Hybrid Geo-Solar GeoVision Case Study Analysis: CSP power plant with geothermal boiler feedwater heating

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Keywords

GeoVision Study; concentrated solar power; hybrid geo-solar; steam Rankine cycle; thermal energy storage

ABSTRACT

A case study analysis of hybrid CSP-GT power plants using the geothermal boiler feedwater heating plant configuration was performed. The hybrid CSP-GT plant converts geothermal energy to electricity at a higher efficiency than a stand-alone geothermal plant. Additionally, the hybrid CSP-GT plant operates with a higher capacity factor than a stand-alone CSP plant.

In general, the hybrid CSP-GT plant is able to provide decreases in LCOE relative to stand-alone geothermal, especially when considering lower geothermal resource temperatures. However, the LCOE for stand-alone CSP tends to be lower than for the hybrid plant at the lowest geothermal resource temperatures evaluated, and the LCOE for stand-alone geothermal is lower than that of the hybrid plant at the highest geothermal resource temperatures evaluated. The hybrid configuration therefore tends to be the lowest LCOE option for an intermediate range of geothermal resource temperatures, which will vary on a site-by-site basis.

Introduction

The United States Department of Energy (DOE) Geothermal Technologies Office (GTO) has undertaken a vision study (GeoVision Study) to conduct a credible analysis of potential geothermal growth scenarios across multiple market sectors including geothermal electric generation, thermal applications, and other additive value streams. The GeoVision Hybrid Systems task force evaluated aspects of hybrid technology that could increase the utilization of geothermal energy. Important aspects of the hybrid systems analysis include evaluating conditions where hybrid technologies could decrease the costs of geothermal power generation and/or increase the viability of low temperature geothermal resources.

Stand-alone concentrated solar power (CSP) plants are able to operate at higher temperatures, and consequently higher efficiencies, than geothermal (GT) power plants. This analysis evaluates the cost and performance of a hybrid CSP-GT plant configuration in which geothermal heat is used to provide boiler feedwater heating in a steam Rankine cycle CSP plant (Figure 1). Using geothermal heat for the boiler feedwater heating reduces the extraction of low pressure steam for this purpose, such that a greater fraction of the steam can be used to drive the turbines for electrical power generation.

