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Design and Analysis of Parabolic Trough Collector Power Plant in Saudi Arabia

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Abstract

The increasing demand for electricity due to massive industrialization and rapid growth of population is a major challenge of today's world. The conventional electricity generation methods with the help of fossil fuels result in disastrous emissions which have a devastating effect on human health in the long run. Therefore, an imminent fix to these problems is essential. Exploration of renewable energy could answer all these problems. This paper presents the design and detailed analysis of the energy and economic performance of a 100MW parabolic trough based concentrated solar power (CSP) plant in central Saudi Arabia. The annual energy production of the 100MW plant is recorded to be 324781 MWh and the capacity utilization factor is 37.1%. The payback period of the plant is less than the lifespan of the plant therefore the proposed CSP plant is economically feasible at the proposed location.

Disciplinary: Renewable Energy, Sustainable Energy, Electrical Engineering and Technology.

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1. Introduction

Renewable energy can be extracted from renewable resources, such as wind, solar, waves, geothermal heat, etc. [1]. These resources are endless and naturally, replenish without vanishing. Wind and solar are very commonly available in renewable resources. Although both have an intermittent pattern, wind resource is more fluctuating than solar. Therefore, solar energy can be considered a relatively better option especially in solar belt regions such as the Middle East. Sun is an enormous source of energy and using around 1% of solar energy available from the sun, we can make the environment stable by reducing greenhouse gas emissions [2]. Harnessing solar energy arriving at earth in one hour could fulfill the energy demand of the whole world for one year [3].

The utilization of solar energy for electricity generation can solve many energy-related problems such as ever-increasing energy demand around the world [4], global warming [5], and depletion of fossil fuels [6]. The electrical energy is extracted from solar energy by using solar energy technologies namely photovoltaic (PV) and concentrated solar power (CSP). In case of PV technology, solar energy is directly transformed into electricity. However, in hot regions such as the Middle East, the temperature in summer is very high and this high temperature has an adverse effect on the energy production of the PV system. The cell temperature of PVs is even higher than the ambient temperature because of their dark color [7, 8]. In the CSP method, the solar concentrators are used to collect thermal energy from the sun to provide heat for a thermodynamic cycle where a steam or gas turbine is used to run an electrical generator [9]. The CSP technologies have four main types, which are subdivided into two groups line focused and point focused technologies. The line focused technologies are linear Fresnel and parabolic trough while The point focused technologies called parabolic dish system and solar tower [10, 11]. Figure 1 shows CSP technologies and their share in the total CSP based renewable power generation. The share of the parabolic trough is more than 82% followed by solar power tower with a contribution of 13%. The share of linear Fresnel is about 4% and the parabolic dish system has a very small share of less than 1%. The dish system is used only in small-scale power generation.

