Renewable hybrid energy systems using geothermal energy: hybrid solar thermal–geothermal power plant

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Abstract

New and innovative solutions are being developed to overcome the challenges of detrimental effects that the traditional energy systems cause. This means that sustainable methods are implemented to do so, noting that when such developments are taken into consideration and are studied, this leads to a significant drop in the cost of renewable energy systems. In this work, a hybrid system consisting of a single flash steam geothermal power plant and a solar thermal system using a parabolic trough collector (PTC) is studied. Based on the available works in literature, the required design materials and modeling equations are chosen and discussed. The heat transfer fluid (HTF) as water is chosen as the working fluid for the PTC due to its low cost and high specific heat capacity. The calculations are carried out for the PTC on a specific day, time and location, and the simulations for the geothermal power plant (GPP) are carried out using System Advisor Model (SAM) software, assuming a specific increase in the temperature of the geofluid due to the additional heat transfer from the HTF of the PTC. The power plant output is 20 MW powered by four production wells. The results show that the energy production is ~15 GWh in January, which is the highest during the year due to the required energy demand for electricity consumption and district heating. Moreover, a mini review of the mathematical modeling of PTC and single flash geothermal power plant is presented.

Keywords: renewable energy; geothermal single flash power plant; parabolic trough collector; economic analysis

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1. INTRODUCTION

Recently, there has been a global shift from complete dependence on conventional energy sources to dependence on both conventional and renewable energy sources, with further goals of renewable energy having a share of ~75% of power generation by the year 2040 as stated by IRENA [1]. Many countries are leading the way in renewable energy to overcome the challenges of sustainable approaches for energy production [2–4].

The reasons for such a transformation include climate change, greenhouse gas emissions and drastic increase in energy consumption and cost, which are all essential to be taken into consideration as they can have detrimental impacts [5,6]. However, as renewable energy sources such as the sun and wind are not continuous in providing energy, many researchers proposed the
hybridization of renewables, and on-site projects have already been tested and implemented [7–11].

Hence, in order to alleviate the carbon footprint from conventional plants and to preserve those resources due to their depletion, hybridization is one of many innovative solutions to take place in the energy industry where the energy output can be significant with minimum environmental, social and economic impacts [12–16].

Renewable sources come in various types, and those are as follows: (a) solar energy; (b) wind energy; (c) hydropower; (d) geothermal energy; and (e) biomass energy, each with its advantages and disadvantages. Geothermal energy (GE) is thermal energy stored within the ground. One of the advantages that make GE more reliable than solar and wind energy is that it is available all year regardless of weather conditions, whereas solar and wind energy sources are variable. Even though studies on GE are not to a great extent, they still have the potential to grow due to their competitive operational prices for electricity production, and costs are predicted to continue dropping through the year 2050 [17]. Furthermore, studies have shown that over 82 countries are directly making use of geothermal energy resources, and over 26 countries utilize geothermal resources for power generation, with the USA being one of the top 10 countries in generating electrical power of ∼3.45 GWe for the installed geothermal power plants [18]. Geothermal energy can be obtained in different ways as shown in Figure 1 [19].

The direct use of geothermal energy has significantly increased from utilization of 1.124×10^5 TJ/year in 1995 to 5.93×10^5 TJ/year in 2015, and from 8.7 GtW in 1995 to 71 GtW in 2015 [20]. Moreover, geothermal energy is used in a variety of applications including heat generation [21], electricity production [22] and hydrogen production [23,24] and even in powering thermal desalination units [25].

Different storage methods of geothermal energy are in both aquifers and boreholes, with either steam or heat as the two primary outcomes where geofluid is then extracted and used in either dry steam plants, flash steam plants or binary-cycle plants to produce electricity for the purpose of powering either residential or industrial areas [26].

Table 1 shows the operating electrical capacity and annual energy production of wind, solar and geothermal energy sources. The table shows that geothermal energy reached the highest annual energy production in 1998 compared to other renewable energy sources.

Moreover, geothermal energy was found to have a potential of greater energy production which is more than 100 PJ a year, which makes it one of the most attractive sources in sustainable development [28]. Its cumulative capacity for power generation is also expected to reach 25 GW in the year of 2030 [29].

