Hybrid power system for effective utilization of natural energy resources

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Abstract. An evaluation on the technoeconomic assessment of a hybrid solar-geothermal power plant is performed taking into account the geothermal and solar energy resources available at Tendaho -1 (Dubti) geothermal site in Ethiopia. A hybrid power plant in which a single-flash geothermal power plant integrated with a parabolic trough concentrated solar power system is used as a base for the technoeconomic analysis. The technoeconomic performance of the hybrid system was compared with a power generation system composed of stand-alone solar and geothermal power plants. Results showed that the that by combining the solar and geothermal energies, in hybrid power system it is possible to generate 10.4% more electricity than it would be generated by two-stand-alone power plants. Moreover, the economic figure of merit values is found to be 3.42 and 2.62 for the hybrid power plant with and without TES respectively. This mean that the specific cost of utilizing the solar energy in the hybrid power system is lower by 70.5% and 61.5% than the specific cost of utilizing the solar energy in stand-alone solar power plant.

1. Introduction
Access to electricity is one of the key factors in determining the economic development of a country. The lower the access to electricity is the lower the economic development and Ethiopia, as a developing nation is best example for this. In 2018 the per capita electricity consumption in Ethiopia was around 144 kWh and it was only 44.3% of the total households that was connected to the basic electricity supply. On the other hand, following the economic development of the country the electricity demand is growing exponentially and it is forecasted to reach to 111388 GWh by 2037. This growing demand in electricity requires the development of unutilized energy resources and improvement of the efficiency of the electricity generation.

Geothermal and solar energy resources are among the renewable energy resources that are almost neglected from being developed. The potential of geothermal energy resources located in the Ethiopian Rift valley is estimated to be 10000 GB and most of the areas located in this valley receive a direct normal irradiance (DNI) of more than 4 kWh/m2/day. However, the utilization of these resources is so far limited to a 7 MW pilot geothermal power plant, which is less than %1 of the mentioned available potential [1].

Since the beginning of the geothermal resource exploration in 1980, 120 geothermal sites were identified in the Ethiopian rift valley, among which 22 sites were identified as potential for high enthalpy application. The resources are characterized by high temperature with a range from 200°C to 335°C, shallow reservoirs from 500m to 2000m and lower content of non-condensable gases [1].
Therefore, the objective of this article is to highlight on the actual potential of the unutilized natural energy resources available in the Ethiopian rift valley and the option of effective utilization of these resources through the introduction of a hybrid power generation system.

2. Method
In order to assess the potential of an area for the realization of a concentrated solar power technology, it is necessary take into account series of factors which determine the suitability of the area for the type of the CSP technology intended to implement. Among these factors, minimum direct normal irradiance not less than 4 kWh/m^2/day [2] and slope of the land not greater than 0.02 are the major. Table 2 presents the geothermal sites located in the Ethiopian rift valley, the amount of the direct normal irradiance the geothermal sites receive, and the land slope of the respective areas.

| №  | Geothermal Sites                  | DNI (kWh/m^2/day) | Slope |
|----|----------------------------------|-------------------|-------|
| 1  | Tendaho – 1 (Dubti)              | 6.330             | < 0.02|
| 2  | Tendaho – 3 (Allalobeda)         | 5.240             | < 0.02|
| 3  | Boseti                           | 5.240             | < 0.02|
| 4  | Tendaho – 2 (Ayrobera)           | 5.224             | < 0.02|
| 5  | Meteka                           | 5.058             | > 0.02|
| 6  | Dofan                            | 4.897             | > 0.02|
| 7  | Nazareth                         | 4.675             | > 0.02|
| 8  | Alyto – 2 (Finkilo)              | 4.205             | > 0.02|
| 9  | Alyto – 1 (Langano)              | 4.205             | > 0.02|
| 10 | Alyto – 3 (Bobesa)               | 4.188             | > 0.02|

A schematic for hybrid solar-geothermal power plant is developed and patented [2, 3] (see figure 1). Thermodynamic and a figure of merit analyses [4] was performed to evaluate the energy efficiency of the hybrid power plant, taking into account the geothermal and solar energy resources available at Tendaho – 1 (Dubti). Optimization of the solar thermal system was performed using a computer program known as System Advisor Model (SAM).

