Design of a Geothermal Power Plant With Solar Thermal Topping Cycle

Preprint

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Keywords

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ABSTRACT

Geothermal power plants are a reliable source of low-carbon power generation. However, modern electricity markets comprise relatively large proportions of variable renewable energy generation that may require power plants to flexibly dispatch energy. The power output, efficiency, and dispatch flexibility of a geothermal plant can be enhanced by integrating solar thermal energy into the system, as well as possibly compensating against ambient temperature variations. Concentrating solar thermal (CST) can generate temperatures much higher than conventional geothermal systems. Using a solar topping cycle is one way to efficiently convert high-temperature solar heat to electricity while also cascading lower-temperature heat to the geothermal power cycle, thereby increasing its power output and possibly its efficiency.

A hybrid power cycle design is proposed and simulated using SimTech IPSEpro process modeling software. The design configuration depends on the expected temperature of the geothermal resource and the quantity of solar heat added at the design point. These design considerations are described and expected performance is calculated. The solar heat addition varies throughout the day and year; therefore, off-design models are necessary to assess the impact of solar availability (and ambient temperature) on the power plant performance. Off-design models are developed and combined with hourly weather data to facilitate an evaluation of annual system performance.

1. Introduction

Low-temperature geothermal resources are an underutilized source of low-carbon energy but low conversion efficiencies often result in high generation costs that cannot compete with wind and solar photovoltaics. However, in the absence of grid-scale energy storage, the variable nature of wind and solar typically necessitates flexible power generation from fossil-fuel power plants. Therefore, a hybrid plant that integrates geothermal with concentrating solar thermal (CST) technologies could provide both baseload capacity and peaking power plant capabilities.

Where previous studies have considered retrofitting geothermal plants with CST, in this article, a new build hybrid plant is investigated. A greenfield geothermal-CST system has several potential advantages which may reduce the LCOE and increase the revenue compared to a geothermal-only greenfield installation. First, using CST in combination with thermal energy storage (TES) enables the plant to dispatch power at the most profitable times. Second, high ambient temperatures reduce the power output of geothermal plants (particularly air-cooled systems); increasing the ambient temperature by 10°C was found to result in about a 20% reduction in power output (Manente et al. 2013; Keshvarparast, Ajarostaghi, and Delavar 2020). Using the solar energy available at these times (or via TES) provides supplemental heat and power that can compensate for this loss. Third, additional CST can be installed over the lifetime of the system to compensate for any reductions in geothermal temperature or mass flow rate. Finally, in the United States, geothermal plants have traditionally been deployed in locations such as California and Nevada, where high resource temperatures exist. Hybridizing with solar thermal reveals the possibility of deploying geothermal systems in less traditional areas and therefore increasing the market for geothermal technologies.

One of the first studies in this area investigated using solar thermal to add supplemental heat to the geothermal brine (Lentz and Almanza 2006). Adding supplemental heat to the geothermal brine was also considered by Bassetti et al. (2018), Hu et al. (2021), and Tranamil-Maripe et al. (2022). Others, such as Astolfi et al. (2011) and Zhou (2014), have considered adding solar thermal heat directly to the organic Rankine cycle (ORC) working fluid.

To improve efficiency and make better use of the high temperatures that CST can deliver, more recent research has considered using a solar thermal topping cycle with a geothermal bottoming cycle (Bonyadi, Johnson, and Baker 2018; Boukelia, Arslan, and Bouraoui 2021; Song et al. 2021). Based on a report (McTigue, Kincaid, Zhu, et al. 2018), using a topping cycle to add heat to the bottoming cycle working fluid was found to have the highest efficiency out of the options that were considered. This concept is further examined in more detail in Song et al. (2021) and McTigue et al. (2020).

Most published studies have focused on adding solar thermal or geothermal to an existing power plant. For example, solar thermal can be used to boost power production at an underperforming geothermal plant (Lentz and Almanza 2006; McTigue, Castro, Mungas, et al. 2018). Few have studied greenfield installations (Hu et al. 2021) and, to the authors' knowledge, none have studied greenfield installations with a solar topping and geothermal bottoming cycle. The optimal design for a greenfield system may be different than that of a retrofitted hybrid plant.