Geothermal power plants normally refer to those used for electricity generation, where they are known for having a considerably smaller area requirement than the traditional plants and are sustainable because of the nature of the source and CO₂ emissions that reach up to 12 times less than that of conventional plants [29].

There are three types of geothermal power plants: dry steam, flash steam and binary geothermal power plants. The flash steam power plant can be single or double flash steam geothermal power plant, where in the former, there is only the single separator to separate vapor from liquid but in the double flash power plant, there are two separators namely a high-pressure separator and a low-pressure separator.

Although environmental concerns cannot be completely eliminated from geothermal energy power plants, they can still substantially minimize CO₂ emissions and are known to have significantly lower emissions compared to other technologies and can be considered negligible [30].

The sun’s direct radiation is a renewable source that can be utilized in several renewable energy technologies, either solar photovoltaics (PV) or solar thermal technologies in which different types of collectors are used [31–36]. Solar thermal collectors are mainly two types: (i) direct solar collectors and (ii) concentrating solar collectors (CSC). Solar PV systems are mainly used to generate direct electricity in which usually an inverter is required to convert the resulting direct current to alternating current to match electrical grid connection requirements, whereas solar thermal collectors collect and concentrate the sun’s thermal energy which is then stored in a fluid that is flowing in an absorber tube. This fluid is called heat transfer fluid (HTF). Solar thermal collectors can be stationary or they can have a tracking system. Flat plate collectors (FPC) and evacuated tube collectors (ETC) are stationary.

FPCs and ETCs are widely used for applications that require low temperature, and they have a concentration ratio (CR) equal to 1, but they have low outlet temperature of HTF and low efficiency compared to other collectors [37].

Table 2 shows summarized the operating temperature range and concentration ratio of different types of solar thermal collectors.

The most important component in all collectors is the absorber which can be linear, point or tubular type. The selection of the HTF inside the absorber depends on the absorber application. Oils such as Therminol VP-1 or Dowtherm A oils are the most widely used in PTCs. Despite the fact that such fluids have excellent properties, they still have economic and environmental
Table 1. Capacity and production comparison of RE sources.

| Operating capacity | Production per year | Reference |
|--------------------|---------------------|-----------|
| GWe                | TWh/year            | %         |
| Wind               | 10                  | 52.1      | 18        | 27.2 | [27] |
| Solar              | 0.9                 | 4.7       | 1.5       | 2.3  |     |
| Geothermal         | 8                   | 41.7      | 46        | 69.6 |     |

Table 2. Operating temperatures and CR of solar collectors.

| Collector                             | Operating temperature range (°C) | Concentration ratio |
|---------------------------------------|----------------------------------|---------------------|
| Flat plate collector (FPC)            | 30–80                            | 1                   |
| Evacuated tube collector (ETC)        | 50–200                           | 1                   |
| Linear Fresnel reflector (LFR)        | 60–250                           | 10–40               |
| Parabolic trough collector (PTC)      | 60–300                           | 15–45               |
| Parabolic dish reflector (PDR)        | 100–500                          | 100–1000            |
| Heliostat field collector (HPC)       | 150–2000                         | 100–1500            |

Impacts such as high cost, flammability and maximum working temperature limitation. Other than oils, saltwater, water, air or CO₂ can be used as the HTF [38].

Parabolic trough collectors (PTC) are widely used in solar thermal technology, which are made up of a steel structure to hold the collector, a parabolic shape reflector and an absorber tube where the HTF is flowing.

2. PTC THERMAL RESISTANCE NETWORK

The heat transfer modes and thermal resistance network of PTC are shown in Figure 2, which will serve as the key element in developing the thermal analysis of PTC.

The heat transfer modes are summarized as follows:

- Convection and radiation heat transfer between the ambient and outer glass cover
- Conduction heat transfer within the thickness of the glass cover and thickness of absorber tube
- Convection heat transfer between the inner absorber layer and the heat transfer fluid
- Radiation heat transfer between the inner glass cover and outer absorber tube

In addition to the thermal requirements need for analyzing the performance of PTC, optical requirements are also needed for the analysis. The schematic diagram of PTC is shown in Figure 3 where it shows the rim angle, focal length, aperture and acceptance angle.

