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Hybrid Geo-Solar Binary Power Plant Supply Curve Analysis

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Keywords

GeoVision Study; hybrid geo-solar; supercritical air-cooled binary cycle; supercritical air-cooled organic Rankine cycle; supply curve; time-of-delivery pricing

ABSTRACT

This analysis evaluated a hybrid geo-solar air-cooled supercritical binary cycle power plant configuration for selected scenarios defined in the GeoVision Study. General benefits of hybrid geo-solar technology include the ability to decrease the risks and mitigate impacts associated with geothermal resource productivity decline. Hybrid geo-solar power plants also improve the temporal correlation between generation and load. Use of geo-solar hybrid plants could therefore largely defend against the economic penalties that would otherwise be associated with air-cooled geothermal power generation in a time-of-delivery electricity pricing market.

This analysis indicates that hybrid geo-solar technology generally provides the greatest reductions in LCOE when paired with low-temperature geothermal resources (where costs of stand-alone geothermal power generation tend to be highest). If the costs of solar collectors can be reduced to the targets set by DOE and the concentrating solar power industry, hybrid geo-solar technology will allow LCOE reductions in locations with good solar resource and where stand-alone geothermal power generation costs are moderate (~$0.10/kWh) to high (≫$0.15/kWh). For all geothermal resource types evaluated, there is a threshold LCOE where a geothermal industry that utilizes hybrid geo-solar plants would be able to provide increased capacity at an equal or lower LCOE than a geothermal industry comprised solely of stand-alone geothermal plants.

1. Introduction and Overview

1.1 General Background

Geothermal and solar are renewable energy resources that can provide thermal energy for electrical power generation or other thermal applications. Geothermal and solar resources have attributes that differ considerably, but can be combined to obtain a hybrid heat source with superior characteristics to the individual resources.

Geothermal energy is steady and reliable, but is subject to resource productivity declines over long time periods. Additionally, air-cooled geothermal power plant performance suffers during mid-day periods when the ambient temperature is elevated. Since geothermal heat is supplied at a relatively low temperature, stand-alone geothermal power plants operate with relatively low thermal efficiency. Another consequence of the relatively low temperature of geothermal resources is that variations in the geothermal resource productivity (temperature or flow rate) and the ambient temperature can have significant negative impacts on power plant performance.

Solar energy is an intermittent renewable energy source. While long term solar resource performance can be accurately predicted for a given location, short term performance can be highly variable. Solar energy is only available during the day time, with additional variability introduced by the presence or absence of cloud cover at a given geographic location. Solar energy can be directly converted to electricity via photovoltaic (PV) technology, or heat via concentrating solar collectors. Solar heat can be converted to electricity in a thermoelectric power plant. Concentrating solar technology can supply heat at temperatures of 500°C or greater, which allows concentrating solar power (CSP) plants to operate with greater efficiency than stand-alone geothermal plants. However, the intermittent nature of solar heat requires use of thermal storage for reliable plant operations.

Solar thermal energy can be combined with geothermal energy in a thermo-electric power plant. A hybrid geothermal solar-thermal power plant can synergistically combine the attributes of both heat sources to produce a power plant with superior performance. Solar heat input to an air-cooled geothermal power plant can increase power generation during the mid-day hours when stand-alone geothermal plant performance is typically lowest. The hybrid plant can continue to operate during periods when solar energy is unavailable without use of thermal storage. Shared use of a common power block can reduce capital costs relative to separate stand-alone geothermal and solar-thermal plants. Additionally, the solar field can be resized in the event of long term geothermal resource productivity decline to mitigate risks associated with underutilization of the power block.

Commercial geo-solar hybrid plant deployment is currently limited to Enel Green Power’s Stillwater plant. The Stillwater geothermal solar hybrid plant is a retrofit configuration in which the solar heat supplements the geothermal heat input to the organic Rankine cycle (ORC) power block. The Stillwater hybrid plant uses a “brine preheating” configuration in which the solar heat is added to the geothermal production fluid en-route to the power block. The solar field operates as a closed-loop with a pressurized water heat transfer fluid (HTF). Heat from the solar field HTF is transferred to the production fluid from the site’s coolest production wells via a heat exchanger. The solar heat addition increases the production fluid temperature. The power block then utilizes the greater energy content of the solar-heated production fluid to increase net power generation.

CSP deployment in stand-alone and hybrid applications is currently limited by the costs of the solar collectors. Hybrid geo-solar applications where the elevated temperature of the solar heat is not effectively utilized suffer an efficiency penalty that exacerbates the relatively high costs of solar heat. Future hybrid plant configurations that can take full advantage of the high temperature solar heat while maintaining the ability to reduce capital costs through elimination of thermal storage and/or use of a common power block will increase the economic competitiveness of geothermal solar hybrid power plants. Possible next generation geothermal solar hybrid plant configurations include ORC cycles with solar heat input to the ORC working fluid; dual pressure level or dual fluid power cycles with high temperature solar heat and intermediate temperature geothermal heat utilization/integration; and concentrating solar power plants utilizing geothermal heat for boiler feedwater heating (see Appendix A for a case study analysis of the latter hybrid plant configuration).

1.2 GeoVision Analysis

The GeoVision hybrid systems analysis focused on aspects of hybrid technology that can increase the utilization of geothermal energy. Important aspects of the hybrid systems analysis therefore include evaluating conditions where hybrid technologies could decrease the costs of geothermal power generation and/or increase the viability of low temperature geothermal resources.

As previously mentioned, the brine-preheating configuration is currently utilized in the single commercially deployed hybrid geo-solar power plant. A next-generation implementation of hybrid geo-solar binary power plants could realize performance benefits from heating the working fluid in an air-cooled supercritical binary power plant (Figure 1); this next-generation hybrid power plant configuration is examined in this analysis.

