

TECHNO-ECONOMIC FEASIBILITY OF CONCENTRATED SOLAR POWER-THERMAL ENERGY STORAGE (CSP-TES) PLANTS IN MENA REGION USING SAM IN A DESERTEC CONCEPT

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DOI: <https://doi.org/10.5281/zenodo.17577832>

Keywords

Article History

Received: 18 September 2025

Accepted: 27 October 2025

Published: 11 November 2025

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Abstract

In this study the Concentrated Solar Power Plants (CSP) coupled with Thermal Energy Storage (TES) are modelled using System Advisor Model (SAM) in the MENA region to estimate the technical and economic feasibility of these plants. The overall energy crisis and trends in the MENA region, the DESERTEC concept of the CSP-TES, has been evaluated. The required energy system modelling regarding design sizing of plants of various capacities at different locations has been conceptualized and implemented. The required flowrate and pressure operating conditions for the given molten salt are determined analytically. The required number of solar collector assemblies are also evaluated. The levelized Cost of Energy (LCoE), Internal Rate of Return (IRR), Net Present Value (NPV), design capacity factors are obtained using SAM and are validated against the commercial CSP-TES plants. The techno-economic analysis of DESERTEC mapped Renewable Energy plants in MENA region has manifested to be a technically viable energy system. TES backup of 7 hrs is financially viable and can provide stable electricity at the most economical unit rates throughout the lifetime of 25 years. A maximum CSP-TES capacity factor of 40% is possible for an optimized design. The Levelized Purchasing Power Agreement (LPPAs) & LCoEs of various MENA countries particularly in range of 50MW to 300MW simulated falls within the allowable range by International Renewable Energy Agency (IRENA).

INTRODUCTION

Literature Review

The Sustainable Development Goals (SDGs), followed by United Nations General Assembly (UNGA) in 2015 has focused on achieving sustainable future for the earth. Among 17 SDGs, one of the objectives is to conserve and protect the earth's environment. The SDG-7 is constituted of three key targets of reliable energy resources, making it affordable and the universal access to modern energy services. And this has been targeted to increase the share of renewable energy in energy mix and double the global rate for the system's efficiency (ESCAP, 2016). The world's ever rising energy demand has been satisfied mainly through fossil

fuels for the last four decades. The share of coal, natural gas, hydroelectric, nuclear energy, and renewables has been estimated to be 33.6%, 27.2%, 23.9%, 6.8%, 4.4% and 4% respectively of the total consumption for 2018. Fossil fuels accounted for almost 84.7% of the total consumption of energy in 2018 (BP 2019). The demographic megatrends in 2040 will be population growth, urbanization and social indicators of global energy system (UN 2019). Economic growth is directly linked to the rising energy demand (Bhattacharyya 2011) and to the technological development in domain of energy systems (Nakicenovic et al. 1998). Technological

development is quite crucial to increase the share of renewable energy as they reduce the GHG emissions significantly and the renewable energy share considering its current pace is expected to increase to 63% by 2050 from 9.5% in 2015 (Gielen et al. 2019).

1. Challenges and limitations of fossil fuel-based energy sources

According to the study by (Ghasemian et al. 2020) stated that Natural gas through upstream technological development has an ever-increasing share and since natural gas is more environmentally friendly than oil it has gained more focus quite recent years. Due to awareness, environmental policies are strictly influencing energy policies. Nuclear energy has proved to be a sustainable energy source, but the European countries are retiring it because of the disastrous accidents of the past whereas China and India are planning to launch more nuclear power plants. Through this study it has been concluded that global economic growth and low emissions of GHG are realizable only through good governance and investment in energy infrastructure tied with the technological development of renewable energy systems. From the study it has been concluded that tension between global financial system and geopolitical relationships will determine the success of global energy transition.

The residential sector represents about 27% of global energy consumption and 17% of the total CO₂ emissions and therefore is a major stakeholder of climate change. According to the study of (Nejat et al. 2015), ten countries including China, the US, India, Russia, Japan, Germany, South Korea, Canada, Iran, and the UK, account for almost two-third of the global CO₂ emissions. According to the study, all countries have shown a reduction trend in emissions apart from Japan and the US, that has shown a rise of 4%. The residential energy market is dominated by traditional biomass about 40% of the total which includes 20% natural gas, although the proportion of fossil fuel is decreasing over the past decade. It requires some serious energy policies if they are coupled with the mandatory regulations. In these regulations the net-zero energy building, increasing public awareness about sustainable energy resources can play a pivotal role if they are coupled with incentivization it would further ease out the

process of transitioning. The developing countries such as China, Iran and India are encountering the GHG emissions which are tied to the absence of strong and efficient energy transition policies.

Through the changes in technology, Toronto is intending to reduce GHG emissions by 80% by 2050. This target seems impossible to achieve, however, importing renewable energy from other cities could lead to meeting the goal (Mohareb and Kennedy, 2014). In Seattle a scenario was proposed by Lazarus et al. (2013) to reduce GHG emissions by 34% in 2020 and to 91% by 2050. However, these propositions are tied to hypothetical situations like the exponential rise to the efficiency of vehicles and energy systems. Among major GHG emissions contributors, transportation has a significant impact and from the study by (Hassan and Lee, 2015), it has received a score of 24 points considering summation of qualitative and quantitative gauges. Therefore, it can be concluded that for global energy transition transportation shift from conventional to electric or non-emissive sources is quite crucial to attain the sustainable development. Therefore, it can be said that fossil fuels at present are being majorly used in the transportation sector and is emitting large volumes of conventional fuel. Among the developed nations like UK and USA are shifting towards EV and shifting the Heavy Industrial Vehicles to Hydrogen Fuel cells. But no such initiative is being taken in the underdeveloped countries of Africa, South Asia especially Pakistan and Bangladesh. India, however started making progress in this domain but again the major contributors are the heavy industrial vehicle which are not yet planned in the near future to be replaced.

2. Introduction to the DESERTEC project

The Trans Mediterranean Renewable Energy Cooperation (TREC) is where the Desertec concept first emerged. The Hamburg Climate Protection Foundation (HKF), the Club of Rome, and the National Energy Research Centre (NRC) of Jordan collaborated to create TREC in 2003. In 2009, the nonprofit Desertec Foundation was founded. The German Club of Rome, several TREC experts, and individual supporters of the Desertec idea were founding members of the organisation (Desertec Foundation 2011). The Desertec Industrial Initiative (DII) was formally established in October 2009 by the Desertec Foundation, twelve major corporations,

including Siemens, Munich Re, Deutsche Bank, and Schott Solar. While the Desertec Foundation can be thought of as "the guardian" of the concept (Richter 2010), DII intends to take additional actions in order to put the Desertec concept into practice, such as setting up favorable framework conditions, conducting feasibility studies, and creating project plans (DII 2011). The DII improved its network in 2010: Presently, there are 18 shareholders and 32 associated partners representing 13 different nations who are part of the DII (DII 2010, 1-2).

DESERTEC aims to tackle multiple global challenges simultaneously, through the deployment of Concentrating Solar Power (CSP) in the Middle East and North Africa (MENA) region. It aims to provide low-carbon or zero carbon emissions energy in the future for the EU-MENA region and in addition providing drinking water and food security and ensuring prosperity and development. The estimated cost to provide such energy is estimated to be EUR 400 billion (Vallentin and Viebahn 2009, 30; Werenfels et Westphal 2009, 8). The concept envisioned to supply the energy via the High-Voltage Direct Current (HVDC) lines. The 15% of the European Electric demand can be provided by electricity being generated in the MENA region (TREC 2008, 52; Trieb and Mueller-Steinhagen 2007, 213-214).

The concept mentioned a reduction of CO₂ to 38% in the year 2050 considering the emissions of year 2000 (Desertec Foundation, 2009B, 44). Combining the desalination technologies with CSP it aims to produce drinking water as a byproduct.

Solar PV systems use semiconductor materials, which produce an electron flow when exposed to sunshine, to convert sunlight directly into electricity. The PV cells are normally assembled into modules, and by connecting many modules, solar arrays can be created. Solar PV is widely used in both small- and large-scale applications, including rooftop solar panels (R. Perez et al 2004). In CSP systems, sunlight is focused onto a receiver using mirrors or lenses. The receiver then receives the solar energy and turns it into heat. Following that, this heat is used to produce electricity using standard power cycles, like steam turbines. The dispatchability of the power plant is improved by CSP technology's ability to store thermal energy, which may then be utilized to

create electricity at night or during overcast conditions (L. Boudouris et al, 2014).

Since 2011, MENA has faced quite a critical turn of events including high demographic growth, the unsustainable agricultural growth coupled with climate change, and all these have contributed to food insecurity. The combined effects of such events had hampered the social and economic development of MENA countries (IEA 2011). Many countries, are suffering from high hydrocarbon prices because of limiting presence of such fuels. Therefore, in era of rising fossil fuel and food prices on upward trajectory, balancing the national accounts, and providing citizens with commodities and sources of employment have become a difficult task in the region especially for non-oiling producing countries. MENA is also facing negative environmental trends, for example, among 20 nations worldwide having freshwater availability resources below 1000 m³ per capita, 15 of them are in MENA (Brooks 2007, 34). The water deficit in MENA is expected to increase to 150 billion m³ by the year 2050 from 60 billion m³ currently. The DESERTEC main idea for the technical breakthrough is to use solar energy through large mirrors to heat the medium or coolant through parabolic trough power plants. The advantage of CSP technology is that it is regenerative in contrast to solar PV and wind. To some extent the power generated is controllable and can be stored and harvested when required. This is made possible by large storage units of molten salt technology which absorb the energy and undergo a phase change and therefore store the energy and the energy can be stored for several hours to weeks (Klawitter and Schinke, 2011).

The transmission losses from Morocco to German border at Aachen are estimated only about 10 to 15% considering the conversion losses from DC to AC and vis a vis. The DESERTEC project gained popularity that it can overcome the North-South division in the Mediterranean area and therefore would not only supply electricity to EU but would also realize the green desert idea into reality. The North would gain energy security, and large investments in manufacturing and other sectors. The MENA would also gain social stability and jobs which would result in mitigating Islamic extremism. A study by (Fadlallah et. al, 2022), of PV farm utilization is discovered to be economically viable, and sustainable against volatile diesel fuel prices, and

it is anticipated to avoid nearly between 1 million tons/year and 25.5 million tons/year of pollutants while lowering energy costs by between US\$0.07117/kWh and US\$1.1046/kWh across six countries. PV farm utilization was compared to power plants with similar targeted capacity using diesel fuel. By examining the impacts PV costs can have on the cost of electricity for the most important locations in each nation, it will be possible to determine how fundamentally more appealing PV

systems will become in each nation's energy mix as a result of the predicted further decline in PV costs. The study provides a generalized design guideline and recommendation for government officials and policymakers to select the best solutions based on national preferences, either by concentrating on one site and intensifying the farms at that site or choosing multiple sites out of the top five locations highlighted in each country and scattering the farms across them.

