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Research Article

Thermo-economic evaluation of solar boiler power plant

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ABSTRACT

Today, the world is turning to use renewable energy to solve the problems of fuel shortage and pollution due to CO_2 emissions from the use of fossil fuels. In this study, parabolic trough solar collectors (PTC) with two types of heat transfer fluids HTF are used to investigate the performance of a retrofitted steam power plant using solar energy. A thermo-economic analysis was performed for a 10 MW simple steam power plant with different boiler pressure from 10 to 100 bar and located in the city of Basra in Iraq which receives high levels of solar radiation. Basra's weather conditions are used to simulate the solar-assisted regenerative system using a parabolic trough collector (PTC). According to the system analysis, it was found that increasing the boiler pressure reduces the area required for the PTC heater for constant power output. For 10 bar operating pressure the required PTC area is 64233,562 m^2 while for 100 bar operating pressure the required PTC area is 42907.59 m^2. Also, it was estimated that the Levelized Cost of Energy (LCOE) decreased with increasing operating pressure. The decrease in LCOE for PV1 heating fluid is 43.25% and the decrease in LCOE is 43.16% for the pressure range from 10 to 100 bar.

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INTRODUCTION

Environmental and energy problems have increased at the beginning of the 21st century, because of the huge use of non-renewable resources such as fossil fuels, and nuclear energy. Due to the use of these materials, global warming and climate change have occurred. In order to avoid continued climatic and energy shortage problems, solar energy was developed to generate electricity.

Benabdellah et al., 2021 [1] studied energy and economic analysis for an 80MW gas turbine and solar plant based on PTC. Hassi R'mel (Algerian Sahara) is where the plant is located and the area is characterized by intense solar radiation. 56 lines, 224 collectors, 183,120 m2 of the solar field area, and synthetic oil (VP-1) were used in the study. The obtained results show that energy efficiency are 56.06% and LCOE was 9.75 ¢/kWh. Wang et al., 2021 [2] studied the economic analysis of (PTC) power plant, for three typical sites, Mojave Desert, Dunhuang, and Quarzazate. This plant has 100-meter-long PTC and 800-meter-long rows connected in a series in the form of eight loops. The temperature at the inlet was 290C and the temperature at the outlet was 550C. According to the economic analysis of the plant, the LCOE (¢ /kWh)

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This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç was 9.34, 9.34, and 13.50 respectively for the three sites. Alotaibi et al., 2020 [3] performed a 300 MW steam plant modified by solar collectors using (PTC) type LS-3. This solar power plant was located in Kuwait. The results show, the total area needed by the solar plant was 25,850 m2 and the (LCOE) was 0.129/kWh. Collector and thermal efficiencies were 76.5%, and 51.9% respectively. Agyekum & Velkin, 2020 [4] analyzed the economics and energy of a 200 MW solar plant for two locations in Ghana (Navrongo and Tamale). Reflective aperture area 656 m2, the HTF operating Temperature 593°C, and collector Length was 115 m utilized to design and analyze this plant. According to the results, the LCOE ¢/kWh for Navrongo and Tamale were 25.83 and 28.60, respectively. Mehrpooya et al., 2019 [5] replaced energy produced by the Rajaee power plant with a capacity 250 MW by parabolic trough collectors, which generated the same amount of energy as the combustion of natural gas. MATLAB software was used to analyzed the energy and economic. DNI 1050 kWh/m2, Therminol VP-1 (HTF), total solar field area 120,000 m2, and economic life of solar plant 20 Years were used in the software. The obtained results that, thermal efficiency was 39.1% and a cost saving was 80.0 US$/kWh. AlZahrani et al., 2018 [6] studied exergy and energy analysis for (PTC) within a solar power plant. The plant consists of 100-meter long rows connected in the series form to raise fluid temperature using LS-3 type collectors. This power plant was located in Saudi Arabia in the city of Al Madinah and has a capacity of 12.58 MW. Thermal analysis of the plant shows that the PTC is found to have 66.35% and 38.51% for energy and exergy efficiencies, respectively. ALAİN et al., 2018 [7] conducted an economic and energy analysis of a small 1 MW solar power plant in Izmir, Turkey. The plant was consisting of a PTC and power block while it worked by Rankine cycle. To perform the analysis, they used an aperture area of 7285 m2, average irradiation of 523.7 W/m2, heat transfer fluid Therminol VP-1, and collector LS-2. According to the results, LCOE was 19.3 cents/kWh and overall energy efficiency was 32.7 percent. Askari & Ameri 2017 [8] integrated a distillation system with a solar power plant to produce both fresh water and electricity. To achieve the results, they used north-south solar collectors of type PTC, Reflective aperture area of 470.3 m2, collector length of 8.33 m, annual DNI of 2300 kWh/m2/year, and Therminol-VP1 as HTF. Results were obtained with the MATLAB program where LCOE was 0.2288 $/kWh and Power cycle thermal efficiency was 32.45%. Sadati et al., 2015 [9] utilized renewable energy sources to produce electricity due economic difficulties of importing oil in Pakistan. Energy and economic analysis for a 10MW power plant in Multan, Pakistan was performed. Parabolic trough collectors (PTC), 45,100 m2 without a storage system, and DNI 1800kWh/m2 were used in the plant. According to the results, LCOE was 0.273USD/kWh. Desai et al., 2015 2013 [10] utilized economics and energy analysis for a 1MW solar power plant with 4 storage capacities in Jodhpur (India). PTC with a full tracking system, solar field inlet, and outlet temperatures are 165, 265 °C, and Therminol-VP1 as HTF are used to analyzed. According to the results, electrical efficiency was 20.7% and LCOE was 19.3 €/kWh. Jain et al., 2013 [11] studied economic analysis for 100MW PTC plant in India. Therminol oil is used as HTF. According to the results, LCOE was 35 US cents/kWh. Reddy et al., (2012) [12] studied an energy analysis for a solar plant in India. They examined the energy losses, as well as the efficiency for variable operating conditions. By change in cycle pressure from (9 to 10.5) MPa therefore, the energy efficiency of the plant increased by 1.49%. Suresh et al., 2010 [13] performed an energy and economics analysis for a 500 MW solar power plant in India. They have integrated a coal thermal plant with a solar plant. The results show that a reduction of 14–19% in coal can save in fuel costs of 73.5–74.5 (INR) and LCOE was 14.46 (INR/kWh). Montes et al., 2009 [14] performed an energy and economic analysis for a 50MW power plant in Madrid, Spain. Five parabolic trough collector plants were studied, with identical parameters but different field sizes. The boiler pressure was 90 bars, the inlet temperature at the turbine was 370 degrees Celsius, and the solar beam radiation was 850 watts per square meter. Based on the results, thermal efficiency was 38.21%, collector efficiency 70.23 %, and LCOE was 15 €/kWh.