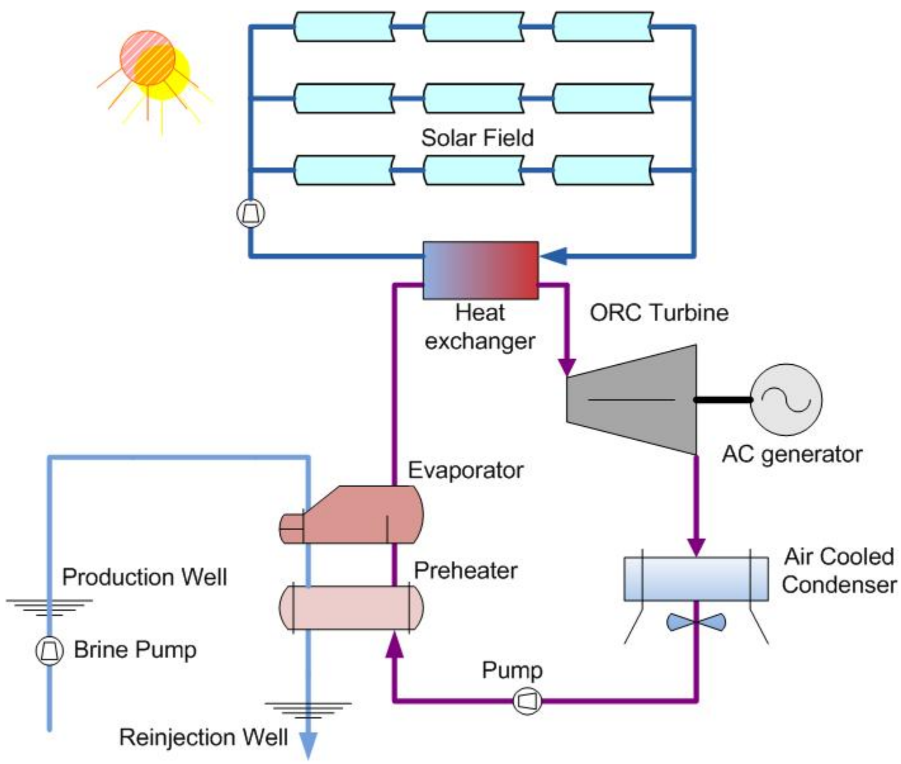

Figure 1. ORC working fluid hybrid plant configuration (Wendt et al., 2015a)

2. Hybrid Geo-Solar Power Plant Supply Curve Analysis

A number of scenarios have been investigated as part of the GeoVision Study market penetration analysis performed by the Potential to Penetration (P2P) task force. Each of these scenarios is defined by a set of technical, economic, and market conditions that may be representative of the future energy market. The GeoVision Study market penetration analysis predicts the quantity of geothermal power that would deploy in each of the selected scenarios. The market penetration analysis uses the Regional Energy Deployment System (ReEDS) model to predict deployment of geothermal power plants. The ReEDS model is currently unable to evaluate hybrid power plants, and it was therefore not possible to evaluate the potential market penetration from hybrid geo-solar power plants in the current GeoVision analysis.

This analysis of hybrid geo-solar power plants attempts to emulate many of the important aspects of the stand-alone geothermal plant market penetration analysis. These include the development of a model to evaluate the performance and cost of hybrid geo-solar power plants under various geothermal and solar resource conditions, the use of a geothermal and solar resource dataset to establish supply curves that characterize the quantity of electrical power that could be deployed at various costs, and the analysis of scenarios under which hybrid geo-solar power plants may provide advantages relative to stand-alone geothermal plants.

Although the stand-alone geothermal supply curves generated for each scenario of the GeoVision market penetration analysis present capital costs (in terms of $/kW of capacity) as a function of total available capacity, the hybrid geo-solar supply curves were presented as levelized cost of electricity (LCOE) as a function of total available capacity. Whereas the stand-alone geothermal supply curves are an intermediate market penetration analysis result and are used as input to the ReEDS model, the hybrid geo-solar market analysis cannot currently be performed in ReEDS and the supply curves are one of the final results of the analysis. Since the capital costs do not represent all costs associated with deployment of a hybrid power plant, LCOE (which includes CAPEX, OPEX, and financial contributions) was used to designate the cost associated with deployment of various quantities of hybrid geo-solar power.

Of the GeoVision Scenarios, the hybrid geo-solar analysis was performed for the Business-As-Usual (BAU) and Technology Transfer Scenarios. The Business-As-Usual Scenario represents conditions corresponding to the status quo, i.e. the geothermal industry continues to operate under present baseline conditions. The Technology Transfer Scenario is an improvement scenario in which exploration & well development incorporate improvements from other industry technology transfers. The hybrid geo-solar analysis is consistent with the GeoVision market analysis Technology Transfer Scenario but also includes an assumed reduction in the capital cost of the solar collectors as described below.

The hybrid geo-solar analysis includes the evaluation of two electricity pricing schedules. The first is a level pricing schedule in which the price of electricity is constant with time. The second is a time-of-delivery (TOD) pricing schedule in which the price of electricity varies throughout the day. In the TOD pricing schedule, electricity pricing is generally higher when demand (or load) is greater such that consumers have an incentive to shift usage to times of off-peak demand. The power output from hybrid geo-solar plants is generally known to correspond more closely to the periods of greater power demand and hybrid plants are expected to offer economic advantages in a TOD electricity pricing market. This analysis utilizes the SAM/CSP Physical

Trough TES Dispatch/Generic Summer Peak TOD pricing schedule (National Renewable Energy Laboratory, 2017) in calculating the LCOE of stand-alone and hybrid plants operating in a TOC pricing power market.

As previously noted, major advantages of solar resources include that they can be easily characterized and have consistent long-term performance. These characteristics effectively reduce the risk associated with solar resource development, which should ultimately have the impact of reducing discount rates for developing power plants utilizing these resources. Despite the potential for solar resource utilization to reduce discount rates associated with hybrid plant development, this analysis assumes identical WACC for stand-alone and hybrid geo-solar plants (as well as geothermal resource and solar resource infrastructure). If a decreased WACC were implemented for solar hardware the LCOE for hybrid geo-solar power generation would decrease from the values reported in this analysis.

2.1 Geothermal and Solar Resource Data

Analysis of hybrid geo-solar power plants requires a dataset that includes geothermal and solar resource data at each geographic location to be evaluated. The P2P Task Force supplied the Hybrid Systems Task Force with a dataset that includes geothermal resource data for four geothermal resource types (identified hydrothermal, undiscovered hydrothermal, near-field EGS, and deep EGS). By using the geothermal resource dataset used by the P2P Task Force, the geothermal resource data used by the Hybrid Systems Task Force is consistent with that used to construct the GeoVision Study market penetration analysis supply curves.

The Hybrid Systems Task Force developed a combined geothermal-solar resource dataset by augmenting the P2P Task Force geothermal resource dataset with solar resource data from the National Solar Radiation Database (NSRDB) (National Renewable Energy Laboratory). Solar data was coupled with the geothermal resource data for each of the geothermal resource types as detailed below.

The geothermal resource database characterizes Identified Hydrothermal and Near-Field EGS resources at specific geographic sites by reservoir temperature and reservoir depth. Identified Hydrothermal and Near-Field EGS resource site latitude/longitude coordinates were entered into the NSRDB Viewer “find location” query tool to obtain the corresponding average solar DNI data.

The geothermal resource database characterizes Deep EGS resources by temperature and depth (data not provided in a geographic site-specific format that can be further parsed to include solar resource data). The Deep EGS hybrid geo-solar plant analysis therefore includes a general analysis in which all Deep EGS sites are evaluated using a solar resource value of 6.0 $kWh/m^2/day$ (a value assumed to represent the lower end of solar resources for which hybrid geo-solar plants would be viable).

A supply curve analysis of hybrid geo-solar power plants was not performed for undiscovered hydrothermal resources due to the limited number of sites with geothermal resource temperature in the range modeled for the hybrid plant analysis. Additionally, the undiscovered hydrothermal resource capacity was characterized by state, which provides too broad of a geographic area for accurate solar resource characterization. A simplified evaluation of hybrid plant LCOE relative to stand-alone plant LCOE was performed for the sites in the applicable geothermal resource temperature range using the average solar resource data from the identified hydrothermal sites in each state.