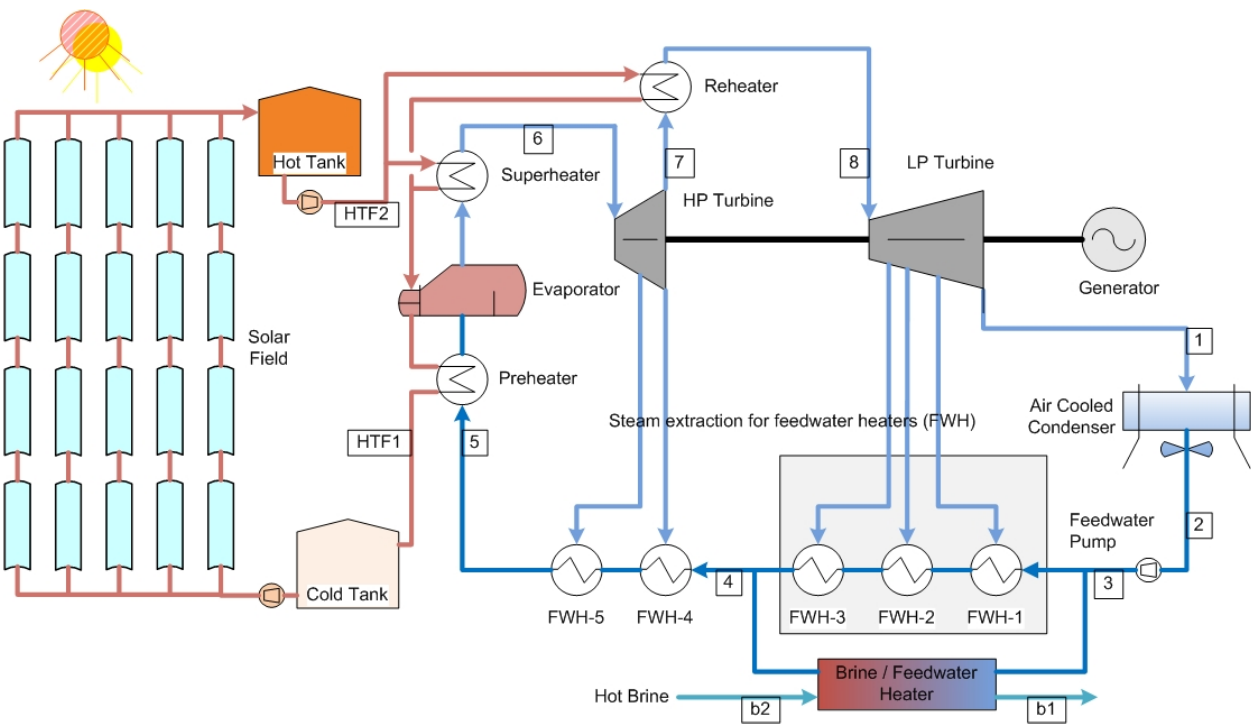

Figure 1. Schematic of a representative CSP plant showing energy from geothermal brine replacing the three low-temperature feedwater heaters (FWH-1, FWH-2, and FWH-3), thereby eliminating steam extractions from the low-pressure turbine. Open, hot (direct contact) FWHs are shown for simplicity, although the model uses closed FWHs (Turchi et al., 2014).

This analysis investigated stand-alone and hybrid CSP plant configurations in which the solar field size and thermal energy storage capacity were modified to provide an increased capacity factor relative to the default System Advisor Model (SAM) CSP plant configuration. A CSP plant with higher capacity factor is better able to utilize geothermal energy by minimizing the amount of time the plant is offline and the geothermal energy cannot be used.

Methods

This analysis compares the cost and performance of hybrid CSP-GT plants against the cost and performance of stand-alone GT and stand-alone CSP plants. These plant configurations were evaluated in two case studies: (1) an undiscovered hydrothermal geothermal resource type with GeoVision Business-As-Usual Scenario (reference scenario) GETEM input values and reference solar hardware costs, and (2) a deep Enhanced Geothermal System (EGS) geothermal resource type with GeoVision Exploration De-Risk Scenario (improved scenario) GETEM input values and improved solar hardware costs. In both of these case studies, stand-alone and hybrid plant performance was evaluated for specified geothermal resource temperature and depth combinations using Daggett, CA solar insolation and ambient temperature TMY data.

The cost and performance of the stand-alone GT plants was estimated using the GeoVision 2016 version of the Geothermal Electricity Technology Evaluation Model (GETEM), which is the standard modeling tool utilized in the GeoVision study for evaluating geothermal power plant performance. GETEM was also used to compute the well field performance and capital and operating costs for the geothermal resources utilized in the hybrid CSP-GT power plants.

The cost and performance of the stand-alone CSP plants was estimated using version 2017.1.17 rev1 of SAM (National Renewable Energy Laboratory, 2017). SAM was also used to compute the hourly solar field and thermal energy storage performance (thermal output and parasitic loads) and provide typical meteorological year (TMY) data for the hybrid CSP-GT plant analysis.

The solar field size was adjusted to provide an increased CSP plant capacity factor by increasing the solar multiple (SM) and the thermal energy storage (TES) capacity as specified in Table 1. With the exception of the modifications listed in Table 1, the SAM default CSP parabolic trough (physical) model solar field specifications were used for both stand-alone and hybrid CSP plant evaluation. The reference costs listed in Table 1 are used for evaluating the GeoVision Business-As-Usual (BAU) Scenario. The improved costs listed in Table 1 are used for evaluating the GeoVision Exploration De-Risk Scenario.