One benefit of considering a greenfield hybrid geothermal-solar plant is the opportunity to consider geothermal resources that might not have been viable with a binary geothermal plant alone. A review of the hybrid systems literature found a range of temperatures considered for the geothermal brine—from 90°C to 265°C— but the majority were around 150°C. This project considers lower geothermal brine temperatures to allow for a wider range of potential sites.

The objective of this article is to introduce greenfield geothermal-CST hybrid power plants and to consider some of the major design decisions. One possible configuration of such a plant is described and a technical model is developed. Ambient temperature and solar heat addition vary considerably over the course of a year and have a significant impact on plant performance. Therefore, off-design models are also developed. Finally, a simple dispatch scheme is devised which enables the hourly and annual performance of the hybrid plant to be evaluated. Future work will evaluate the cost and value of such plants and examine a range of solar and geothermal resources in more detail.

2. System Design and Methods

The hybrid geothermal-solar system comprises a topping steam turbine driven by solar power and a bottoming ORC driven by heat from the steam turbine exit and geothermal, as illustrated in Figure 1. At the design point, solar heat is used to preheat and vaporize steam which powers a back-pressure steam turbine: the outlet pressure and temperature of the turbine are relatively high compared to condensing steam turbines. This heat is then added to the bottoming cycle, which is a single pressure level recuperated ORC. The working fluid in this case is isopentane, although other fluids are being considered. After being preheated by the geothermal fluid, the isopentane stream is split; one portion is vaporized by the produced geothermal fluid and the other portion is vaporized by the steam turbine exit flow. This arrangement effectively eases pinch-point constraints and enables the isopentane to be vaporized at higher temperatures and pressures than a geothermal-only system could manage. As a result, the ORC efficiency is improved slightly when heat from the back-pressure turbine is available.

The CST system uses parabolic trough collectors (PTC) to concentrate sunlight onto a linear receiver in which a fluid is heated. The PTCs are modeled using the System Advisor Model (SAM) (National Renewable Energy Laboratory (NREL) 2022). In SAM, the geometry and optical properties of the PTC are defined. SAM is used to calculate the solar heat generated by the PTC for each hour of the year for a specific location, in this case—Elk Hills, California. This location is close to Bakersfield, California, which is a region of high solar resource (annual average DNI = 7 kWh/m^2/day) which makes it suitable for CST applications.

In this conceptual design, the PTCs heat a nitrate molten salt to 560°C: this temperature is higher than those in commercial PTCs and is chosen to increase the steam turbine efficiency and allow the molten salt to be used for TES to store excess solar energy. As such, the solar field is oversized relative to the design power output. A solar field that generates the design thermal input to the power cycle on a day with nominal irradiance (1000 W/m^2) at normal incidence angles (maximum optical efficiency) has a solar multiple of one. Increasing the solar field area relative to this size increases the proportion of the year in which the solar field can produce the design power. Thus, a system with a solar multiple of two will have double the area, and at the design solar irradiance, it will generate double the thermal energy. The excess energy is stored and later dispatched when solar irradiance decreases below the design levels. This enables the CST subsystem to deliver the design thermal input for a greater proportion of the year.

When the thermal storage is fully discharged and the solar irradiance is less than the design value, the heat delivered to the steam turbine is reduced. As a result, the steam turbine power output decreases as does the heat delivered to the bottoming cycle. To manage this, the isopentane mass flow rate is reduced so that the geothermal energy does a larger proportion of the vaporization than the steam turbine exit. If no solar heat is available, the geothermal energy provides all the energy for vaporization and the isopentane mass flow rate (and resulting ORC power output) is reduced to enable the energy balance. (The isopentane pressure is also reduced slightly so that the volumetric flow through the ORC turbine remains relatively constant and does not significantly compromise the turbine efficiency.)