2.2 Solar Field Model

The solar field was modeled using the System Advisor Model (SAM) with a solar field configuration similar to that used in the EGP Stillwater hybrid geo-solar power plant. The Stillwater solar field is constructed of SkyFuel SkyTrough parabolic trough solar concentrators and uses pressurized water as the heat transfer fluid (Wendt et al., 2015b). The solar field size and thermal output of this reference configuration were scaled as required to meet the hybrid plant requirements at each site evaluated. The maximum solar field size evaluated for each site corresponded to that resulting in solar heat input equal to 25% of the stand-alone geothermal plant operating from an equivalent geothermal resource.

A breakdown of the solar hybridization capital costs used in this analysis is presented in Table 1. Full projects costs also include heat exchanger, contingency, and indirect costs (Wendt et al., 2015a). Solar field operating and maintenance (O&M) costs are estimated as 30% of total CSP plant O&M from the SAM CSP Parabolic Trough Model (National Renewable Energy Laboratory, 2017).

Table 1. Solar field capital costs assumed in GeoVision hybrid geo-solar analysis

Cost item	**BAU Scenario CAPEX**	**Tech Transfer Scenario CAPEX**	**Reference or comment**
Site preparation	$10/m²$	$10/m²$	assuming an existing plant site (Turchi, 2010)
Solar collector field	$150/m²$	$75/m²$	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)
HTF system	$33/m²$	$33/m²$	based on water-HTF solar field as in SAM's linear Fresnel model (National Renewable Energy Laboratory, 2017)

2.3 Power Block Model

Geo-solar air-cooled binary plant performance is impacted by changes in solar heat input and ambient temperature. In order to accurately characterize geo-solar plant performance relative to stand-alone geothermal plants, an evaluation technique that can account for time-dependent variations in power plant output as a function of changing resource and ambient conditions is required. This approach required simulation of power plant performance at on- and off-design conditions. Power plant "design" models developed in Aspen Plus were used to establish representative equipment specifications for three geothermal resource design conditions (150, 175, and 200°C). Aspen Plus-based power plant "rating" models were subsequently used to establish a map of plant performance as a function of geothermal resource temperature, solar heat input, and ambient temperature. These performance maps were established for each of the three plant designs corresponding to the three geothermal resource temperatures evaluated.

The power block evaluated in this analysis is a supercritical basic (non-recuperated) air-cooled binary cycle. The working fluid selection was dependent on the geothermal resource design temperature (R-134a, iC4, and R-245fa were selected for geothermal resource temperatures of 150°C, 175°C, and 200°C, respectively). In all cases a power plant ambient design temperature of 10°C was selected.

Hybrid plant power block capital costs were set equal to those of a stand-alone plant with equal geothermal heat input (assumes no major equipment configuration changes relative to stand-alone geothermal plant power block). Significant changes to the base power block configuration would negatively impact plant performance during periods without solar heat input while introducing additional capital costs. In order to ensure the model does not predict performance that would require equipment performance ratings be exceeded, the hybrid plant gross power generation is limited to 125% of design point gross power generation in the hybrid plant rating model (comparable to the max output of the stand-alone plant). Since the maximum hybrid plant output generally coincides with periods when stand-alone plant output would typically be lowest (mid-day periods when ambient temperature is high), this constraint does not in practice limit the hybrid plant performance.

The total hybridization costs include the costs of the solar field listed in the previous section (site preparation, solar collectors, and HTF system) and the heat exchanger used to transfer heat from the solar field HTF to the binary cycle working fluid. The HTF-to-WF heat exchanger is assumed to have an overall heat transfer coefficient equal to 1000 $W/m^2/K$ and a log-mean temperature difference (LMTD) of 30 K. The HTF-to-WF heat exchanger was costed using a shell & tube heat exchanger installed capital cost correlation (Loh et al., 2002) and updated to reference year dollars using the Producer Price Index (PPI) heat exchanger table included in the Geothermal Electricity Technology Evaluation Model (GETEM).

2.4 Hybrid GETEM Model

A Microsoft Excel spreadsheet-based model was developed to couple power plant performance maps with geographic location-specific typical meteorological year (TMY) data sets in order to estimate plant performance at one hour time intervals. TMY data sets were obtained for four representative geographic sites with average daily solar direct normal irradiance (DNI) values ranging from 4.5 to 7.5 $kWh/m^2/day$. The coupling of the plant performance maps with the TMY data allows estimation of geo-solar hybrid plant for any combination of geothermal resource temperature and average solar DNI in the ranges evaluated.

A spreadsheet-based model infrastructure was utilized to maximize compatibility and interoperability with GETEM (the model used in for techno-economic evaluation of stand-alone geothermal power plant projects for the various scenarios evaluated in the GeoVision study). In the hybrid plant analyses, GETEM was used to estimate geothermal resource performance and cost for each site evaluated, while the hybrid spreadsheet model was used to evaluate power plant performance and cost (using GETEM-derived power plant capital and operating cost calculations as applicable). GeoVision scenario-specific GETEM input parameters compiled by the P2P task force were used in evaluating each site.

As previously described, the geothermal resource database supplied by the P2P task force was modified to include solar resource data at each site. A VBA macro was utilized to evaluate geo-solar hybrid plants at all sites designated for each of the geothermal resource types in this database (identified hydrothermal, undiscovered hydrothermal, near-field EGS, and deep EGS). Geothermal and solar resource parameters for each site are passed by the macro to the linked GETEM and Hybrid GETEM spreadsheet models, where GETEM calculates geothermal reservoir performance and cost, and the Hybrid GETEM spreadsheet pairs the geothermal and solar resource conditions with the corresponding power plant performance map (based on geothermal resource temperature) and geographic site TMY data (based on average solar DNI). The model then adjusts plant performance for project size and brine effectiveness (as optimized by GETEM) and outputs hourly power generation, capital costs and O&M costs of the stand-alone and hybrid plants.

A sample plot of estimated hourly power generation for the stand-alone and hybrid plants is included below in Figure 2. The power generation profiles shown are calculated for stand-alone and hybrid power plants operating from a 175°C geothermal resource located in Reno, Nevada during a TMY week in early June. The geothermal resource in these simulations is specified to provide the thermal energy necessary to operate a 30 MW_e (design) stand-alone geothermal power plant, while the hybrid plant solar field is sized to provide thermal input equal to 25% of the design point geothermal heat input.