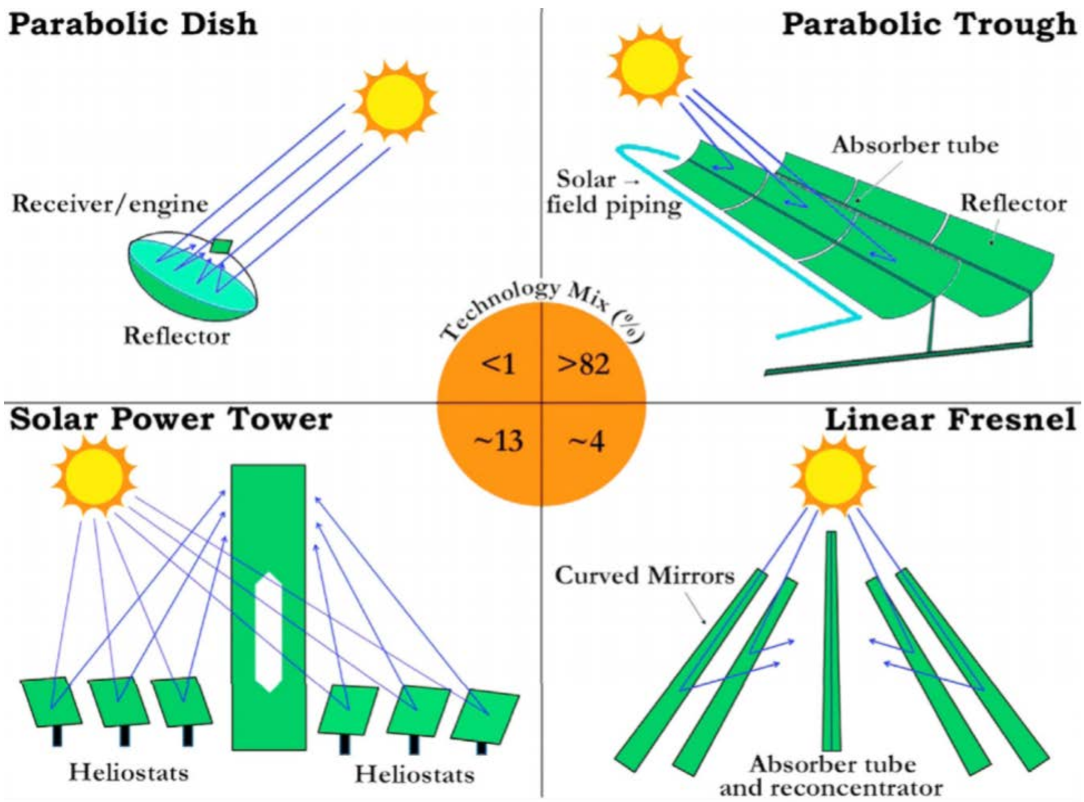

Figure 1: Concentrated solar power technologies.

The heat collected by the parabolic dish is directly focused on the Stirling engine to generate electricity. It is an external combustion engine having a fixed amount of working gas. The gas is heated by the external heat and then it cools to run a Stirling cycle [12]. The remaining three technologies collect the heat and then transfer it to a power block for running the thermodynamic cycle. The heat is transferred by using a heat transfer fluid (HTF) circulating in the receiver tubes. The selection of HTF is decided based on the temperature capturing heat from the sun. The thermal energy storage (TES) capability of these technologies makes them dispatchable [13][14] which is a huge plus point of CSP over PV technology. The addition of the TES system in the CSP plants helps to increase the capacity utilization factor (CUF) and decrease the cost of generated electricity.

Presently, thermal oil and molten salts being employed as HTF for TES in large-scale power plants. The thermal oil remains stable in the range of 12°C to 400°C [15]. There are various options of thermal oils such as Therminol VP-1 (biphenyl-diphenyl oxide eutectic mixture) and other synthetic oils. However, most of the organic materials have many drawbacks of high pressure, flammability, low density, and low decomposition temperature. Therefore, molten salts are the most common heat transfer fluids for TES storage in commercial power plants [16]. The inclusion of the TES system prolongs the plant's working hours and the plant can generate electricity even after sunset. Therefore, the TES integrated CSP plant can satisfy peak load in the evening which is very common in most countries.

This paper presents a detailed performance analysis of the parabolic trough CSP plant. The energy analysis is based on annual and life-time electrical output, CUF, and economic analysis is based on a payback period and levelized cost of energy (LCE).

2. Site Selection and Solar Resource

The site selection to install a CSP plant is one of the major decision parameters to harness maximum energy and economic benefits from the project. The locations that have an average DNI level greater than 1800 kWh/m^2/year (5.5 kWh/m^2/day) are generally economically feasible for the installation of a parabolic trough CSP pant [17]. Qassim region in the central part of Saudi Arabia (located at 26.39°N, 43.80°E) is selected for the installing CSP plant. The solar resource data for the proposed location is taken from King Abdullah City of Atomic and Renewable Energy (KACARE). Figure 2 presents the daily average DNI solar resource data on monthly basis. The overall average direct normal irradiance (DNI) at the proposed location is 6.38 kWh/m^2/day. The DNI is minimum (5.22 kWh/m^2/day) in December and maximum (7.74 kWh/m^2/day) in July.

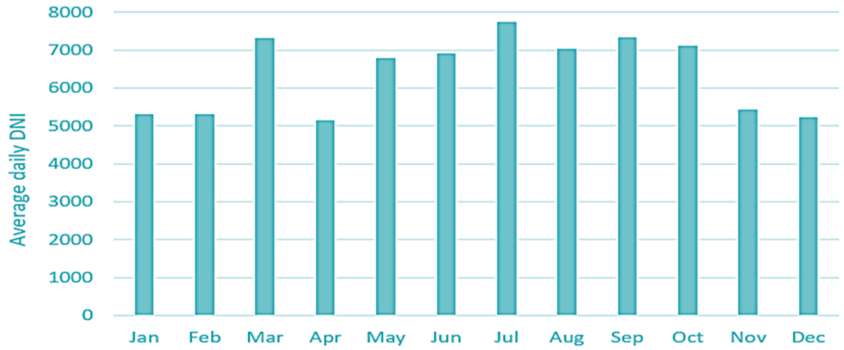

Figure 2: Average daily DNI.

