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Analysis and Simulation of CSP and Hybridized Systems

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Hybridization of Concentrated Solar Thermal With Geothermal and Biomass Power

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Abstract. While Geothermal Power Plants (GPPs) can be a reliable renewable energy source, this reliability can decrease over the years due to brine mass flow declining. This reduced mass flow causes extra capacity unused in the GPP turbines. This problem can be overcome by hybridizing GPPs with CST and biomass. These three thermal technologies can, in theory, complement each other if all the resources are present at the exact location. This is the scenario for this study, as the location for the case study is the Kızıldere 2 (KZD2) GPP in Denizli, Turkiye, operated by Zorlu Energy. This region has sufficient potential for all three technologies: CST, geothermal, and biomass. Furthermore, by building a topping cycle using CST and biomass, it is possible to generate additional power. This study utilizes a topping steam Rankine cycle run equally by CST and biomass, and, as a result, the 20% excess capacity in the GPP turbine is used while generating an additional 20 MW_e of power.

Keywords: CST, Hybridization, Geothermal Power Plants, Biomass

Nomenclature

BC	Biomass Combustion
CST	Concentrated Solar Thermal
HEX	Heat Exchanger
P_{CST}	Power produced by CST only.
P_{Bio}	Power produced by biomass only.
P_{Top}	Power produced by the topping cycle, CST, and biomass combined.
P_{IPT}	Power produced by utilizing the excess IPT capacity.
P_{Tot}	Total additional power produced.

1. Introduction

Geothermal power plants (GPPs) operate continuously throughout the day, and if proper care is taken, they can offer baseload power during the year. This care includes the proper reinjection of the brine at well-monitored temperature, pressure, and mass flow rates [1]. If this care is not taken appropriately, and mostly even if the care is taken, the geothermal resource underground degrades over the years. This source depletion reveals itself in the form of a decreased enthalpy of the geothermal brine (i.e., decreases in temperature, pressure, and/or mass flow rates). This decrease in enthalpy also affects the power block since the steam enthalpy entering the turbines decreases, and hence, the power output declines. Thus, many older GPPs have excess turbine capacities. This paper demonstrates how to utilize the excess capacities in the GPP turbine by hybridizing it with other renewable technologies, namely Concentrated Solar Thermal (CST) and biomass.

The hybridization scenarios for combinations of CST, geothermal, and biomass have been previously studied in many papers. The hybridization of CST and geothermal was studied by Lentz et al. [2], where they showed two scenarios to add additional steam mass flow to an existing GPP in Mexico using Parabolic Trough Collectors (PTCs) as direct steam generation. The first scenario uses PTCs to heat the geothermal brine before entering the first separator, and the second uses PTCs to heat the residual heat from the first separator before entering the second separator. It was illustrated that increased steam mass flow is possible at the limit of salts dissolved in the liquid. Another CST-geothermal hybridization is analyzed by Bonyadi et al. [3], where a binary GPP using R134a is combined with a steam Rankine topping cycle using a PTC field. In this study, the declining performance of GPPs during hot summer times is boosted by power supplied by the topping cycle and the additional power from GPP due to topping cycle waste heat utilization. DiMarzio et al. [4] show the Stillwater power plant, which is a hybrid PV-CST-geothermal power plant, in operation in Nevada, USA. In this plant, CST is used to increase the enthalpy of the geothermal brine using a HEX before entering the GPP power block. This power plant shows that the GPP performance decline during noon time on a spring day associated with condenser performance decrease can be overcome by additional enthalpy provided by CST. Srinivas et al. [5] studied the hybridization of CST-biomass, in which CST and biomass produce steam simultaneously, and they get mixed before going to the turbine. This study shows constant power generation by varying the biomass combustion and utilizing CST when solar resources are present. Hussain et al. [6] studied CST-biomass hybrid systems with and without Thermal Energy Storage (TES) and showed how the levelized cost and biomass fuel consumption change with each case. Middelhoff et al. [7] consider a CST-biomass hybridization by using a solar tower and rice straw as local biomass resource and producing steam concurrently. The analyses show the reduction in cost compared to standalone systems while also studying the public impact. The hybridization of geothermal-biomass is studied by Briola et al. [8] in extreme weather conditions where water is scarce and air-cooled condensers are utilized. They studied adjusting biomass combustion rates to overcome the performance decline of GPPs with high ambient temperatures and during operation over the years. Chen et al. [9] investigated a hybrid geothermal-biomass scenario to both generate power and supply district heating as a cogeneration plant. They showed the thermodynamic and economic advantages of such hybridization. Porto et al. [10] explain how an actual GPP is hybridized with biomass to bring an under-performing GPP to nominal power. This study gives the whole process of how this hybridization is planned and executed. While all these papers mentioned here contributed significantly to the literature, this study presented hereafter aims to examine a novel triple-hybrid plant of CST-geothermal-biomass with another novel topping cycle to boost the performance of a GPP and make it flexible and dispatchable.