THE MAIN OBJECTIVES OF THE STUDY

1. Studying energy analysis of solar boiler at different operating pressures.
2. Studying the effect of using different (HTF) on the solar boiler performance.
3. Economic analysis to study the economic impact of using a solar boiler instead of fuel burning boiler.
4. Studying the environmental impact of using solar boilers for power generation.
2. Fuel Burning Steam Boiler

Fuel-burning Steam boilers are widely used in power plants around the world. Figure 1 refer to the simple steam power plant was selected in this study with a capacity of 10MW that generates steam by using natural gas as a fuel in the boiler. We need to know how much energy is required to generate the specified steam flow rate for different boiler pressures in order to replace the fuel-burning boiler with a solar boiler (PTC). The energy requirements for different boiler pressures are shown in Table 1.

Solar Power Plant

Environmental and energy problems have increased at beginning of the 21st century, because of non-renewable resources such as coal, fossil fuels, and nuclear energy. Due to the use of these materials, global warming and climate change have occurred. To avoid continued climatic

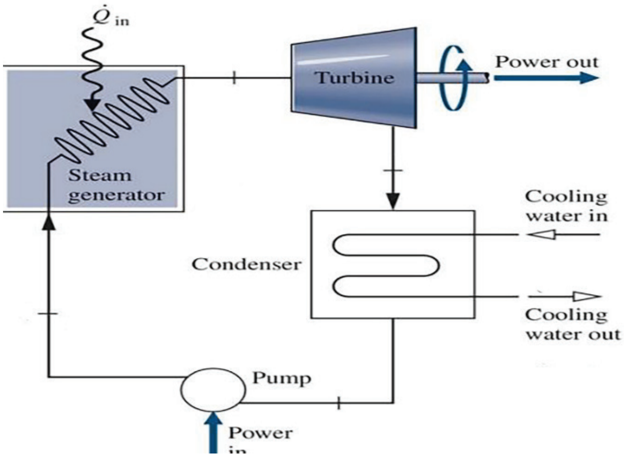

Figure 1. Simple steam power plant working by Rankin cycle.

Table 1. Simple steam power plant requirements for constant power output 10MW

Boiler pressure (bar)	Boiler Temperature (°C)	Boiler Energy (kw)
10	279	40126.534
20	312.38	34701.483
30	333.85	32170.638
40	350	30663.468
50	363.94	29590.473
60	375.59	28783.922
70	385.83	28142.921
80	395.01	27619.122
90	403.35	27179.106
100	411	26804.262

problems, solar energy was developed to generate electricity [15]. The Technologies of concentrated solar power (CSP) utilize the heat of the sun to generate electricity. Parabolic trough collectors are the most common technology used by the CSP. The Parabolic trough power plant consists of solar collectors, HTF, and a power block. Solar collectors are arranged in arrays, each with a parabola-shaped surface that reflects and focuses sunlight onto a receiver pipe through which a Heat transfer fluid (HTF) flows that is heated by sunlight. The hot fluid, a synthetic oil, heats water producing steam, which turns turbines to generate electricity [16]. In the Mojave Desert of California, Luz Company installed 354 MW of solar electric plant in the 1980s [15]. During the SEGS process, long parabolic mirrors are used with pipes, where circulating oil is heated to a temperature of700 Fahrenheit (371 Celsius). Heat is transferred from hot oil to water in heat exchangers to create high-pressure steam that drives the generators of the turbine [17].