Country	Solar PV (MW)	CSP (MW)	Wind (MW)	Renewable Hydro Power (MW)	Bioenergy (MW)	Total RE capacity (MW)	% age Share of RE
Morocco	318	540	1556	1306	7	3727	33.6
Algeria	435	25	10	129	~	599	2.3
Libya	6	~	~	~	~	6	0.1
Tunisia	197	~	245	66	~	508	7.7
Egypt	20	~	1643	2832	123	6322	10.6
Sudan	14	~	~	1482	199	1871	49.2
Mauritania	89	~	34	~	~	123	19.7
Saudi Arabia	390	50 e	3	~	~	443	0.5
Jordan	1914	~	614	14	13	2555	39.1
Yemen	257	~	~	~	~	257	12.8
Israel	4169	242	27	6	26	4470	20.8
Iraq	42	~	~	1557	~	1599	5.1
Syria AR	60	~	1	1490	7	1557	15.3
Kuwait	43	50	12	~	~	106	0.5

Table 1: The Share of Renewable Energy of each prospective technology of MENA countries (Renewable Capacity Statistics-IRENA, 2023)

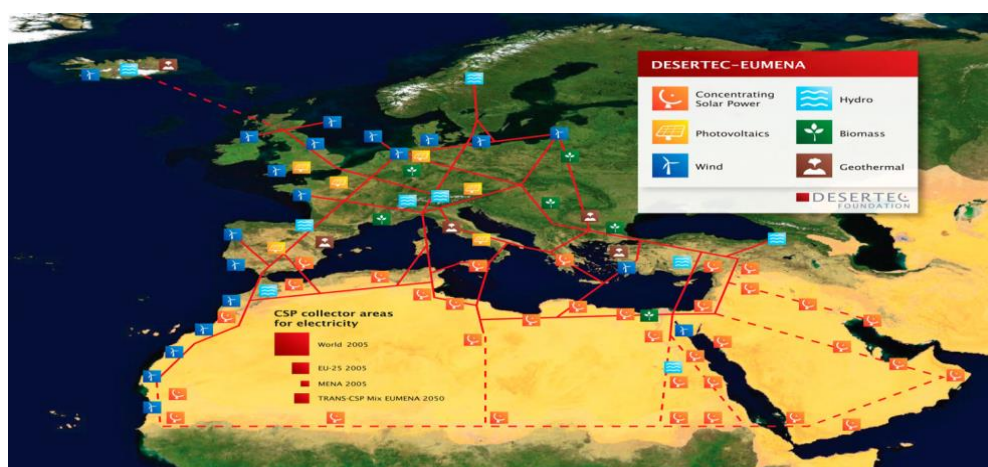


Figure 1: Illustration of DESERTEC concept by the DESERTEC foundation and the participating MENA countries in CSP commissioning (Desertec Foundation 2011)

From figure 1, it can be observed that the Middle East and North Africa countries which have been selected by DESERTEC includes countries which

have direct access to the sea. The countries as shown in Figure 1 starting from the left Western Sahara, Morocco, Algeria, Libya, Tunisia, Egypt,

Sudan, Eritrea, Chad and Mauritania are the North African countries. Among the Middle East this include, Jordan, Yemen, Saudi Arabia, Oman, Israel, Syria, Iraq and Kuwait. The distribution lines are also shown in figure 1 which are interconnecting these power stations and are also providing the grid stations of EU. From Table 2 & Table 3 the renewable energy potential available in the MENA region is listed and by comparing it with Table 1 we can observe that just a few % of the potential has been exploited to date. From

Table 1 we have observed that Israel has an installed capacity of 4.5GW whereas if we cover just 0.001% of its area it comes out to be 0.0521 GW. Therefore, Israel has almost 86 times more capacity than estimated and this is the potential of solar PV that is enormous and depends largely on the countries policy and vision to mitigate GHG emissions. Furthermore, from Tables 2 and 3 it is evident that Israel doesn't have the hydroelectric potential or any wind energy potential.

Country	Solar intensity in kWh/m ² /year	Solar Potential in kW/m ²	Area in sq. meters	Covered Area by Solar PV** m ²	Estimated Capacity GW
Saudi Arabia	2900	0.3311	2.14E+12	21496900	7.1166
Algeria	3200	0.3653	2.38E+12	23817410	8.7004
Iran	2200	0.2511	1.65E+12	16481950	4.1393
Egypt	2000	0.2283	1.01E+12	10104080	2.3069
Morocco	3000	0.3425	4.47E+11	4465500	1.5293
Israel	2200	0.25114	2.08E+10	207700	0.0521

Table 2: The Estimated Solar PV potential of MENA countries (Solar Intensity of MENA region-IRENA, 2016)

** The covered area of solar PV installation has been estimated to be 0.001% of the total area of the given country

Country	Wind Potential MW	Hydro Potential MW	Biomass (Million tons per year)
Saudi Arabia	8200	--	2.0
Algeria	1200	2000	1.0
Iran	30000	24000	3.0
Egypt	53000	--	12.0
Morocco	25000	--	2.0
Israel	--	--	0.3
Tunisia	3800	--	2.0

Table 3: The Wind, Hydro and Biomass capacity of MENA countries (IRENA-MENA countries RE-potential, 2016)

4. Previous research on DESERTEC and its challenges

Despite providing a fascinating idea, DESERTEC just touched the surface impacts and inclusion for the human development dimension, and this contributed in the longer term a great hurdle in its implementation. A study by (Klawitter and Schinke, 2011) showed that the human rights-based approach to DESERTEC would gather large

benefits including attention today poor and marginalized and the effectiveness and sustainability of masses and also preventing the elite capture. The social inclusion deemed a necessary index for saving the DESERTEC idea because through social inclusion people are informed fully at early stages of project are guided that how this project is going to change their lives. The project must highlight that it aims to mitigate

poverty and is aimed to provide the job security to the local community. In addition, an active participation of the relevant stake holders would empower them and the DESERTEC project would have been welcomed by the political systems of the countries mentioned. A fair dialogue would have been held between the duty bearers and right stake holders especially those who were on the verge to be strictly affected, which include local communities and small startup companies. The social and environmental issues should be valued with the same importance as economic and technical issues.

There is a need to create a reliable framework to respect and support human rights and encourage non-state actors to protect human rights and impose the requirements for non-state actors mainly for the transactional companies. The framework needs to analyze the human development risks and determine the associated opportunities and challenges. Hermann Scheer, one of the pioneers of the global renewable energy argued that DESERTEC was kind of like a Trojan horse among the big power suppliers, and they are being dependent on the nuclear and coal powered had rather prevented the development of renewable energy in Germany (Schmitt, 2018).

As DESERTEC is an NGO, therefore, it claimed to be technologically open strategy and large number of people of the renewable industry were saying that generation costs for electricity from PV or wind were lower than the CSP and CSP price per kWh would rise but DESERTEC stressed that being the volatile nature of PV and wind, the large scale development is not possible. This was a major technological conflict which was debated at large in media and multiple energy conferences. In the early 2000s, the first basic DLR study MED-CSP estimated that CSP technology will cost about 8 cents per kWh at locations in the MENA region and 25 to 30 cents per kWh for PV. The Fraunhofer Institute for Solar Energy Systems (ISE) published a more recent forecast in 2014 that revealed the DLR's 2000 calculation was incorrect and that the cost of PV was only about 8 cents/kWh in 2013 and was expected to moderately decline to about 6 cents by 2030. The forecast also revealed that the cost of CSP technology was higher than that of photovoltaics in

2013 (with an assumed cost of 14-19 cents/kWh) (ISE, 2014).

Another pressing issue arose when Paul van Son, CEO of DESERTEC announced publicly in 2012, that the idea of exporting electricity from North Africa to EU is unrealizable in the coming future. However, Aglaia Wieland, the co-CEO of DESERTEC foundation, opposed it and this rivalry ended when Aglaia Wieland resigned later that year. Therefore, there were ideological conflicts found within the organization which also posed a serious blow to DESERTEC execution (Schmitt, 2018). Straight lines representing the new high-voltage direct current transmission system were drawn across North Africa in the cartographic illustrations created by the Desertec Foundation to advertise the project (Figure 1). These lines appeared to ignore physical features and (colonial) national borders. The DII requested the opinion of NGOs like Germanwatch in order to investigate or refute claims made in the media that large CSP projects, like the one in Ouarzazate, Morocco, purportedly pose a threat to the interests of the local population, including the objectives of nomads.

In the interview that followed, Ernst Rauch brought up two crucial points:

- (1) Political shifts, the Middle East's post-winter 2010-2011 political unrest, and North Africa.
- (2) Technological advancements, in particular the "rapid development of renewable energies" in Europe as the "demand region," "driven by the lower cost of photovoltaics," "led to the overproduction of electricity in Europe."

As a result, it appeared that the popular discourse in global society was in support of a large-scale renewable energy project; such concepts had transcended the intellectual and discursive enclaves of environmentalists, legislators, and scientists to enter the global political mainstream. Therefore, being influenced and involving so many countries and the global politics just dampened the DESERTEC idea. Also, the creation of the UfM (Union for Mediterranean) was delayed and enthusiasm for this significant political project was dampened after Israel's attacks on the Gaza Strip at the end of 2008 and the beginning of 2009; following the attacks, Arab nations refused to cooperate with Israel, even in the multilateral

context of the Mediterranean Union, which prevented the establishment of the new structures. Spain, which experienced a recession and a huge decline in government revenue after the national real estate bubble burst, was particularly crucial for the Desertec context. Spain would be a key participant in the "orthodox" Desertec concept as a country of transit for the transportation of power and perhaps even as a consumer. Through the development of RE, Spain had amassed an excess supply of energy that grew even larger as a result of the economic downturn that followed the financial crisis because there was a lower demand for electric power. Therefore, it was a massive blow to the whole DESERTEC idea (Lawhon and Murphy, 2012). After Fukushima, Germany saw an incredible surge in the building of decentralized renewable energy systems, but there was no shared understanding of how to eventually supply all the demand with renewable energies. And therefore, the local renewable energy companies just covered the whole demand and there wasn't enough time for the DESERTEC idea to supply the electricity from 9000km away.

(Schmitt, 2018) in his study has declared that the idea of the DII should have become the sociotechnical system of energy supply and shifted from mere technological niche. However, this has not happened yet and rather it has become part of sociotechnical system just virtually and has sunk back into a technological niche. In short, it can be said that DESERTEC concept was a technology without sociology because there were large numbers of stakeholders that were missing or even not know of the vision of the idea by the foundation. To implement the idea large number of considerations mentioned like human rights, technical viability, peace and stability, support of the local masses needs to be revised and reconsidered.

Methodology

In this study, a predictive model will be created to describe and forecast the system's power output at any given moment for a specific Direct Normal Irradiance (DNI) level. The System Advisor Model (SAM), software developed by the National Renewable Energy Laboratory (NREL) with assistance from the U.S. Department of Energy for modelling and analyzing renewable energy systems,

will be used to design the model. The objective is to accurately estimate the amount of energy the system can generate over a given period and assess the financial viability of CSP parabolic trough plants which are molten salt based as their thermal energy storage (Blair et al. 2014).