3. Parabolic Trough CSP Technology

Parabolic trough collector is a proven technology and is most commonly used in the existing CSP plants. In this type of power plant large solar field, containing a huge number of parabolic collectors, collect the solar thermal energy. In this process, the large curved mirrors direct the solar radiations onto a tubular receiver where an HTF is circulating. The HTF receives this heat from concentrated solar radiations and takes it to the steam generator in the power block section of the CSP plant with the help of a heat exchanger. The high-temperature steam is fed to the steam turbine. The steam turbine moves the rotor of the electrical generator to produce electrical energy. Most of the CSP plants contain a TES unit which stores this thermal energy to be utilized in the power block in the time when the sun is not available. The HTF stocks the excess heat to the TES unit via another heat exchanger. The schematic diagram of such a CSP plant showing all the major parts is presented in Figure 3. Three main sections of the CSP power plant are:

1) Solar field
2) Thermal energy storage
3) Power block

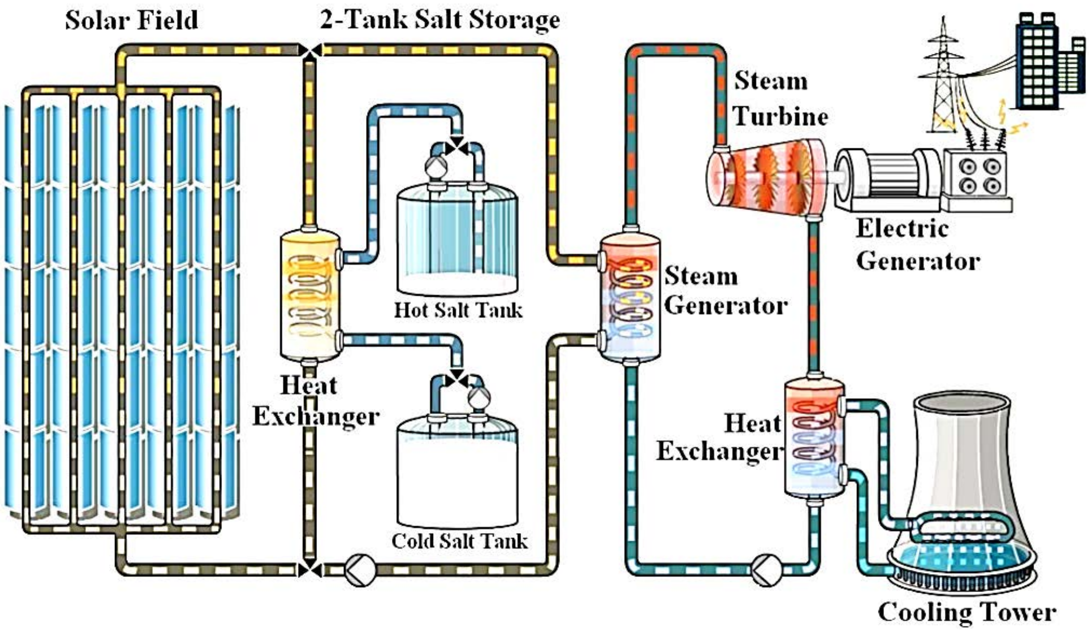

Figure 3: Schematic of parabolic trough collector CSP plant [18]

3.1 Solar Field

The solar field contains a huge number of curved mirrors called parabolic troughs which concentrate the sun rays onto the evacuated tube receiver where the thermal energy of concentrated solar radiations is received by the heat transfer fluid to be transferred to the thermal energy storage system and power block.

3.1.1 Parabolic Trough Collectors

The PTCs can produce temperatures in the range of 50°C to 400°C. The parabolic collector assemblies are organized in a series configuration called loops. The shape and length of the loop depend on PTC performance but usually, the shape is U type. The main parts of the parabolic trough collectors are the concentrator, absorber tube, tracking system, support structure.

3.1.1.1 Concentrator

The concentrator of the PTC is parabolic in shape. It is parabolic in shape and made of reflective material to focus the collected solar rays on to its focal line. When the parabolic concentrator is facing the sun, the coming solar rays are reflected on to receiver tube as shown in Figure 4.

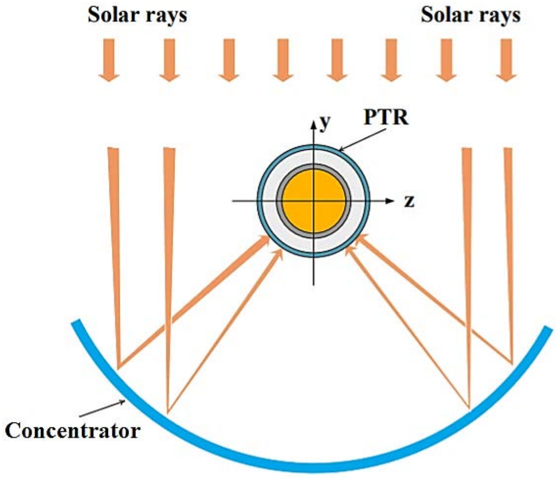

Figure 4: Parabolic trough concentrator and receiver.