Parabolic Trough Collectors

Solar concentrating systems with collectors that are parabolic in shape and made from materials with reflection properties. Solar collectors concentrate and reflect solar radiation toward a receiver heating the oil inside. The operating temperature range of the parabolic trough system is 500–700K [18]. Parabolic trough collectors consist of the following components shown in Figure 2.

1. Solar collector mirrors
2. Solar collector receiver tubes (absorber)
3. Glass cover protection
4. Solar collector Foundations and support structures
5. motor and controls unit
6. Heat transfer fluid

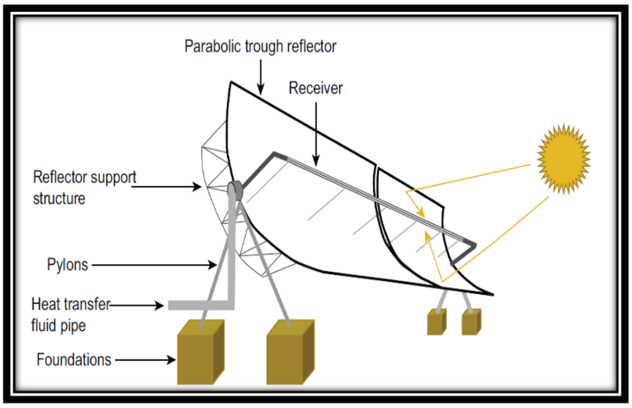

Figure 2. Schematic of a parabolic trough collector.

Solar Boiler Power Plant Model

According to Basra's weather conditions, a solar boiler steam plant will be designed. A focus of this study was the design of CSP systems, cycle parameters, and cycle efficiency. Basra is within an area with significant potential for concentrating solar power, as mentioned in the introduction. There are many factors that affect solar irradiation, such as location, local time, solar angles, and weather conditions. Hottel 1976 has provided a simple model for evaluating beam radiation. Only the elevation, day number, and zenith angle of the location must be entered [15].

The plant consists of three parts as shown in Figure 3 solar collector fields, heat transfers fluid HTF (synthetic oil), and power block (turbine, condensers, and pumps). The collector concentrates a direct beam of solar radiation onto the receiver tube, which is located at the parabola's focal point, via a parabolic surface. The HTF is pumped through the receiver tube. These tubes utilize concentrated solar radiation to heat thermal oil, which is heating the water in the heat exchanger to produce steam and return to complete the cycle.

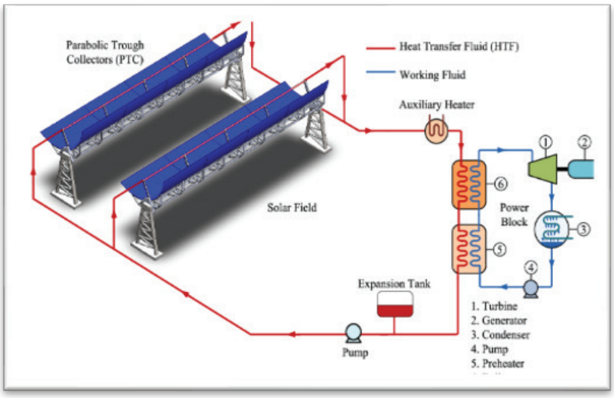

Figure 3. Solar boiler power plant plant.

Solar Collector Field

The solar parabolic trough collectors, all stander types, are made by a flexible sheet of reflective material (mirrors) into a parabolic shape, which focuses sunlight onto the focal line of the trough [15]. The solar collector is equipped with a solar tracking system that tracks the sun as it changes its position from east to west so that it maintains continuous radiation concentration [17]. The heat collection tube is made up of an absorber enclosed in a glass envelope, as illustrated in Figure 4. An absorber is made from stainless steel or copper, and it has an inner and outer diameter. The outer surface of the absorber is coated with a material to improve the optical properties. In order to reduce thermal radiation losses, the coating has a high absorption of solar energy and a low emittance of solar radiation [1819].

PTC System Model

To estimate the useful heat energy from a HTF, the model was used base on the basic equation for PTC.

