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# Techno-economic Assessment of Geothermal Power Plants Hybridized with Solar Heat and Thermal Storage

Joshua McTigue [1], Jose Castro [2], Greg Mungas [3], John King [3], Nick Kramer [3], Daniel Wendt [4], Kevin Kitz [5], Joshua Gunderson [6], Craig Turchi [1], Nick Kincaid [1], Guangdong Zhu [1,*]

[1] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401

[2] Coso Operating Company

[3] Hyperlight Energy

[4] Idaho National Laboratory

[5] KitzWorks Ltd.

[6] Power Engineers

* Guangdong.Zhu@nrel.gov

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## ABSTRACT

Geothermal power plants may experience a decrease in power output over time due to a reduction in either mass flow rate, temperature or pressure of the resource. A recent study quantified the temperature drawdown of U.S. double-flash geothermal power plants at 0.8% per year. Hybridizing existing geothermal plants with other renewable power sources to exploit the unused capacity of the geothermal power block has become an area of increasing interest. For instance, a geothermal power plant may be retrofitted with heat from a concentrating solar field. In addition, geothermal may be integrated with solar in a new-build site with the aim of combining the benefits of both technologies – i.e. the baseload generation of geothermal, plus the relatively high efficiency of concentrating solar power.

In this article, we give an overview of hybrid geothermal-solar projects undertaken at the National Renewable Energy Laboratory in collaboration with various partners. We investigate the retrofit of double-flash and binary geothermal plants with solar heat. Off-design models are developed and validated with operational data. Annual simulations evaluate the hourly performance, the benefits of thermal storage, and are used to calculate economic metrics. Finally, we discuss the implications of integrating solar and geothermal in a new greenfield site.

## 1. INTRODUCTION

Geothermal power may be combined with solar energy to harness the advantages of both technologies. Solar energy is inherently intermittent while geothermal can provide baseload power. However, geothermal resources can decline in temperature or flow rate over time. Integrating solar and geothermal can take advantage of the overlap in equipment and the fact that many active geothermal regions also have high solar resources (see Figure 1). There are several methods of hybridizing solar and geothermal technologies, and the viability of certain methods depends on factors such as location, relative geothermal and solar resource quality, and whether an existing plant is being retrofitted or a new one is being built.

Most previous work has concentrated on the retrofit of geothermal power plants. A geothermal resource typically experiences a reduction in the temperature, pressure, or mass flow rate of its production fluids over time, leading to decreased power generation and underutilized equipment. The extent of any resource decline is unique to that geothermal field and a survey of geothermal power plants in California and Nevada found that flash plants typically experienced a temperature decrease of 0.8 % per year, while the value was 0.5 % for binary plants (Snyder et al. 2017). Underperforming plants may be brought back to full capacity by the addition of thermal heat. The unused capacity of the geothermal plant therefore provides an opportunity to install a concentrating solar plant (CSP) at reduced cost since investment in a power unit and condenser are not required. Integrating thermal storage provides the plant with flexibility and dispatchability. Previously, various hybrid plants have been suggested for both flash plants and binary plants. For flash plants, solar collectors can directly heat geothermal fluids, thereby increasing the fluid enthalpy and the steam generation (Lentz and Almanza 2006). Alternatively, superheating the steam after the flash tanks was found to be more effective than evaporating the brine (Miguel Cardemil et al. 2016). Other studies concluded that recirculating and heating brine after the first flash plant was the most practicable and effective method, and also evaluated the benefit of thermal storage (J. McTigue et al. 2017; J. D. McTigue, Castro, et al. 2018).

Hybridization of solar heat with binary geothermal plants typically involves different integration methods to flash plants, although pre-heating the geothermal fluids has also been investigated in this context (Ghasemi et al. 2014) . Strategies involve superheating the binary-cycle working fluid (Astolfi et al. 2011) or using the solar heat to drive a topping cycle – either as part of the binary plant (Zhou, Doroodchi, and Moghtaderi 2013) or in a steam turbine (Bonyadi, Johnson, and Baker 2018), thereby making better use of relatively high-exergy solar heat. These studies find the LCOE to be relatively high compared to stand-alone geothermal and CSP plants – with obtained values such as 0.163 \$ / $kWh_e$ (Bonyadi, Johnson, and Baker 2018) and 0.22 – 0.43 \$ / $kWh_e$ (Astolfi et al. 2011). However, estimated solar field costs in the range of 250 – 300 \$ / $m^2$ were used, which are high compared to recent estimates which are closer to 150 – 200 \$ / $m^2$. This is particularly relevant given that the solar field cost dominates the total capital cost of a geothermal plant that is retrofitted with solar.

In this article, hybrid geothermal-solar case studies undertaken at the National Renewable Energy Laboratory in collaboration with various partners are described. The necessary metrics for evaluating hybrid plants are first described in section 1.1. In section 2, the hybridization of an existing double-flash power plant is described. In section 3, a binary geothermal power plant is retrofitted with solar heat. Finally, section 4 describes some challenges facing the hybridization of a greenfield geothermal-solar power plant.