When the sun rays fall on the reflector, they are reflected and concentrated on the tube to heat up the HTF flowing inside the tube to reach up a high temperature. The sun is a fluctuating source which results in a need for a thermal energy system (TES) to store the thermal energy of the HTF during the night or when the solar radiation is not sufficient.

3. STORAGE MATERIALS

Among the used TES systems is the latent heat energy storage which uses phase change materials (PCMs). The properties of different PCM are shown in Table 3. The advantages of using PCM as
Table 3. Properties of PCMs.

| Phase change material       | Melting temperature (°C) | Melting enthalpy (kJ/kg) | Density (kg/m³) | Dynamic viscosity (kg/m·s) |
|-----------------------------|--------------------------|--------------------------|-----------------|---------------------------|
| Paraffin                    | −5–120                   | 150–240                  | 770             | 1.90 × 10⁻³               |
| Erytritol                   | 118                      | 340                      | 802             | -                         |
| Na-acetate Trihydrate       | 58                       | 250                      | 1300            | -                         |

Figure 3. Optical analysis of PTC.

Figure 4. PTC-SINGLE FLASH GEOTHERMAL POWER PLANT

4. PTC-SINGLE FLASH GEOTHERMAL POWER PLANT

The increase in detrimental effects of climate change and emissions on the environment has recently caused to search for new technologies that result in low greenhouse gas emissions to secure a safe and sustainable environment. New and innovative solutions are being proposed and tested on-site by researchers, which include the combination of different energy sources for power generation and other purposes such as space cooling, district heating and freshwater production. Hybridization of renewable energy systems is currently one of the most innovative solutions, which is given special attention. Geothermal power plants can be integrated with other renewable energy systems such as solar PV/solar thermal, wind and biomass [21,22,23] where these studies showed that such hybridizations could significantly improve the turbine power output and the system thermal efficiency when they are used to increase the pressure of the geofluid from the geothermal well.

Solar energy is an intermittent source of energy due to its dependency on weather conditions, which means that solar energy is not available during nights, cloudy and dusty days. On the other hand, geothermal energy is a continuous source of energy which is independent of climate conditions; hence, the combination of solar energy with geothermal energy makes it an excellent alternative in having the desired energy output. Moreover, such combination will increase the lifetime of the geothermal wells. The integration of solar thermal system with the geothermal power plant will help in obtaining the required power output especially during the day. The PTC receiver will absorb the direct radiation of the sun to heat up the HTF flowing inside the absorber tube, which is then pumped to a thermal energy storage tank or directly to a solar heat exchanger to heat up the steam from the production wells that will be evaporated and used to run the steam turbine for electricity production. The residual steam is then condensed in an air-cooled condenser and pumped back to the injection well and the cycle is repeated. The schematic diagram of the proposed hybrid system is shown in Figure 4.

In this proposed work, the PTC was chosen to be integrated with the single flash geothermal power plant. To judge the feasibility and to study the performance of this system, some simulations with detailed mathematical modeling are presented. The required solar angles are computed, and the optical analysis of the PTC is done, which depends on several properties of the materials used. The glass cover of the receiver must have a high transmittivity, the absorber has high absorptivity and low thermal emissivity and the reflector has high reflectivity. Such properties help in capturing as much direct sun radiation as possible to be reflected on the receiver via the reflector. This results in enhancing the output from the PTC system as the exit temperature of the HTF increases. Moreover, water is chosen as the HTF for this application because it has high specific heat capacity and low cost compared to other heat transfer fluids. Following the optical analysis, the thermal analysis is carried out to estimate the useful energy and thermal efficiency of the PTC system. Finally, an analysis of the single flash geothermal power plant is presented. Table 4 shows the details of
Table 4. Details of chosen location of the system operation.

| Location                      | Abu Dhabi, United Arab Emirates |
|-------------------------------|---------------------------------|
| Latitude                      | 25.2° N                         |
| Longitude                     | 55.27° E                        |
| Average annual temperature    | 27.58                           |
| Average annual solar          | 2285                            |
| Average daily solar           | 6.3                             |
| Date and time of calculations | July 5, 2019, at 2 pm solar time |

Table 5. Materials and properties of PTC system.

| Material    | Absorptivity | Reflectivity | Transmittivity | Emissivity |
|-------------|--------------|--------------|----------------|------------|
| Reflector   | Highly polished pure aluminum sheet | - | 0.85 | - |
| Glass cover | Anti-reflective glass | - | - | 0.70 | 0.84 |
| Absorber    | Black Nickel selective surface | 0.96 | - | - | 0.07 |

Figure 4. Schematic diagram of hybrid solar/geothermal power plant.