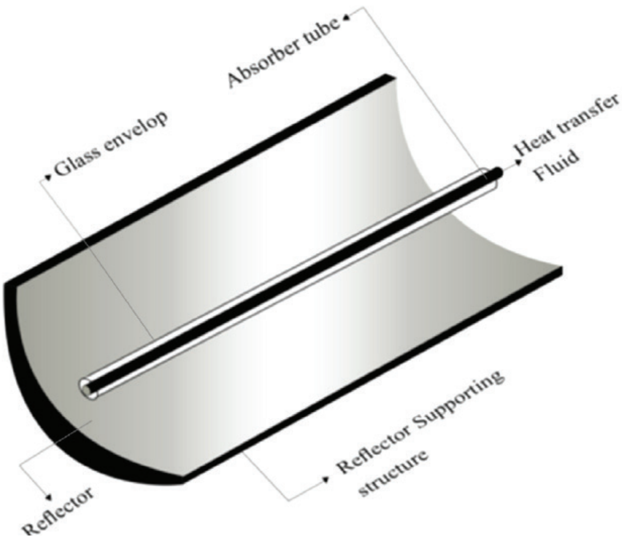

Figure 4. Solar boiler power plant plant.

By using second method, Useful energy (Qu) can be calculated from the equation below [20]

$$Q_u = F_R\left(DNI \cdot \eta_{opt} \cdot A_a - A_r \cdot U_L \cdot (T_{in} - T_{am})\right) \quad (1)$$

Where:
F_R: Heat removal factor can be defined from below

$$F_R = \frac{m_C \cdot C_p}{A_{ro} \cdot U_L} \cdot \left[1\text{-}exp\left(\frac{-A_{ro} \cdot U_L \cdot F'}{m_C \cdot C_p}\right)\right] \quad (2)$$

Where:
F': Collector efficiency factor

$$F' = \frac{1/U_L}{1/U_L + \frac{D_{ro}}{h_{in} \cdot D_{ri}} + \frac{D_{ro}}{2k_{cop}} \cdot \left[ln\left(\frac{D_{ro}}{D_{ri}}\right)\right]} \quad (3)$$

h_{in}: Heat transfer coefficient for HTF
k_{cop} : Thermal conductivity for copper equal to 400 W/m.K.

Overall heat loss (U_L) coefficient refers to the amount of heat lost from the collector. Can be calculated from the equation below [21].

$$U_L = \left[\frac{A_{ro}}{\left(h_{c,c\text{-}am} + h_{r,c\text{-}am}\right) \cdot A_{co}} + \frac{1}{h_{r,r\text{-}c}}\right]^{-1} \quad (4)$$

The collector's thermal efficiency in second method can be an expression [22].

$$\eta = \frac{Q_u}{Qs} \quad (5)$$

Heat Transfer Coefficients

The collector tube has three heat transfer coefficients as shown in Figure 5. The radiation coefficient between receiver and cover (hr,r-c), then the radiation coefficient between cover and sky (hr,c-am). Finally, the convection coefficient between cover and air (hc.c-am). [23]

1- Radiation coefficient from receiver to cover:

$$h_{r,r\text{-}c} = \frac{\sigma \cdot \left(T_r^2 + T_c^2\right) \cdot \left(T_r + T_c\right)}{\frac{1}{\varepsilon_r} + \left(\frac{1}{\varepsilon_c} - 1\right) \cdot \left(\frac{A_r}{A_c}\right)} \quad (6)$$

2- Radiation coefficient from cover to sky:

$$h_{r,c\text{-}am} = \varepsilon_c \cdot \sigma \cdot \left(T_c^2 + T_{sky}^2\right) \cdot \left(T_c + T_{sky}\right) \quad (7)$$

$$T_{sky} = 0.0552 T_{am}^{1.5} \quad (8)$$

3- Convection coefficient from cover to air:

$$h_{c.c\text{-}am} = h_{out} \quad (9)$$

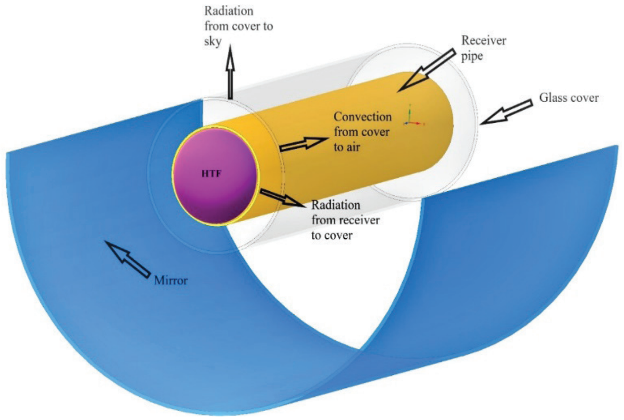

Figure 5. Heat transfer coefficients in PTC.

Economic Analysis of Solar Power Plant

A solar power plant's economic analysis will be presented in this section. Economic analysis of solar plant represented by the LCOS (Levelized Cost of Electricity) calculation, which includes two main components (1) Total capital cost. (2) Operating cost [24].