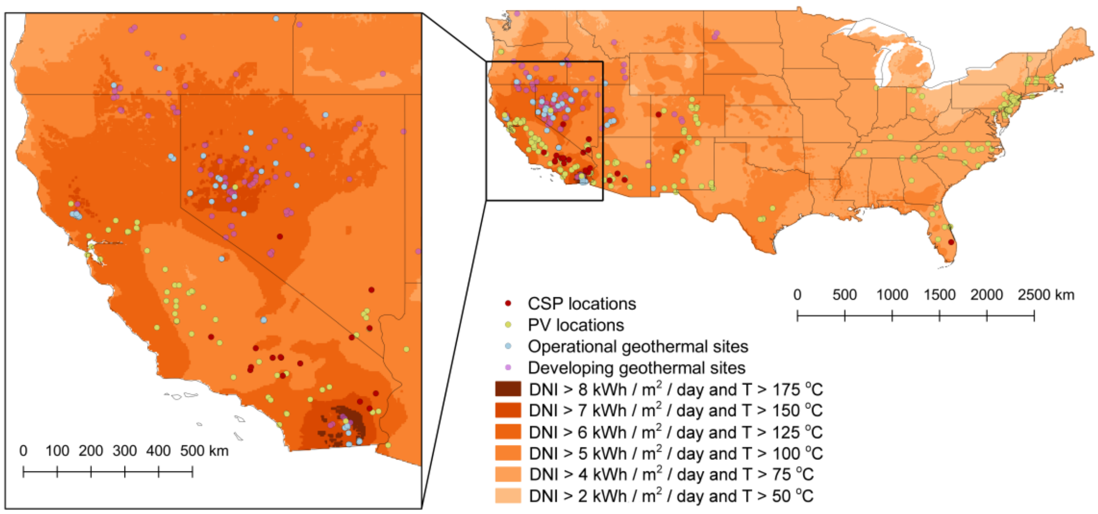


**Figure 1: Potential locations for geothermal-solar hybrid plants. Map of the USA showing locations of high solar irradiance and geothermal temperatures at a depth of 3000 m. Data from (National Solar Radiation Database 2017).**

### 1.1 Hybrid Plant Performance Metrics

*Hybrid Plant Efficiency*

Different metrics may be used depending on whether the hybrid plant is a retrofitted geothermal system or a greenfield plant. For a retrofit, the metrics should consider the additional heat input from the solar resource and the additional power output. The solar-conversion efficiency, also referred to as the incremental or marginal solar efficiency, measures how effective the hybrid configuration is at converting the additional thermal input (i.e. the solar energy added) into useful work (net power, which is the gross power minus the associated parasitic loads). Two definitions exist and differ in the denominator. In one definition, the incremental solar energy added to the cycle is that which is actually collected and transferred to the main power cycle. The second is where the incremental solar energy is that which actually falls on the collector. The first definition is preferred here since this was a study of cycle efficiency, rather than collector efficiency.

Thus, the first version of the incremental solar efficiency is defined as:

$$\eta_{\text{inc},1} = \frac{\dot{W}_{\text{net}} - \dot{W}^{o}_{\text{net}}}{\dot{Q}_{\text{add}}} \tag{1}$$

Where $\dot{W}_{\text{net}}$ is the net work produced by the hybrid plant, $\dot{W}^{o}_{\text{net}}$ is the net work that would have been produced by the geothermal plant in isolation, and $\dot{Q}_{\text{add}}$ is the thermal power added to the hybrid power cycle. $\eta_{\text{sol},1}$ may be used to compare the performance of different power systems proposed in the literature without considering differences in the solar collection technology (including project specific choices of collector efficiency, or advancement over time in solar collector efficiency) or differences in modeling of the solar field (which can be done to variable degrees of complexity).

For a greenfield plant, the efficiency $\eta_{\text{hyb},1}$ is simply related to the total power output and the total heat input. Again, two definitions exist depending on whether the solar energy input is defined as the solar irradiance that falls on the collector, or as the solar heat input to the cycle. Following Eq. (1) the latter definition is preferred here, so that the hybrid efficiency of a greenfield plant is given by

$$\eta_{\text{hyb},1} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{solar}} + \dot{Q}_{\text{geo}}} \tag{2}$$

*Levelized Cost of Electricity (LCOE)*

One commonly used metric to assess the economic feasibility of power generation is the levelized cost of electricity (LCOE). This is the cost that, if assigned to every unit of electrical energy produced over the lifetime of the plant, will equal the total life-cycle costs when both are discounted back to the current year (Short and Packey 1995). In the case of the hybrid plant where the power block and geothermal wells already exist, the annual electrical energy generated by the solar equipment addition is the marginal increase in electrical energy above the base rate provided by the geothermal plant. Thus, for retrofit geothermal-solar systems the costs and power generation of the existing geothermal plant are not included in the LCOE calculation.

The LCOE is calculated using the fixed charge rate (FCR) method, where

$$\text{LCOE} = \frac{C_{\text{cap}} \cdot \text{FCR} + M}{E} \quad (3)$$

Where $C_{\text{cap}}$ is the capital cost, *M* is the annual operations and maintenance cost, *E* is the annual electricity generation, and FCR is the fixed charge rate. FCR is defined as the revenue per unit of investment that must be collected annually to pay for the carrying charges of the investment. Details of how to calculate the FCR may be found in (Short and Packey 1995), and the economic assumptions used in this study are given in (J. D. McTigue, Castro, et al. 2018).

## 2. RETROFITTING A DOUBLE-FLASH GEOTHERMAL POWER PLANT

### 2.1 Plant Description

In a double-flash geothermal power plant, geothermal fluids are flashed in a flash tank to produce steam which is sent to the high-pressure stage of a steam turbine. The remaining brine enters a second flash tank, and the produced steam is injected into the low-pressure steam turbine stage. In this case study, the power plant model is based on the units at the Coso geothermal field which is operated by the Coso Operating Company at the Naval Air Weapons Base in China Lake, California. Coso operates with between 80–90 production wells and 30–40 injection wells. Each well has its own characteristics and fluid properties which can vary with time and the operation of other wells. There are nine 30-MW$_e$ turbine sets, and numerous pipelines, headers, separators and flash tanks. A simplified model was developed in the IPSEpro heat balance software, developed by SimTech (SimTech 2017) and contains one production well, one injection well, and one turbine set. Design and off-design performance were validated against operational data with model results agreeing with power plant data to within ±5%. Differences between the model results and the operational data may be attributed to the simplifications in the power plant configuration.