5. MATHEMATICAL EQUATIONS

In this section, all the mathematical equations that are utilized for the computation of the solar angles as well as the PTC’s optical and thermal analyses [51, 52, 53] are given as follows:

- Solar declination

\[ \delta = 23.45 \sin \left( \frac{360 \times 284 + N}{365} \right) \] (1)

where \( N \) is the day number.

- Solar altitude

\[ \alpha = \cos^{-1} \left( \sin L \cdot \sin \delta + \cos L \cdot \cos \delta \cdot \cos h \right) \] (2)

where \( L \) is the latitude, \( \delta \) is the solar declination angle and \( h \) is the hour angle.

- Solar azimuth

\[ z = \sin^{-1} \left( \frac{\cos \delta \cdot \sin h}{\cos \alpha} \right) \] (3)

- Solar zenith

\[ \theta_z = \sin^{-1} \left( \sin L \cdot \sin \delta + \cos L \cdot \cos \delta \cdot \cos h \right) \] (4)

- Sunset hour angle

\[ h_{ss} = \cos^{-1} \left( -\tan(L) \tan(\delta) \right) \] (5)
Table 6. Effect of tracking modes on AOI.

| Tracking mode                       | Angle of incidence (AOI) |
|-------------------------------------|--------------------------|
| Full tracking                       | 0°                       |
| Polar N–S axis with E–W tracking    | 22.79°                   |
| Horizontal E–W axis with N–S tracking | 27.46°               |
| Horizontal N–S axis with E–W tracking | 27.61°               |

- Sunset hour

\[ H_{ss} = \frac{\cos^{-1} \left( -\tan(L) \tan(\delta) \right)}{15} \] (6)

- Sunrise hour

\[ H_{sr} = 12 - H_{ss} \] (7)

- Day length

\[ DL = \frac{2}{15} \cos^{-1} \left[ -\tan(L) \tan(\delta) \right] \] (8)

- Angle of incidence (AOI)

\[ \theta = \cos^{-1} \left( \sin(L) \sin(\delta) \cos(\beta) \right. \\
- \cos(L) \sin(\delta) \sin(\beta) + \cos(L) \cos(\delta) \cos(h) \cos(\beta) \right. \\
+ \sin(L) \cos(\delta) \cos(h) \sin(\beta) \left. \right) \] (9)

Adding to the above mathematical formulations, different types of tracking were tested to observe the effect of each on the AOI which is desired to be at or close to zero degrees. The obtained results are demonstrated in Table 6 as

- Full tracking

\[ \theta = 0° \] (10)

- Polar N–S axis with E–W tracking

\[ \theta = \left( \cos^{-1} \cos(\delta) \right) \] (11)

- Horizontal E–W axis with N–S tracking

\[ \theta = \cos^{-1} \sqrt{1 - \cos^2(\theta) \sin^2(h)} \] (12)

- Horizontal N–S axis with E–W tracking

\[ \theta = \cos^{-1} \sin^2(\delta) + \cos^2(\delta) \cos(h) \] (13)

- Optical efficiency

The optical efficiency of the PTC can be calculated from Equation (14) as

\[ \eta_{optical} = \rho \tau \alpha \gamma K(\theta) \] (14)

where \( \rho \) is the reflector reflectivity, \( \tau \) is glass cover transmittance, \( \alpha \) is absorber solar absorptivity, \( \gamma \) is the shape factor due to the inexact concentrator orientation (taken as 0.7) and \( K(\theta) \) is the AOI modifier (taken as 1).

- AOI modifier

\[ K(\theta) = \cos(\theta) + 0.000884(\theta) - 0.00005369(\theta)^2 \] (15)

Further, the rim angle of the PTC is assumed equal to 85°.