The performance of the stand-alone CSP and hybrid CSP-GT power plants were simulated using Aspen Plus based models. The design parameters for the stand-alone and hybrid CSP power cycles used in the Aspen Plus power cycle models are listed in Table 2. The Aspen Plus stand-alone and hybrid CSP power cycle models utilized the WILS-LR property method to compute Therminol VP-1 solar field heat transfer fluid (HTF) properties, the STEAMNBS property method to compute the water and steam properties (geofluid and steam Rankine cycle working fluid), and the IDEAL property method to compute air properties. Hybrid CSP-GT plant performance was evaluated for selected geothermal resource design point temperatures of 125°C, 150°C, 175°C, 200°C, 225°C, and 250°C.

The Aspen Plus models were also used to simulate the off-design performance of the hybrid CSP-GT power plants over a range of operating conditions. The power plant models calculated off-design performance using an approach similar to that used by Patnode (2006) and Padilla (2011): The pressure drop of each turbine stage was calculated using Stodola Law (Stodola and Loewenstein, 1945), the efficiency of each turbine stage was calculated using an efficiency reduction factor (Bartlett, 1958), and the heat exchanger performance was calculated using the effectiveness-NTU method (Incropera and DeWitt, 2002).

Independent variables that were varied to characterize the hybrid plant off-design performance included (1) solar field thermal output, (2) geothermal resource temperature [analysis assumes 0.5%/yr temperature decline], and (3) dry bulb ambient temperature. A unique regression function was established to predict hybrid plant performance as a function of these independent variables for each geothermal resource design temperature investigated (125°C, 150°C, 175°C, 200°C, 225°C, and 250°C). The regression functions were then used in combination with SAM TMY hourly data to estimate power plant performance. The power plant performance, capital costs, and operating and maintenance (O&M) costs were then used to compute levelized cost of electricity (LCOE) using the DOE Energy Efficiency and Renewable Energy (EERE) approach as implemented in GETEM.

Table 1. Reference and improved scenario solar field configuration and costs

	reference	improved	Reference or comment
Hybrid Plant Configuration			
Solar multiple	4	4	SAM default SM = 2 (National Renewable Energy Laboratory, 2017)
Thermal energy storage (hr)	16	16	SAM default TES = 6 hr (National Renewable Energy Laboratory, 2017)
Turbine inlet pressure control	Sliding	Sliding	SAM default is fixed turbine inlet pressure control (National Renewable Energy Laboratory, 2017)
Condenser type	Air-cooled	Air-cooled	Consistent with SAM default (National Renewable Energy Laboratory, 2017)
Geographic location	Daggett, CA	Daggett, CA	SAM TMY solar resource and ambient temperature data used for hourly calculation of plant performance (National Renewable Energy Laboratory, 2017)
Hybrid Plant Economic Analysis Parameters			
Site improvements ($\$/m^2$)	20	10	CSP trough roadmap and target values (U.S. Department of Energy, 2012)
Solar field ($\$/m^2$)	150	75	SAM default CSP parabolic trough (physical) model solar field cost (National Renewable Energy Laboratory, 2017); SunShot CSP trough target cost (U.S. Department of Energy, 2012)
Heat transfer fluid system ($\$/m^2$)	50	50	CSP trough roadmap (U.S. Department of Energy, 2012);
Storage ($\$/kWh_t$)	25	15	CSP trough roadmap and target values (U.S. Department of Energy, 2012)
Plant/project life	25 years	25 years	GeoVision Scenario GETEM input value
Annual rate of GT resource temperature decline	0.5%/yr	0.5%/yr	GeoVision Scenario GETEM input value
Contingency	15%	15%	GeoVision Scenario GETEM input value
Indirect costs	12%	12%	GeoVision Scenario GETEM input value
Discount rate during operation	7%	7%	GeoVision Scenario GETEM input value
Taxes	39.2%	39.2%	GeoVision Scenario GETEM input value