Work output that would be generated by the parabolic trough solar power plant, \( N_{sl} \), kW, is defined as [5]:

\[
N_{sl} = Q_{sl} \cdot \eta_{sl}
\]

Where: \( Q_{sl} \) – thermal power delivered by the solar thermal unit, kW; \( \eta_{sl} \) – conversion efficiency of the solar power block.

Gross power generated by the hybrid solar-geothermal power plant, \( N_{hb} \), kW, is calculated as [4]:

\[
N_{hb} = D_{st} \cdot \left[ \left( i_{o} + \frac{Q_{sl}}{D_{st}} \right) - i_{i} \right] \cdot \eta_{e}
\]

Where: \( i_{o} \) – enthalpy of the steam leaving the separator, \( i_{o} = 2738 \) kJ/kg; \( D_{st} \) – steam flowrate, \( D_{st} = 10.93 \) kg/s; \( i_{i} \) – enthalpy of exhaust steam at the exit of the turbine, kJ/kg; \( \eta_{e} \) – electromechanical efficiency of the turbine-generator assembly, \( \eta_{e} = 0.98 \).
Figure 1. Schematic diagram of hybrid solar-geothermal power plant: 1 – production well; 2 – separator; 3 – turbine; 4 – condenser; 5 – steam superheater; 6 – thermal energy storage unit; 7 – solar collector-receiver assembly.

Figure of merit is one of the parameters used to compare if the hybrid power plant produces more power than the power produced by the power plants that constitute it. It is in another word the ratio of the power generated by the hybrid power plant to the sum of the power generated by the stand-alone geothermal and solar power plants. Mathematically it is expressed as [6]:

$$F_{fig} = \frac{N_{bb}}{N_{geo} + N_{sl}}$$  \hspace{1cm} (3)

Where:
- $N_{geo}$ – power generated by the stand-alone geothermal power plant, kW.

Two options of power generation technologies are compared in order to assess the economic effectiveness of the hybrid solar-geothermal power plant. In the first option geothermal and solar energy resources are integrated to form a hybrid power generation system. This hybrid power system is based on a single-flash geothermal power plant and a parabolic trough solar thermal power system. In this system, a geothermal steam at a temperature of 143°C [4] is superheated to the possible maximum enthalpy (in this specific case an enthalpy of 3264 kJ/kg is achieved by adding a solar thermal heat of 5750 kW to the superheater). The enthalpy level reached by the geothermal steam depends on the amount of heat delivered by the solar thermal power system. The superheated steam then expands in the turbine and produces work.

The second option considers the utilization of the geothermal and solar energy resources independently. Therefore, in this system of power generation, two independently working stand-alone single flash geothermal and parabolic trough solar power plants generate electricity.

Net present value (NPV), Levelized cost of electricity, payback period and economic figure of merit are the parameters used to evaluate the economic performance of the power generation systems. The net present value for a one-time capital investment is defined in a formula as [7]:

$$NPV = \sum_{n=1}^{T} \frac{CF_n}{(1+i)^n} - I$$  \hspace{1cm} (4)

Where:
- $CF_n$ - Cash flow in the nth period, USD; $i$ - discount rate, $i=10\%$; $n$ –period of time, year; $T$ – project life, $T=30$ years; $I$ – Initial investment cost, USD.

Economic figure of merit is a ratio of specific capital cost of stand-alone parabolic trough power plant to the specific cost of the solar thermal system in the hybrid power plant. This parameter is an indicator that shows the economic performance of utilization of the solar energy in hybrid power [6]. The economic figure of merit, $F_{eco}$, mathematically expressed as:
\[ F_{eco} = \frac{I_{sl} \left( N_{hb} - N_{geo} \right)}{I_{geo} \left( I_{hb} - I_{geo} \right)} \]  

(5)

Where: \( I_{sl}, I_{geo}, \) and \( I_{hb} \) are initial investment costs of the solar, geothermal, and hybrid power plants respectively.