The design in Figure 1 uses an air-cooled condenser (ACC) in the bottoming cycle. This condenser is the only heat rejection unit in the system, so it is sized to reject all heat from both the topping and bottoming cycle. Thus, it is oversized for scenarios where solar energy is below the design point and should therefore provide efficient heat rejection in those cases. Although the ACC means that the cycle is more sensitive to ambient temperature variations than a water-cooled system, it does enable the design to operate in a wider variety of locations, which is particularly for regions with more limited water availability.

The above discussion illustrates that the hybrid plant power output is sensitive to highly variable parameters such as solar energy and ambient temperature. The system is therefore modelled using SimTech IPSEpro (SimTech 2022), which is a powerful flow-sheet software that enables off-design performance of power plants to be evaluated. The software requires the off-design behavior of each component (compressors, turbines, heat exchangers, etc.) to be specified via either tables or correlations. The full power plant performance is then calculated for a range of ambient temperatures and solar heat inputs to enable the plant output to be interpolated for any combination of values.

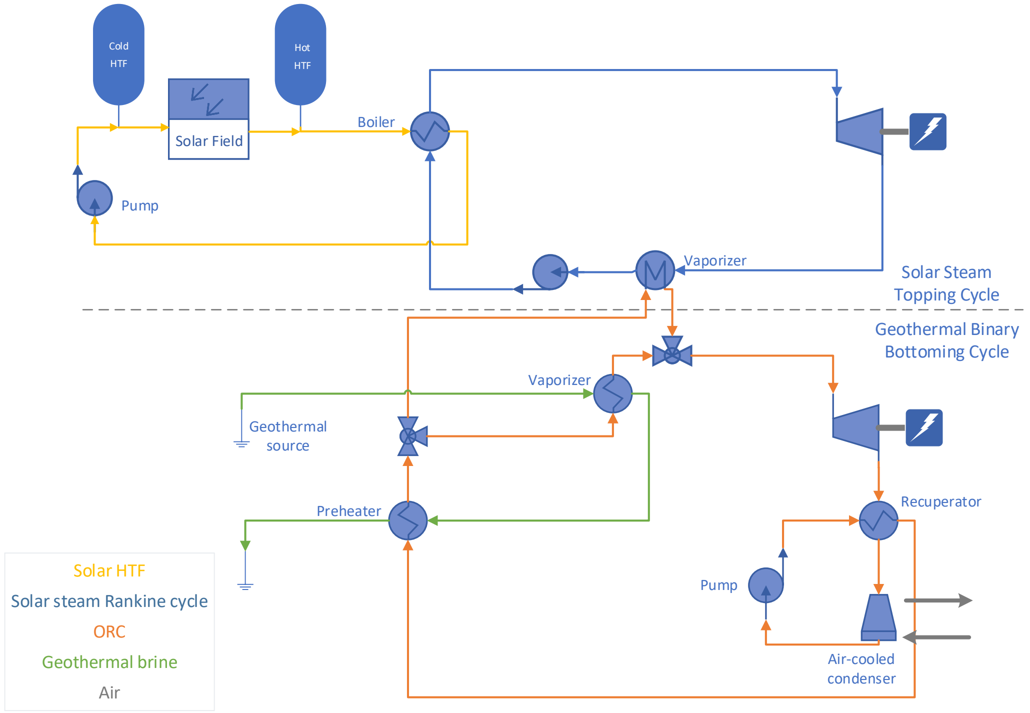

Figure 1: Hybrid geothermal-solar power cycle diagram. In this example, the solar HTF is nitrate molten salt and the ORC working fluid is isopentane.

3. Design Point Performance

The design point power output depends on numerous assumptions about component efficiency and the relative sizes of each subsystem. The effect of the geothermal temperature and the relative power output of the topping and bottoming cycles are explored in Table 1. Net power includes parasitic losses such as air-cooled condenser fans and working fluid pumps.