Total Capital Cost

The total capital cost (DC) is represented by the direct cost, which includes site improvement (*SI*), solar field (*SF*), power block (C_{PB}), and HTF system (HTF_{system}) cost [22] Table 2 includes the components of direct cost.

$$DC=\left[\left(SI+SF+HTF_{system}\right)A_{SF}+C_{PB}\right] \quad (10)$$

Where:

A_{SF}: Solar field area can be calculated from the equation below:

$$solar\ field\ area=(A_a\times N_c)+(L_{space}\times L_{collector}\times(N_c-1)) \quad (11)$$

where:

N_c: Is collector's number

$$N_c=\frac{Q_{steam}}{Q_u} \quad (12)$$

L_{space}: Space between rows

The minimum space among rows is 7m where chosen in this study.

C_{PB}: The power block cost

Table 2. Capital cost components

Direct cost	Value	Unit
Site improvement	25	$/m^2
Solar field	295	$/m^2
HTF system	90	$/m^2
The power block	70	$/m^2

Operating Cost

The annual operating costs (O&M) include the costs associated with maintaining all solar collector parts, which can be calculated as follows [25].

$$O\&M=1.5\%\ of\ direct\ cost \quad (13)$$

Finally, the cost of electricity for solar power plant can be calculated as follows [26].

$$LCO\ E(\$/kWh)=\frac{DC+O\&M}{plant\ capacity\ in\ (Kw)\times runing\ hours(\frac{H}{yr}} \quad (14)$$

RESULTS AND DISCUSSION

In this section, the simulation results of the solar boiler power plant will be viewed. The simulation was performed for two types of heat transfer fluids which are PV1 and SYS800 and for the range of boiler pressure from 10Bar to 100Bar. Firstly, the results for the month of maximum intensity June month are viewed. The solar power plant specifications are listed in Table 3.

Effect of Boiler Pressure on the Solar Plant Parameters

The effect of variation boiler pressure on the HTF mass flow rate, number of solar boiler rows, total solar boiler aperture area, solar field area, and electric cost for solar power plants are given in the Figures 1-6. The results are for two types of HTF for June month at 12 O'clock where solar beam radiation is 832 W/m2. For PV1 fluid the collectors are 162 m long for each row, and for SYS800 the collectors are 124 m long for each row. The results indicate that as the steam pressure increases, the HTF mass flow rate decreases due to increasing the flow energy and decreasing the heat required for evaporation in the steam generator with increasing the pressure as shown in Figure 7. The percentage decrease in the HTF mass flow rate for PV1 and SYS 800 is 49.69% and 49.73% respectively. The number of PTC collector rows as shown in Figure 8 decreases with increasing steam pressure due to a decrease in the heat required for steam generation. The percentage decrease in the number of PTC collectors for PV1 and SYS 800, is 48.71% and 49.67%, respectively. The total aperture area as shown in Figure 9 decreases with increasing the steam pressure due to a decrease in steam generation energy requirement. The total aperture area decreased by 49.70% for PV1 and 49.60% for SYS 800. The electric costs as shown in Figure 10 decrease with increasing steam pressure due to the reduction in total aperture area and the number of PTC collector rows. The electric cost decreased by 43.25% for PV1 and 43.16% for SYS 800. The solar field area as shown in Figure 11 decreases with increasing steam pressure due to the decrease in the aperture area and the PTC collector rows. due to a decrease, Total aperture areas decreased by 50.30% for PV1 and 50.15%for SYS 800, respectively.

Table 3. Explained the assumed specifications for parabolic trough solar collector assemblies [27]

Symbols	Parameter	Value	Unit
L	Collector mirror length	12	m
w	Aperture width of the collector	5.77	m
$D_{r,i}$	Receiver inner diameter	0.066	m
$D_{r,o}$	Receiver outer diameter	0.07	m
$D_{c,i}$	Cover inner diameter	0.115	m
$D_{c,o}$	Cover outer diameter	0.121	m
ε_{cv}	Emittance of the cover	0.86	-
ε_r	Emittance of the receiver	0.15	-
ρ_c	Reflectance of the mirror	0.93	-
γ_i	Intercept factor	0.93	-
τ	Transmittance of the glass cover	0.94	-
α	Absorbance of the receiver	0.94	-
Kr	Incidence angle modifier	1	-
T_{in} ,T_{out}	Inlet and outlet temperatures	65, 400	^0C
V	volumetric flow rate	0.00091	m^3/s

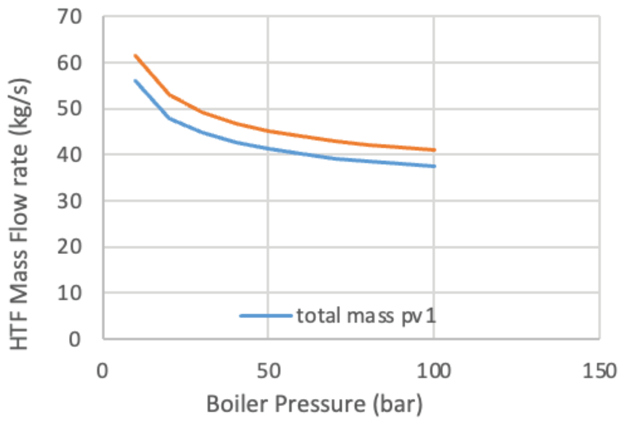

Figure 7. Variation of HTF mass flow rate with boiler pressure.