3.1.1.2 Absorber Tube

The concentrated solar radiations from the concentrator are mainly focused on the bottom periphery of the absorber tube. Therefore, the intensity heat flux on the bottom section is much higher than the top portion which is only receiving the non-concentrated solar radiations from the sun.

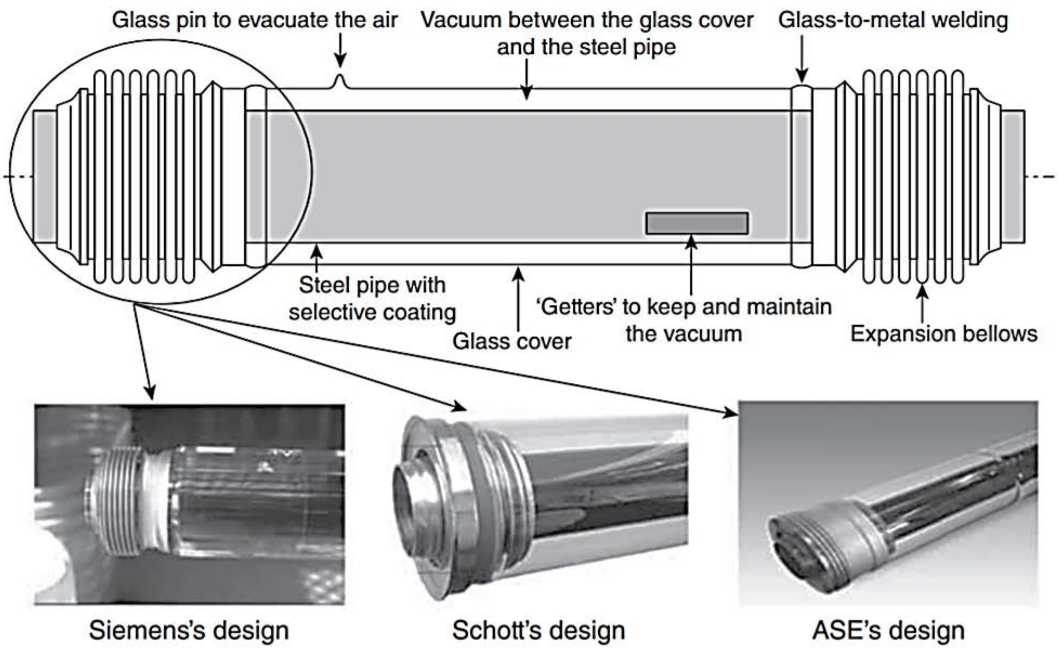

Figure 5: Absorber tube receiver [19]

The absorber tube is constructed of stainless steel having a selective coating. This coating helps to augment absorption and reduce energy emission. Figure 5 shows the main parts of the absorber tube. The *metal tube* is enclosed in a *glass cover*. To decrease the heat loss, the area between the metal tube and glass cover is filled with a *vacuum*. Hence it is also called an evacuated tube receiver. The connection between the metal tube and glass cover is established via *expansion bellows*. The expansion bellows solve the problem of different thermal expansion of metal and glass under nominal working temperature. The expansion bellows are connected to the glass cover by using *glass-to-metal welding*. It is shielded to provide protection against mechanical and thermal stress that may have an adverse effect on the durability of welding. The loss of vacuum due to hydrogen diffusion of oil-based heat transfer fluids from the wall of metal pipe is a major degradation issue that has been noticed in the existing parabolic trough CSP plants. Getters are employed in vacuum space to curtail the hydrogen partial pressure [19].

3.1.1.3 Tracking system

The tracking system of parabolic collectors must accurately track the sun with high reliability. The original position of the collector is restored during the nighttime. An additional benefit of the tracking system is to protect the collector by defocusing the collector during a bad working environment, like a failure of HTF flow, overheating, and wind gusts. There are various types of tracking systems such as a single axis, dual-axis, and rotating axis. They are further subdivided into two types called electrical and mechanical. Generally, the electrical tracking mechanism shows better accuracy and reliability. They have further improved the category where the motor is electronically controlled using sensors. This system tracks the sun using feedback control based on the solar flux signal coming from sensors [20, 21].

3.1.2 Power Block

The power block is the part of the CSP plant where the actual conversion of thermal energy to electrical energy takes place. The power block of CSP plants is mostly based on the Rankine cycle for electricity generation. Its main parts are the steam generator, steam turbine, and electrical generator [22].