As indicated by Table 1, the power output at the Coso field is about 75% of the design power output. As a result, solar heat may be added to the geothermal plant to improve performance. A description of the hybrid system is given in the next section.

**Table 1:** Design and off-design inputs and performance data used to model a two-stage steam turbine unit. Data provided by Coso Operating Company and is representative of the Coso geothermal power plant.

| | | Design conditions | | Current operating conditions | |
|---|---|---|---|---|---|
| | | *High pressure* | *Low pressure* | *High pressure* | *Low pressure* |
| Mass flow | kg s$^{-1}$ | 48.0 | 25.0 | 43.8 | 7.1 |
| Temperature | °C | 169.2 | 132.5 | 159.8 | 98.3 |
| Inlet pressure | bar | 6.3 | 1.4 | 5.7 | 0.95 |
| Gross power | MW$_e$ | 29.6 | | 22.5 | |
| Net power | MW$_e$ | 29.4 | | 22.2 | |
| Efficiency | % | 19.7 | | 16.9 | |

### 2.2 Solar Heat Input to Double-Flash Power Plant

The hybrid plant consists of a double-flash geothermal power plant, an array of mirrors to concentrate sunlight, a heat transfer fluid (HTF) that transports heat from the solar field to the geothermal plant, and two liquid tanks that contain the HTF and are used as thermal storage. Various methods of adding solar heat to the geothermal plant configurations have been considered, including heating the production fluids, the injection fluids, and the steam condensate, and further details are provided in (J. D. McTigue, Castro, et al. 2018). The most practicable and promising method involves heating the brine that leaves the first flash tank. This brine is heated by the solar energy, and then mixed with the production fluids. Figure 2 shows a simplified schematic. The system model calculated the incremental solar efficiency to be $\eta_{\text{inc},1} = 24.3$ %, and Table 2 provides other operating point data.

**Table 2. Operating point of a double-flash geothermal plant supplemented by solar heat.**

| | | HP stage | LP stage |
|---|---|---|---|
| Temperature | °C | 162.6 | 100.0 |
| Pressure | bar | 6.10 | 1.01 |
| Mass flow rate | kg/s | 47.2 | 54.2 |
| Recirculated temperature | °C | 162.6 | |
| Recirculated pressure | bar | 6.60 | |
| Recirculated mass flow rate | kg/s | 147.9 | |
| Gross power | $MW_e$ | 24.5 | |
| Net power | $MW_e$ | 24.2 | |
| Solar thermal conversion efficiency, $\eta_{\mathrm{inc},1}$ | % | 24.3 | |

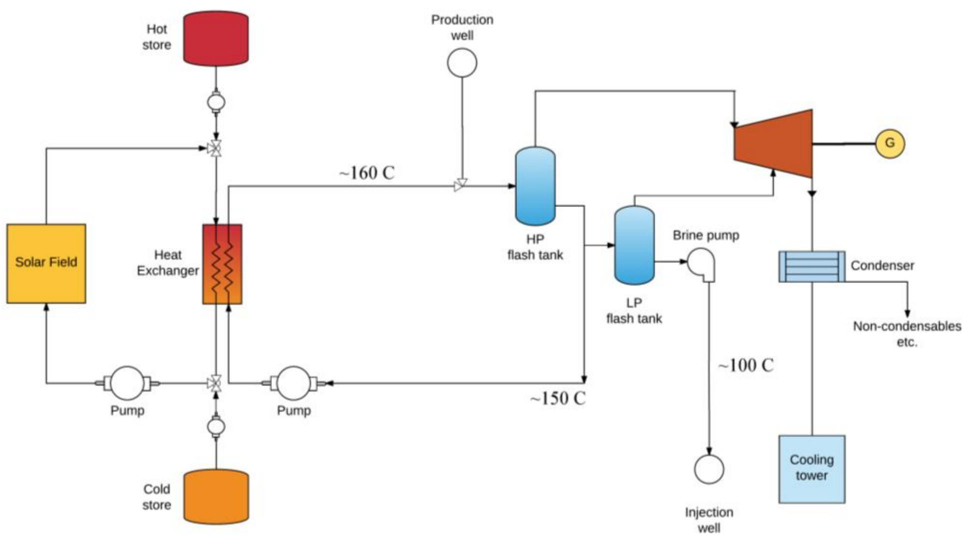


**Figure 2: Schematic of a double-flash geothermal power plant that is retrofitted with solar heat. The solar heat is added to the brine that leaves the first flash tank.**

### 2.3 Annual Performance Results

Using off-design models of the hybrid plant, and hourly data for the solar irradiance, the annual performance and incremental LCOE of the hybrid plant was evaluated. A key design parameter is the size of the solar field relative to the geothermal plant, and is defined here by the *solar multiple*. A solar field with a solar multiple of 1 is sized so that enough thermal power is produced on a sunny day (an irradiance of 950 W / $m^2$) to increase the geothermal plant power output to its design point. Since these conditions occur for a fraction of the year, a system with a solar multiple of one would frequently operate below design conditions. To improve the number of hours that the hybrid plant operates at or above the design conditions of the hybrid plant, the solar field area is increased, and the solar multiple increases proportionally. However, large solar multiples can produce too much thermal power for the geothermal plant to absorb on sunny days. This excess heat is either curtailed or stored in liquid tanks, and the sizing of the thermal storage is also an important parameter.