Table 2. CSP Steam Rankine cycle design parameters

Variable	Value	Reference or Comment
Heat Exchangers		
HTF inlet temperature	393.3°C	Appendix B in Turchi (2010)
HTF flow rate	5,017,440 kg/hr	Appendix B in Turchi (2010)
Evaporator pressure	91.4 bar	Appendix B in Turchi (2010)
Evaporator minimum internal temperature approach	5°C	steam mass flow rate varied to achieve design specification
Reheat steam conditions	371°C 25 bar	Appendix B in Turchi (2010)
geofluid mass flow rate	500,000 kg/hr	
geofluid heat exchanger minimum internal temperature approach	5°C	cold side heat duty varied to achieve design specification
Steam Turbines		
turbine inlet conditions	371°C 91.4 bar	Appendix B in Turchi (2010)
number of stages	2 HP 5 LP	Montes et al. (2009), Padilla (2011), Patnode (2006)
turbine isentropic efficiencies (all stages)	0.90	adjusted to match SAM simulation gross power output results
HP turbine steam extraction pressures	49.85 bar 25 bar	HP steam extraction pressures set to achieve equal Δh_s w.r.t. steam extraction saturation pressures (Kostyuk and Frolov, 1988, Nag, 2002)
LP turbine steam extraction pressures	12.44 bar 5.43 bar 1.99 bar 0.63 bar	LP steam extraction pressures set to achieve equal Δh_s w.r.t. steam extraction saturation pressures (Kostyuk and Frolov, 1988, Nag, 2002)
Air-Cooled Condenser		
ambient temperature	42.2°C	Appendix B in Turchi (2010)
condensing pressure	0.166 bar	Appendix B in Turchi (2010)
hot side ΔT	3°C	Table 16 in Wagner and Gilman (2011)
condenser air pressure ratio	1.0028	Table 16 in Wagner and Gilman (2011)
fan isentropic efficiency	0.80	Table 16 in Wagner and Gilman (2011)
fan mechanical efficiency	0.94	Table 16 in Wagner and Gilman (2011)
Feedwater Heaters		
LP steam FW heater configuration	3 closed FW heaters; 1 deaerator	Montes et al. (2009), Padilla (2011), Patnode (2006)
HP steam FW heater configuration	2 closed FW heaters	Montes et al. (2009), Padilla (2011), Patnode (2006)
terminal temperature difference	2.8°C	Drbal et al. (1996), Padilla (2011)
Boiler Feed Pumps		
pump isentropic efficiencies (all)	0.695	Table 12 in Wagner and Gilman (2011)

Results and Discussion

A stand-alone CSP plant with the default SM and TES capacity located in Daggett, CA (solar resource of 7.6 kWh/m^2/day) is calculated to have a LCOE of $0.133/kWh and $0.093/kWh with the reference and improved scenario solar hardware costs, respectively. The stand-alone CSP plant with the modified SM and TES capacity in the same location has LCOE values of \$0.126/kWh and \$0.084/kWh for the reference and improved scenario solar hardware costs, respectively.

The modified configuration (high capacity factor) stand-alone CSP plant LCOE was used as the basis for comparing stand-alone and hybrid CSP plant economics. Since the modified CSP plant configuration has a lower LCOE than the SAM default CSP plant configuration when using the solar field costs specified in this analysis, cases in which the hybrid plant LCOE is lower than the stand-alone plant LCOE will be applicable for both the default and modified stand-alone CSP plant configurations (i.e., if the hybrid geo-solar plant LCOE is lower than the stand-alone CSP plant LCOE, it will be lower regardless of whether the CSP plant configuration resembles the SAM default configuration or the GeoVision modified configuration).

Business-As-Usual Scenario with Undiscovered Hydrothermal Resource

The case study analysis of the Business-As-Usual Scenario with an undiscovered hydrothermal resource utilized the reference solar hardware costs listed in Table 1 and the resource and hybrid plant specifications listed in Table 3.