Hybridizing renewable energy systems, for instance, geothermal and solar, can offer some advantages and help cover the deficiency of each technology [11]. Although initially, the capital cost of the hybrid systems seems to be higher, by sharing equipment, personnel, etc., the investment and operation and maintenance costs can get lower than standalone systems. Another deficiency of GPPs is the decrease in performance occurring during summer due to elevated ambient and, therefore, condenser temperatures. This is an especially acute problem for systems with Dry Cooling Towers (DCTs) located in areas with large variations in seasonal temperature, but it also impacts Wet Cooling Towers (WCTs). This deficiency can be covered by solar technologies since the Direct Normal Irradiance (DNI), and therefore, the performance of solar technologies is typically higher during the summer. CST without thermal energy storage (TES), utilizing the sun to generate variable thermal energy, can then be used to boost the thermal performance of the GPPs. Biomass, on the other hand, depending on the availability of the biomass resource, can produce electricity on demand. This feature may be utilized to boost electricity generation at high-demand times during the day. However, many biomass sources are only available in some seasons throughout the year. Thus, hybridizing geothermal with CST and biomass can offer daily and seasonal flexibilities by the variations in solar and biomass variations and can increase dispatchability by adjusting the biomass combustion rate. Moreover, it can improve the GPP performance by providing additional thermal energy (with increased mass flow). It can potentially generate a more economical hybrid renewable system compared to three standalone systems in the long run.

One problem with hybrid technologies is the need for sufficient and co-located resources for each technology [11]. For this study, though, this does not pose a significant issue. This case study is based on the triple flash and binary Kızıldere-2 (KZD2) GPP in Denizli, Turkiye, operated by Zorlu Energy. KZD2 generates 80 MW_e in total, 60 MW_e of which is steam power in the flash part, generated in three stages of turbines: High, Intermediate, and Low-Pressure Turbines (HPT, IPT, LPT) [12]. Denizli is located in the southwestern, or Aegean, part of Turkiye. The Kızıldere field is the largest in Turkiye in terms of power production [12]. It also receives a good amount of solar energy, having around 1800 kWh/m^2 annual DNI value [13], the threshold value for Turkiye to build CST plants [14]. Also, the local biomass source, olive residue, offers high calorific values and is mainly found during the winter season [15], and thus its availability complements seasonal DNI resources.

2. Methodology

This paper aims to utilize the excess capacities in the GPP turbines, offering more flexibility and making the system more dispatchable. To use the excess capacity in the GPP turbines, it is planned to provide the turbines with an additional steam mass flow rate at the vacant amount. For this, which turbine to use in the hybridization must be selected among the HPT, IPT, and LPT. The HPT exit fluid feeds the binary part of KZD2 rather than the IPT, which poses complexity to the hybridization. Also, the HPT has a much higher non-condensable gas percentage than IPT, 16.7%, compared to 0.40% by weight [12], degrading the turbine's energetic performance. Hence, the IPT feed, whose outlet feeds the LPT, was chosen for hybridization work.

The hybridization is done by adding a topping cycle to the existing GPP. This topping cycle is to both generate power on its own and provide additional steam flow to the IPT of the GPP, utilizing the excess capacity. The topping cycle is a steam Rankine CST-biomass hybrid cycle using Parabolic Trough Collectors (PTCs) and olive residue combustion. The simplified diagram of the triple-hybrid plant is given in Figure 1. At the top of the figure is the PTC field, converting the incident radiation into thermal energy by heating the Heat Transfer Fluid (HTF), a thermal oil. This heated HTF converts the condensed water into steam in three stages of heat exchangers, preheater, evaporator, and superheater. Concurrently, by biomass combustion, another steam mass flow is generated at the same conditions as the steam generated by the PTC field. These two steam flows, then, are mixed and expanded through a steam turbine, generating power. The condenser of the topping cycle couples the topping cycle to the GPP, and the extra thermal energy is used to utilize the excess IPT capacity of the GPP. This condenser uses the condensed water from the WCT of the GPP as the feedwater and also serves as the preheater of the bottoming steam cycle. This preheated water, afterward, is superheated to the inlet conditions of the IPT of GPP by utilizing the heat from biomass. The crucial part is determining the amount of excess capacity in the turbine. From the literature and the previous study on the same field, the extra capacity is assumed to be around 20% [12, 15]. Finally, the condensed water for the topping cycle is pumped and diverted into two flows for CST and biomass.