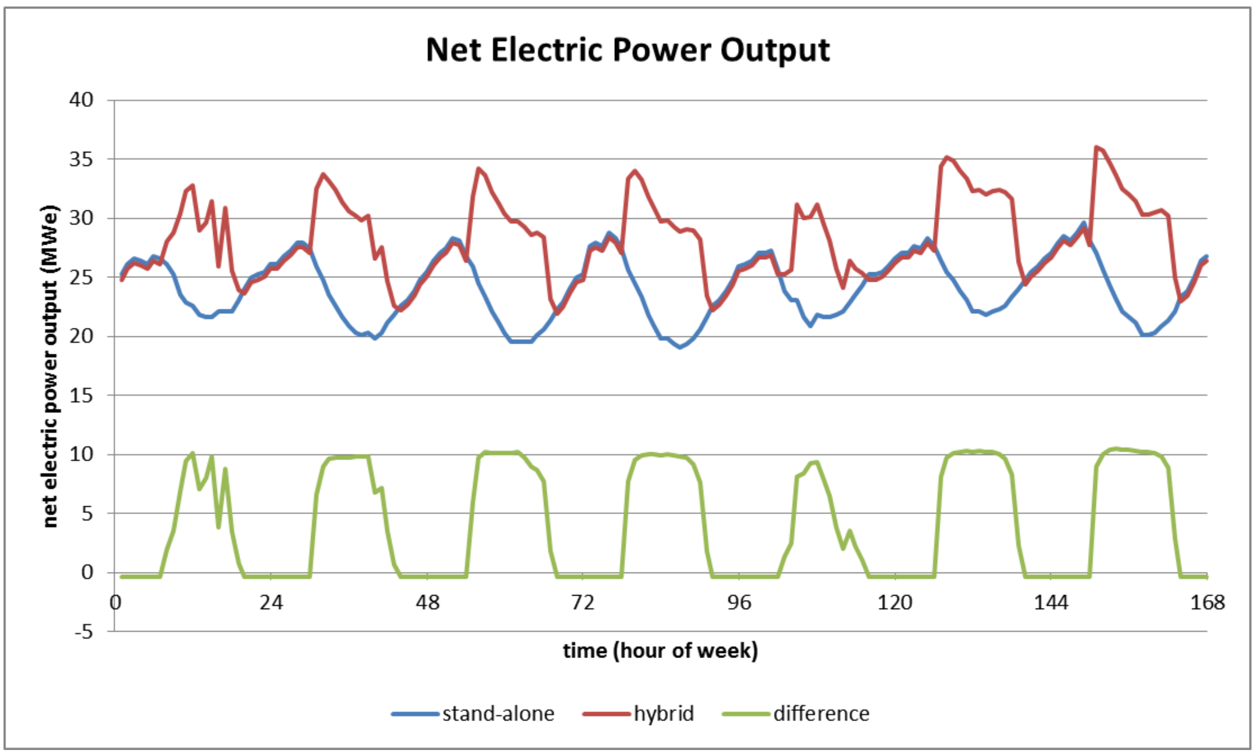

Figure 2. Sample comparison of stand-alone geothermal and hybrid geo-solar hourly power generation

3. Results

In this analysis, hybrid and stand-alone geothermal plant supply curves are presented for the subset of geothermal resources in the P2P supply curve dataset with temperatures in the range of

150°C < T < 225°C and solar resources with average annual DNI > 4.8 kWh/m^2/day. While it would be possible to operate hybrid geo-solar plants with resources outside of these ranges, power plant performance models have not yet been developed for resource conditions outside of the specified ranges. However, the majority of the geothermal resources included in the P2P supply curve dataset fall within the range of conditions for which hybrid plant performance models do exist, so the results and conclusions presented in this analysis are generally representative and applicable, although the supply curves in this analysis will differ from those generated by the P2P task force where geothermal resources of all temperatures are considered.

Whereas the P2P supply curves are presented in terms of installed capital cost versus available capacity, in this analysis supply curves are plotted in terms of LCOE versus available capacity. This alteration was made in order to evaluate the resource types and scenarios for which hybrid geo-solar plant economics are favorable relative to stand-alone geothermal plants using a metric that incorporates capital costs, operating costs, and electric power generation over the specified power plant operating life (these inputs would normally be incorporated into the ReEDS market penetration modeling, which is not currently able to evaluate hybrid systems).

Due to the difference in the way P2P and Hybrid Systems task force supply curves are generated for stand-alone and hybrid plants, respectively, the supply curves generated in this analysis cannot be directly compared against P2P supply curves. Nonetheless, the P2P ReEDS analysis predicts significant deployment of certain geothermal resource types in the improved scenarios evaluated; when the hybrid geo-solar analysis predicts LCOE reductions relative to stand-alone geothermal plants over a significant range of the available capacity for these resource types, it is expected that hybrid plants would increase deployment (by providing power at lower cost and/or providing increased capacity at the same cost).

It is also important to note that in the supply curves presented in this analysis, stand-alone and hybrid plant capacity is calculated as the average value during the first year of operation. Since the power output of both air-cooled stand-alone plants and hybrid plants is highly variable, use of the annual average capacity is considered more representative than the design point capacity for this analysis. The stand-alone and hybrid plant capacities presented in the supply curves are referenced to the plant sales value listed for each site in the stand-alone geothermal resource database, which appropriately scales the calculated stand-alone and hybrid plant results to match the available geothermal resource at each site considered.

3.1 Identified Hydrothermal

There are no significant LCOE drivers that favor the use of hybrid geo-solar technology relative to stand-alone geothermal for the Business-As-Usual Scenario (Figure 3). The primary motivation for using hybrid geo-solar technology in this scenario would be to increase the temporal correlation between electrical power generation and electrical load, to decrease the risks associated with the development of a stand-alone geothermal reservoir (solar resource can be characterized with more certainty), and/or to decrease the negative impacts associated with geothermal resource productivity decline.

Hybrid geo-solar electricity generation costs are similar to those for stand-alone geothermal technology in the Technology Transfer Scenario. Figure 4 provides a comparison of the Technology Transfer Scenario supply curves for two discrete cases; a resource base comprised completely of stand-alone geothermal plants versus a resource base comprised completely of hybrid geo-solar plants. In reality, if both stand-alone and hybrid geo-solar technology were available at all sites, each site would deploy using the technology that resulted in the lowest LCOE. Merged supply curves that utilize the least cost option (stand-alone or hybrid geo-solar) for each site are presented in Figure 5 (level pricing) and Figure 6 (TOD pricing).

The incremental capacity provided by hybrid geo-solar technology becomes more economical than stand-alone geothermal at an LCOE threshold value of $0.133/kWh for the Technology Transfer level pricing scenario (Figure 5) and $0.087/kWh for the Technology Transfer TOD pricing scenario (Figure 6). Greater than 1600 MW (level pricing market) or 880 MW (TOD pricing market) of identified hydrothermal deployment would be required to include capacity from hybrid geo-solar power plants.