Table 3. Resource and hybrid plant specifications for case study analysis based on Business-As-Usual Scenario

Plant type	Hybrid geo-solar (solar CSP with GT boiler feedwater heating)					
TMY data	Daggett, CA (7.6 kWh/m^2/day annual average DNI)					
Solar resource	Parabolic trough solar field @ 1,892,453 m^2 (SM=4)					
Geothermal resource	Greenfield hydrothermal @ 138.8 kg/s (2 production wells)					
T (°C)	250	225	200	175	150	125
depth (m)	2,000	2,000	2,000	2,000	2,000	2,000
geofluid pumping parasitic load (kW)	864.6	598.1	463.6	517.2	582.2	658.9
Plant capacity (MWe)	120.1	115.1	111.8	107.8	104.4	101.9
Net efficiency	29.0%	29.0%	29.0%	29.2%	29.5%	30.0%
Capacity factor	81.2%	81.2%	81.6%	81.5%	81.4%	81.1%

A stand-alone CSP plant using the solar resource specified in Table 3 has a capacity of 100 MW and a net efficiency of 32.0% with a calculated capacity factor of 45.7% (SM=2) or 80.1% (SM=4). Stand-alone geothermal binary cycle plants (geothermal flash plants were not considered in this analysis) using the geothermal resource flow rate and temperatures specified in Table 3 have capacity ranging from 4.9 MW (125°C) to 15.4 MW (250°C) with a GETEM specified capacity factor of 95%.

The hybrid plant generally operates with a higher capacity factor than the stand-alone solar plant and with greater output and efficiency than the stand-alone geothermal plant. The hybrid plant efficiency is slightly lower than the stand-alone CSP plant as a result of the lower average heat source temperature (geothermal heat input is supplied at a lower temperature than the solar heat). The hybrid plant efficiency increases with decreasing GT resource T due to the corresponding decrease in GT heat input (a greater fraction of the hybrid plant heat input is from solar heat supplied at temperatures approaching 400°C).

The LCOE of the stand-alone geothermal, stand-alone CSP, and hybrid geo-solar power plants are shown as a function of geothermal resource temperature in Figure 2. The results plotted in Figure 2 are based on the use of a binary power cycle for all stand-alone geothermal plants, independent of resource temperature. While the LCOE for a stand-alone CSP plant is plotted in Figure 2, this value does not change with geothermal resource temperature. The range of geothermal resource temperatures where the hybrid plant LCOE is lower than the stand-alone GT and stand-alone CSP plant LCOE is designated by green shading.

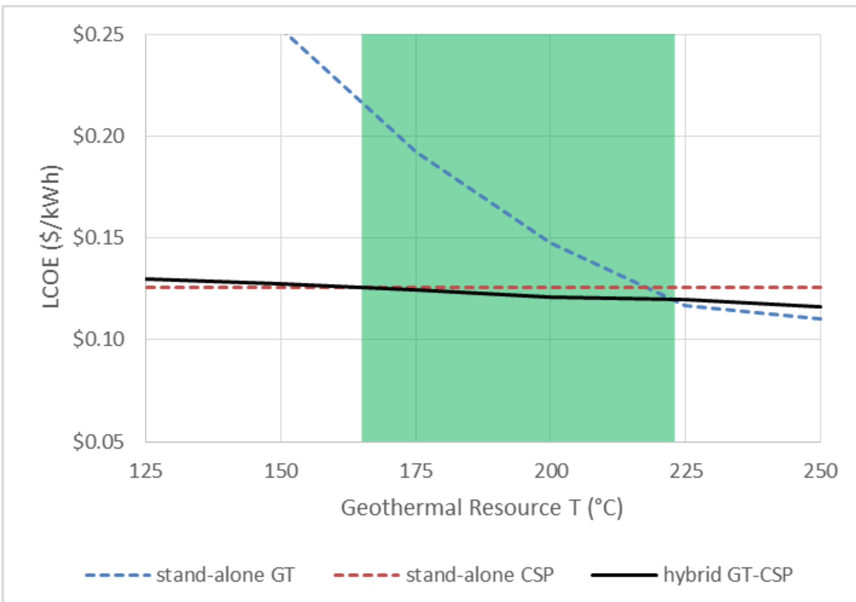

Figure 2. Undiscovered Hydrothermal LCOE for stand-alone binary GT, stand-alone CSP, and hybrid CSP-GT power plants in Business-As-Usual Scenario. The LCOE for the hybrid plant is lower than the LCOE for both stand-alone GT and CSP plants in the range of geothermal resource temperatures designated by the shaded plot area.