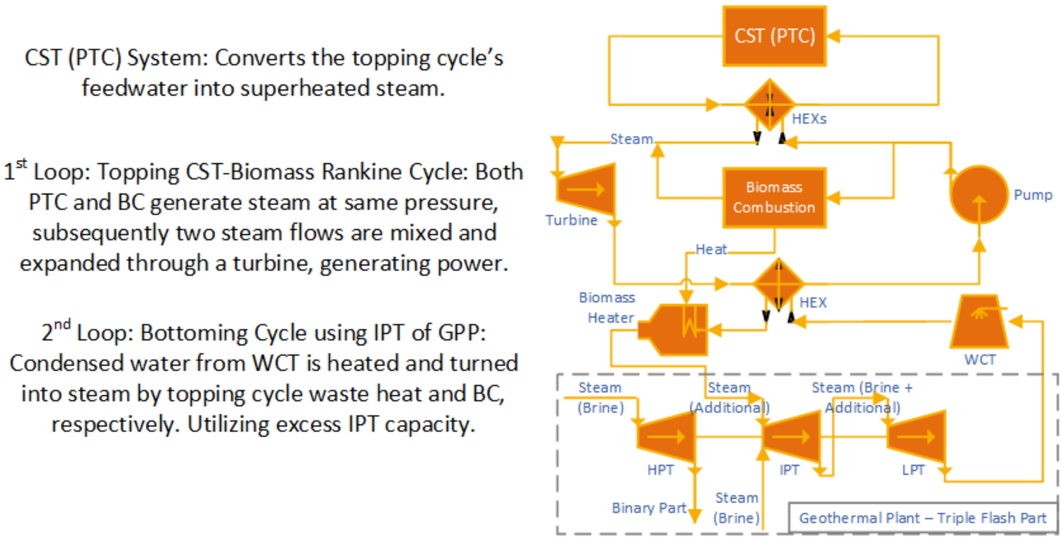

Figure 1. *Simplified diagram of the hybrid plant*

2.1 Available Land

The land initially proposed for hybridization was presented in another study [16]. The land area available shown in Figure 2 is approximately 20 km^2; on it, a PTC field of 6 rows with 24 collectors can be placed. Using this field to heat the HTF from 293 °C to 393 °C, only 22 kg/s of flow is possible. However, for the design purposes of this study, a larger mass flow, hence a larger PTC field, is required. To achieve this, a larger area is sought near the GPP for theoretical modeling.

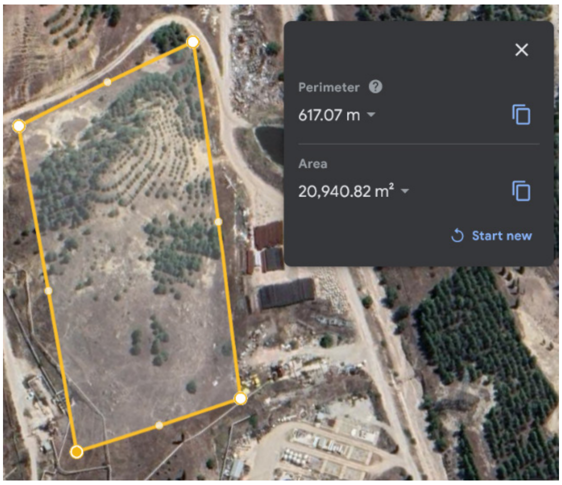

Figure 2. *The available proposed land for the CST field at the KZD2 site on Google Earth*

2.2 Designed Hybrid Plant

The design point of this hybrid plant is based on filling the 20% excess capacity in the IPT and LPT and generating additional power at a desired level. That level is set as 20 MW$_e$, shared equally between CST and biomass at design conditions. To achieve the 10 MW$_e$ power generation by CST, it is required to build a PTC field that can heat 193.3 kg/s HTF from 293 °C to

393 °C at design conditions. Hence, a PTC field with an H-type configuration comprising 4 symmetric fields, each with 7 rows of collectors with 7 solar collector assemblies (SCAs) for each row, is designed. To have a constant temperature HTF outlet of around 393 °C, the HTF mass flow varies depending on the available solar irradiance. Moreover, to superheat the topping cycle water to the same conditions throughout the day, the water mass flow rate is varied in accordance with the HTF mass flow rate. Due to this feature, steam at constant conditions is obtained, and problems that would arise when mixing with the biomass steam at different conditions are prevented, such as pressure and/or temperature loss. During the night, the CST field does not operate, and only biomass is used at a constant rate. The specifications of the hybrid plant are given in Table 1.