The incremental LCOE was calculated for hybrid plants with varying solar field and thermal storage sizing, and results are shown in Figure 3. (Cost correlations are provided in (J. D. McTigue, Castro, et al. 2018)). Larger solar fields initially reduce the LCOE as more energy is delivered to the hybrid plant over the course of the year. However, increasing the solar multiple further leads to higher LCOEs because of increased curtailment. Curtailment can be reduced by increasing the storage duration, which explains why the lines begin to converge at large solar multiples. However, larger thermal stores lead to higher LCOEs, as the total electricity generation remains roughly the same while the investment increases. The LCOE implies that the optimal storage size is zero as it does not reflect the value that storage provides to the plant or the grid by enabling the flexible dispatch of energy (Denholm, Eichman, and Margolis 2017).

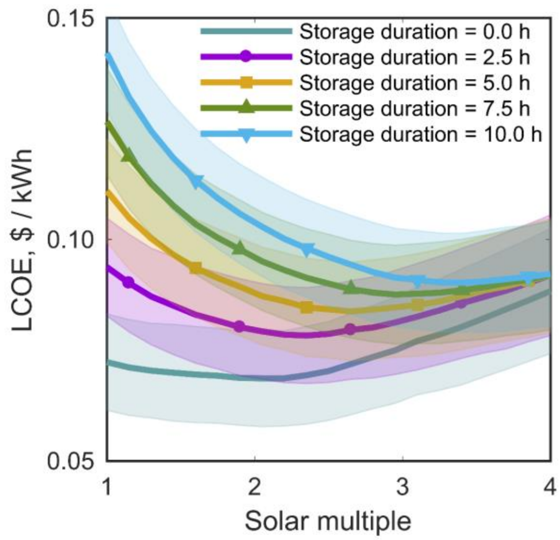


**Figure 3: Effect of solar field size and thermal storage sizing on the levelized cost of energy. The hot thermal store is at 400°C with DPO (Therminol VP-1) as the storage medium. The cold store is at 190°C. The shaded bars indicate the mean LCOE plus/minus one standard deviation.**

### 2.4 Comparison with Photovoltaics Plus Battery Storage

Photovoltaic (PV) systems have been widely deployed in recent years – particularly in California due to lower capital costs. For hybrid systems to be considered a worthwhile investment, they must achieve LCOEs competitive with conventional renewable technologies. The hybrid plant is compared to a PV plus battery energy storage (BES) that produces the equivalent annual energy. Photovoltaic and battery cost assumptions are described in (J. D. McTigue, Castro, et al. 2018). The PV field energy output was modelling using the 'System Advisor Model' (SAM) (NREL 2017). The PV field LCOE is evaluated with the FCR method and has the same economic assumptions as the hybrid LCOE calculations, so that the results are directly comparable. The nominal PV power capacity is set to be equal to the design increase in power that solar heat provides to the hybrid plant. The PV field is sized so that it produces the same annual quantity of energy as the equivalent hybrid plant. It is assumed that all the power produced by the PV field can be absorbed by the grid. Thus, no power is curtailed.

Two cases were considered, which correspond to hybrid plants with solar multiples of 2 and 3, and results are presented in Table 3. When storage is not included PV arrays have similar costs to the hybrid-geothermal system. However, batteries have higher capital costs (200–800 $/kWh) and shorter lifetimes (10 years) than thermal storage (Feldman et al. 2016; Lai et al. 2017). Consequently, the LCOE of the hybrid plant with storage is lower than the PV+BES system. The wide variance in battery cost estimates leads to a large spread of possible LCOEs, but it is worth noting that even the lowest cost batteries (200 $/kWh$_e$) lead to systems with higher LCOEs than the hybrid system. These results suggest there is a compelling economic argument to consider hybrid plants as a competitor to PV systems with batteries. A major factor in the high LCOE of the PV+BES system is the high cost of batteries, the requirement to replace them periodically, and the limited maximum depth of discharge.

**Table 3: LCOE comparison of hybrid geothermal-solar-storage with photovoltaic cells with battery storage.**

| | | LCOE, $ / kWh | |
|---|---|---|---|
| Annual energy generation, GWh$_e$ | Storage duration, h | Hybrid plant | PV+BES |
| 6.98 | 0 | 0.067 ± 0.011 | 0.062 ± 0.014 |
| | 3 | 0.081 ± 0.011 | 0.148 ± 0.066 |
| 9.34 | 0 | 0.076 ± 0.012 | 0.062 ± 0.014 |
| | 10 | 0.091 ± 0.011 | 0.254 ± 0.130 |

## 3. RETROFITTING A BINARY GEOTHERMAL POWER PLANT

### 3.1 Plant Description

Binary geothermal power plants may also be retrofitted with solar heat, although the method of integration is different to in a double-flash geothermal plant. For this case study, operational data was obtained for the Raft River binary geothermal plant in Burley, Idaho. This cycle uses a dual-pressure-level binary cycle (organic Rankine cycle) and was designed and constructed by Ormat. The basic power cycle was described in detail in two previous publications (DiPippo, 2016; DiPippo & Kitz, 2015). A high-pressure and low-pressure turbine are connected on either side of a common generator. Both sides are separated from each other and use isopentane as the working fluid. The heat rejection system is a shell and tube condenser with a 4-cell cooling tower. Geothermal brine flows into the high pressure (HP) and low pressure (LP) evaporators in series, and then the brine splits to feed the pre-heaters of both systems. The cooled brine is finally injected into the geothermal reservoir.

The plant began commercial operation in 2006 and has run at a high plant availability since. However, the reservoir is unable to provide sufficient flow to the plant (averaging 86% of design flow). While the reduced power output of the plant (87% of design output) meets the minimum contract requirements, the output is below the contract maximum. The current performance is compared to design performance in Table 4.