The receiver, sometimes referred to as the Heat Collector Element (HCE), which houses the heat transfer fluid (HTF), is where solar energy—the DNI component—is focused in a CSP plant. At the heat exchanger (boiler), the HTF is heated before being utilized to vaporize the working fluid. As a result, the working fluid is enlarged in the turbine to produce power. The physical trough and the empirical trough are the two choices offered by SAM for creating the CSP parabolic trough system. Physical trough is founded on the fundamentals of thermodynamic relations and energy balance, as stated by (Wagner and Gilman, 2011). When prior knowledge of system performance is unknown, the physical trough performs better than the empirical model because performance is generalized over the entire operational range of the power plant. The physical model is subject to various ambiguities and mistakes, though, because it is theoretically based and some assumptions must be made.

The models for the solar field, power cycle, thermal storage, and parasitic losses were taken into consideration when modelling the parabolic trough system. The performance model and the financial model are the two fundamental components of the SAM software. Calculating the electrical power (or energy) produced by the various renewable energy systems is the basis of the performance model. In order to undertake some financial analysis and ascertain the project's economic viability, the output of the performance model is fed into the financial model Blair, Dobos & Gilman, 2013); (Turchi & Heath, 2013).

The levelized cost of energy (LCOE) calculator option is the foundation for the current analysis. When evaluating the financial sustainability of a specific renewable energy system, one of the most important financial measures is the Levelized Cost of Energy (LCOE). The overall cost of producing energy (construction and operation) divided by the total amount of energy produced during a certain analysis period is known as the LCOE (cents/kWh) (Short, Packey & Holt, 1995). Other financial metrics of interest include the internal

rate of return (IRR), net present value (NPV), and power purchase agreement (PPA) cost. All these metrics are incorporated within the financial model of SAM to help inform the stakeholders' decisions on the financial benefits of a given renewable energy project (Mendelsohn et al. 2012). The process used to create the SAM model for the 150 MWe concentrated solar power (CSP) plant in Southern Algeria, is described in depth in this section. The strategy basically adheres to (Wagner and Zhu, 2011) recommendations. Due to the numerous fields that must be given, Wagner suggested the following strategy:

1. Configuration of Receiver Heat Collector Element (HCE)

The heat collector element (also known as the receiver tube) used for the power plant is a Schott PTR 70 2008 (Chambers, Raush & Russo, 2014).

Annulus gas type	Hydrogen	Air	Air (Broken Glass)
Est. Avg. Heat loss at design W/m	310	590	4518
Annulus pressure (torr)	0.0001	750	750

Table 4: Heat loss at design for the 3 variations of HCE

2. Configuration of Solar Collector Assemblies (SCA)

For the SCA, Solargenix SGX-1 was selected for our case in the physical trough models for the CSP simulation. Equation below was used to calculate the average surface to focus path length, with

This model was selected from the SAM Library for HCEs. The receiver has an inner diameter of 0.066 m, with a glass envelope outer diameter of 0.12 m. In the receiver modelling, the parameters were set, and three different variations cases were considered. These variations consist of elements that result in degradation and the addition of heat losses. The SAM thus averages these variations. For our case of molten salt system as we are operating at relatively higher temperatures than the typical synthetic oils, therefore, estimated average heat loss at design will be considered higher. Such heat loss is used for the calculation of solar conversion efficiency to generate heat and would therefore impact the field size (Freeman et al. 2018).

reference to the (NREL's System Advisor Model help documentation, 2017) using Eq. 1.

$$F_{avg} = w \sqrt{\frac{\left(4a^2 + \left(\frac{w}{2}\right)^2\right)^2}{a^2} \frac{12a^2 + \left(\frac{w}{2}\right)^2}{12w\left(4a^2 + \left(\frac{w}{2}\right)^2\right)}} \quad 1$$

Where

a = focal length ; w = solar collector aperture width

Reflective Aperture Area (m^2)	470.3
Number of modules per assembly	20
Solar collector aperture width (w) m	5.0
Focal length (a) m	2.7
Piping distance between assemblies m	1.0
Average Surface to focal path length (F_{avg}) m	1.8

Table 4: Geometry of SGX SCA

Geometry effects	0.98
Mirror reflectance	0.935
Dirt on mirror	0.95
General optical mirror	0.95

Table 5 Optical parameters of SCA

3. Solar Field Minimum and Maximum Flowrate (Transportation limits)

The heat transfer Fluid (HTF) selected is Hitec Solar Salt. As the salt is selected the field min and max temperature changes accordingly to 238 °C & 593 °C respectively. And therefore, the loop design inlet and outlet temperature must be fed in within

the field temperature range. The inlet temperature is the temperature which is the saturated steam temperature in the boiler. The design outlet loop temperature was set at 550 °C. Then, the flowrates are required to be set which is a crucial parameter while modelling in SAM since it affects the pump size we selected and governs overall the practical feasibility and the temperature achievement after the heating in the solar collector assembly. The primary concern is the maximum pressure drop. Since the pressure drop in case exceeding the tube pressure design limit would result in the tube rupture. Special consideration is required when considering the molten salt as the HTF because the molten salts have higher viscosity and therefore leads to higher pressure drops across the tube length. Therefore, when using pumps of higher discharge pressure to pump the HTF it might cause the rupture due to excessive pressure at the inlet header. The recommended pressure drop as per SAM help documentation is within 2MPa across the entire field (NREL's System Advisor Model help documentation, 2017). To solve this issue we have two available methods:

1. Manually trying different flow rates and loop lengths while solving in SAM
 2. Matching the pressure with the synthetic oil (Therminol VP-1) by iteratively solving the pressure drop equations
- Method 2 was used in which the pressure loss equation was solved iteratively to determine the intended flowrates (Wagner, 2008).

4. Calculating pressure loss in a pipe

The friction factor was obtained through the Moody's chart by using the Reynold's number and the pipe roughness which are given in Eq. 2

$$Re = \frac{pv d}{\mu} \quad 2$$

$$\text{Pipe roughness} = e/d$$

Where Re = Reynolds number; v = fluid velocity; d = internal diameter of pipe; μ = dynamic viscosity; e = Surface roughness of the pipe

In our case we modelled the pipe as the smooth pipe with negligible roughness. The friction factor is obtained through Eq. 3:

$$f = \frac{2d}{pv^2 l} \Delta P \quad 3$$

5. Establishing a reference pressure loss:

The therminol VP-1 setting was used to calculate the reference pressure loss. The reference pressure obtained served as the constant to compare and to bring the pressure drop using the molten salt as the HTF within the acceptable range as to match therminol VP-1. The maximum field velocity for the therminol VP-1 was used which is approximately 5 m/s. The internal diameter is 0.066m. Therefore, the Re was calculated using Eq. 4.

$$Re(t) = \frac{p(t)v(t)d(t)}{\mu(t)} = 1.39 \exp 06 \quad 4$$

From looking up at the moody chart the friction factor equals $f(t) = 0.011$. The study aimed to calculate the number of SCAs required for our design case. Therefore, the pressure drop was calculated using the initial guess for the reference length $l' = 1.0$ m. Using the friction factor equation for the pressure drop the reference pressure was obtained using Eq. 5.

$$\Delta P(\text{ref}) = 1610 \text{ Pa} \quad 5$$

This is the pressure that was obtained using the Therminol VP-1 as the HTF and this was used to determine the pressure drop while using the molten salt as the HTF and matching this pressure limit to stay within the design limits of SAM simulation.

6. Calculating the salt mass flow rate

For the calculation of the mass flowrate the energy balance was applied across the SCA using Eqs. 6 & 7. The absorption energy = Energy delivered to HTF

$$q_{loop} = A_{sca} \eta_{abs} N_{sca} I_{bn} \quad 6$$

$$q_{loop} = \dot{m}_s C_{ps} \Delta T_s \quad 7$$

Where

$$A_{sca} = \text{Area of the collector (470.3 m}^2\text{); } \eta_{abs} = \text{Absorption efficiency (0.689)}$$

$$N_{sca} = \text{Number of SCA (Initial guess: \# 8); } I_{bn} = \text{DNI at design point (950 } \frac{\text{W}}{\text{m}^2}\text{)}$$

\dot{m} = mass flowrate of HTF (Molten Salt); C_{ps}
 = Specific Heat capacity of HT ($1520 \frac{J}{kgK}$)

$$\Delta T_s = 550 - 293 = 257^\circ C$$

Balancing the above equations the mass flowrate is

$$\dot{m}_s = 6.4 \frac{kg}{s}$$

7. Calculating velocity and new length:

Based on the mass flowrate obtained for HTF we will calculate the corresponding velocity using Eq. 8.

$$V_s = \frac{\dot{m}_s}{\rho_s \pi \left(\frac{D}{2}\right)^2} = 1.02 \frac{m}{s} \tag{8}$$

Therefore, for the same geometry for the Synthetic oil, for the Molten Salt as HTF this is the velocity that we have obtained. From the Reynolds equation (2), $Re = 75254$. From the Moody's chart the friction factor comes out to be $f(Res) = 0.0195$. Solving for the effective length modifying Eq. 3. The Eq. 9 is obtained.

$$l'_{ref} = \frac{\Delta P_{ref} 2D}{\rho_s V_s^2 f_{fs}} = 5.75 \tag{9}$$

Therefore, the new length has come out to be 5.75 times the initial guess value. Therefore, considering

Iter. No.	m kg/s	V _s m/s	Re _s	F _{fs} (Re _s)	l' (m)	No. of SCAs
1	6.4	1.02	75251	0.0195	5.75	16
2	12.8	2.04	151242	0.0166	1.65	14
3	11.2	1.81	132805	0.0171	1.13	16

Table 6: Iterations to convergence for effective length

Iteration No. 2 with SCA =14 seems closer to the fact that in contrast to Iteration No. 3 the SCAs are lesser therefore, the pressure drop would be

a standard length of 1m SCA for each. We obtained the new value of SCA $N_{sca} = 46$.

This estimate didn't seem right because with such larger number of SCAs, the associated mass flowrate required to reach the design point temperatures for the HTF increases and this in turn increases the pressure losses across the field and therefore, the pressure at the inlet header must be increased to address such losses. This would result in higher pumping cost and would also make the inlet header or the initial tube in series vulnerable to rupture as also suggested by (Wagner and Gilman, 2011). Also, as the pressure has a nonlinear behavior therefore, we required more conservative approach and therefore thorough iterations as shown in the table below. By varying the initial guess for the number of SCAs, the corresponding mass flowrates and velocity are obtained. And subsequently the effective length for the SCA. And from there we can determine the number of SCAs required.

less across the field. Therefore, the velocity and mass flowrate used in the simulation are of the iteration 02 as shown in table 04.

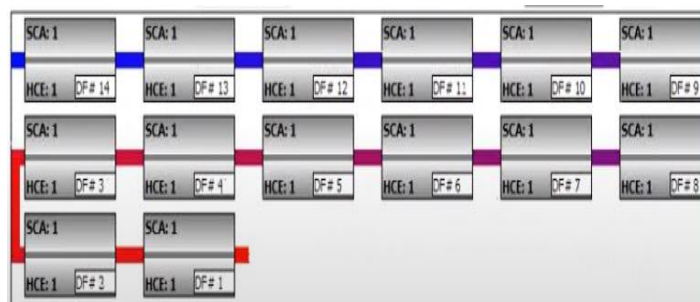


Figure 2: The number of SCAs and their loop configuration

8. Power Cycle Design and Configuration

The condenser selected is of air-cooled type and the ambient design temperature is set at 42 °C.