- Concentration ratio

\[ C = \frac{A_r}{A_a} \] (16)

where \( A_a \) is the aperture area, \((2-D_a)*L \) and \( A_r \) is the receiver area, \( \pi D_{ov}L \).

- Thermal loss coefficient

\[ U_L = \left[ \frac{A_r}{(h_w + h_{r,c-a})A_c} + \frac{1}{h_{r,r-c}} \right]^{-1} \] (17)

where \( A_c \) is the cover area, \( h_w \) is the convective heat transfer coefficient due to wind at 4 m/s, \( h_{r,c-a} \) is the radiative heat transfer coefficient between the outer glass cover and the ambient and \( h_{r,r-c} \) is the radiative heat transfer coefficient between the inner glass cover and the outer absorber surface.

- Radiative heat transfer coefficient between the outer glass cover and the ambient

\[ h_{r,c-a} = \sigma \epsilon_c \frac{(T_c^4 - T_{sky}^4)}{(T_c - T_{sky})} \] (18)

where \( \sigma \) is the Stefan Boltzmann constant \((5.67 \times 10^{-8} \text{ W/m}^2 \text{K}^4)\), \( \epsilon_c \) is the emissivity of the glass cover, \( T_c \) is the temperature of the glass cover, \( T_a \) is the ambient temperature and \( T_{sky} \) is the sky temperature.

- Radiative heat transfer coefficient between the inner glass cover and the outer absorber surface

\[ h_{r,r-c} = \frac{\sigma (T_r^4 + T_c^4)}{\frac{1}{\epsilon_r} + \frac{A_r}{A_c} \left( \frac{1}{\epsilon_c} - 1 \right)} \] (19)
where $T_r$ is the absorber temperature and $\epsilon_r$ is the absorber emissivity.

- **Overall heat transfer coefficient**

\[
U_o = \left[ \frac{1}{U_L} + \frac{D_o}{h_f D_i} + \frac{D_o \ln (D_o/D_i)}{2k} \right]^{-1}
\] (20)

where $h_f$ is the convective heat transfer coefficient of fluid, $D_o$ is the receiver outer diameter, $D_i$ is the receiver inner diameter and $k$ is the absorber wall thermal conductivity.

- **Convective heat transfer coefficient of fluid**

The Nusselt number for laminar flow is given as

\[ Nu = 4.364 \] (21)

For turbulent flow ($Re > 2300$) which is the case of this work, Nu is expressed as

\[ Nu = 0.023 \cdot (Re)^{0.8} \cdot (Pr)^{0.4} \] (22)

where the Prandtl number (Pr) is

\[ Pr = \frac{\mu C_p}{k} \] (23)

- **Reynolds number**

\[ Re = \frac{\rho V D_i}{\mu} \] (24)

The convective heat transfer coefficient is then obtained from Nu as

\[ h_f = Nu \cdot \frac{k}{D_i} \] (25)

- **Heat removal factor**

\[ F_R = \frac{\dot{m} C_p}{A_r U_L \left[ 1 - \exp \left( -\frac{U_L F \cdot A_r}{\dot{m} C_p} \right) \right]} \] (26)

where $\dot{m}$ is the mass flow rate of the fluid, $C_p$ is the specific heat of the fluid and $F$ is the efficiency factor.

- **Efficiency factor**

\[ F' = \frac{U_o}{U_L} \] (27)

- **Useful energy of PTC**

\[ Qu = F_R \left[ GB \cdot \eta_{optical} \cdot A_a - A_r \cdot U_L \cdot (T_i - T_a) \right] \] (28)

where GB is the solar irradiance and $T_i$ is the inlet temperature of the fluid.

- **PTC thermal efficiency**

\[ \eta_{thermal} = F_R \left[ \eta_{optical} - U_L \cdot \left( \frac{T_i - T_a}{GB \cdot C} \right) \right] \] (29)

where $C$ is the concentration ratio.