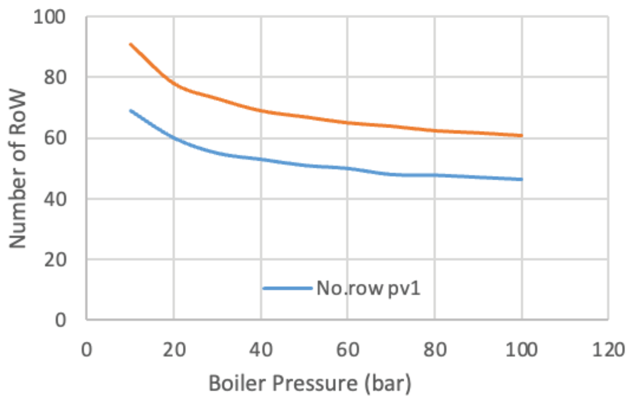

Figure 8. Variation number of rows with boiler pressure.

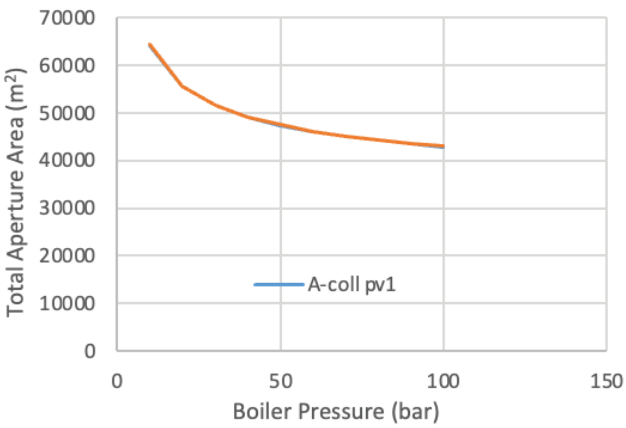

Figure 9. Variation total aperture area with boiler pressure.

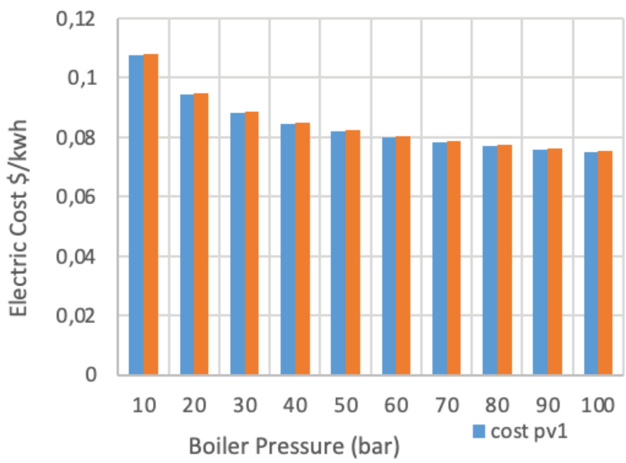

Figure 10. Variation electric cost with boiler pressure.

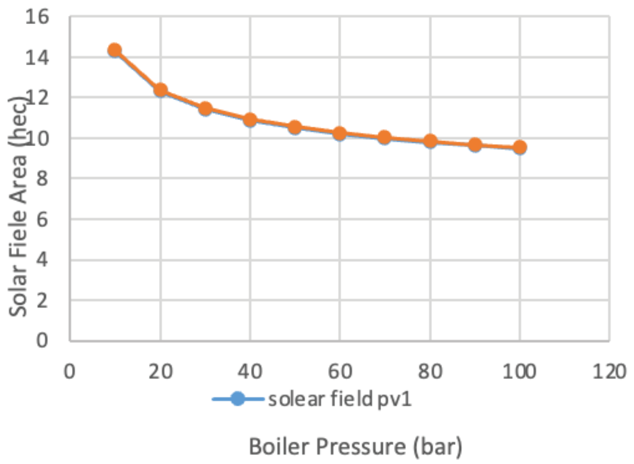

Figure 11. Variation solar field area with boiler pressure.

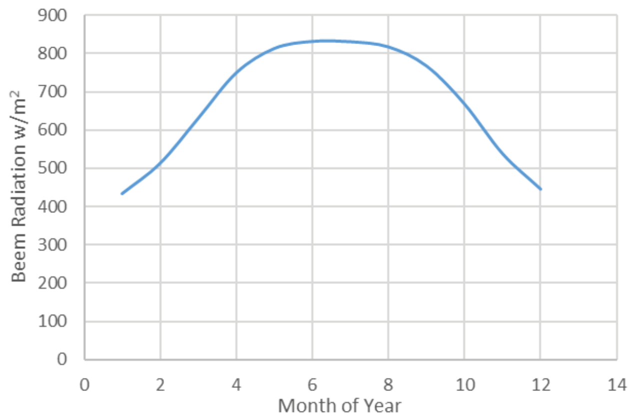

Figure 12. Variation beam radiation with months of year.