And therefore, the condensing temperature is obtained using Eq. 10.

$$T_{cond.} = T_{amb} + \Delta T_{ITD} = 58^\circ C \tag{10}$$

The condensing temperature is a bit higher than a conventional power plant but for the case of CSP it seems fine [ref]. Where the ΔT_{ITD} represents the overall change in temperature after condensation. For the power cycle efficiency, we used the known efficiency for the power tower molten salt CSP and scale it for our case of molten salt trough. The power tower has an efficiency of 41.2% having steam inlet to the turbine at 550 °C. We assume that in our case from the conversion of salt to the water the heat loss in the form of temperature comes out to be 20 °C. Therefore, the Carnot scaling has been used Kapooria, Kumar & Kasana, 2008) using Eqs. 11 through 13.

$$\eta_1 = 1 - \frac{T_{out}}{T_{in}} = 1 - \frac{58+273.15}{550+273.15} = 0.5977 \quad 11$$

$$\eta_2 = 1 - \frac{T_{out-trough}}{T_{in-trough}} = 0.5877 \quad 12$$

$$\eta_1 = 0.412 \frac{\eta_2}{\eta_1} = 0.412 \frac{0.5877}{0.5977} = 0.4051 \quad 13$$

The Estimated gross to net efficiency is 0.9. This is by default in SAM, due to the parasitic loss. Therefore, the design gross output was set at 167MWe. Thus, we obtained the net energy output as 150MWe.

9. Thermal Energy Storage Setup:

Following are the settings established for the thermal energy storage system as shown in table 7.

Tank Height (m)	15.0
Parallel Tank pairs	2.0
Cold Tank heater set point	260.0 °C
Generally, set same as the freezing point temperature of the salt	
Hot Tank Heater set point	525.0 °C
The significant delay is generally not allowed in hot TES temperature	

Table 7: Thermal Energy Storage Setting for Molten Salt

10. Financial Parameter:

As previously said, there are various financial models that could be applied to SAM. But in this instance, the straightforward LCOE Calculator (based on the FCR approach) is employed as the financial model. In this instance, the Fixed 34 Charge Rate (FCR) approach is used to determine the Levelized Cost of Energy (LCOE). The use of intricate financial information is not necessary for basic, preliminary, or feasibility project analysis when using this method. Referring to field (NREL's System Advisor Model help documentation, 2017), the following is the formula for calculating the LCOE taking the FCR into account. Mathematically it is given in Eq.

$$LCOE = \frac{TLCC}{\sum_{n=1}^N \left[\frac{Q_n}{(1+d)^n} \right]} \quad 14$$

Where TLCC = Total Life Cycle Cost

Q_n = Energy delivered as output

n = year of analysis

d = discount rate

N = Analysis period

Results & Discussions

The SAM model has been seen to be accurate in simulating the Andasol-1 plant (System Advisor Model (SAM) Case Study: Andasol-1, 2013), so the data it generates is used as an appropriate replacement of actual plant data. The CSP plants with Thermal Storage Energy storage have 7 hrs. backup power are simulated in SAM for various MENA countries. According to the methodology, the calculation for the required mass flow rate keeping the reference pressure as a constant was performed. The required mass flowrate depends on the Design Point Natural Irradiance (DNI) of the location (Wagner and Gilman, 2011). The required Solar Collectors SCA are also obtained by iterating the SCAs to obtain the required effective length. The obtained mass flowrates & number of SCAs required are presented in Table 8. The Ad. Value (Adjusted) columns are taking even values of the obtained N-Sca since SAM uses even SCA values for simulation in pairs (CSP - System Advisor Model - SAM., 2018).

1. Plant performance

The plant performance is highly influenced by the DNI and by the sun hrs. according to the

meteorological data. In the plant performance metric, the plant capacity factor capacity factor is the ratio of the system's electrical output in the first year of operation to the system's electrical output if it operated at its nameplate capacity for every hour of the year.

$$\text{Capacity Factor} = \frac{\text{Net Annual Energy (kWhac/yr)}}{\text{System Capacity (kWdc or kWac)} * 8760 \text{ (h/yr)}}$$

Where Net Annual Energy is the total annual electric generation in the first year of operation, System Capacity is the system's nameplate capacity (see table below), and 8760 is the number of hours in one year. Another important parameter is the annual energy which is a measure of the total quantity of electricity generated by the system over a single year(Nate Blair, 2014) . The graphs of Net

power production (kW) and the HTF pumping field power requirement (MW) for various MENA countries are listed from Figure 0. Along the x axis time in hrs. is presented. Along the primary Y-axis the power generated in kW is presented. On the secondary Y-axis the power in MWe is presented which is the axis for the HTF pumping field power.

- Power Generated by the CSP (kW)
- HTF pumping field power (MWe)

For the mega power systems like Beer Shiva of Palestine, Sirte of Libya and Doz of Tunisia the power generated is way too less than the designed setting. And the reason behind that could be the CSP power extraction limitations because to produce power at such high rate the losses from

Country	Location	Required output capacity	DNI	vs	ms	Res	f	leff	N-sca	Ad. Value	Initial guess
		MW	W/m2	m/s	kg/s			m			
Tunisia	Doz	4700	875.818	3.4972	21.7948	1.40E+05	0.01633	0.5839	18	18	30
	Al jamil	100	844.364	3.3716	21.0120	1.35E+05	0.01648	0.6225	19	18	30
Libya	sabha	100	875.000	3.4940	21.7744	1.40E+05	0.01633	0.5849	18	18	30
	sirte	100	827.455	3.3041	20.5913	1.32E+05	0.01656	0.6450	19	18	30
	Al batnan	100	869.364	3.4715	21.6342	1.39E+05	0.01631	0.5915	18	18	30
Sudan	Kassala	25	857.636	3.6530	22.7652	1.46E+05	0.01614	0.5411	17	16	32
	North Kordofan	25	843.917	3.5945	22.4010	1.44E+05	0.0162	0.5566	18	18	32
Saudi Arabia	Tabuk	150	875.500	3.4960	21.7869	1.40E+05	0.01633	0.5843	18	18	30
	Al hufuf	150	729.500	3.1072	19.3639	1.25E+05	0.01681	0.7182	23	18	32
Syria	Der Ezzor	25	760.667	3.2399	20.1912	1.30E+05	0.01664	0.667	21	20	32
	Al Hasaka	25	884.000	3.7652	23.4650	1.51E+05	0.01603	0.5131	16	16	32
Palestine	Beer Sheva	16000	794.917	2.9626	18.4628	1.19E+05	0.01703	0.7807	22	22	28
UAE	Abu Dhabi	8800	758	3.0268	18.8629	1.21E+05	0.01693	0.7519	23	22	30
Yemen	Sana	50	928.000	3.4586	21.5538	1.39E+05	0.01637	0.5954	17	16	28
	Hadramawt	50	793.000	3.3776	21.0494	1.35E+05	0.01644	0.6206	20	20	32
Morocco	Massa	5500	700.000	2.9815	18.5808	1.20E+05	0.01696	0.7720	25	24	32
	Taza	5500	875.000	3.2610	20.3228	1.31E+05	0.01661	0.6600	18	18	28
	Matrouh	2750	650.000	3.4607	21.5671	1.39E+05	0.01637	0.5948	24	24	40
	Al fayoum	2750	730.000	3.3036	20.5882	1.32E+05	0.01655	0.6451	22	22	34
Egypt	Al baher al ahmer	2750	800.000	3.3010	20.5717	1.32E+05	0.01659	0.6460	20	20	31
	Aswan	2750	725.000	3.0880	19.2444	1.24E+05	0.01647	0.7260	23	22	32
Oman	Ash Shargiyah	770	810.000	3.0188	18.8131	1.21E+05	0.01693	0.7554	21	20	28
Iran	Fars	10000	910.000	3.1492	19.6260	1.26E+05	0.01675	0.7013	18	18	26
Algeria	Batna	1000	700.000	2.9815	18.5808	1.20E+05	0.01696	0.7720	25	24	32
	Adrar	1000	800.000	3.1945	19.9081	1.28E+05	0.01605	0.6842	21	20	30

Table 8: The required mass flow rates & No. of SCAs for MENA countries at given DNI

Country	location	No. of loops	Area of solar field Acres	Required capacity MW	output
Tunisia	Doz	7261	63,792	4700	
Libya	Al jamil	172	1343	100	
	sabha	103	905	100	
	sirte	164	1,441	100	
	Al batnan	156	1,371	100	
Sudan	Kassala	143	1,117	25	
	North Kordofan	41	360	25	
Saudi Arabia	Tabuk	242	2,126	150	
	Al hufuf	231	2,480	150	
Syria	Der Ezzor	59	403	25	
	Al Hasaka	44	344	25	
Palestine	Beer Sheva	22863	245,501	16000	
UAE	Abu Dhabi	12965	139,217	8800	
Yemen	Sana	82	640	50	
	Hadramawt	64	625	50	
Morrocco	Massa	8090	94,767	5500	
	Taza	8504	74,712	5500	
Egypt	Matrouh	4381	51,319	2750	
	Al fayoum	4219	45,303	2750	
	Al baher al ahmer	4209	41,087	2750	
	Aswan	4250	45,636	2750	
Oman	Ash Shargiyah	1164	11,363	770	
Iran	Fars	14829	130,281	10000	
	Batna	1471	17,231	1000	
Algeria	Adrar	1530	14,935	1000	

Table 9: The number of loops and the area of each simulated country and location

the field increases. Therefore, for thermal energy storage to provide as a backup you required quite a heavy energy storage system and therefore the field pumping costs are much higher in comparison to 25MW to 150 MW systems. Therefore, it can be concluded that such CSP plants having power capacities in GW don't appear to be successful. From the other CSPs, the required output can be obtained as is shown in the plots above. However, in the case of Hadramawt in Figure 14, the pumping field cost is exceeding the output power capacity and has a capacity factor in negative and therefore, the location at which the plant is designed doesn't appear to be suitable for such power plant capacity.

From figures 1 to 13, the advantage of using the TES as an energy storage medium is quite visible. During the bright and high Natural irradiance hours the extra power capacity is being utilized to store the energy in the phase change molten salts. And this energy is being utilized at nighttime to deliver the required loads. Because it can be observed that the sharp drop in peak has been averted due to the use of the TES medium. And this has contributed to an overall increase in the annual capacity factor. The highest DNI values from the weather sheet are at Sudan locations of Kassala and North Kordofan and therefore, from figures 3 & 4 it can be observed that such plants are reaching quite close to the designed output

power capacity of 25MWe. And from these simulations in SAM, it can be concluded that Sudan can serve as the highest CSP-generating zone with largest capacity factors. From figure 15, it can be observed that for a CSP plant of 16GW capacity it is simply impossible to design such a power plant because the required input power is much greater than the output power. There is a drop in the required input power at peak irradiation hrs but even at the highest irradiance the plant is not achieving breakeven. The fundamental reason is the limitations of high pumping cost to produce such the required temperatures at the collector's outlet and therefore; to manage such a huge inventory of solar salt, the pumping requirement exceeds the practical feasible limit to provide the required output power.