Exploration De-Risk Scenario with Deep EGS Resource

The case study analysis of the Exploration De-Risk Scenario with a deep EGS resource utilized the reference solar hardware costs listed in Table 1 and the resource and hybrid plant specifications listed in Table 4.

The stand-alone CSP plant performance is unchanged between the BAU and Exploration De-Risk Scenarios with a capacity of 100 MW, a net efficiency of 32.0%, and a calculated capacity factor of 45.7% (SM=2) or 80.1% (SM=4). Stand-alone geothermal binary cycle plants using the geothermal resource flow rate and temperatures specified in Table 4 have capacity ranging from

Table 4. Resource and hybrid plant specifications for case study analysis based on Exploration De-Risk Scenario

Plant type	Hybrid geo-solar (solar CSP with GT boiler feedwater heating)					
TMY data	Daggett, CA (7.6 kWh/m^2/day annual average DNI)					
Solar resource	Parabolic trough solar field @ 1,892,453 m^2 (SM=4)					
Geothermal resource	Greenfield EGS @ 138.8 kg/s (2 production wells)					
T (°C)	250	225	200	175	150	125
depth (m)	6,000	6,000	5,000	5,000	4,000	4,000
geofluid pumping parasitic load (kW)	1.6	1.6	123.4	313.3	625.7	786.6
Plant capacity (MWe)	121.0	115.7	112.2	108.0	104.3	101.8
Net efficiency	29.2%	29.2%	29.1%	29.3%	29.5%	29.9%
Capacity factor	81.3%	81.3%	81.6%	81.5%	81.4%	81.1%

3.9 MW (125°C) to 16.0 MW (250°C) with a GETEM specified capacity factor of 95%. The discrepancies in hybrid plant capacity between the BAU and Exploration De-Risk Scenarios are due to the differences in geofluid pumping requirements associated with the different resource types utilized in each scenario.

The same general conclusions from the BAU scenario analysis hold for the Exploration De-Risk scenario regarding hybrid plant efficiency and capacity factor relative to the stand-alone GT and CSP plants. Figure 3 presents the LCOE of the stand-alone geothermal, stand-alone CSP, and hybrid geo-solar plants as a function of geothermal resource temperature. As in Figure 2, the range of geothermal resource temperatures where the hybrid plant LCOE is lower than the stand-alone GT plant LCOE and stand-alone CSP plant LCOE is designated by green shading.

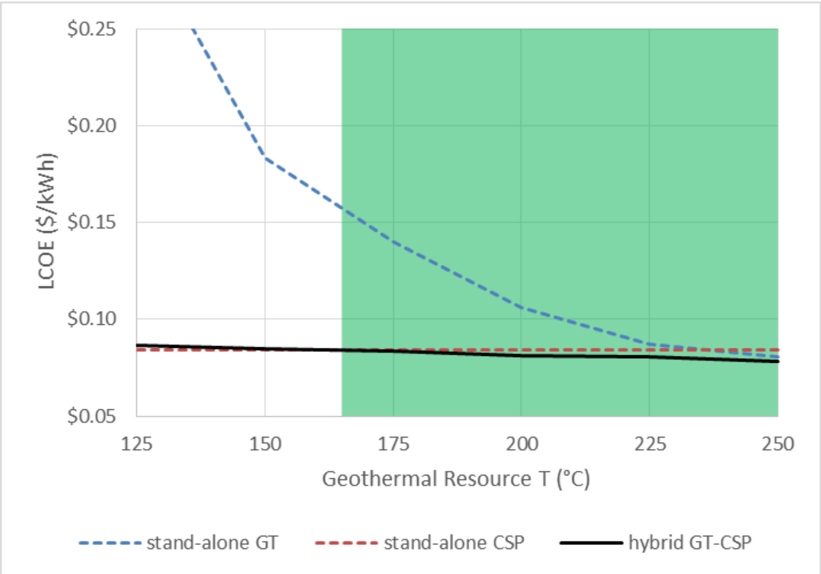

Figure 3. Deep EGS LCOE for stand-alone GT, stand-alone CSP, and hybrid CSP-GT power plants in Exploration De-Risk Scenario. The LCOE for the hybrid plant is lower than the LCOE for both stand-alone GT and CSP plants in the range of geothermal resource temperatures designated by the shaded plot area.