Several geothermal temperatures from 100°–140°C are considered—with the production fluids assumed to be saturated liquid at the surface. As expected, increasing the geothermal temperature increases the power output of the bottoming cycle and makes parasitic losses due to the ACC and working fluid pumps less significant. The relative size of the topping cycle also has an impact, and two steam turbine power ratings are considered: the 'smaller' turbine is 5 MW_e and the 'larger' turbine is 10 MW_e. Increasing the power rating of the topping cycle also increases the quantity of heat delivered from the back-pressure turbine to the bottoming cycle power, and consequently the ORC power output increases.

Table 1: Initial design iterations, considering the effect of geothermal brine temperature and topping cycle rated power on total plant net power

		Smaller topping cycle				Larger topping cycle			
Geo. temp., °C	Geo. flow rate, kg/s	Topping cycle, MW	Bottom cycle, MW	Parasitic loss, MW	Net power, MW	Topping cycle, MW	Bottom cycle, MW	Parasitic loss, MW	Net power, MW
100	300	5	2.76	0.35	7.41	10	4.53	0.62	13.91
120	300	5	5.39	0.55	9.84	10	7.16	0.82	16.34
140	300	5	8.04	0.75	12.29	10	9.81	1.02	18.79

4. Off-Design Models and Annual Performance Evaluation

The effect of ambient temperature and solar heat input on power output are investigated for one design in this section. At the design point, both the topping and bottoming cycles have a gross power output of 10 MW_e, and the geothermal production fluids are assumed to be saturated liquid at 120°C. The geothermal mass flow rate and solar field size are calculated to meet these design power requirements. Other design assumptions are summarized in Table 2

Table 2: Operating conditions and assumptions for major components

Component	Design settings
Working fluid	Isopentane
ORC turbine	$\eta_{\text{isen}} = 90\%$, $T_{\text{inlet}} = 100°\text{C}$ saturated vapor
Ambient conditions	$T_{\text{amb}} = 15°\text{C}$
Geothermal brine	$T_{\text{prod}} = 120°\text{C}$, saturated liquid
Steam Rankine turbine	$\eta_{\text{isen}} = 85\%$

The ambient temperature and solar heat input are varied, and the off-design gross power output is shown in Figure 2. The solar gross power output does not vary significantly with ambient temperature (see black squares in Figure 2b which are coincident for different ambient temperatures), as this cycle is somewhat decoupled from the ACC. However, the bottoming cycle power output is significantly influenced by the ambient temperature and topping cycle thermal input. As expected, increasing the solar heat input increases the power output. (Note that the solar thermal input is the quantity of heat transferred from the solar collectors to the Rankine topping cycle. A smaller quantity of heat is then transferred to the bottoming cycle via a second vaporizer)

The ambient temperature effectively controls the condenser temperature and pressure and therefore also has a strong influence on power output. The design point temperature of the ACC is also an important consideration as it determines the cooling performance at higher temperatures, the ACC cost, and the air fan parasitic loads. This example is designed for an ambient temperature of 15°C. Thus, if temperatures at the chosen location are frequently higher than this, the power output will be compromised. This loss can be compensated for if solar heat is available to boost the hybrid power output. Increasing the design point ambient temperature would enable the ACC to operate more efficiently at high temperatures and therefore improve the power output. However, this will also increase the ACC cost, as greater air flow rates will be required. Thus, choosing a design point must weigh this trade-off with the expected temperatures in an area and the electrical market it will be selling into.