The capacity factors for the various power plants are shown in Figure 16. The capacity factor from the figure for the Sudan region of Kassala and North Kordofan has come out to be the highest and quite within the range of 30 to 40% with 7 hrs TES as recommended by (IRENA, 2012). From the figure it can be observed that locations with highest Natural irradiance (W/m^2) produce the highest energy. Therefore, it can be concluded that regions with high natural irradiance are the key players when selecting the locations for a CSP.

The figure 24, is showing the capacity factor of each simulated CSPs coupled with TCES, from the figure it is quite self-explanatory that those locations that have the irradiance value greater than $875 W/m^2$ have the highest capacity factors



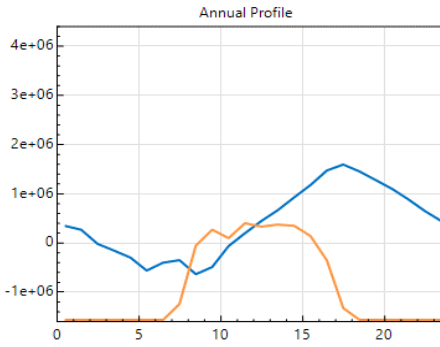


Figure 3: Annual power profile for Doz, Tunisia 4700MW

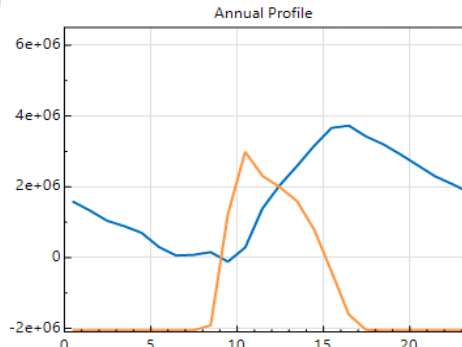


Figure 4: Annual power profile for Abu Dhabi, UAE 8800 MW CSP

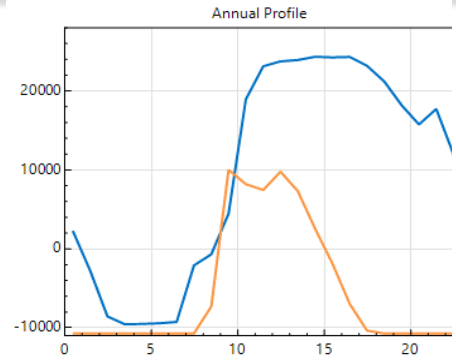


Figure 5: Annual power profile for Kassala, Sudan 25MW CSP

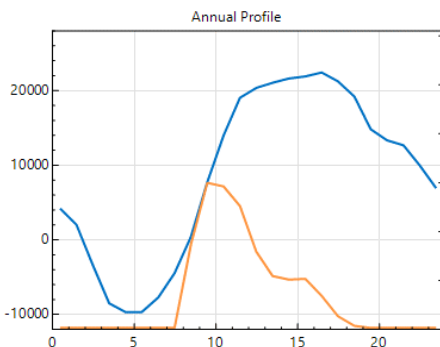


Figure 6: Annual power profile for North Kordofan, Sudan 25MW CSP

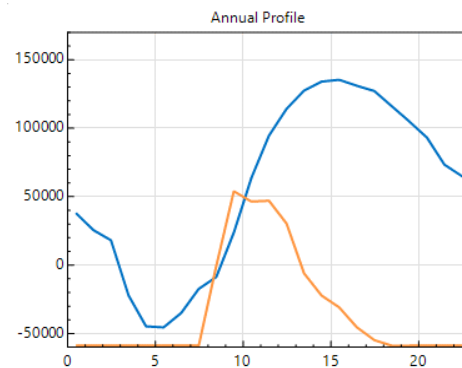


Figure 7: Annual power profile for Tabuk, KSA 150MW

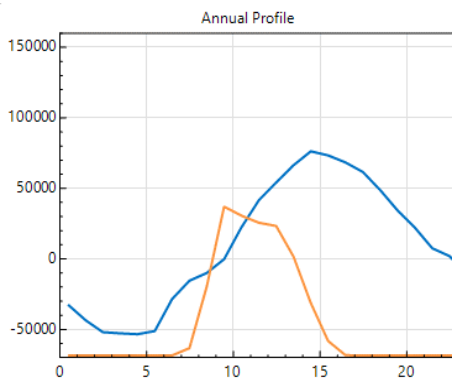


Figure 8: Annual power profile for Al-Hufuf, KSA 150MW

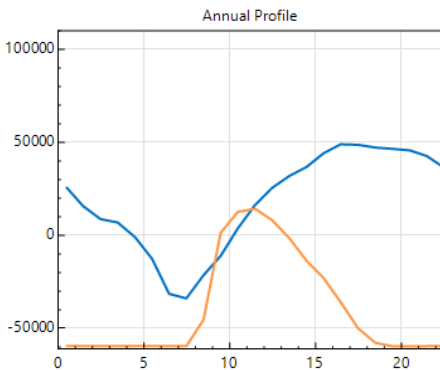


Figure 9: Annual power profile for Al-Jamil, Libya 100MW

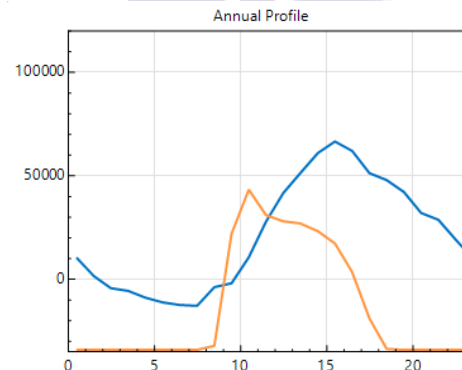


Figure 10: Annual power profile for Sabha, Libya 100MW

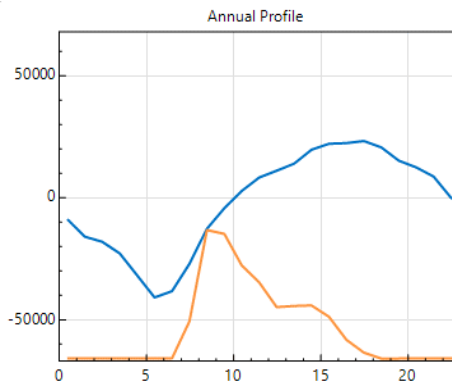


Figure 11: Annual power profile for Sirte, Libya 100MW

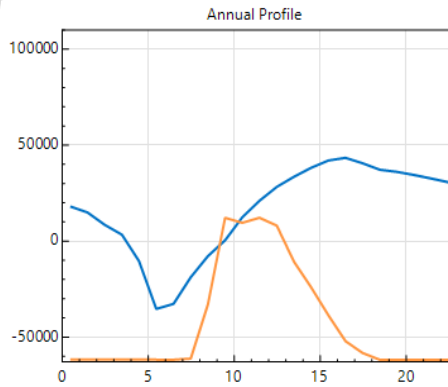


Figure 12: Annual power profile for Al-Batnan, Libya 100MW

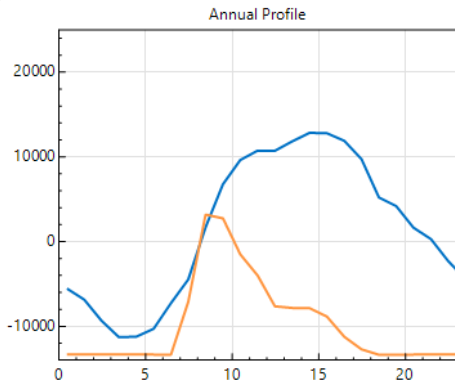


Figure 13: Annual power profile for Der Ezzor, Syria 25MW

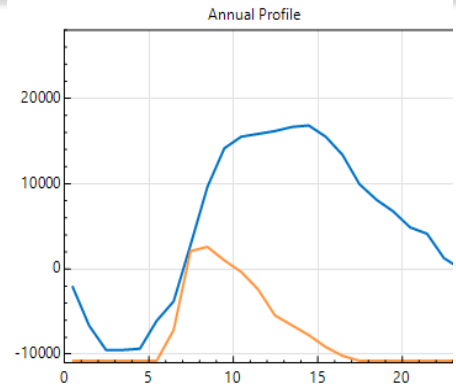


Figure 14: Annual power profile for Al-Hasaka, Syria 25MW

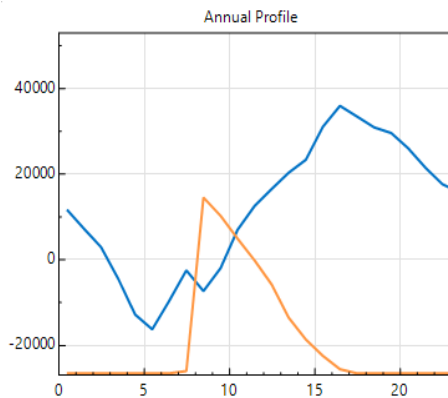


Figure 15: Annual power profile for Sana, Yem en 50MW

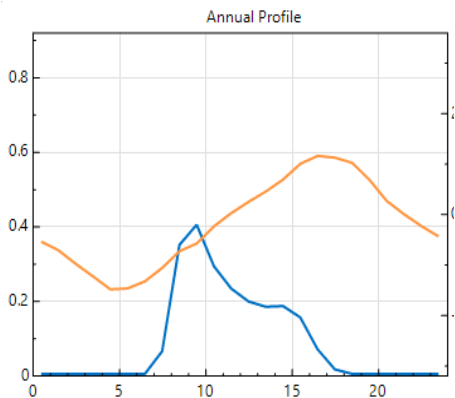


Figure 16: Annual power profile for Hadramawt, Yemen 50MW

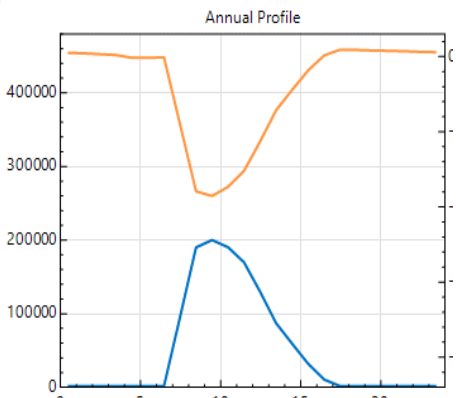


Figure 17: Annual Power profile for Beer Sheva, Palestine 16GW

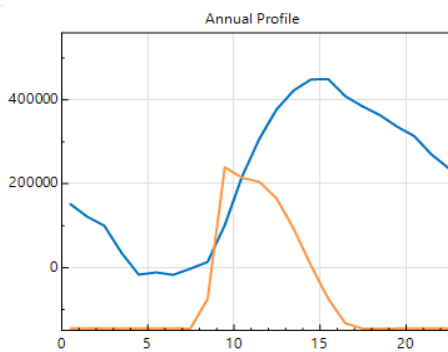


Figure 18: Annual power profile for Ash Shargiyah, Oman 770MW

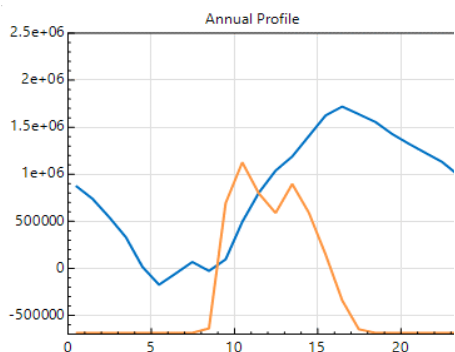


Figure 19: Annual power profile for Massa, Morroco 3366MW

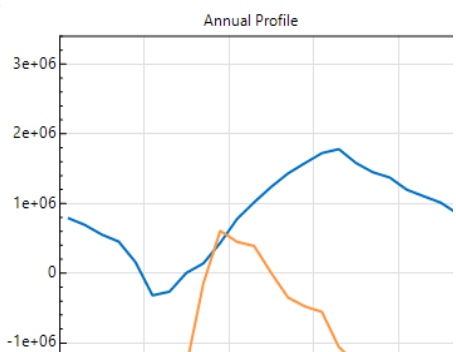


Figure 20: Annual power profile for Taza, Morroco 3366MW

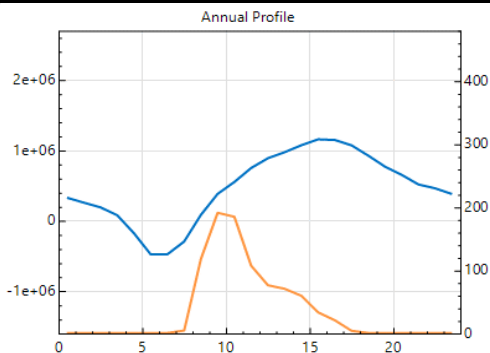


Figure 21: Annual power profile for Matrouh, Egypt 2750MW

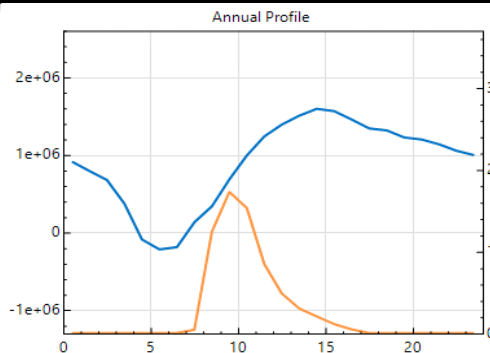


Figure 22: Annual power profile for Al Fayom, Egypt 2750MW

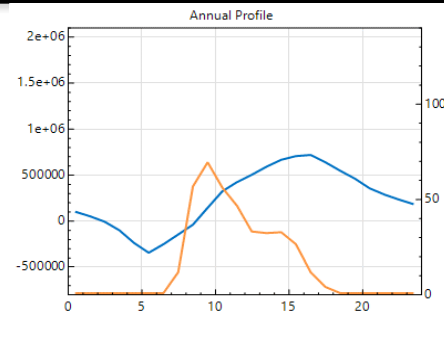


Figure 23: Annual power profile for Al baher al ahmer, Egypt 2750MW

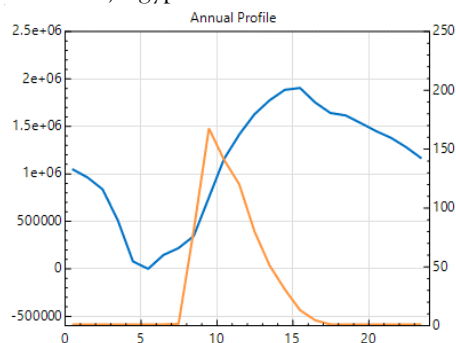


Figure 24: Annual power profile for Aswan, Egypt 2750MW

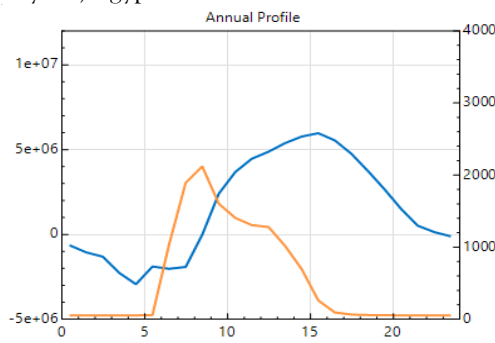


Figure 25: Annual power profile for Fars, Iran 10GW

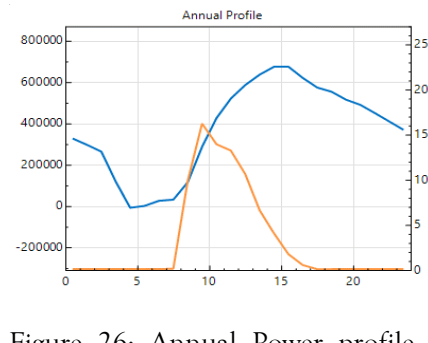


Figure 26: Annual Power profile of Adrar, Algeria 1000MW

because such plants are fed with the solar energy required to reach the rated capacity whereas for the CSPs with lower capacity factors are the result of lower irradiance and therefore, the field pumping requirements also increases in such cases so therefore, the net energy import from the local grid also increases. For example, consider the power import profile of Al-Hasaka & Der Ezzor (Syria) in figure 11 & 12, Der Ezzor has a capacity factor 5.9% whereas Al-Hasaka has a capacity factor of 20.4%, now the fundamental reason is the lower irradiance for Der Ezzor, but if the figures are observed closely, it is noticeable that for Der Ezzor, there is a flat demand for the energy imports which stays for 2 to 3 hrs. on average, and this is because to store the requisite backup, the more cycles of heat inputs to TCES are required which results in the higher energy imports. And therefore, the capacity factor is also reduced due to the higher energy imports from the local grid. Similar, is the case for the same power capacity plants of Libya, Egypt & Saudia Arabia. The Sirte, Libya although being a power plant of 100MW yet still its not technically feasible and the main reason behind is the lack of DNI in the region around the year as it can be observed from figure 29, that even in the