**Table 4: Comparison of Design and Actual Operating Conditions and Generation**

| Description | Design Point | | Actual Operation | |
|---|---|---|---|---|
| Geothermal Brine | Flow (Klbs/hr) | Temp. (°F) | Flow (Klbs/hr) | Temp (°F) |
| To Plant | 3,150 | 280 | 2,700 | 272 |
| From Plant | 3,150 | 150 | 2,700 | 145 |
| Generation | $MW_{gross}$ | $MW_{net}$ | $MW_{gross}$ | $MW_{net}$ |
| Power Cycle, no brine pumps | 15.9 | 13.7 | 13.8 | ~11.7 |

### 3.2 Solar Heat Input to Binary Power Plant

Solar heat may be added in several ways to a binary geothermal power plant, and several configurations are compared in (J. D. McTigue, Wendt, et al. 2018). For instance, solar heat may be added directly to the geothermal brine or the binary working fluid. However, during the course of the previous investigation (section 2) it became apparent that there was a disparity between the geothermal brine temperature (up to 160˚C) and the temperature that could be provided by the solar plant (up to 400˚C for a parabolic trough system using synthetic oils). The higher temperature solar heat can be converted to electricity at higher efficiencies than the geothermal heat. Adding solar heat directly to a geothermal power plant therefore constitutes a waste of high-grade heat. A good solution is to convert the solar heat to electricity directly in a steam turbine. Back-pressure steam turbines have relatively hot exit temperatures, which can then be used to add heat at the correct temperature to the binary cycle. One potential configuration is shown in Figure 4. In this case, two steam turbines with different exit pressures and temperatures are used, so that heat is added to both the high-pressure and low-pressure loops in the binary plant.

A model of the hybrid plant was developed in IPSEpro, using operational data from the Raft River power plant. Hourly ambient temperatures and solar thermal power were calculated with SAM. The output of these two models were combined in an Excel spreadsheet and the hybrid plant performance was calculated for every hour of the year. The annual calculations were then used to evaluate the LCOE. Additional details of the modeling methodology may be found in (J. D. McTigue, Wendt, et al. 2018).

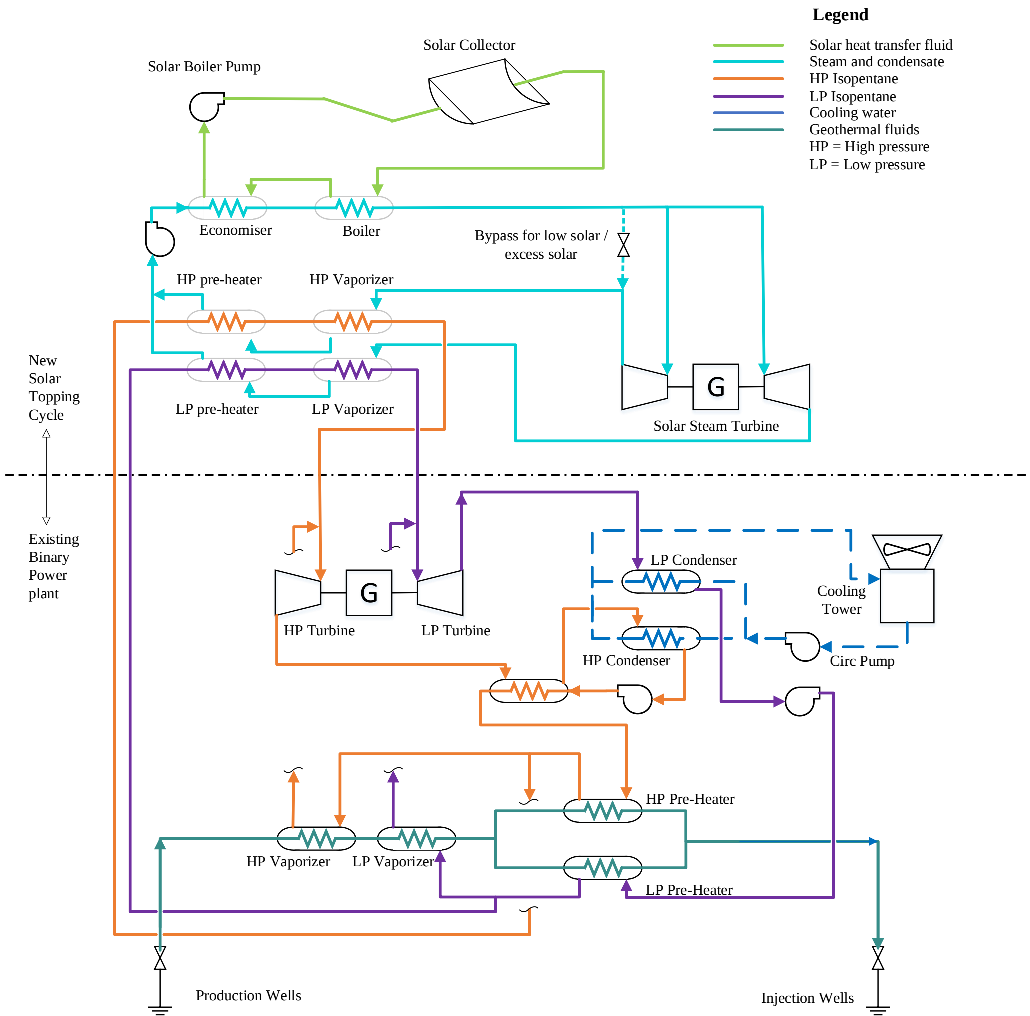


**Figure 4: Process flow diagram of the hybrid solar-geothermal system with two steam turbines.**

### 3.3 Annual Hybrid Plant Performance

While the Raft River geothermal plant is located in Burley, Idaho, it was interesting to consider how a similar hybrid plant would perform in geothermal locations with a better solar resource. Results are presented in Table 5 for the annual performance of systems in Burley ID, Reno NV, and Imperial, CA. Compared to the hybrid double-flash plants in section 2, these plants achieve much higher incremental efficiencies of around 28% which emphasizes the benefits of the topping steam turbine. (Note, that the LCOEs are not comparable between these two sections as slightly different economic assumptions were made). The additional work output due to solar heat is higher in Imperial CA where the solar resource is better. However, it is notable that the geothermal work output is lower, which is due to higher average temperatures. (The components are sized based on the Burley plant, therefore, the heat rejection system is undersized for warmer locations).