Effect of Solar Intensity on the Solar Collector Parameters

The variation of the beam radiation for each month is given in Figure 10 and the effect of solar intensity variation for each month on useful heat energy, thermal collector efficiency, collector length, heat exchanger area, and cost for solar power plants are given in the Figures 12-15. Table 4 illustrated beam radiation each month at 12 o'clock.

Basrah city is located in the south of Iraq, where there is a great abundance of solar radiation, which varies throughout the months of the year. The lowest radiation intensity during the year occurs on 1th day of January month which is 433.63 w/m2 and the highest radiation intensity of 832 W/m2 occurs the June month. This occurs because of the perpendicularity of the sun's rays on the Tropic of Cancer and Basra is located at a latitude of 7 degrees from the Tropic of Cancer, so it has the highest intensity of the rays in this month, as shown in Figure 12. Figure 13 show the effect of solar intensity on the useful heat energy at 12 o'clock on the first day of each month for both HTF PV1 and SYS800 HTF and with a 12-meter long collector, have different useful heat energy. the maximum and minimum heat gain occurs during the summer month of June and Jan respectively. Figure 14 shows the variation of collector thermal efficiency with the months of the year. the thermal efficiency variation has the same trend as solar intensity and the maximum thermal efficiency occurs during the hot summer months of June, July, and August. Figure 15, shows the collector length variation on the first day of each month of the year for PV1 and SYS800, the two types of fluid have different lengths to reach a temperature of 400°C. The difference in the length of the thermal collector is a result of the difference in heat capacity for two fluids.

Table 4. Maximum solar beam radiation for 1st day

Month	Solar Beam radiation w/m²
Jan	433.63
Feb	513.26
Mar	630.82
Apr	749.88
May	813.56
June	832.02
July	831.08
Aug	817.47
Sep	767.64
Oct	667.82
Nov	537.98
Dec	445.56

Effect of PTC Collector Rows on the Solar Plant Cost

This section described how the cost of electricity is affected by the distance between the rows, as well as the comparison of the cost between the solar plant and the steam plant as shown in Figure 16.

Figure 16 shows how the row spacing affects the cost of electricity. For the 10 bar plant, PV1 collectors measure 162 meters and SYS800 collectors measure 124 meters, so electric costs differ between the two types of fluid on the first

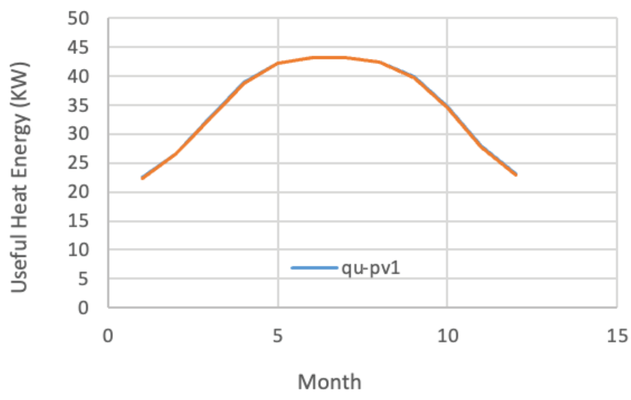

Figure 13. variation useful heat energy with month.

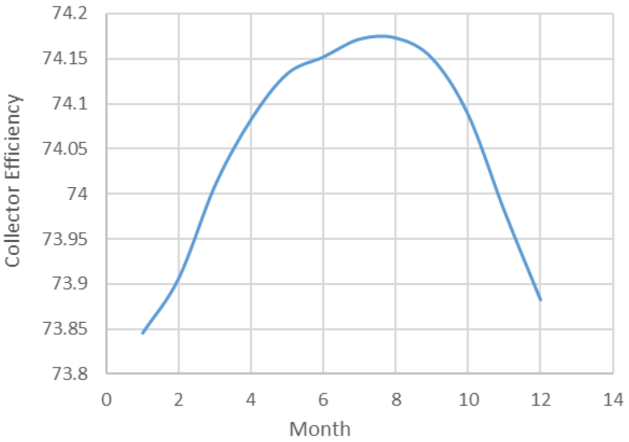

Figure 14. Variation thermal collector efficiency with month.

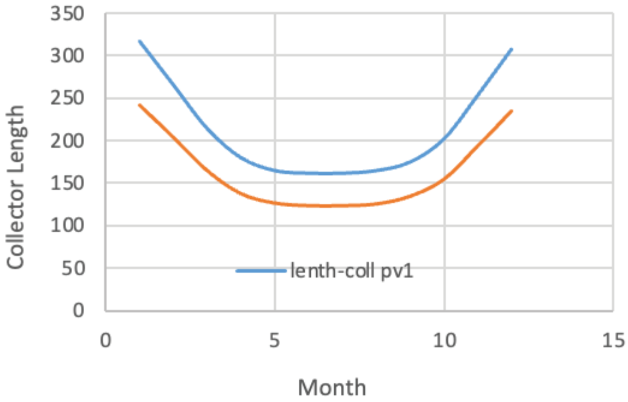

Figure 15. Variation collector length with month.

