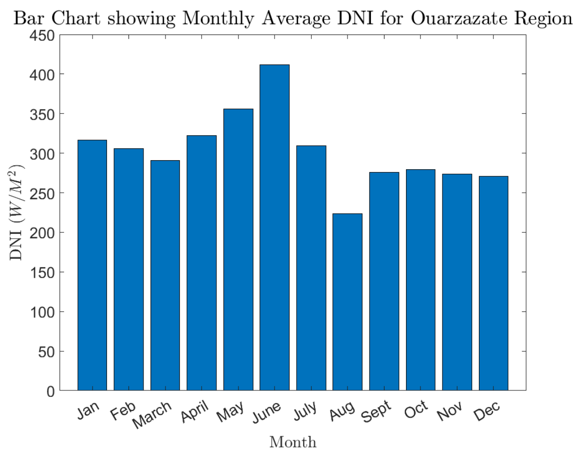

Figure 8: Plot showing Average Monthly DNI for Ouarzazate

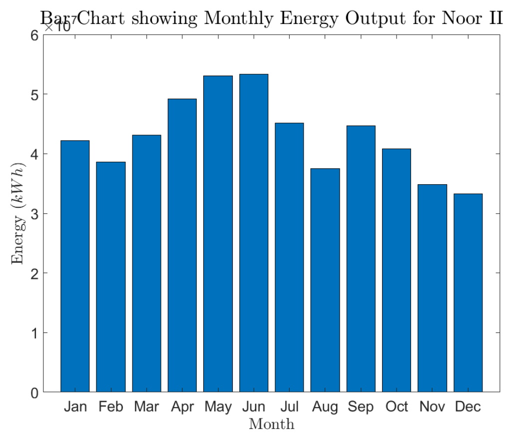

Figure 11: SAM Plot Showing Monthly Energy of Noor II

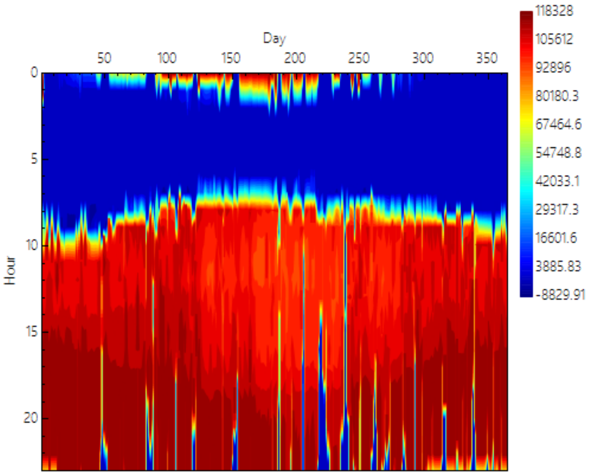

Figure 12: SAM Plot showing Power Generation in kW of Noor IV at different Hours of the Day

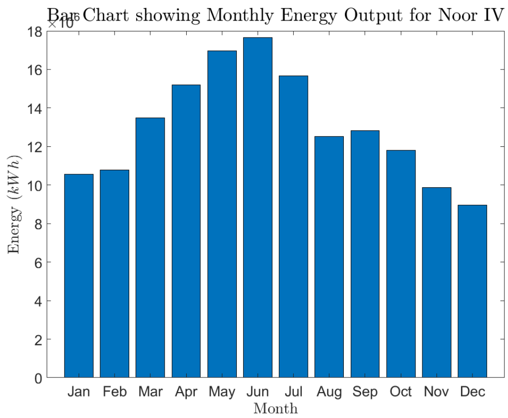

Figure 13: SAM Plot Showing Monthly Energy of Noor IV