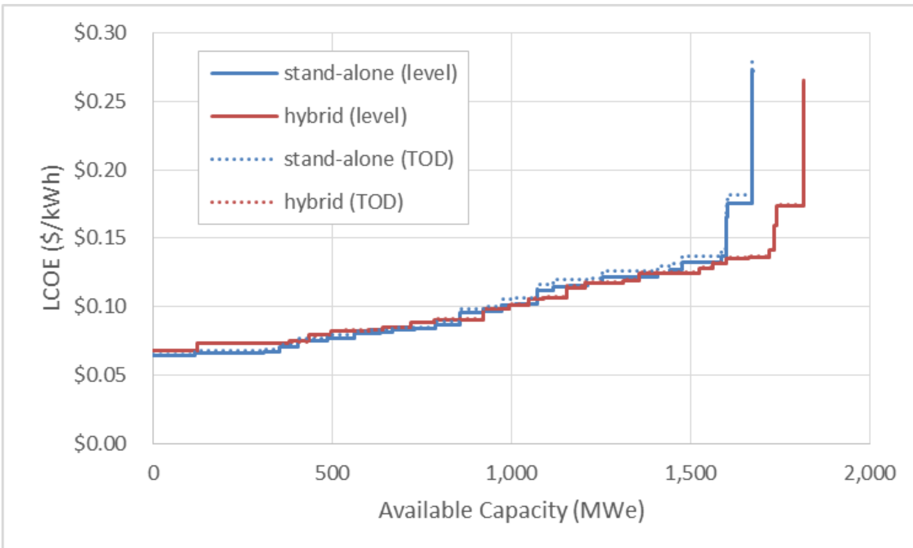

Figure 3. Identified Hydrothermal Supply Curve (BAU scenario)

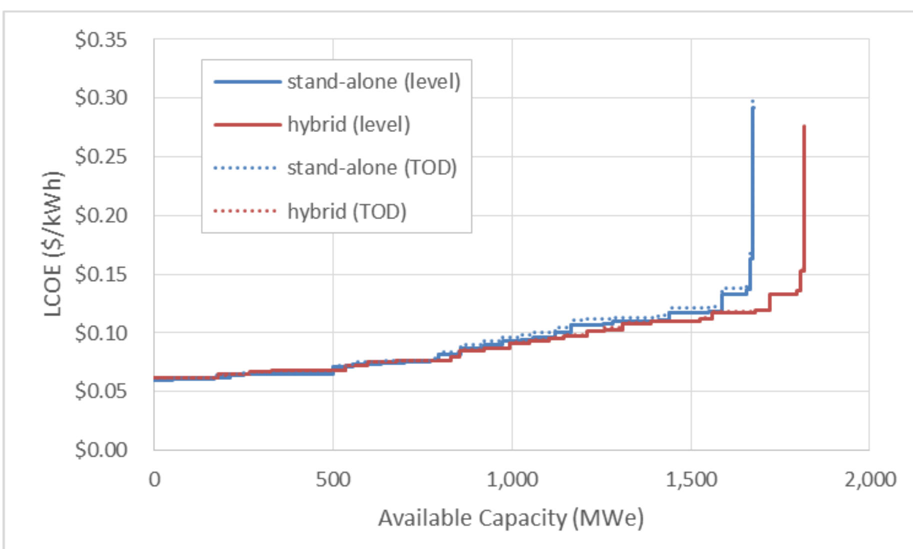

Figure 4. Identified Hydrothermal Supply Curve (Tech Transfer scenario)

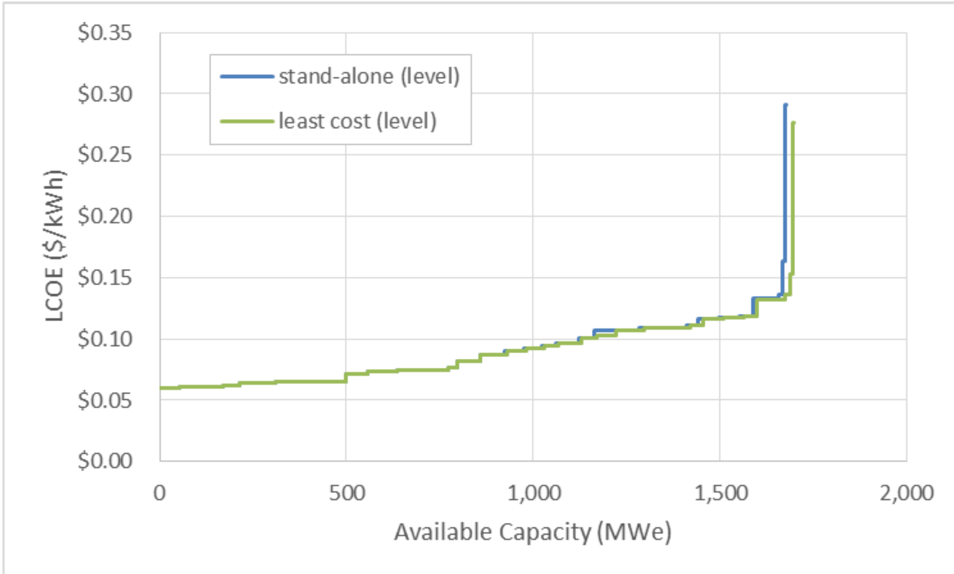

Figure 5. Merged stand-alone and hybrid geo-solar Identified Hydrothermal supply curve (Technology Transfer Scenario, level pricing)

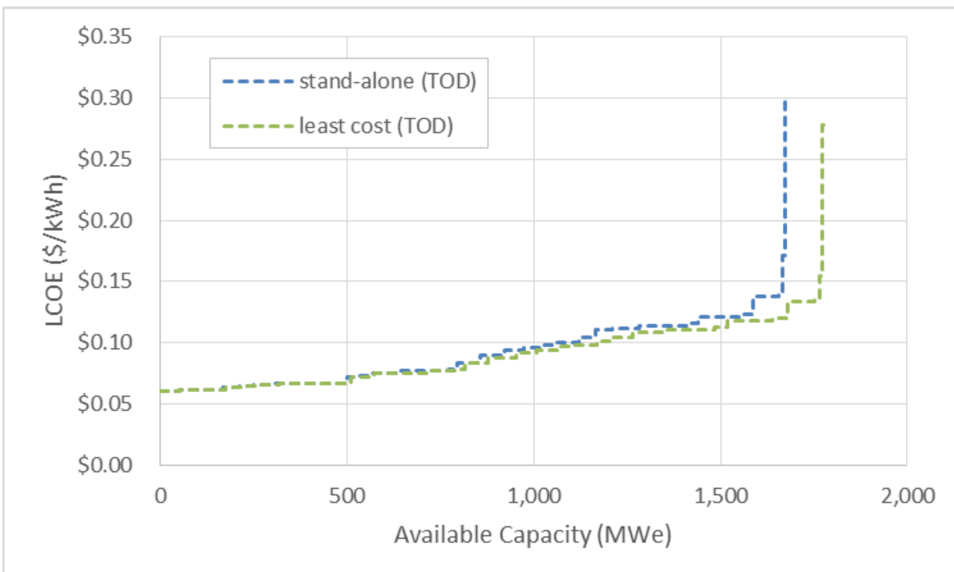

Figure 6. Merged stand-alone and hybrid geo-solar Identified Hydrothermal supply curve (Technology Transfer Scenario, TOD pricing)

3.2 Undiscovered Hydrothermal

Undiscovered hydrothermal resource capacity is reported at the state level in the P2P supply curve database, which results in large uncertainties regarding the TMY specific data (i.e., solar radiation and ambient temperature). Also, undiscovered hydrothermal supply curve dataset entries with temperatures within the range modeled for hybrid geo-solar power plants in this analysis (150-200°C) represent less than 25% of the plant sales (available capacity) in the undiscovered hydrothermal supply curve dataset. Therefore, the undiscovered hydrothermal resource assessment data does not include sufficient data to establish supply curves for the comparison of stand-alone geothermal and hybrid geo-solar power plants.