In both scenarios evaluated, the boiler feedwater heating hybrid plant LCOE is lower than both the stand-alone GT LCOE and stand-alone CSP LCOE for a significant range of geothermal resource temperatures. This temperature range generally corresponds to the conditions where stand-alone geothermal plant LCOE and stand-alone CSP plant LCOE are similar, i.e. the hybrid plant outperforms both stand-alone plants in situations where the stand-alone plants are cost-competitive with each other. When one of the stand-alone power plants has a significantly lower LCOE than the other, hybridization does not overcome this cost differential and use of the least-cost stand-alone plant would result in the lowest LCOE.

Another way of viewing this result is that the hybrid plant significantly extends the range of geothermal resource temperatures over which a power plant that utilizes geothermal heat is cost-competitive with stand-alone CSP (e.g., in both cases evaluated a stand-alone CSP plant has lower LCOE than a stand-alone GT plant using a 200°C geothermal resource, but the hybrid plant LCOE is lower than either stand-alone option resulting in the theoretical deployment of a power plant that uses geothermal energy instead of one that does not).

In addition to the results presented in Figure 2 and Figure 3, numerous other geothermal resource temperature and depth combinations, geographic locations with lower average DNI solar resource, as well as the GeoVision Technology Transfer improved scenario were investigated. For nearly all of the alternate conditions evaluated, there was a subset of geothermal resource temperatures where the hybrid plant LCOE was lower than both stand-alone plants. This suggests that in scenarios where stand-alone geothermal and stand-alone CSP LCOE is similar, use of hybrid CSP-GT technology could provide performance and economic benefits.

It is important to note that the geothermal resources considered in this case study analysis were of intermediate size (total production fluid flow rate of approximately 140 kg/s). The geothermal levelized cost of heat (LCOH) would decrease at sites where larger volumes of production fluid are available, which would shift the stand-alone GT and hybrid plant LCOE curves in Figure 2 and Figure 3 downward having the net effect of narrowing the range of geothermal resource temperatures at which the LCOE of the hybrid plant is lower than both of the stand-alone plants.

Conclusions

The hybrid CSP-GT plant offers several performance advantages relative to stand-alone GT and stand-alone CSP plants. The hybrid CSP-GT plant converts geothermal energy to electricity at a higher efficiency than a stand-alone geothermal plant. Additionally, the hybrid CSP-GT plant operates with a higher capacity factor than a stand-alone CSP plant.

In general, the hybrid CSP-GT plant is able to provide significant decreases in LCOE relative to stand-alone geothermal, especially when considering lower geothermal resource temperatures. However, the LCOE for stand-alone CSP tends to be lower than for the hybrid plant at the lowest geothermal resource temperatures evaluated. The hybrid CSP-GT configuration therefore tends to be the lowest LCOE option for an intermediate range of geothermal resource temperatures, which will vary on a site-by-site basis.

In the cases evaluated, the geothermal resource temperatures for which the hybrid plant lowers LCOE are in the range of approximately 175°C to 225°C, for which there is a significant quantity of geothermal resource availability (these cases considered a location with a solar resource greater than 7 $kWh/m^2/day$, although unpublished results from this analysis indicates that these general conclusions are also applicable in cases with a solar resource between 5 and 7 $kWh/m^2/day$). The hybrid plant could therefore be widely applicable, deploying before stand-alone GT and stand-alone CSP at locations (and in scenarios) where the LCOE of the stand-alone plants are comparable such that the hybrid plant could provide the lowest LCOE alternative.

Acknowledgement

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