peak summer seasons of October and November, the power output is just reaching 50 MW only and therefore, due to this the capacity factor is negative indicating that, power generated is not sufficient and is not a suitable option to install a CSP plant at this site.

2. Financial Metrics

The financial analysis is performed by keeping IRR value constant at 12% for all the MENA countries, basically the IRR target is the recommended target set by the IRENA (IRENA, 2012). The value of LCoE which is the Levelized Cost of Energy, is quite important in our scenario due to fixed IRR value, therefore, for the given CSP to deliver a lower value of LCoE would justify the financial feasibility of the simulated CSP. According the to (IRENA, 2012), the LCoE should be below 40 cents/kW/hr for the CSP equipped with TES to be financially viable. Another important factor is the real PPA of the CSP plant, if through simulation, the plant is getting higher unit price than the electricity that is required to be sold is at higher prices and would therefore make the project economically unviable. From the figure 17, the LCoE obtained for various MENA countries can

be observed, and from the graph it can be concluded that those plants that has the highest capacity factor would yield the lowest LCoE and the analogy is simple because due to highest output power round the year, the LCoE would be quite lower because per \$ of investment the energy produced is relatively higher (Yang et al., 2018).

For projects selling electricity under a power purchase agreement (utility), SAM calculates the LCOE from the revenue cash flow, so that the LCOE also includes the developer's margin defined by the project's internal rate of return (Nate Blair, 2014). The Levelized PPA prices are quite crucial because they determine the units which the plant must sell to the national grid to reach the targeted IRR. And therefore, having a higher PPA would mean that you have to sell the electricity to the grid at higher rates and would therefore, comprise the whole PPA and the local or national grid wouldn't be willing to sign the agreement at such high levels because if the power production is ample and you are producing electricity in the competition so therefore, the PPA cost to reach the IRR must be significantly lower. The Levelized PPA for the various MENA countries simulated is presented in figure 18. From the figure it can observed that for

those CSPs that have the PPAs below 30 cents/kWhr are the most ideal CSPs because the clean energy being produced for the 25 years considering the 1% increase each year seems quite reasonable.

Although the current price of commercial units in these countries is relatively lower but the unit price trend for the electricity from the conventional resources is escalating exponentially and therefore, the PPAs for the high-capacity factor plants is adequate and make the plants financially feasible (Renewable Energy Agency, 2012). The NPV value for the simulated plants is always positive since we have fixed the IRR value to 12% therefore, the financial feasibility completely relies on the LPPA & LCoE. The LPPA of Hadramawt & Beer Sheva are 41.16 ¢/kWhr & 160.09 ¢/kWhr respectively. Therefore, these CSPs are not financially viable due to high LPPAs and therefore, such plants wouldn't be able to reach agreement to their local grid. The fundamental reason behind such LPPAs is that the produced energy is quite low, and these plants are of quite higher capacity and thus, required significantly higher electricity imports from the local grid to keep running the inverters which are necessary for the plant operation.

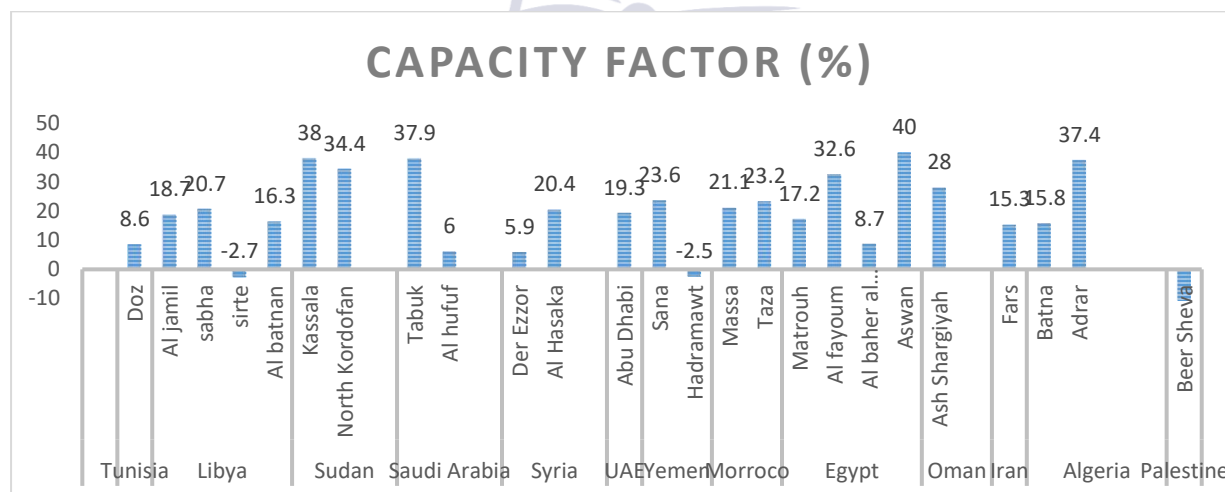


Figure 27: Capacity factor for the simulated CSPs with 7 hrs. TES backup at various locations in MENA region