- **Outlet temperature of heat transfer fluid**

\[ T_{out} = T_i + \frac{Qu}{\dot{m} C_p} \] (30)

### 5.1. Single flash steam GPP

The thermodynamic analysis of the single flash geothermal power plant presented in Figure 4 is presented in this section. This can be done by writing the mass and energy balance equations for each component in the power plant. The separator in the power plant is operating at constant temperature and pressure, and the turbine is isentropic. The thermodynamic analysis is outlined as follows:

#### State 1: Saturated liquid

\[ h_1 = h_f (T_1 or P_1) \] (31)

where $h_1$ is the specific enthalpy of the geofluid in the production well, $h_f$ is specific enthalpy of the saturated liquid, $T_1$ is the temperature at state 1 and $P_1$ is the pressure at state 1.

#### State 2: Two phase

\[ h_2 = h_1 \] (32)

\[ h_2 = h_f (P_2) + x_2 h_{fg} (P_2) \] (33)

where $h_2$ is the specific enthalpy of the mixture at the outlet of the expansion valve, $h_{fg}$ is the phase change specific enthalpy and $P_2$ is the separator pressure.

#### State 3: Saturated liquid

\[ h_3 = h_f (P_3) \] (34)

where $h_3$ is the specific enthalpy of the saturated liquid at the outlet of the separator (bottom) and $P_3$ is the separator pressure.

#### State 4: Saturated vapor

\[ h_4 = h_g (P_4) \] (35)
where \( h_4 \) is the specific enthalpy of the saturated vapor at the outlet of the separator (top), \( h_8 \) is the saturated vapor specific enthalpy and \( P_4 \) is the separator pressure.

The specific entropy of the saturated vapor at the turbine inlet is obtained as

\[
s_4 = s_8 (P_4) \tag{36}
\]

where \( s_8 \) is the saturated vapor entropy.

**State 5: Superheated vapor which can be calculated from**

\[
\dot{Q}_{PTC} = \dot{m}_4 (h_5 - h_4) \tag{37}
\]

**State 6: Two phase**

The steam quality and specific enthalpy at state 5 can be obtained from Equations (39) to (40), respectively, as

\[
s_6 = s_5 \tag{38}
\]

\[
s_6 = s_f (P_6) + x_6 s_g (P_6) \tag{39}
\]

\[
h_6 = h_f (P_6) + x_6 h_g (P_6) \tag{40}
\]

where \( P_6 \) is the condenser pressure, \( s_g \) is the phase change-specific entropy.

**State 7: Saturated liquid**

\[
h_7 = h_f (P_7) \tag{41}
\]

where \( h_7 \) is the specific enthalpy of the saturated liquid and \( P_7 \) is the condenser pressure which is equal to \( P_6 \).

**State 8: Sub-cooled liquid**

The specific enthalpy of State 7 can be calculated from the isentropic efficiency and the power of pump. For isentropic pump, Equations (42) and (43) are obtained as

\[
s_{8s} = s_7 \tag{42}
\]

\[
h_{8s} - h_7 = v_7 (P_8 - P_7) \tag{43}
\]

where \( v \) is the specific volume.

The isentropic pump efficiency is defined as

\[
\eta_p = \frac{h_{8s} - h_7}{h_8 - h_7} \tag{44}
\]

and the pump power is expressed as

\[
\dot{W}_p = \dot{m}_7 (h_8 - h_7) \tag{45}
\]

- **Mass flow rates**

The mass flow rates at each state are obtained in the following equations as:

\[
\dot{m}_{production well} = \dot{m}_1 = \dot{m}_2 \tag{46}
\]

\[
\dot{m}_4 = x_2 \dot{m}_2 \tag{47}
\]

\[
\dot{m}_3 = \dot{m}_2 - \dot{m}_4 \tag{48}
\]

\[
\dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8 \tag{49}
\]

- **Turbine power output**

\[
\dot{W} = \dot{m}_5 (h_5 - h_6) \tag{50}
\]

- **Condenser heat rate**

\[
\dot{Q} = \dot{m}_6 (h_6 - h_7) \tag{51}
\]

6. **RESULTS AND DISCUSSION**

Table 7 shows the input parameters that are used for analyzing the PTC performance. The useful energy of PTC resulted in providing an outlet temperature of the heat transfer fluid of \( \sim 250^\circ C \) as shown in Table 8. This temperature is higher than that of the geofluid that enters the turbine; hence, it will enhance the turbine power output. The HTF with water in this case is used in a heat exchanger that exchanges heat with the saturated vapor leaving the separator toward the steam turbine to enhance its turbine performance. The results of the sample calculations of PTC are given in Table 8 where all the optical and thermal parameters are computed.