4. Modeling of the Parabolic Trough CSP plant

The thermal energy received by the active area of parabolic collectors is

$$E_C = A_{SF}.cos\theta.DNI \qquad (1),$$

where DNI is direct normal irradiance, and A_{SF} is the solar field aperture area. The amount of thermal energy supplied to the steam generator in the power block is [3]

$$E_{PB} = m_f.\left(H_{SF_{out}} - H_{SF_{in}}\right) \qquad (2),$$

where, m_f is the mass flow rate of HTF, $H_{SF_{in}}$ and $H_{SF_{out}}$ are the enthalpies at the inlet and outlet of the solar field.

The solar field efficiency which is defined as the ratio of the amount of thermal energy delivered to the power block and TES system to the amount of thermal energy collected in the solar field is

$$\eta = \frac{E_U}{E_C} \qquad (3),$$

where E_u is the amount of useful thermal energy delivered to the TES system and power block. The efficiency of the power block is

$$\eta_{PB} = \frac{E_{net}}{E_{PB}} \quad (4),$$

where E_{PB} is the thermal energy input of the power block and E_{net} is the net energy output. Plant overall efficiency is

$$\eta_{overall} = \frac{E_{net}}{E_C} \quad (5).$$

The excess thermal energy in the daytime can be stocked in the TES system. The size of the TES system is the number of hours for which the TES system can run the plant at its full capacity. The size of the TES system is calculated as [23].

$$E_{tes} = \frac{P_{des} h_{tes}}{\eta_{PB}\eta_{tes}\eta_{tg}} \quad (6)$$

Where h_{tes} is the number of stored hours, P_{des} is the nominal capacity of the plant, η_{tg} is turbine-generator efficiency, and η_{tes} is the efficiency of the TES system.

In the case of the plant containing the TES option, the solar multiple of the plant must be greater than one. Solar multiple represents the factor by which the solar field size is bigger than the size of the power cycle. It is expressed by the ratio of heat energy collected in the collector field for design point solar irradiance and the power block required thermal energy for the design electrical output and is computed as [24].

$$Solar\ Multiple = \frac{E_{SF\_d}}{E_{th\_PB}} \quad (7)$$

Where E_{SF_d} is the thermal energy collected in the solar field and E_{th_PB} is thermal energy required in the power block to generate design electrical power.

5. Modeling of Plant

The 100 MW parabolic trough based CSP plant is designed and simulated in SAM software. SAM performs in-depth economic and energy analysis of the proposed plant for user-defined design parameter, and installation and operating costs. The most important part of a CSP plant is its solar field. It is the main constituent of the plant which is responsible for the collection of thermal energy of the sun. The parabolic collectors in the solar field can be arranged along East-West or North-South orientation.

Table 1: Solar field's design characteristics

Design Parameter	Value
Plant size	100 MW
Solar Multiple	2
Collector assembly length	95 m
Modules in an assembly	10
Total loops	205
Single loop aperture area	4360 m^2
Total reflective area of the aperture	893800 m^2
The total land area of the solar field	2165070 m^2
Distance between parallel rows	14 m

The proposed plant is designed for North-South orientation because this gives better energy output compared to East-West orientation [23]. The collectors use single-axis tracking of the sun to maximize the concentration of reflected solar radiation to the absorber tube throughout the day. Table 1 shows The solar field's design characteristics. Solar collector efficiency is given by the ratio of the active area of collector aperture and absorber tube area. Siemens Sunfield 6 solar collector along with Siemens UVAC 2010 receiver are used. Table 2 presents the characteristic of the receiver and collector. To prolong the working hours of the plant to generate electricity after sunset, 6 hours of TES system is included in the design of the plant. Table 3 lists the design parameters of the 6 hours TES system. Solar field and TES system sizes depend on the characteristics of the power block. Table 4 presents the power block design characteristics.

Table 2: Characteristics of the solar collector and receiver

Parameter characteristics	Value
Siemens Sunfield 6 solar collector	
Module length	9.5 m
Module width	5.776 m
Mirror reflectance	0.925
Optical	0.859
Focal length	2.17 m
Siemens UVAC 2010 receiver	
Absorber tube's internal diameter	0.066 m
Glass envelope's internal diameter	0.109 m
Absorber tube's external diameter	0.07 m
Glass envelope's external diameter	0.115 m
HTF	Therminol VP-I
Inlet temperature	293 ^{o}C
Outlet temperature	391 ^{o}C

Table 3: TES system design parameters

Design Parameter	Value
Full load thermal storage duration	6 h
Number of the storage tank	2
Storage medium	Hitec solar salt
The volume of the storage tank	25304.4 m^3
Thermal energy capacity	1870.79 MWh_t
Maximum operating temperature	238°C
Minimum operating temperature	593°C

Table 4: Design characteristics of the power block

Parameter	Value
Design output	111 MWh
Net output	100 MW
Net output Gross to net efficiency	0.9
Temperature (Inlet)	391 ^{o}C
Temperature (Outlet)	293 ^{o}C
Conversion efficiency	0.356
HTF mass flow rate	1,296 kg/s
Operating pressure of the boiler	100 bar
Condenser type	Air cool