Although the combined geothermal and solar resource data was insufficient to develop undiscovered hydrothermal hybrid plant supply curves, the LCOE for hybrid and stand-alone plants were calculated for sites in the dataset that fall into the geothermal resource temperature range for which hybrid plants were evaluated (150-200°C) using solar resource data corresponding to the average of all identified hydrothermal sites in the same state. While hybrid plants did not generally result in LCOE improvements in the BAU Scenario, the hybrid LCOE was lower at all undiscovered hydrothermal sites evaluated in the Tech Transfer Scenario with TOD pricing. The capacity weighted average LCOE reduction from use of hybrid plants at sites for which the minimal resource data was available is summarized in Table 2 along with the results for other geothermal resource types.

3.3 Near Field EGS

Hybrid geo-solar technology reduces LCOE for all sites evaluated in the Near Field EGS Business-As-Usual Scenario. The hybrid geo-solar capacity-weighted average LCOE is 85.9% of that for stand-alone geothermal with level pricing, and 81.9% of that for stand-alone geothermal with TOD pricing. However, as can be seen from Figure 7, a substantial fraction of both the hybrid geo-solar and stand-alone geothermal Near Field EGS sites have LCOE greater than \$0.50/kWh and are considered unlikely to deploy in a deregulated electricity market where other less expensive electricity sources (e.g., wind, solar PV, fossil, etc.) are likely to be available. Nonetheless, hybrid geo-solar technology significantly increases the available capacity of electrical power with LCOE < \$0.50/kWh in the BAU Scenario to (730 MW of hybrid geo-solar capacity versus 510 MW of stand-alone geothermal capacity).

The Technology Transfer Scenario supply curve (Figure 9) indicates less available capacity for the hybrid geo-solar plant than in the BAU Scenario supply curve (Figure 7). This is due to the difference in geofluid pumping parasitic losses between the two scenarios. Parasitic losses are much higher in BAU Scenario than in the Technology Transfer Scenario, which causes GETEM to select a power plant design with higher brine efficiency. Therefore, the power plant efficiency used in the BAU Scenario is greater than that used in the Technology Transfer Scenario, which results more electrical power generation from the available solar heat in the BAU Scenario.

The Technology Transfer Scenario results in a significant decrease in LCOE relative to the Business-As-Usual Scenario for both stand-alone geothermal and hybrid geo-solar power plants using Near Field EGS resources. Figure 9 provides a comparison of the Technology Transfer Scenario supply curves for two discrete cases; a resource base comprised completely of stand-alone geothermal plants versus a resource base comprised completely of hybrid geo-solar plants. In reality, if both stand-alone and hybrid geo-solar technology were available at all sites, each site would deploy using the technology that resulted in the lowest LCOE. Merged supply curves that utilize the least cost option (stand-alone or hybrid geo-solar) for each site are presented in Figure 10 (level pricing) and Figure 11 (TOD pricing).

The availability of hybrid geo-solar technology would result in LCOE reductions at Near Field EGS sites where the stand-alone geothermal LCOE would be approximately \$0.111/kWh or greater for a level pricing market (Figure 10). Greater than 585 MW of Near Field EGS deployment would be required to include capacity from hybrid geo-solar power plants in a level pricing market. However, in a TOD pricing market, hybrid geo-solar technology results in a lower LCOE than stand-alone plants at all sites evaluated (Figure 11). The deployment of predominantly hybrid plants would therefore be expected in the Technology Transfer Scenario with TOD pricing.

Hybrid geo-solar technology provides the greatest LCOE reduction for Near Field EGS sites with lower geothermal reservoir temperatures. This is illustrated in plots of the hybrid geo-solar LCOE as a percentage of the stand-alone plant LCOE for the Near Field EGS sites evaluated in the BAU and Tech Transfer Scenarios presented as Figure 8 and Figure 12, respectively. The economic advantages of combining geothermal and solar heat are most significant when geothermal heat costs are high (as is the case for the lower temperature Near Field EGS sites) such that the addition of solar heat can reduce the overall cost of the heat input to the power block.

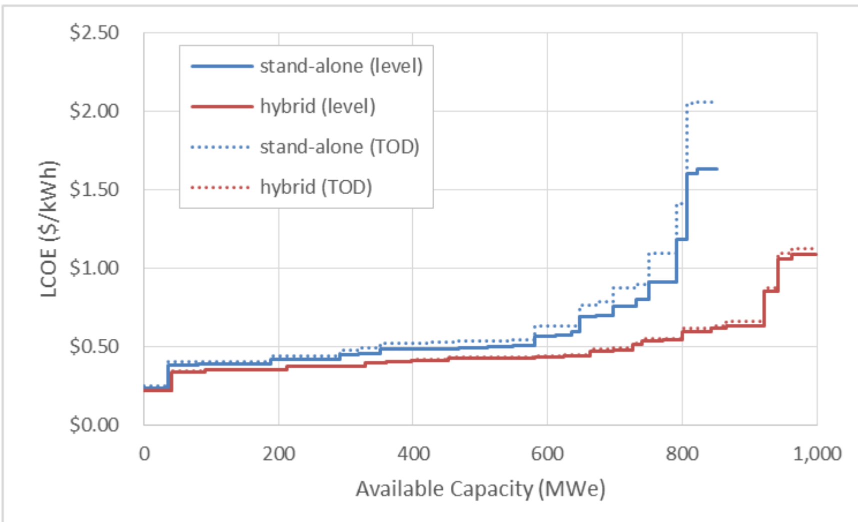

Figure 7. Near Field EGS Supply Curve (BAU scenario)

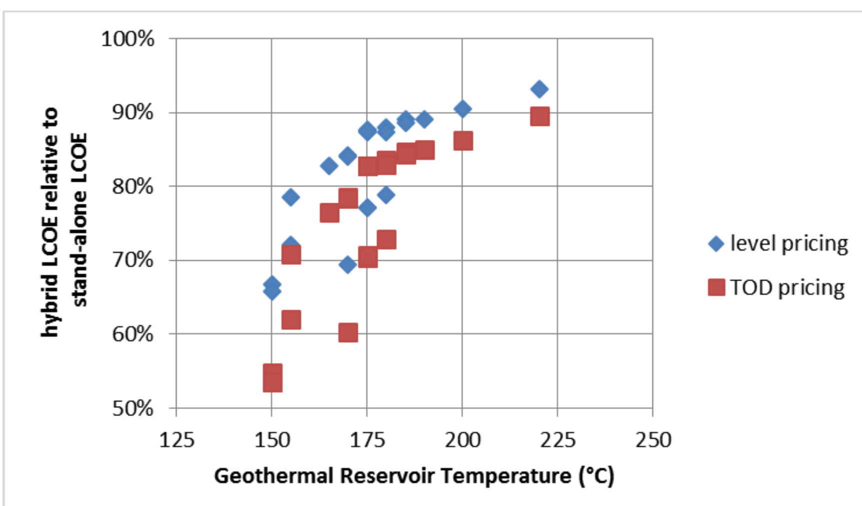

Figure 8. Near-Field EGS hybrid geo-solar LCOE as percentage of stand-alone geothermal LCOE for Business-As-Usual Scenario