Figure 5 shows the solar radiation database for the city of Abu Dhabi in UAE, where the average wind speed is 3.6 m/s, the average temperature 27.1\(^\circ\)C and the direct normal (beam) is 6.29 kWh/m\(^2\)/day. The calculations for the single-flash GPP can be obtained through the equations. However, in this work, simulations were done using System Advisor Model (SAM), where the location for the weather conditions was chosen to be Abu Dhabi, United Arab Emirates, with the coordinates of the latitude and longitude specified earlier above, and a time zone of GMT+4. Moreover, there is a slight difference to the values of the ambient temperature and average wind speed used for the calculations of the PTC system. Furthermore, the resource characterization chosen shows that the resource has a depth of 2000 m and a total potential of 210 MW, as shown in Figure 6. In addition, the reservoir average temperature is 200\(^\circ\)C and the production well bottom hole pressure is 21.463 bar (2.1463 MPa), which is affected by the mass flow rate of the production well, which is taken as 170 kg/s per well, as shown in Figure 6.

Figure 7 shows that the plant output is \( \sim 20 \) MW when using four production wells for which the gross plant output is 41.6 MW.
The conversion plant type was chosen to be single flash having a plant efficiency of 8% as shown in Figure 6, which is a typical value of geothermal power plants. The results are obtained for the geofluid with temperature of 200°C and the production well flow rate equal of 170 kg/s per well. Additional plant configurations including the pump details are shown in Figure 7. The same simulations can be repeated assuming that the source temperature increases by 50°C as a result of the additional heat from the PTC system in the solar heat exchanger. When assuming that the resource temperature is increased from 200 to 250°C, the production well bottom hole pressure increased from 21.463 to 41.7902 bar, indicating that the pressure was increased by 94.71%. To obtain most of the results, the Geothermal Electricity Technology Evaluation Model (GETEM) approach and calculations were built-in in SAM with the equations from the user manual [57].

**7. CONCLUSIONS**

To achieve the aim of this work, the hybridization of a GPP with a PTC system was investigated. Literature study was carried...
out, and the required calculations were obtained to carry out the necessary calculations. The PTC system was studied over a certain day and hour of the day, showing a useful energy output of 4.6 kW. The single flash steam GPP was simulated using the System Advisor Model (SAM) software, and the obtained results were illustrated, showing that GETEM was used for the built-in calculations in the software. Plots were demonstrated to show the energy production for the first year of operation of the GPP and revenue during that year as well, showing that the highest energy production was during the first month of the first year of operation. The net power output of the power plant was \( \sim 20 \) MW when the number of wells was set to 4. It was concluded that due to the cold weather in January, the energy production was \( \sim 15 \) GWh, as the maximum value among the other months of the year. The increase in temperature due to the presence of PTC that results in an increase of \( \sim 50^\circ \text{C} \) in

Figure 5. Solar radiation Abu Dhabi.

Figure 6. Geothermal resource characterization and reservoir parameters.
the geofluid temperature is equivalent to \(~95\%\) increase in the production well pressure, which would result in enhancing the geothermal power plant output and hence improving the system efficiency.

**AVAILABILITY OF DATA AND MATERIALS**

All of the used materials and data are expressed and reported in the manuscript.
COMPETING INTERESTS

The authors declare no conflict of interest.

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AUTHOR’S CONTRIBUTIONS

All authors designed the workflow of this study and took part in the interpretation of results. Conceptualization: M. El-Haj Assad and A. Yasin; methodology: M. El Haj Assad, M.H. Ahmadi and M. Sadeghzadeh; software: A. Yasin; validation: A. Yasin, formal analysis: M. Sadeghzadeh and A. Issakhov; investigation: M. El-Haj Assad and M. Sadeghzadeh; resources: M. El Haj Assad, A. Yasin; writing—original draft preparation: M. El Haj Assad, A. Yasin and M. Sadeghzadeh; writing—review and editing: M.H. Ahmadi; supervision: M. El-Haj Assad and M.H. Ahmadi. All authors read and approved the final manuscript.

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