**Table 5: Electrical work output, solar conversion efficiencies, and LCOEs of hybrid plants in different geographical locations**

| | | Burley, ID | Reno, NV | Imperial, CA |
|---|---|---|---|---|
| Stand-alone geothermal work | $GWh_e$ | 95.4 | 95.7 | 82.4 |
| Additional work | $GWh_e$ | 12.0 | 12.4 | 14.8 |
| Total work | $GWh_e$ | 107.4 | 108.1 | 97.7 |
| Percentage increase | % | 12.6 | 13.0 | 18.6 |
| | | | | |
| Solar conversion $\eta_{inc,1}$ | % | 28.6 | 28.2 | 27.8 |
| Incremental LCOE | $ / $kWh_e$ | 0.126 | 0.122 | 0.118 |

### 3.4 Sizing of Solar Field and Thermal Storage

As with the double-flash plant in section 2, the sizing of the solar field and thermal storage have a significant influence on the performance and cost of the hybrid power plant, and investigations found similar trends to those in Figure 3. The influence of thermal storage costs and the solar multiple is explored in Figure 5 for Burley, ID. The storage duration is fixed at 4 hours in this example. It is notable that when storage has a capital cost of 25 $ / $kWh_{th}$ the optimal LCOE is slightly lower than the system without storage, although this configuration requires a greater up-front investment. Therefore, if storage is sufficiently cheap, then it can reduce the LCOE. Further analysis of storage costs indicated that storage should cost less than 35 $ / $kWh_{th}$ for this to occur. It should be noted that 25 $ / $kWh_{th}$ is currently quite an optimistic value and more realistic values for two-tank liquid storage are 30 – 50 $ / $kWh_{th}$. In section 2, the storage cost around 40 $ / $kWh_{th}$.

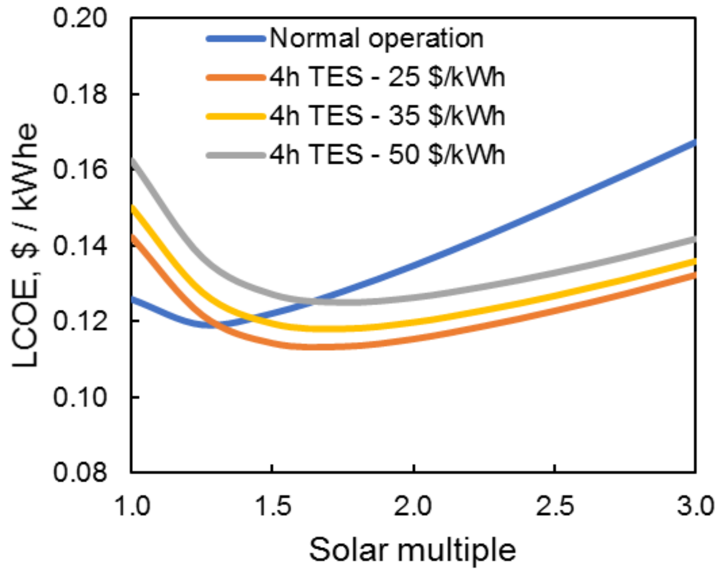


**Figure 5: The effect of the cost of thermal storage on the LCOE of the hybrid plant**

### 3.5 Comparison with Photovoltaics Plus Battery Storage

The LCOE of a hybrid solar-geothermal binary plant is compared to equivalently sized photovoltaic (PV) arrays with battery energy storage (BES) in this section. The PV+BES system is compared to hybrid plants that have a solar multiple of 1.75 and a thermal storage duration of 4 hours because analysis indicated that these plants are the most economically viable. Plants with no storage are also considered. Similar assumptions for the PV+BES system are made to in section 2.4.

Results are presented in Table 6 for a plant in Burley, ID. The PV array is significantly cheaper than the hybrid system when the systems have no storage – PV+BES has an LCOE of 0.074 $/$kWh_e$ compared to the hybrid-plant value of 0.116 $/$kWh_e$. The hybrid plant performs particularly poorly, in part because for a given plant size, the system produced less annual electricity than the PV array. This is due to curtailment of the thermal energy, whereas no PV electrical energy is curtailed (which may not be a realistic assumption).

Storage is an important component for the hybrid plant because it increases the electrical energy that is dispatched. Furthermore, it allows the plant to operate flexibly. This is also an important requirement for PV because the rapid deployment of PV in California has led to a surplus of power in the afternoon. This results in the so-called “duck-curve” whereby flexible power must be rapidly dispatched during the late-afternoon hours. PV should be installed with storage to help reduce this issue. However, as shown in Table 6, batteries significantly increase the LCOE of the PV system—primarily the result of the high cost of batteries, coupled with the requirement to replace them every 10 years.

Thus, this and the previous case study indicate that hybrid geothermal-solar plants with thermal storage can provide greater flexible dispatch of electricity than photovoltaics with battery storage at lower cost.