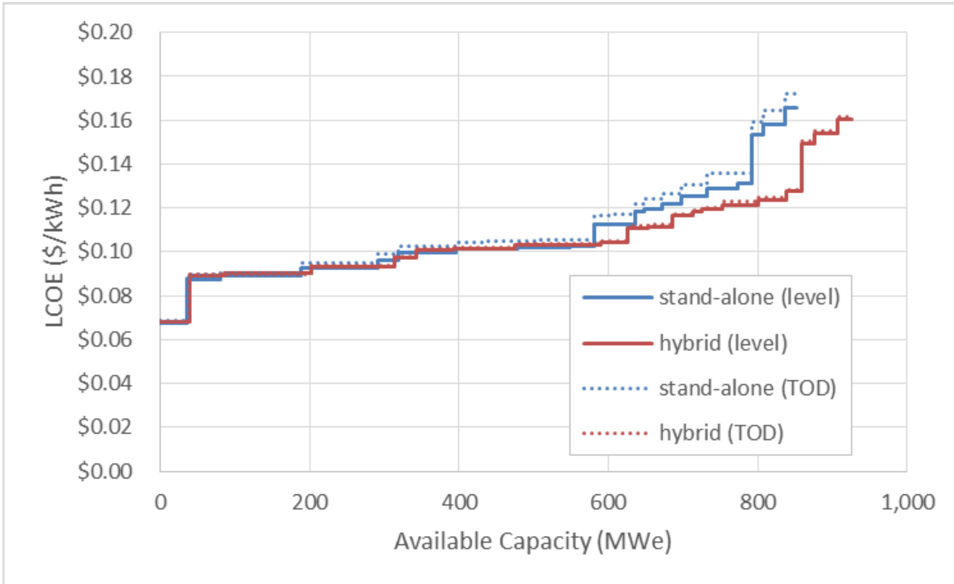

Figure 9. Near Field EGS Supply Curve (Tech Transfer scenario)

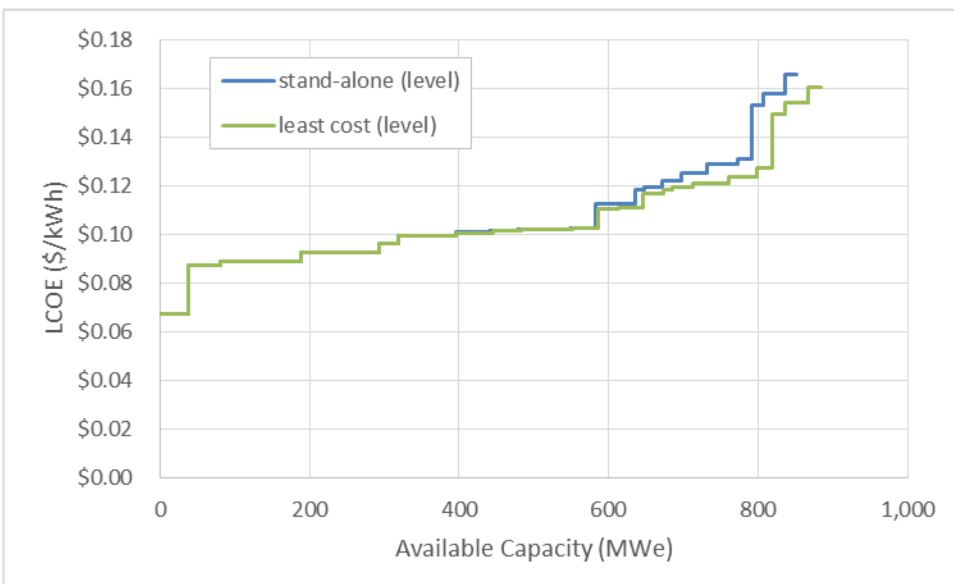

Figure 10. Merged stand-alone and hybrid geo-solar Near Field EGS supply curve (Technology Transfer Scenario, level pricing)

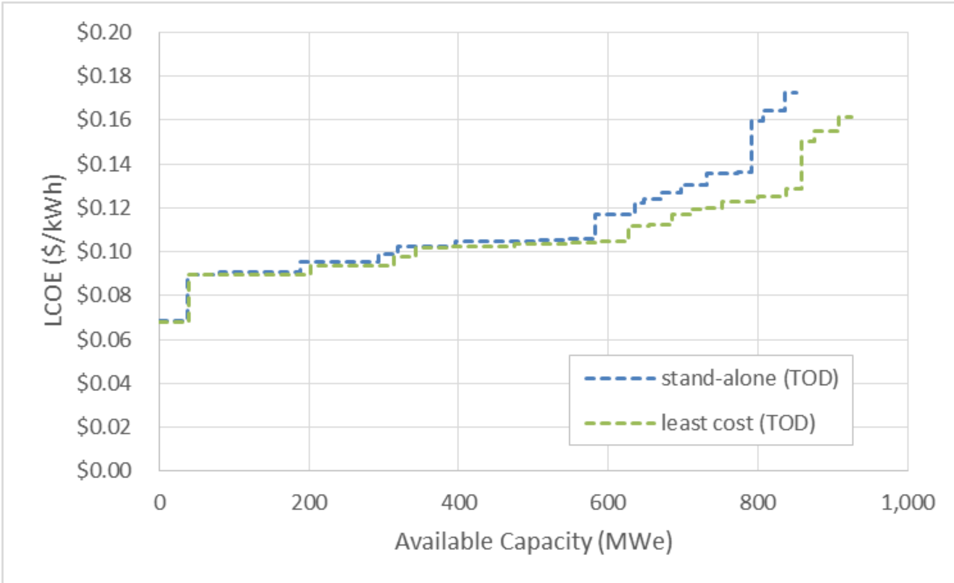

Figure 11. Merged stand-alone and hybrid geo-solar Near Field EGS supply curve (Technology Transfer Scenario, TOD pricing)