6. Performance Analysis

6.1 Energy Analysis

The annual energy of the plant throughout its life span is shown in Figure 6. The plant generates 324781 MWh of energy in year one. The energy output slightly decreases in the coming years because of the degradation of optical efficiencies of the parabolic collector and absorber tube receiver. The proposed 100 MW CSP plant generates 7927623 MWh of electrical energy during the project lifetime of 25 years. The hourly average energy generated in all months is shown in Figure 7. The generated energy follows the DNI pattern at the proposed plant location. The maximum hourly average energy output of 53.7 MWh is produced in June while a minimum of 14.3 MW in December. The energy generated is an interesting pattern regarding the electrical load of Saudi Arabia. Saudi Arabia has a long and hot summer season and the temperature in the summer reaches above 50°C. This high temperature demands a high air-conditioning load, therefore stress on the electricity company is high in summer months. As depicted by Figure 7, the generated energy is high from March until October which shows that the energy generation pattern of the CSP plant would help to satisfy the high electrical load during the summer months. The hourly based field incident solar thermal power, power cycle thermal power input, and electrical output of the CSP plant are demonstrated in Figure 8. It is shown that thermal energy is available even after the sunset when no solar field incident thermal energy available from the sun. The electrical power is generated for a longer duration in summer due to high better DNI and TES system. The thermal input of the power cycle is coming from the TES system to produce electricity after sunset. The heat is cumulated in the tank during the day time when solar resource is high. The field incident solar thermal power and thermal energy moving into the TES system are depicted in Figure 9. The excess thermal energy moves into the TES unit during the daytime and during the nighttime, the thermal energy goes out of the TES system to power block which is shown by the negative portion of thermal energy into the storage system curve. It can be observed in Figure 9 that no thermal energy goes into the storage system winter solstice from November to February.

The CUF of the plant can be calculated by

$$Capacity\ utilization\ factor = \frac{E_{net}}{365 \times 24 \times plant\ capacity} \quad (8).$$

The CUF of the proposed plant is 37.1%.

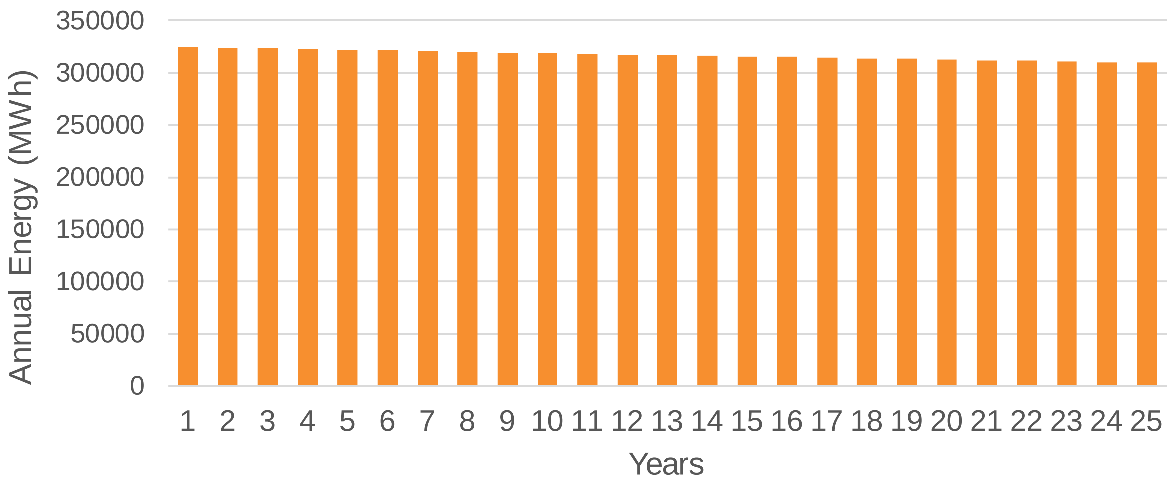

Figure 6: Annual energy output of CSP plant.

Figure 7: Hourly average energy of CSP plant.