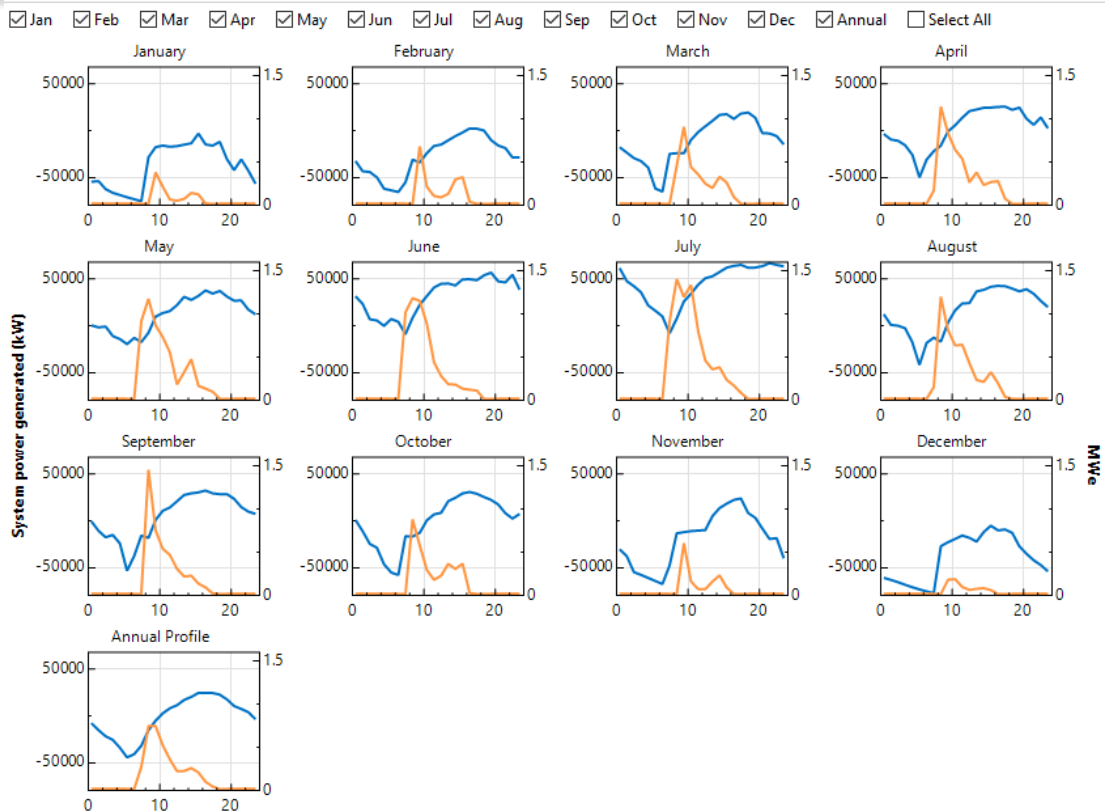


Figure 28: Monthly and annual power profile for Sirte, Libya 100MW

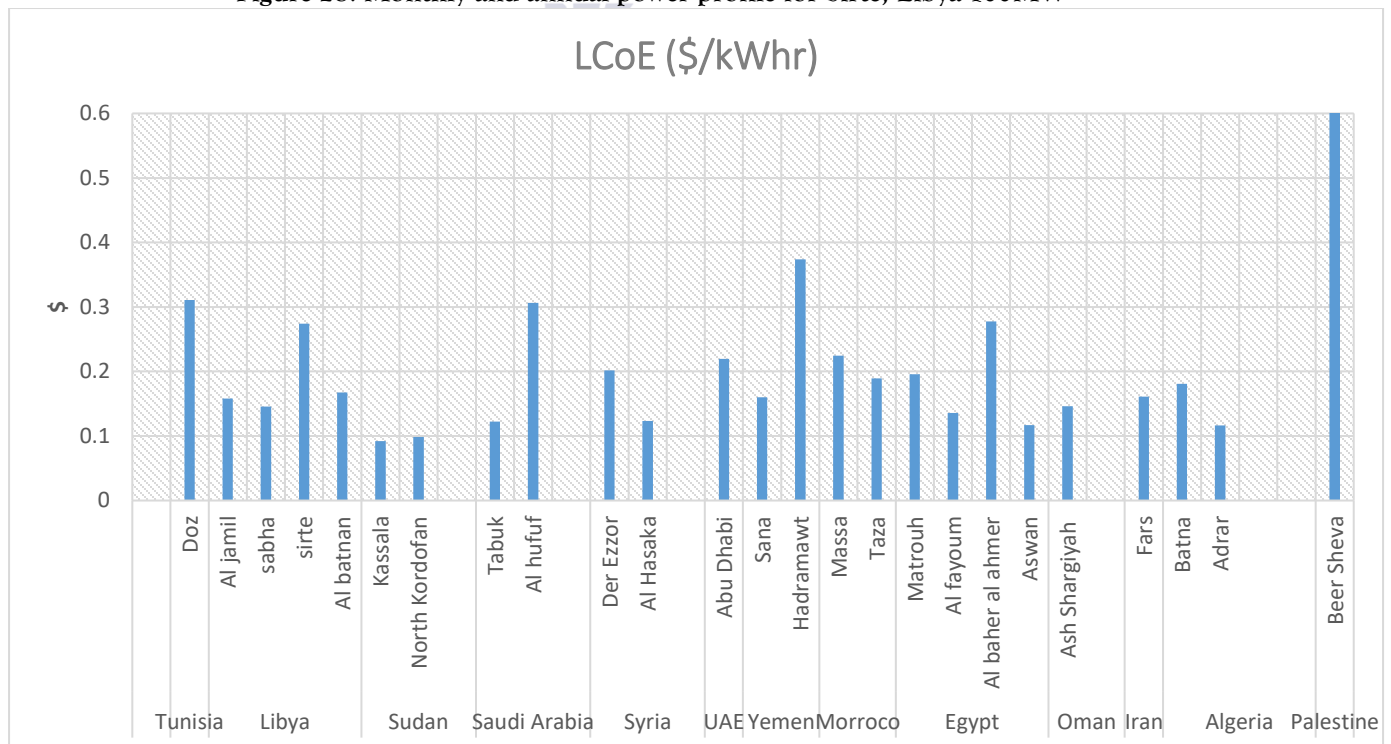


Figure 29: LCoE for various MENA countries simulated using SAM

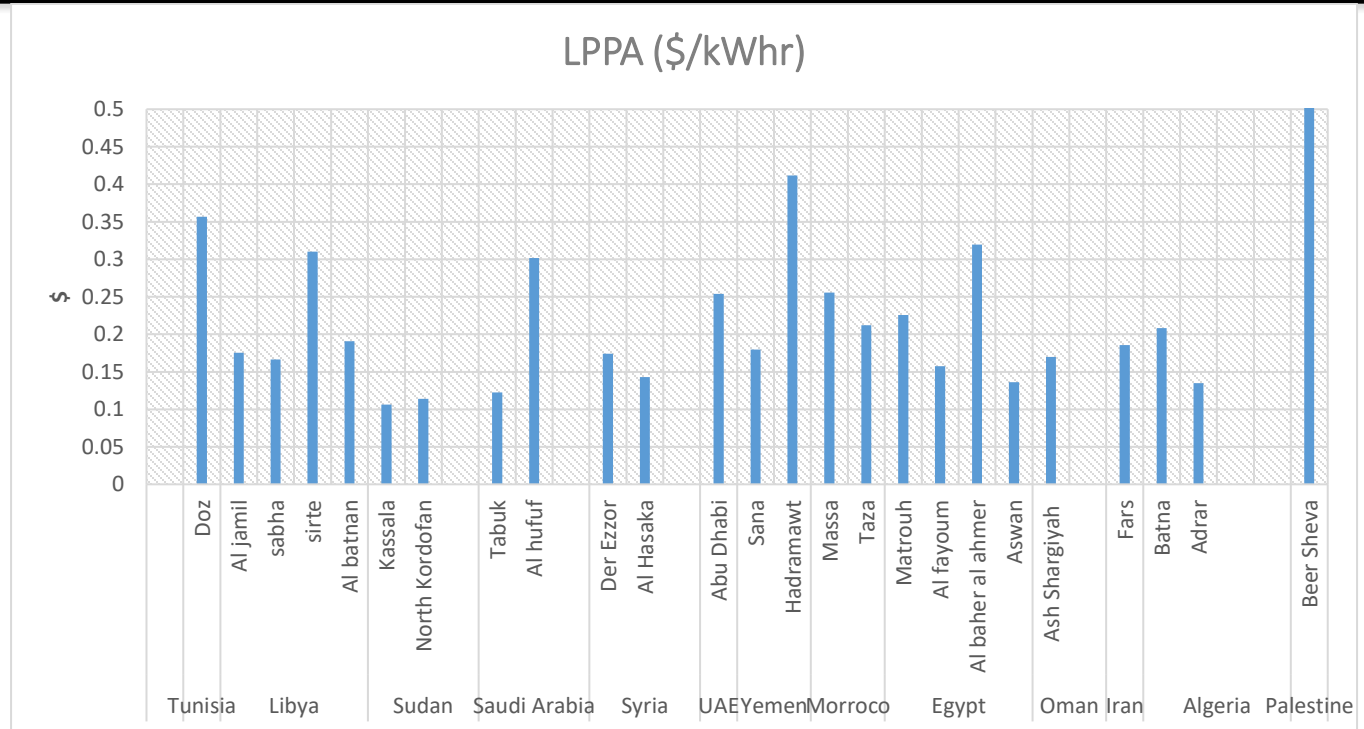


Figure 30: Levelized PPA cost for various MENA countries simulated through SAM

The cash flows for a typical MENA country simulated is shown in figure 19. The same trend has been obtained for all the simulated cases. The positive peaks show the cash inflows. From the figure, it can be observed that after many years of service, the plant reaches the breakeven, and then afterward the plants cash inflows increases and the IRR at the end of the projects for each simulated country reaches 13.56%. In figure 19, the dip of cash inflows is evident, which is due to the debt

that the plant must pay during its operation. For the simulation study, the debt is fixed at 57.8% of the total investment cost for the project. And therefore, as the plant is in a stable running position, the required debt is being paid. And as the debt is cleared there is a rise in the cashflows which can be observed that after almost 18 years the debt is paid out. For the utility type CSPs the debt is generally taken for installation so that the burden of the initial investment can be leveled.

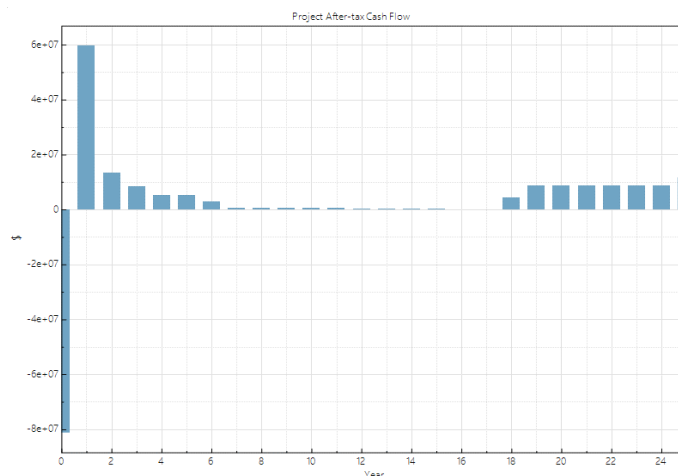


Figure 31: Financial profile (Cash Flows) for Kassala, Sudan over the lifetime: \$ on Y-axis & Years on X-axis

From the table 10, the results of the SAM are validated with the results of the actual power plant NOOR-II currently installed in Morocco and is operating since 2015. The analysis of this CSP plant was cited by NREL as referred. The SAM analysis is compared with the SAM analysis of the same country Sudan for the study performed by (Bashir & Özbey, 2022). From table 2, it is observed that the NOOR-II project, which is the operating CSP, has almost the same capacity factor and the Annual Energy Output and the LCOE are also similar. Therefore, it can be said that the SAM simulation performed is quite consistent with the real time data and other simulation study performed.