**Table 6. Comparison of costs and LCOEs for a hybrid plant and a photovoltaic array with batteries. Both plants are located in Burley, Idaho**

| | | Hybrid | Hybrid + TES | PV | PV + BES |
|---|---|---|---|---|---|
| Storage duration | h | 0 | 4 | 0 | 4 |
| Annual electricity | $GWh_e$ | 18.3 | 22.1 | 22.0 | 22.0 |
| Capital cost | M$ | 17.7 | 21.5 | 14.7 | 39.4 |
| LCOE | $/$kWh_e$ | 0.116 | 0.118 | 0.074 | 0.187 |

## 4. CONSIDERATIONS FOR GREENFIELD HYBRID GEOTHERMAL-SOLAR POWER PLANTS

The previous sections have considered retrofitting under-performing geothermal power plants with solar heat to take advantage of spare capacity and deploy concentrating solar power at low cost. Geothermal and solar power may also be integrated in a new (greenfield) power plant. These systems may be able to take advantage of the baseload supply of geothermal heat, with the relatively high efficiency of concentrating solar systems. Thermal storage would further allow these hybrid plants to dispatch power to the grid flexibly. NREL has investigated the design of greenfield geothermal-solar power plants in collaboration with KitzWorks Ltd. However, this section will just introduce some preliminary concepts.

When designing the greenfield hybrid plant, the relative sizing of the geothermal system and solar system are important design variables. A simple expression for the hybrid plant efficiency is obtained by assuming that both the geothermal and solar heat are converted to electricity with a Carnot cycle. The maximum theoretical, or Carnot, efficiency of a hybrid system can be expressed as a function of the ambient temperature, solar and geothermal resource temperatures, and ratio of geothermal to solar heat input $\bar{Q} = \dot{Q}_{geo}/\dot{Q}_{sol}$:

$$\eta_{\mathrm{hyb}} = \frac{\dot{W}_{\mathrm{geo}} + \dot{W}_{\mathrm{sol}}}{\dot{Q}_{\mathrm{geo}} + \dot{Q}_{\mathrm{sol}}} = \frac{\left(1 - \frac{T_o}{T_{\mathrm{sol}}}\right) + \left(1 - \frac{T_o}{T_{\mathrm{geo}}}\right)\bar{Q}}{1 + \bar{Q}} \quad (4)$$

The Carnot efficiency of the hybrid cycle is shown in Figure 6 as a function of the relative sizes of the geothermal and solar heat input, for $T_{\mathrm{geo}} = 150^\circ$C and $T_{\mathrm{sol}} = 400^\circ$C. Higher temperatures have higher maximum work potential, so it is unsurprising that the hybrid plant efficiency increases as the fraction of solar heat increases. The logical limit of this suggests that no geothermal heat should be installed in order to design an efficient plant. However, the capacity factor – i.e. the quantity and reliability at which energy can be delivered – is also an important factor. Geothermal plants may have capacity factors of around 95% compared to 30% for concentrating solar fields in high irradiance locations (with no thermal storage). (Six hours of storage increases this to 40%). Thus, the quantity of electricity generated over the course of a year is also important.

A suitable metric is to consider is the total annual electricity that each technology provides divided by the total thermal power capacity of the power plant, $\dot{Q}_{\mathrm{geo}} + \dot{Q}_{\mathrm{sol}}$. The total thermal power capacity is effectively a measure of how much infrastructure is required and rewriting in terms of $\bar{Q}$ allows the distribution of investment between the geothermal system and solar system to be investigated. The metric is given by

$$\frac{E_{\mathrm{annual}}}{Q_{\mathrm{tot}}} = \frac{\dot{W}_{\mathrm{geo}} C_{\mathrm{geo}} + \dot{W}_{\mathrm{sol}} C_{\mathrm{sol}}}{\dot{Q}_{\mathrm{geo}} + \dot{Q}_{\mathrm{sol}}} T = \frac{\left(1 - \frac{T_o}{T_{\mathrm{sol}}}\right) C_{\mathrm{sol}} + \left(1 - \frac{T_o}{T_{\mathrm{geo}}}\right) \bar{Q} C_{\mathrm{geo}}}{1 + \bar{Q}} T \quad (5)$$

Where $C$ is the capacity factor of each technology and $T$ is the total number of hours in a year. Figure 6 indicates a clear trade-off between the hybrid efficiency and the electricity delivered, as large quantities of geothermal heat reduce the system efficiency but increase the quantity of electricity that may be delivered. More detailed models should investigate this trade-off and its influence on the system cost.

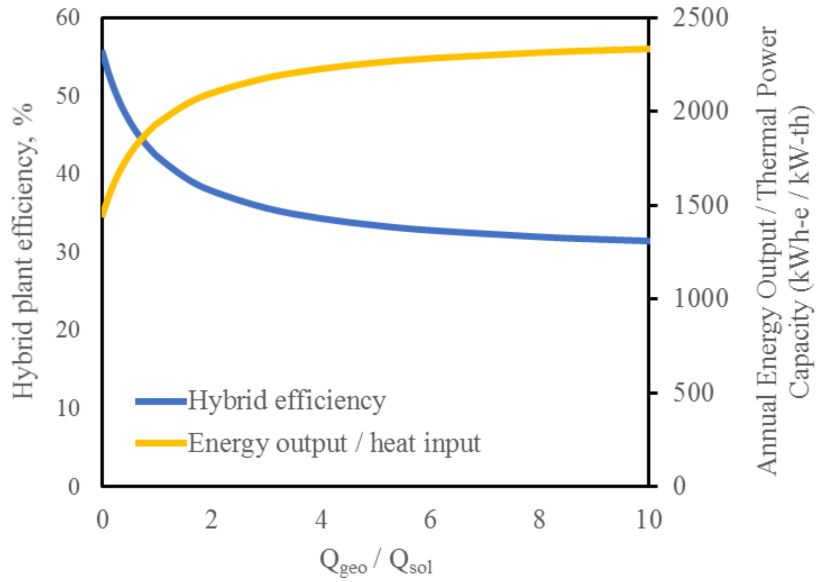


**Figure 6: The efficiency and annual energy output per unit installed thermal power capacity for a hybrid geothermal plant as a function of the relative sizes of the solar and geothermal systems.**