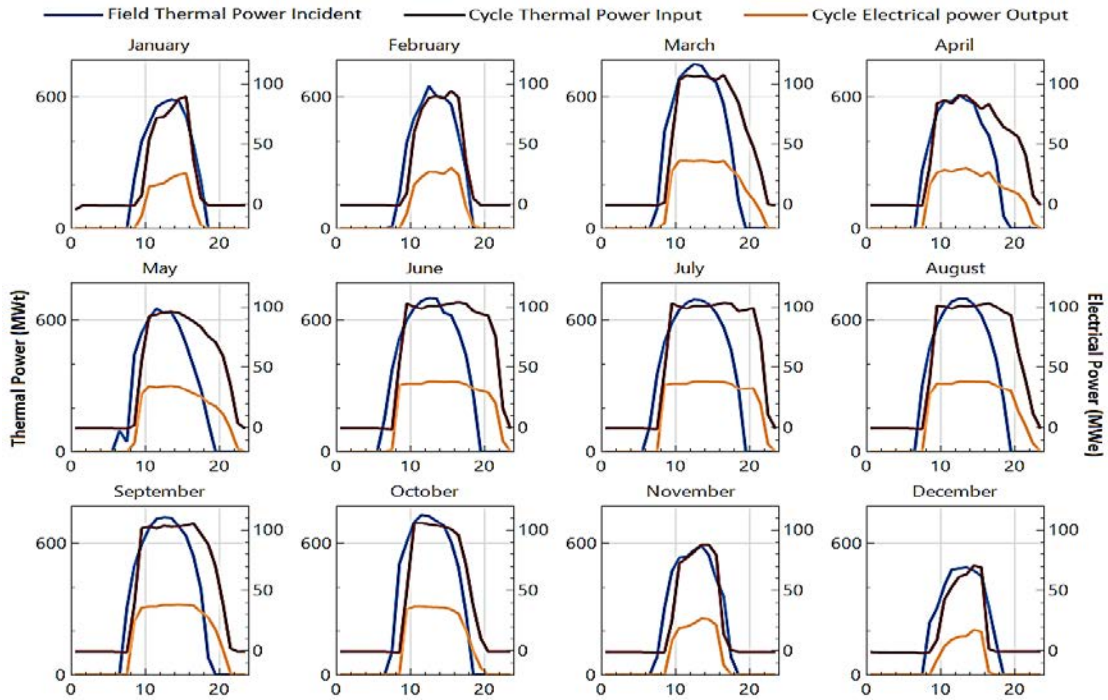

Figure 8: Field incident solar thermal power, thermal power input for a power cycle, and electrical output.

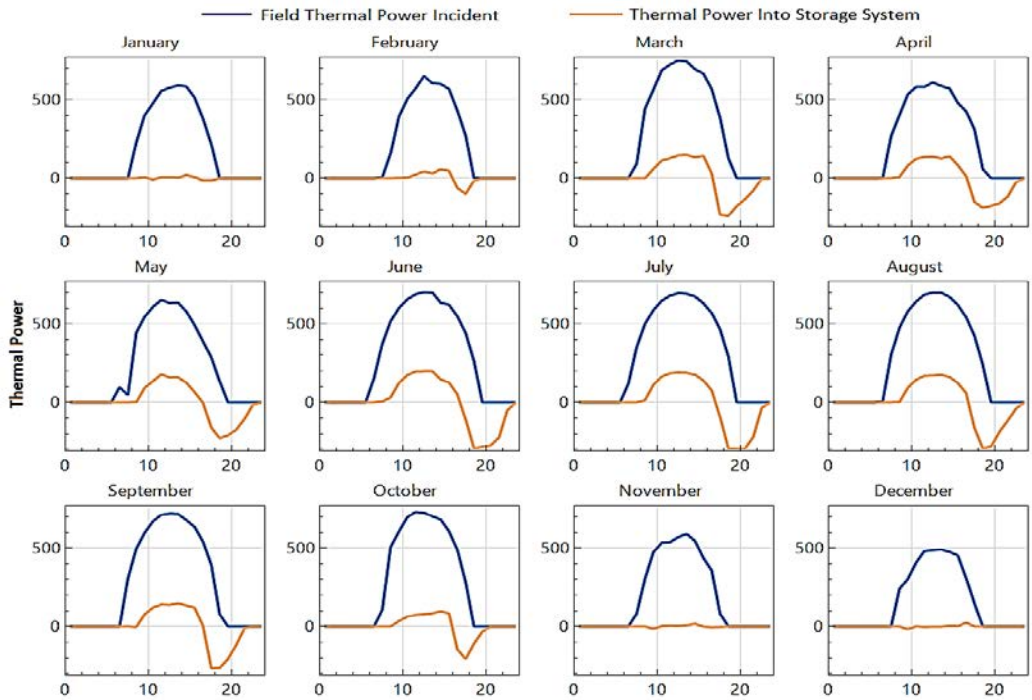

Figure 9: Field incident thermal power and thermal energy into the storage system.