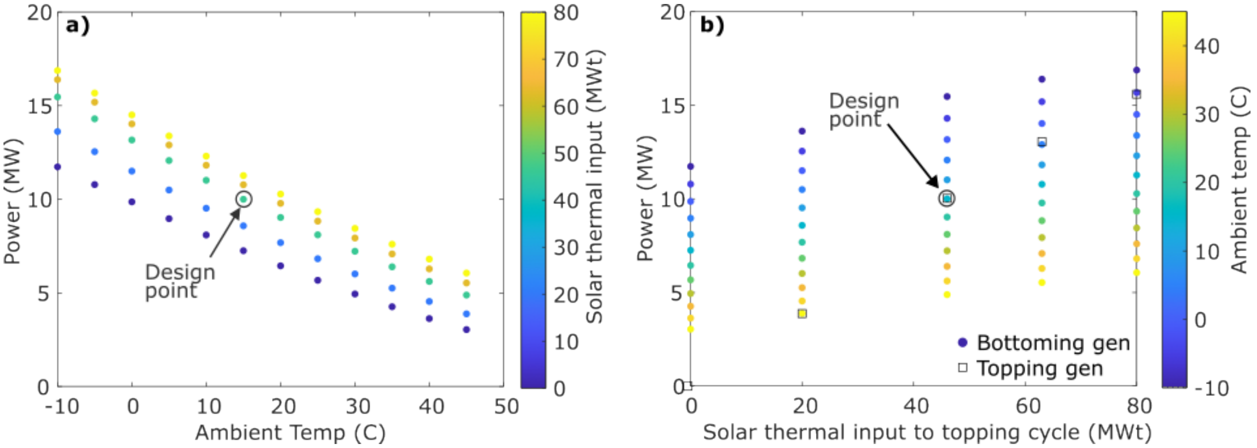

Figure 2: Off-design performance (a) ambient temperature impact on bottoming power cycle and (b) solar heat input on bottoming power cycle (shown in colored circles) and topping cycle (shown in black squares)

Table 3 demonstrates the impact of adding heat from the back-pressure turbine to the ORC. As described in Section 2, the supplemental heat addition is used to vaporize a portion of the ORC working fluid which means the geothermal fluid vaporizes a smaller portion than in a stand-alone geothermal system. As a result, this eases pinch-point constraints and enables the ORC fluid to be vaporized at higher pressures, temperatures, and mass flow rates, which leads to higher power outputs. Figure 2 and Table 3 also indicate that the heat added to the ORC can exceed the design point value. This feature adds another level of flexibility to the plant since the power output can be increased above the design value (albeit at lower conversion efficiency) if so required. This is achievable for CST systems with a solar multiple greater than one: when solar heat availability exceeds the design value, the plant operator can decide whether to charge the TES or generate more power by over-rating the power plant depending on market conditions. The ability to over-rate the design point is also advantageous if the electrical grid unexpectedly requires energy capacity.

Table 3: Off-design performance of the bottoming ORC as a function of heat addition from the back-pressure turbine. Ambient temperature is constant at 15°C. *This row corresponds to the design solar heat of 46 MW$_{th}$.

Solar heat, MW$_{th}$	Heat added to ORC, MW$_{th}$	Heat from geo., MW$_{th}$	ORC mass flow, kg/s	Turbine inlet pressure, bar	Turbine inlet temp., °C	ORC gross power, MW$_{e}$	ORC efficiency, %
0	0	75	193	5.6	88.5	7.5	9.4
23	18	68	219	6.4	94.5	8.8	9.6
46*	34	61	246	7.2	100.0	10.0	9.7
69	53	54	278	8.2	106.1	11.0	9.5
89	74	46	313	9.4	112.5	11.4	8.7

The annual performance is evaluated by calculating the power output for each hour of the year for a given location— in this case, Elk Hills, California. Additional design parameters include the solar field size (solar multiple) and thermal storage size, which together determine the proportion of time that the hybrid plant will have the design thermal input. In this case, a relatively large solar field is chosen (solar multiple = 3) along with 10 hours of storage, meaning that the system should have high capacity factors during the spring and summer and also obtain good performance during the winter months. Full design parameters are listed in Table 4.

For this design and location, the hourly solar thermal energy and ambient temperatures are obtained from SAM. This information is combined with a data table of off-design hybrid plant performance and a simple dispatch procedure that aims to deliver a constant solar thermal power output to the topping cycle. When solar energy exceeds the design solar input, the storage is charged. When solar energy falls below the design requirement, the storage is discharged until it is emptied. Having established the available solar input and ambient temperature for each hour, the off-design performance table is interpolated to find the power output.