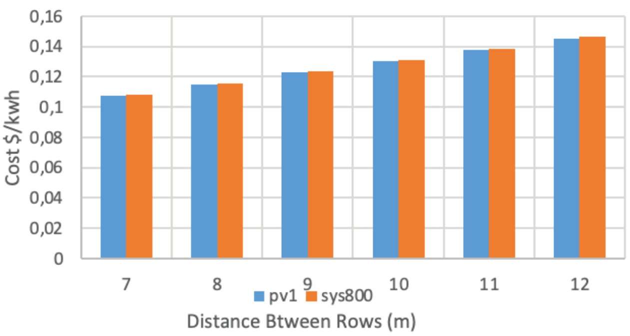

Figure 16. Variation of the cost with distance between rows.

day of June month. The cost increases with increasing distance between rows due to the need for a larger solar field area. The cost of PV1 and SYS 800 each increased by 25.98 and 25.99 percent, respectively.

Environmental Impacts

A major interest of the Society of Engineers has long been the impact of the environment on health. Fossil fuels can have serious environmental impacts, such as reducing forests and fisheries and reducing human health. The impact on the environment can be divided into two parts, fuel saving rate, and CO2 emission.

Fuel Saving Rate

Natural gas-steam power plants consume large amounts of fuel to generate electricity, which increases their cost. In the case of replacing a fuel-burning boiler with a solar collector, electricity generation costs have been significantly reduced. Table 5below shows the amounts of fuel consumed and the costs associated with natural gas plants.

CO_2 Emission

Gas emissions from human activities contribute to climate change by increasing atmospheric concentrations as a result of their emissions. These emissions mainly include carbon dioxide emissions from the combustion of fossil fuels, such as coal and mainly natural gas. To conserve the

Table 5. Environmental impacts

Steam Power Plant According to Boiler Pressure (bar)	Fuel Consumption (m^3/day)	Fuel Cost Consumption ($/day)	Steam Power Plant CO_2 Emission (Ton/h)	Solar Power Plant Fuel Consumption and CO_2 Emission
10	102656	18252	9.34	0
20	88781	15785	8.08	0
30	82306	14634	7.5	0
40	78450	13948	7.14	0
50	75705	13460	6.89	0
60	73642	13093	6.7	0
70	72002	12802	6.56	0
80	70662	12564	6.43	0
90	69536	12363	6.32	0
100	68577	12193	6.2	0

environment and human health, high-cost fossil fuels have been replaced by clean solar energy to generate electricity. Table 5 shows the amount of fuel and CO_2 gas emitted from natural gas and solar power plant.

CONCLUSION

1. Increasing the boiler pressure led to improving the power plant's performance and consequently decreasing the cost of electricity generated. The percentage increase in power plant thermal efficiency is 47.10% while the decrease in the cost of electricity generated is 3.55% and CO_2 emission decreased by 33.61%
2. The intensity of radiation plays a major role in the construction of the solar boiler power plant.
3. In order to replace the steam boiler with a pressure of 10 bar at an estimated cost of 0.0388 $/kWh, we would need 65587.407 m^2 of solar collectors, which would cost 0.1076 $/kWh without storage and 0.1181 $/kWh with storage.
4. To replace the steam boiler with a pressure of 80 bar and an estimated cost of 0.0374 $/kWh, we would require 45143.859 m^2 of solar collectors, which would cost 0.0785 $/kWh without storage and 0.0843 $/kWh with storage.
5. The distance between rows of solar collectors is very important for determining the cost of electricity, which has been set at a distance of 7 meters at minimum.
6. When PV1 is used to operate the plant, the cost is less than when Sys800 is used.
7. As a result of not using fossil fuels when the sun is present, the rate of CO_2 emissions into the atmosphere has been reduced.
8. Electricity generated by Steam plant has a lower cost than electricity generated by a solar plant by 55.95% when using SYS800.
9. Electricity generated by Steam plant has a lower cost than electricity generated by a solar plant by 55.43% when using PV1 for all plants.

SYMBOL

Symbol	Description	SI Unit
η	Efficiency	%
ρ	Density	Kg/m³
ε_r^*	Equivalent emittance	-
μ	Dynamic viscosity	Pa s
σ	Stefan–Boltzmann constant	$W/m^2 K^4$
θ_z	Zenith angle	degree
δ	declination angle.	degree
CSP	Concentrated solar power	
PTC	Parabolic trough collector	
LCOE	Levelized Cost of Energy	
HTF	Heat transfer Fluid	
am	Ambient	
c	Cover	
co	Outer cover	
opt	Optical	
r	Receiver	
ri	Inner receiver	
ro	Outer receiver	
th	Thermal	
u	Useful	

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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