Table 1. *Component Specifications of the Hybrid Plant*

Component	**Description**	**Power Produced [MWe]**
CST – PTC Field	28 rows, 7 collectors each. N-S axis orientation and E-W single-axis tracking.	10
HTF	Therminol VP-1 [17]	-
Collectors	Luz Solar 2 Collector [18]	-
SCA Length	47 m (6 x 7.83 m) [18]	-
SCA Aperture Width	5 m [17]	-
Row Spacing	15 m	-
Temperature Range	293 – 393 °C	-
Mass Flow Rate	193.3 kg/s	-
Biomass	Olive residue	10
Topping Cycle	Both Biomass & CST	20
GPP	Utilizing excess IPT capacity using topping cycle waste heat and biomass heat.	20% increase

3. Results

3.1 PTC Field Results

The simulations are carried out using TRNSYS v18.05.0001 with TESS Libraries v17.2.01. The specifications of the PTC field are given in Section 2.2 and Table 1. The simulations are carried out for a week in August and are displayed in Figure 3. As can be seen in the figure, the main goal of the PTC field, which is to obtain an almost constant HTF outlet temperature of 393-400 °C, is obtained. This is obtained by varying the mass flow rate of the HTF from the design point of 193.3 kg/s. Furthermore, in decent solar conditions, such as August 3 and 6, the same temperature can be obtained close to the design point mass flow rate. Hence, by examining Figure 3, the sizing of the field seems appropriate for this hybrid plant analysis for good summer days.

3.2 Hybrid Plant Results

The hybrid plant results are given in Figure 4 as additional power produced by each component. These powers produced are in addition to the baseload power produced by the GPP, which is 80 MW_e at the design point. Starting from the bottom and making the way to the top, the contributions to power can be analyzed individually. At the bottom with the brown line is the excess capacity utilization of IPT of GPP. It can be seen that the spare capacity of 20% is utilized in complete form during the day when both CST and biomass are running together. However, during the night, the excess capacity of IPT is not used. On top of it, the power coming from CST is shown with the yellow line, and it reaches the design value of 10 MW_e on adequate weather conditions, such as August 2, 3, 5, and 6.

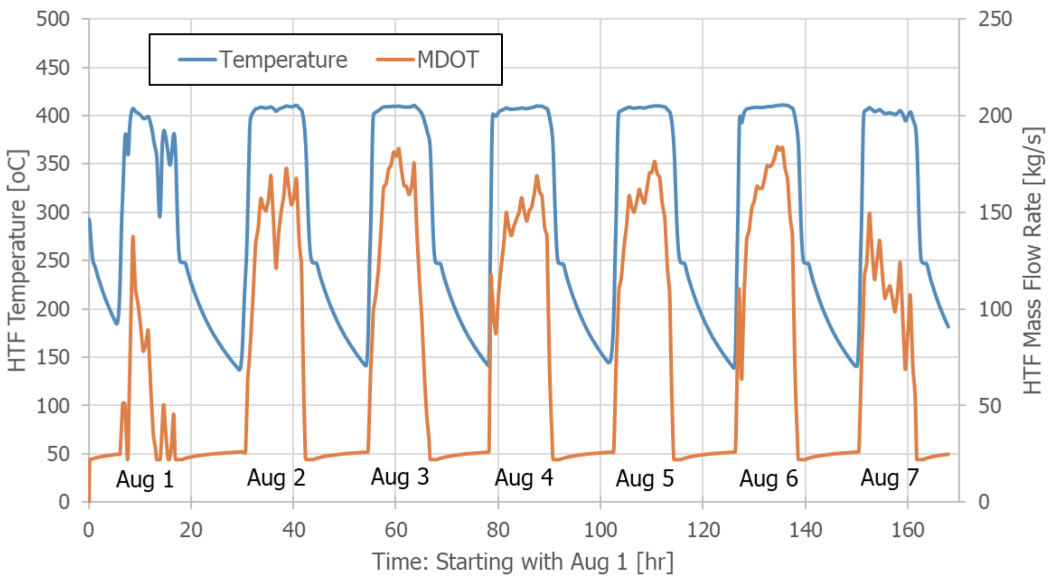

Figure 3. *CST field output parameters, temperature, and flow rate vs. time for a week in August*