Time-series results are provided in Figure 3 for a week in July. As the ambient temperature increases over the course of the day, the bottoming power cycle output dips. However, the availability of solar heat at these times boosts the bottoming cycle power output and compensates for losses due to high ambient temperatures to some extent. The total generation shows clear peaks and valleys based on when solar is and is not producing thermal energy, but the generation never drops to zero because the geothermal cycle is able to provide relatively consistent power output.

The gross power output of the topping and bottoming cycle is shown in Figure 4. Although the two cycles have the same rated power output of 10 MW_e, the hourly power produced by the two systems varies significantly throughout the year. The solar topping cycle tends to either operate at its rated power or turn off (mostly at night). This is in part due to the dispatch scheme applied to the thermal storage, which tries to produce constant topping cycle power for as long as possible. On the other hand, the bottoming cycle provides consistent power generation albeit with diurnal and annual variations due to changes in ambient temperature and topping cycle power input.

The annual simulation found that the hybrid plant produced 107,760 MWh_e of power, which corresponds to a capacity factor of 62%.

Table 4: Inputs to the annual simulation model

Parameter	Value
Geo brine temp	120°C
Geo brine flow rate	576 kg/s
ORC rated power	10 MW
Solar multiple	3
Solar mirror area	4.8×10^5 m^2
Rankine rated power	10 MW
Storage	10 hours
Design ambient temp	15°C
Location	Elk Hills, CA

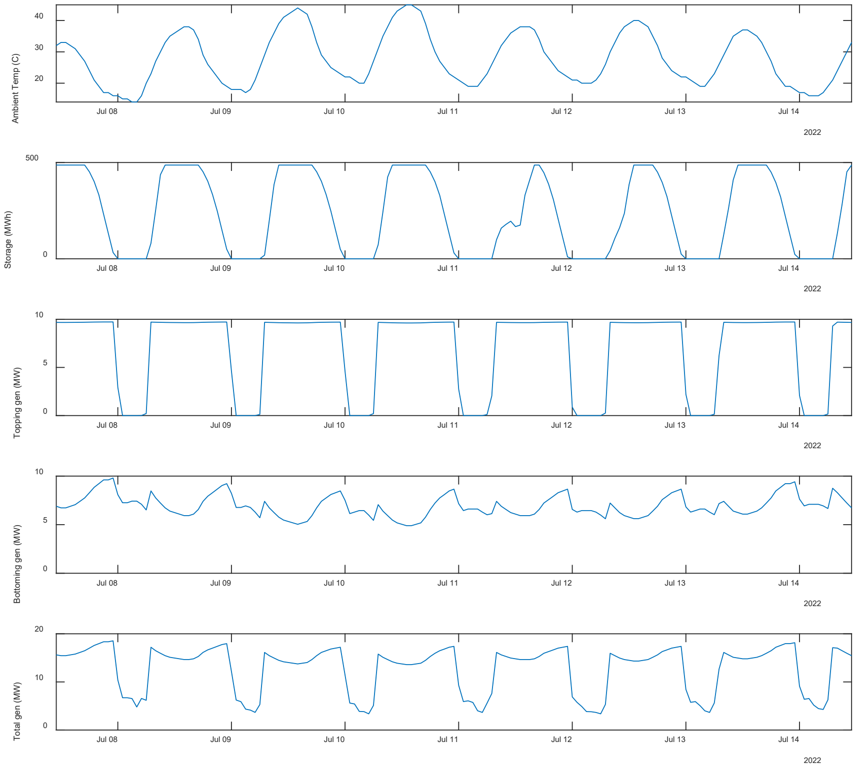

Figure 3: Time-series results from annual simulation of hybrid system for one week showing ambient temperature, storage charge, topping cycle gross generated power, bottoming cycle gross generated power, and total net generated power