6.2 Energy Analysis

The cost associated with various parameters of the proposed CSP plant is shown in Table 5. The net capital cost is US$ 485,469,888. The equity is 25% (US$ 121,267,472) and the remaining 75% of the net capital cost is debt. The lifetime flow of after-tax cash is shown in Figure 10. This after-cash flow is the total cash income by electricity sale during each year after deducting all the expenditures. The cost of electricity sale is considered as US$ 0.08/kWh. The long negative spike at the start of the project has resulted from the initial investment of the project. The cost is again negative in the years afterward because of the installments paid for the loan. The plant starts earning after-tax net positive cash from the year 16 onwards. The simple payback period of the CSP plant is 20.5 years.

The levelized cost of energy (LCE) is the ratio of annual cost and total electricity generated over one year and is calculated by the following relationship,

$$LCE = \frac{annual\ cost}{annual\ generated\ energy} \qquad (9),$$

$$LCE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+D_{nominal})^n}}{\sum_{n=0}^{N} \frac{Q_{an}}{(1+D_{real})^n}} \qquad (10),$$

where Q_{an} is the total generated electricity in year n, C_n is the total cost in year n, $D_{nominal}$ is nominal and D_{real} is the real discount rate. The LCE of the proposed CSP plant is calculated to be 12.21 ¢/kWh.

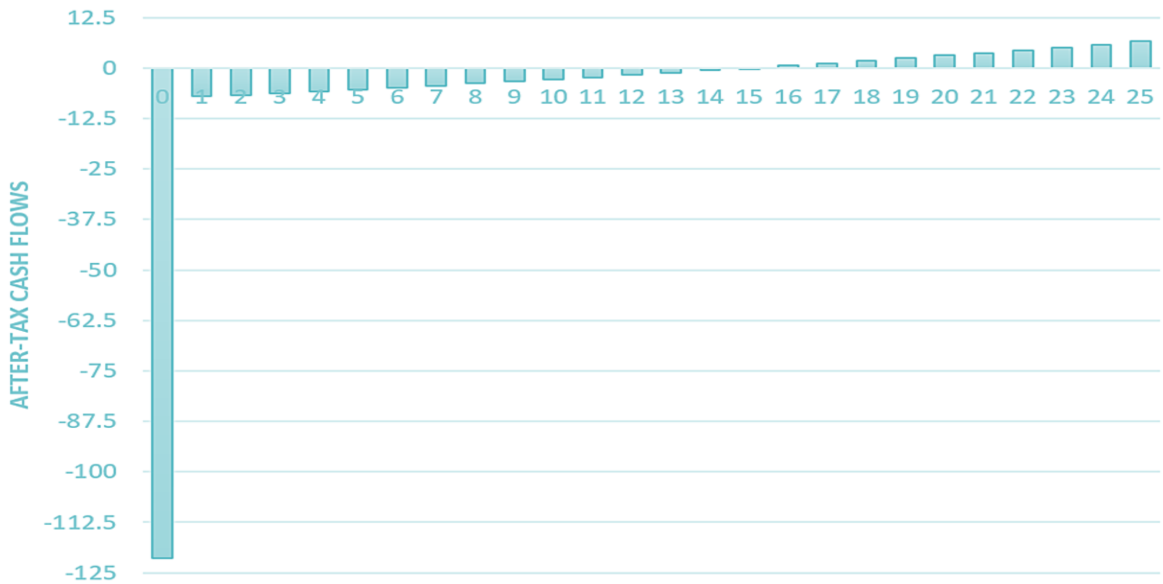

Figure 10: After-tax cash flows of the CSP plant.

Table 5: Cost parameters [25].

Cost Parameter	Value
Power block	1050 US$/kWh
Solar field	120 US$/m^2
Thermal energy storage	60 US$/kWh$_t$
Heat transfer fluid	50 US$/m^3
Site Improvement	20 US$/m2
Land	200 US$/acre
Operation and maintenance	20 US$/kW
Balance of plant	110US$/kW

7. Conclusion

This paper presented the detailed economic and energy analysis of the 100 MW CSP plant. This plant is designed for the Qassim region of Saudi Arabia. The proposed location has promising solar radiations with an average DNI of 6.38 kWh/m²/day. The DNI is minimum in December and maximum in July. The first part of the chapter presented the detailed mathematical modeling of the CSP plant. The proposed CSP plant generates 7927623 MWh of electrical energy during the project lifetime of 25 years. The generated energy follows the DNI pattern with a maximum hourly average energy output of 53.7 MWh in June and a minimum of 14.3 MW in December. The energy generation pattern of the DNI coincides with the load pattern of Saudi Arabia which proves the usefulness of the proposed CSP plant. The net capital cost of the CSP plant is US$ 485,46,9888. The LCE of the proposed CSP plant is 12.21 ¢/kWh and the simple payback period is 20.5 years. The LCE is a little bit high but the payback period within the lifespan (25 years) of the project proves the economic feasibility of this solar power technology at the proposed location.

8. Availability of Data, and Material

Data can be made available by contacting the corresponding author.

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