Basic input data for the techno-economic analysis are presented in table 2.

| Parameters                                      | Values   |
|------------------------------------------------|----------|
| Direct Normal Irradiance at Tendaho – 1 (Dubti), kWh/m²/day | 6.33     |
| Total number of production-well                 | 4        |
| Solar collectors’ type                          | EuroTough ET150 |
| Thermal heat delivered per amount of steam coming from each production well, \( Q_{sl} \), kW | 5750     |
| Capacity of the solar thermal energy storage system in hours | 6        |

3. Results

The energy effectiveness analysis for the condition of Tendaho -1 (Dubti) for every 1 MW of solar thermal power added, the percentage increase in the turbine output of the geothermal power plant was 8%. As it is shown on the graph in figure 2, the technical figure of merit is greater than 1. This means that, the power generated by the hybrid power plant is greater than the sum of the powers generated by the two stand-alone solar and geothermal power plants. The value of this parameter increases as the amount of the thermal power added to the hybrid system increases.

The result of technoeconomic analysis is presented in table 2. The analysis showed that the net present value of the hybrid power plant is higher than the net present value of the power system that was composed of the two stand-alone power plants. As presented in the table, the payback period and generation cost of the hybrid power plant is comparatively lower than the stand-alone power generation systems.

![Figure 2. Turbine output and figure of merit value of a hybrid power plant with respect to the solar thermal heat added to the hybrid system.](image-url)
Table 3. Main results of the technoeconomic parameters of the power plants.

| Indicators                                    | Without TES | With TES |
|-----------------------------------------------|-------------|----------|
|                                               | Hybrid      | Geothermal + Solar | Hybrid     | Geothermal + Solar |
| Turbine output, MW                            | 30.23       | 29.14    | 30.23      | 29.14             |
| Electricity generation in 1st year of operation, GWh | 189.7       | 175.9    | 207.7      | 188.2             |
| Capital cost, million USD                     | 76.8        | 87.79    | 85.36      | 97.2              |
| NPV, million USD                              | 26.1        | 8.7      | 28.8       | 7.3               |
| Cost of generation, $/kWh                     | 0.0575      | 0.0694   | 0.0568     | 0.0707            |
| Economic Figure of Merit value, $F_{eco}$     | 3.42        | –        | 2.62       | –                 |
| Payback period in years                       | 7           | 8        | 8          | 9                 |

The value $F_{eco} > 1$ tells that the specific cost utilizing the solar energy in the hybrid power plant is lower than the specific cost of utilizing the same amount of solar energy in a stand-alone parabolic trough solar power plant. This means that for equivalent amount of turbine output, power generation by the hybrid power plant costs less than the power generation system two independent power plants.

Moreover, the technoeconomic indicators of hybrid power plants, one without a TES and the other with TES of 6 hrs. of capacity are also compared with each other. For the former case, the net present value by the end of the project year is found to be 26.1 million USD, that is lower than the NPV of the hybrid power plant with a TES which is 28.8 million USD. The cost of generation for the hybrid power plant without TES is found to be 0.0575 $/kWh which is a little higher than the cost of generation for its counter type which is 0.0568 $/kWh. However, as it is shown in the table above, the capital cost and payback period for hybrid power plant with TES is higher and this is obviously due to the introduction of the TES and the subsequent increase in cost of operation and maintenance.

The economic figure of merit, which is shown in table 2, has values of 3.42 and 2.62 for the hybrid power plant with and without TES respectively. This mean that the specific cost of utilizing the solar energy in the hybrid power system is lower by 70.5% and 61.5% than the specific cost of utilizing the solar energy in stand-alone solar power plant. On top of that the hybrid power plant with TES shows a higher redaction in cost.

In general, whether the TES is introduced or not, cost of generation of electricity in both of the hybrid power plant options reasonably lower than the two-stand-alone power plants.

4. Conclusion

✓ In the article it is shown that, in countries, endowed with enough amount of solar and geothermal energy resources, such as Ethiopia, it is possible to construct hybrid power plant that make use of the available renewable energy resources.

✓ It is also proved that combined use of solar and geothermal energies, in hybrid solar-geothermal power plant can significantly increase the power output of the hybrid power generation system. It is also found that by implementing the hybrid power generation system it is possible to generate 10.4% more electricity than it would be generated by two-stand-alone power plants.

✓ Results of technoeconomic evaluation show that the combined utilization of energy resources in a hybrid power generation system increases the energy efficiency and economic profitability of the power plant than separately and independently utilizing them.
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