## 5. CONCLUSIONS

In this article, the hybridization of geothermal power plants with heat from a concentrating solar power plant is investigated. Several projects conducted by the National Renewable Energy Laboratory and collaborators are summarized. These projects have so far concentrated on retrofitting existing geothermal power plants with solar heat. Existing geothermal plants may have spare capacity available in the power block and heat rejection system due to declining geothermal resources. Adding heat from a concentrating solar field may be a cost-effective way to bring the power plant back to its design point. Two projects are described which investigate the retrofit of a double-flash geothermal plant (based on the Coso geothermal field) and the retrofit of a binary geothermal plant (based on the Raft River plant), respectively. The influence of solar field sizing and thermal storage sizing and cost are investigated, and it is found that solar fields should be slightly oversized in order to provide sufficient quantities of heat all year round. Thermal storage enables the hybrid plants to operate more flexibly and to dispatch a greater quantity of electricity since curtailment is reduced. However, storage increases the capital cost of the system and can lead to a higher levelized cost of electricity (LCOE). These investigations indicate that if storage is sufficiently cheap then the LCOE can be reduced, although this requires further cost reductions compared to current storage costs. It should be noted that the LCOE is not the most suitable metric for systems that include energy storage since it does not account for other benefits that storage can provide to the system. The hybrid geothermal-solar-storage plants were also compared to equivalently sized solar photovoltaic (PV) farms with battery energy storage (BES), which are being widely-deployed. While it was found that LCOEs were lower for PV systems with no storage, once storage was included, the hybrid plants were more cost effective than PV plus BES. This is due to the relatively high cost and frequently replacement rate of batteries. Geothermal and solar may also be combined in a greenfield plant. Such a system could take advantage of the high capacity factor of geothermal power and the relatively high efficiency of solar power. Some simple analysis is presented that discusses the trade-off between the hybrid system efficiency and annual energy dispatched when choosing the relative sizing of the solar and geothermal systems.

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## REFERENCES

Astolfi, Marco, Luca Xodo, Matteo C Romano, and Ennio Macchi. 2011. "Technical and Economical Analysis of a Solar – Geothermal Hybrid Plant Based on an Organic Rankine Cycle." *Geothermics* 40(1): 58–68. http://dx.doi.org/10.1016/j.geothermics.2010.09.009.

Bonyadi, Nima, Evan Johnson, and Derek Baker. 2018. "Technoeconomic and Exergy Analysis of a Solar Geothermal Hybrid Electric Power Plant Using a Novel Combined Cycle." *Energy Conversion and Management* 156(September 2017): 542–54. https://doi.org/10.1016/j.enconman.2017.11.052.

Denholm, Paul, Josh Eichman, and Robert Margolis. 2017. *Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants*.

DiPippo, Ronald. 2016. *Geothermal Power Plants*. 4th editio. Butterworth-Heinemann.

DiPippo, Ronald, and Kevin Kitz. 2015. "Geothermal Binary Power Plants at Raft River, San Emidio, and Neal Hot Springs: Part 1 — Plant Descriptions and Design Performance Comparison." *GRC Transactions* 39: 833–46.

Feldman, David et al. 2016. *Exploring the Potential Competitiveness of Utility-Scale Photovoltaics plus Batteries with Concentrating Solar Power , 2015 – 2030*.

Ghasemi, Hadi et al. 2014. "Hybrid Solar–geothermal Power Generation: Optimal Retrofitting." *Applied Energy* 131: 158–70.

Lai, Chun Sing et al. 2017. "A Comprehensive Review on Large-Scale Photovoltaic System with Applications of Electrical Energy Storage." *Renewable and Sustainable Energy Reviews* 78(November 2016): 439–51. http://dx.doi.org/10.1016/j.rser.2017.04.078.

Lentz, Alvaro, and Rafael Almanza. 2006. "Solar – Geothermal Hybrid System." *Applied Thermal Engineering* 26: 1537–44.

McTigue, Joshua et al. 2017. "Retrofitting a Geothermal Plant with Solar and Storage to Increase Power Generation." *Transactions - Geothermal Resources Council* 41.

McTigue, Joshua D., Jose Castro, et al. 2018. "Hybridizing a Geothermal Power Plant with Concentrating Solar Power and Thermal Storage to Increase Power Generation and Dispatchability." *Applied Energy* 228: 1837–52. doi: 10.1016/j.apenergy.2018.07.064.

McTigue, Joshua D., Daniel S Wendt, et al. 2018. "Solar Powered Steam-Turbine Topping Cycle for a Binary Geothermal Power Plant." *NREL Technical Report*.

Miguel Cardemil, José, Felipe Cortés, Andrés Díaz, and Rodrigo Escobar. 2016. "Thermodynamic Evaluation of Solar-Geothermal Hybrid Power Plants in Northern Chile." *Energy Conversion and Management* 123: 348–61.

"National Solar Radiation Database." 2017. https://nsrdb.nrel.gov/ (November 12, 2017).

NREL. 2017. "System Advisor Model (SAM)." https://sam.nrel.gov/.

Short, Walter, and Daniel J Packey. 1995. "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies." *NREL Technical Report NREL/TP-462-5173* (March).

SimTech. 2017. "Process Simulation Environment (IPSEpro)." http://www.simtechnology.com/CMS/index.php/ipsepro.

Snyder, Diana M, Koenraad F Beckers, Katherine R Young, and Bud Johnston. 2017. "Analysis of Geothermal Reservoir and Well Operational Conditions Using Monthly Production Reports from Nevada and California." *Transactions - Geothermal Resources Council* 41.

Zhou, Cheng, Elham Doroodchi, and Behdad Moghtaderi. 2013. "An In-Depth Assessment of Hybrid Solar–geothermal Power Generation." *Energy Conversion and Management* 74: 88–101.