On worse days, that value is not reached, yet CST can still generate power around 5-7 MW_e, contributing to the topping cycle power output. Since there is no thermal energy storage, the CST power contribution is not present at night. The biomass power contribution is shown with the green line. For this part of the study, it is held constant at 10 MW_e, both during the day and night. It provides power when the CST system is not running, serving as a storage medium. The blue line shows the power produced by the topping cycle, which is the summation of only CST and biomass contributions. Moreover, its value is around the design level of 20 MW_e, depending on the solar resources available. Finally, the orange line shows the total additional power generated by this triple-hybrid system, which is the summation of the topping cycle (biomass + CST) and the excess capacity utilized in IPT. With decent solar energy, the total additional power can reach 23 MW_e during the day and 10 MW_e during the night with fluctuations.

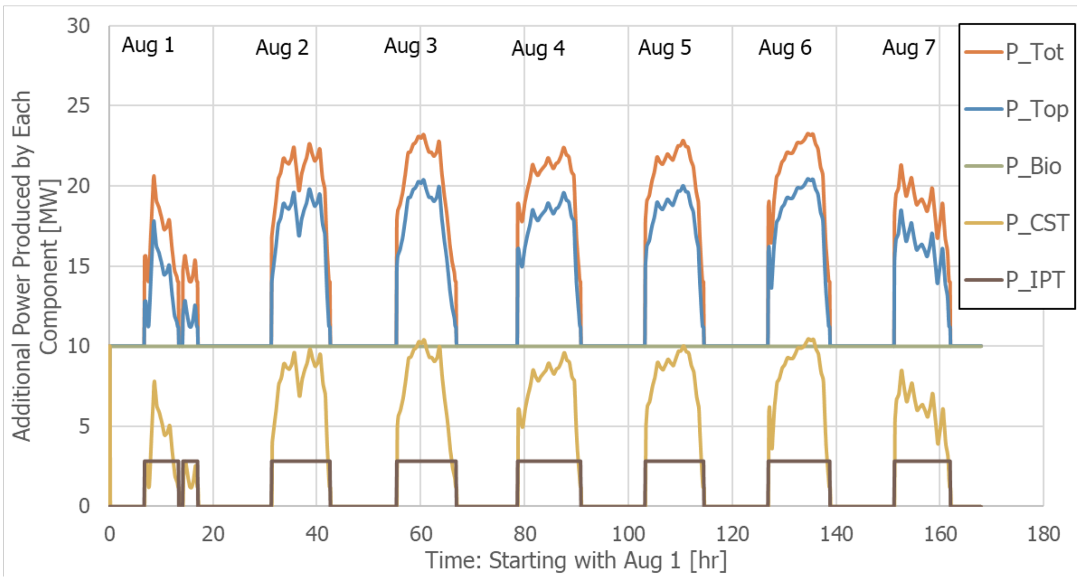

Figure 4. *Power produced by each component and in total vs. time for a week in August*

4. Conclusions and Outlook

A novel triple hybrid CST-geothermal-biomass power plant is modeled and analyzed using the TRNSYS software. The case study is based on the KZD2 GPP in Denizli, Turkiye. It was illustrated that it is possible to cover the problem of source depletion in GPPs by hybridizing CST and biomass into geothermal. Moreover, it is also possible to generate additional flexible power by using a topping CST-biomass cycle. The extra 20% turbine capacity for IPT of GPP was utilized, and a further 20 MW_e was generated, totaling a power generation of around 23 MW_e at the highest level. For future work, biomass power generation can be made variable to make the system more dispatchable, and a comprehensive techno-economic analysis can be carried out to determine the feasibility of the system.

Data availability statement

The data used in this paper can be accessed with DOI: https://doi.org/10.5281/zenodo.10033168.

Author contributions

Bertuğ Çelebi: Conceptualization, Formal Analysis, Methodology, Software, Visualization, Writing – original draft

Shahab Rohani: Funding acquisition, Methodology, Project administration, Writing – review & editing

Derek Baker: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing

Ural Halaçoğlu: Resources, Writing - review & editing

Burcu Ayşe Tanrıverdi: Resources, Writing - review & editing

Competing interests

The authors declare that they have no competing interests.

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