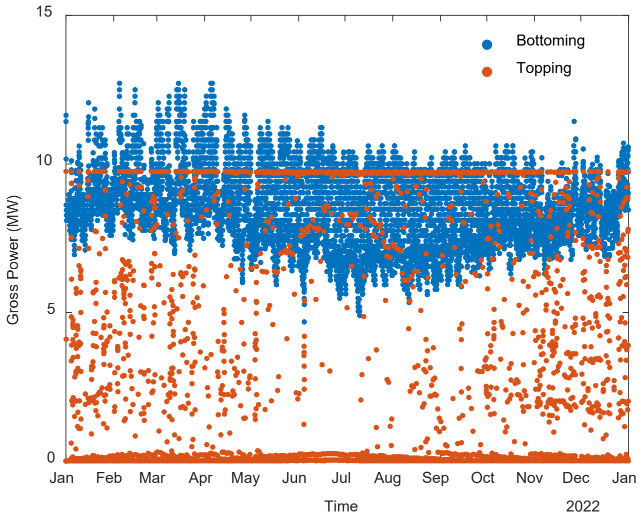

Figure 4: Annual simulation results for topping and bottoming cycle gross power output over one year

5. Conclusions

A greenfield hybrid power cycle that integrates geothermal and Concentrating Solar Thermal (CST) is introduced in this article. The configuration described uses a back-pressure steam topping cycle that enables the solar energy to be converted at high temperatures and therefore good efficiency. Heat is transferred from the exit of the steam turbine to the bottoming organic Rankine cycle (ORC) which also uses heat from a geothermal source. The ORC can deliver power even when no solar heat is available and can therefore provide firm capacity.

This system could potentially provide both baseload electricity capacity via the geothermal energy and flexible peaking power by combining CST with thermal energy storage (TES). This enhanced flexibility could be achieved by co-located geothermal and CST systems. However, directly integrating the two power plants – as described in this article – is expected to have other benefits. For example, the two systems share an air-cooled condenser (ACC) and some of the solar heat is converted to electricity in the geothermal power plant, which may have cost advantages. Furthermore, the addition of solar heat to the ORC eases pinch point constraints in the heat exchangers and enables the ORC working fluid to be vaporized at higher temperatures and pressures than what is possible with only the geothermal resource. Not only does this have some efficiency benefits but it suggests that this concept could be applied to low-temperature geothermal resources that currently are not being developed. Another benefit of directly integrating the two systems is that additional CST can be added over time and therefore be used to compensate for any decline in the geothermal flowrate and temperature. Cost and value analysis over the lifetime of the hybrid plant is required to quantify the magnitude of these potential advantages compared to more conventional systems, and this is the subject of ongoing research.

Design and off-design models of this system are developed, and results show that off-design modeling is an important requirement; the power output is strongly influenced by ambient temperatures and solar heat input. The proposed system uses an air-cooled condenser and consequently, high ambient temperatures have a detrimental effect on power output. However, these losses are compensated for to some extent by the simultaneous availability of solar energy.

The power output is calculated for each hour of the year for one illustrative design case, and a simple dispatch model is used to determine the charge and discharge of the TES. There is considerable scope for investigating improvements to the system design, sizing, and operation. For example, the ORC efficiency could be increased by considering different working fluids (such as isobutane, propane, or CO_2) or alternative power cycle designs, such as a dual-pressure level cycle, supercritical cycle, or Kalina cycle. A comprehensive analysis of the relative sizing of the topping and bottoming cycle power outputs, the solar field size, and the TES size are also required. The optimal combination will depend on the cost of the system and how its power output is valued (and therefore the electricity market that it operates in). Therefore, economic models should be developed, and more sophisticated dispatch schemes should be considered in an effort to maximize value while reducing cost.

Furthermore, individual locations will have different solar resources, geothermal temperatures and flow rates, market patterns and requirements. Therefore, greenfield hybrid plant design will likely depend on the unique characteristics of the proposed location. Future work will investigate the design and operation of hybrid CST-geothermal power plants in several distinct locations throughout the United States—covering a range of solar and geothermal resources—with the aim of evaluating the economic value of these systems.

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