3. System Design Parameters: Solar Multiple and hrs. of storage

Finding the ideal solar field aperture area for a system at a specific location is necessary for sizing the solar field of a parabolic trough system in SAM. Increasing the solar field area generally results in a higher system electric production and a lower levelized cost of energy (LCOE) for the project. However, a field that is too large will create more thermal energy than the power block and

other system components can handle when there is enough solar resource. Additionally, once the size of the solar field exceeds a certain threshold, the greater installation and maintenance expenses offset the advantages of the higher output.

The ideal size of a solar field should:

1. Increasing the amount of time per year the field produces enough thermal energy to operate the power block at its rated capacity.
2. Reduce installation and maintenance expenses.
3. Utilize cost-efficient thermal energy storage and backup power systems.

Analyzing the trade-off between a larger solar field that increases the system's electrical production and project revenue, and a smaller field that minimizes installation and operational expenses, is the problem of selecting an appropriate solar field area. As it considers the amount of power produced by the system, the project installation costs, and the cost of operating and maintaining the system over its lifetime, the levelized cost of energy (LCOE) is a valuable indicator for determining the optimal size of the solar field.

Name	Location	Nominal Capacity (MW)	Storage capacity (hrs.)	Expected annual energy production (GWhr/yr)	Design capacity factor	LCOE (US \$/kWhr)	Reference
NOOR II	Ouarzazate, Morocco	200	7	600	34.25%	0.16	(NREL, 2022)
This Study	Ouarzazate, Morocco	200	7	621.581	35.5%	0.151	~
Ondokuz Mayıs Universitesi, Samsun, Turkey	Wadi Halfa, Sudan	80	6	281.145	40.1%	0.155	(Bashir & Özbey, 2022)
This Study	Kassala, Sudan	80	6	272.680	38.9%	0.0918	~

Table 10: Comparison between CSP with TES plants of Morocco & Sudan with this Study SAM output

Finding the solar field aperture area that yields the lowest LCOE is a necessary step in solar field optimization. The optimization process for systems with thermal energy storage systems entails determining the combination of field area and storage capacity that results in the lowest LCOE. Figure 28, which is obtained from the study of

(Bashir & Özbey, 2022), shows that as you increase the solar multiple there is a decrease in the LCOE but after solar multiple of 3 there is a flat behavior which showed that increasing solar multiple further it would result in increase in the installation and land cost only. Therefore, based

on this observation, the solar multiple for this

simulation was set at 3.0 for all the cases simulated.

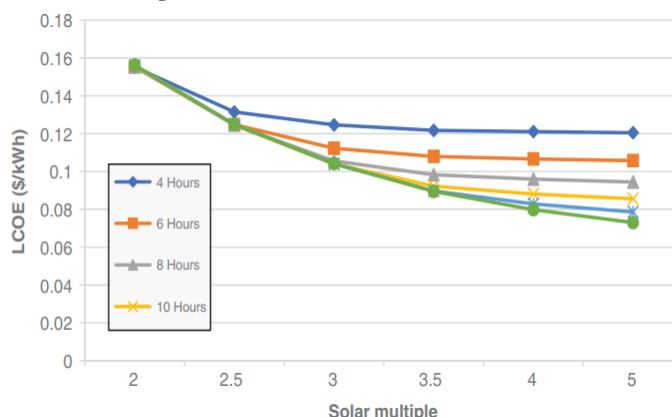


Figure 32: LCOE as a function of solar multiple and storage hours

Similarly, the effect of number of hrs. can also be observed. And therefore, the higher the number of hours the lower is the LCOE but going further from 8 hrs. there is no such sharp decrease in LCOE therefore, the number of storage hours was

kept at 7 hrs. in the simulation study trading off between LCOE and initial investment cost and fabrication cost for thermal energy storage tanks and respective pumping systems of storing energy.

Site improvements	25.00 \$/m ²
Solar field	150.00 \$/m ²
HTF system	60.00 \$/m ²
Storage	62.00 \$/kWh
Power plant	910.00 \$/kWe
Balance of plant	90.00 \$/kWe

Table 11: The unit cost installation values used for simulation in SAM

SAM has taken these values from the ABT NREL resource (NREL, 2023). The data presented on this site is owned by NREL and is updated on concurrent basis considering the market projections in various segments of renewable energy and molten salt storage technology. The values are fundamental for the US market; however, these are the values that are being used in simulation studies using SAM, and these are quite closer to the suggested values to be used for analysis of parabolic trough systems by (IRENA, 2012).

4. Financial Model

The cash flow of a project is determined by SAM's financial models over the analysis period that you define. The cash flow accounts for the value of the electricity produced by the system and incentives, as well as the expenses associated with debt, taxes, and installation, operation, and maintenance costs. To satisfy a set of equity return requirements, PPA projects must sell all the electricity produced by the

power system at a price established under a power purchase agreement (PPA). One or two parties may participate in a PPA project. SAM offers options for determining a target internal rate of return given a power purchase price or for determining the rate of return given a power purchase price. Either a fixed annual escalation rate can be used to change the electricity price annually throughout the study period, or a different price can be assigned to each year. By using time-of-delivery (TOD) variables, which can be either hour-by-month schedules or hourly (or sub hourly) time series factors, the price can be adjusted to vary throughout the day.

The power purchase price for PPA financial models is known as the PPA pricing. SAM assumes that these projects will sell their electricity for a price agreed upon in a power purchase agreement (PPA). As in our case we have specified an IRR of 12% for our project as recommended by IRENA 2023 therefore SAM determines the PPA price

required for project revenues to meet the internal rate of return target. A financially viable project is likely to have a LCOE that is equal to or less than the levelized PPA price to cover project costs and meet internal rate of return requirements. And in our case as represented in figure 26 and figure 27 the LCOE is greater than LPPA which makes the projects financially viable in this bracket. However, few of the projects due to the capacity factor and higher LCOE are not feasible as mentioned.

Conclusion

From the simulations performed, the data has been generated that the given location points of various MENA countries have the required potential for the CSP to be commissioned. Using the TES with CSP has increased the capacity factor since the peak power output generated for each CSP showed that at the off-peak hrs. at highest irradiation rates during the day the energy has been stored to CSP and has been utilized during the lowest or zero irradiation intensity during the nights. In addition, the simulation cases for varying power plant capacity have given us the insights that the high-capacity power plants in a range of GW are generally impractical due to the higher field pumping cost and lower electricity generation rates. And therefore, an unusual DNI for such plants to be designed to get the required output power. The 8.8 GW CSP simulated for Abu Dhabi, UAE has a capacity factor of 19.3% which is a moderate to low-capacity factor and the average irradiation in the summers is 950 W/m^2 . From this it can be concluded that for the CSP of GWs rating it would require the average normal irradiation to be greater than 1050 W/m^2 .

In the next section, the financial analysis was performed for the various MENA countries CSPs simulated using SAM by keeping the IRR fixed at 12% and accordingly getting LCoE & Levelized PPA required for the plant to be financially feasible. And for the MENA countries it has been concluded that CSPs with 7 hrs TES backup are financially viable and can provide stable electricity at the most economical unit rates throughout the lifetime, which is 25 years. The LPPAs & LCoEs of various MENA countries simulated and obtained falls within the allowable range by IRENA. Thus, making the plants financially feasible.

Therefore, it can be concluded that CSP coupled with TES can prove quite a potential opportunity to meet energy demands sustainably. At present, the energy prices delivered through conventional resources are escalating exponentially and are also adding up tons of carbon and resulting in increased GHG emissions. CSPs being one of the proven renewable energy technologies proves to be the most sustainable and stable source of energy. After being coupled with the salt storage technique, the CSP can serve as the base load plant to cope up the energy requirements at the peak hrs.

Recommendations

The model can be evaluated on additional CSP technologies in the future, including LFRs, parabolic dishes, and power towers. The model can be expanded further by accounting for how a CSP project will be received by the community and how it will affect the local environment. In comparison to other power supply options, social acceptance reflects how the local population feels about CSP technology. The environmental impact shows how the CSP plant will lessen environmental effects while still providing energy. And, for the high-power capacities for which the CSP technology has failed to produce the required output results, therefore, the power tower technology can be simulated using SAM to evaluate the said alternative. Furthermore, for the CSPs of higher capacity of GWs the storage capacity for 9 to 13 hrs. should be simulated because, for much larger systems, the capacity factor can be enhanced if their energy output is increased. However, the required capital cost for the installation and commissioning would increase due to the requirement of large storage systems and subsequent pipe networking required to channel such larger molten salt through the network. Therefore, this option can be quantified using the SAM.

It is recommended to run a thorough performance analysis on CSP simulation system. Compared to other forms of renewable energy systems or traditional power sources, evaluate its efficiency, energy output, and overall performance. Think about measurements like the capacity factor, the levelized cost of energy, and the NPV. Examine how the system's dispatchability and capacity for reliable power output can support load balancing,

peak shaving, and grid stability. Consider the opportunities and difficulties of incorporating intermittent renewable energy sources into the system. Conduct an environmental impact analysis of the CSP system, considering elements like emissions, water use, and land use. To demonstrate the environmental advantages of CSP technology, compare these effects to those of conventional power generation techniques. It is recommended to do some research on the CSP technology market dynamics and regulatory environment. Examine how the outcomes of the simulation compare to the market environment and regulatory framework. Talk about the opportunities and potential stumbling blocks for the broad use of CSP systems in different geographical areas. For CSP to work as a standalone as the base load, the modelling on SAM must be done to observe the energy output trends that are stable and can be provided annually. Thus, that energy output can serve as the base load for the given CSP under modelling.

The Determination of CSP system's Levelized Cost of Storage (LCOS) for thermal energy storage. An important indicator that sheds light on the efficiency of energy storage technology is LCOS. To demonstrate the system's economic viability, compare the LCOS with other energy storage methods like batteries. It is recommended to create and examine several scenarios for energy distribution that highlight the adaptability of the CSP system with thermal energy storage. Think about scenarios with various load profiles and solar resource availability. Describe quantitatively the impact of the system's dispatchability and storage capacity on decreasing the requirement for backup power sources and satisfying peak demand. The calculation and evaluation of thermal energy storage system's efficiency at various charge and discharge rates. Determine the exact amount of heat, thermodynamic, and aging losses that were suffered during the storage process. Compare these efficiency figures to the system's total effectiveness. Calculate and evaluate your thermal energy storage system's efficiency at various charge and discharge rates. Determine the exact amount of heat, thermodynamic, and aging losses that were suffered during the storage process. Compare these efficiency figures to the system's total effectiveness.

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