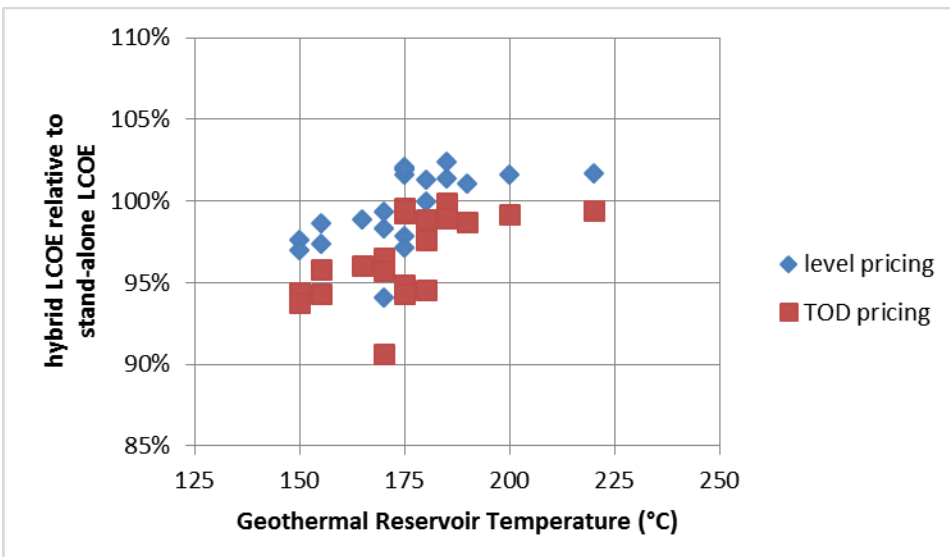

Figure 12. Near Field EGS hybrid geo-solar LCOE as percentage of stand-alone geothermal LCOE for Technology Transfer Scenario.

3.4 Deep EGS

A geothermal resource data set that categorized the availability of Deep EGS heat not only by temperature and depth but also by solar resource was not available for this analysis. Therefore, Deep EGS hybrid geo-solar supply curves are constructed assuming a 6.0 kWh/m^2/day solar resource is available at all sites. Since the average solar resource for the continental U.S. is ~3.5

kWh/m^2/day and it is presumed that hybrid geo-solar technology will only be deployed in areas with above average solar resource, the Deep EGS hybrid geo-solar supply curves generated in this analysis are only approximate. These approximate supply curves are nonetheless instructive for comparing the relative costs of hybrid geo-solar and stand-alone geothermal at locations with solar resource of at least 6.0 kWh/m^2/day. The states of Arizona, California, Colorado, New Mexico, Nevada, and Utah have average annual DNI > 6.0 kWh/m^2/day (National Renewable Energy Laboratory). These states represent approximately 22% of the land area of the 48 contiguous US states.

As with the Near Field EGS resource, hybrid geo-solar technology reduces LCOE for all sites evaluated in the Deep EGS Business-As-Usual Scenario. The hybrid geo-solar capacity-weighted average LCOE is 89.5% of that for stand-alone geothermal with level pricing, and 86.2% of that for stand-alone geothermal with TOD pricing. However, as can be seen from Figure 13, the majority of this capacity has an LCOE > $1.00/kWh which is expected to significantly limit deployment (the capacity-weighted average LCOE reductions described in the previous sentence only consider sites with LCOE < $1.00/kWh). As illustrated in Figure 14, the largest improvements in LCOE result from the use of hybrid geo-solar technology with lower temperature geothermal resources.

The P2P market penetration analysis does not predict any deployment of Deep EGS resources in the BAU Scenario. While the use of hybrid geo-solar plants would lower the LCOE of Deep EGS power generation, the costs are likely still too high for significant deployment in this scenario.

The Technology Transfer Scenario results in an order of magnitude reduction in electricity costs for both Deep EGS stand-alone geothermal and hybrid geo-solar power generation. As was the case for Near Field EGS resources, the Deep EGS Technology Transfer Scenario supply curve (Figure 15) indicates less available capacity for the hybrid geo-solar plant than in the BAU Scenario supply curve (Figure 13). Again this is due to the higher geofluid pumping parasitic losses driving the BAU Scenario toward higher brine efficiency to minimize LCOE, which results in higher plant efficiency and increased power generation from the available solar heat in the BAU Scenario.

Figure 15 provides a comparison of the Technology Transfer Scenario supply curves for two discrete cases; a resource base comprised completely of stand-alone geothermal plants versus a resource base comprised completely of hybrid geo-solar plants. In reality, if both stand-alone and hybrid geo-solar technology were available at all sites, each site would deploy using the technology that resulted in the lowest LCOE. Merged supply curves that utilize the least cost option (stand-alone or hybrid geo-solar) for each site are presented in Figure 16 (level pricing) and Figure 17 (TOD pricing).

Figure 16 indicates that the availability of hybrid geo-solar technology in an electricity market with level pricing would result in LCOE reductions at Deep EGS sites where the stand-alone geothermal LCOE would be approximately $0.138/kWh or greater. Figure 17 indicates that in a TOD pricing market hybrid geo-solar technology results in a lower LCOE than stand-alone plants at all sites evaluated. The deployment of predominantly hybrid plants would therefore be expected at deep EGS sites in the Technology Transfer Scenario with TOD pricing.

Figure 18 indicates that hybrid geo-solar technology tends to be more cost-effective when paired with lower temperature geothermal resources. From a technical and logistical perspective, these would likely be the most readily accessible EGS resources and may therefore be the EGS resources that would be most likely to come online. These results suggest that the use of hybrid geo-solar technology may be desirable in the initial deployment of EGS technology in scenarios resembling both the Business-As-Usual and Technology Transfer Scenarios.

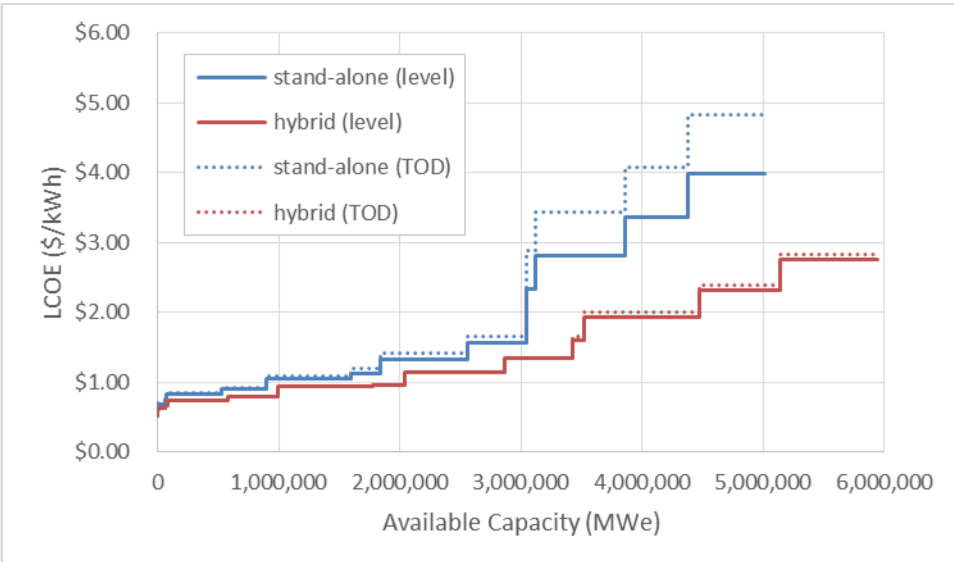

Figure 13. Deep EGS Supply Curve (BAU scenario)

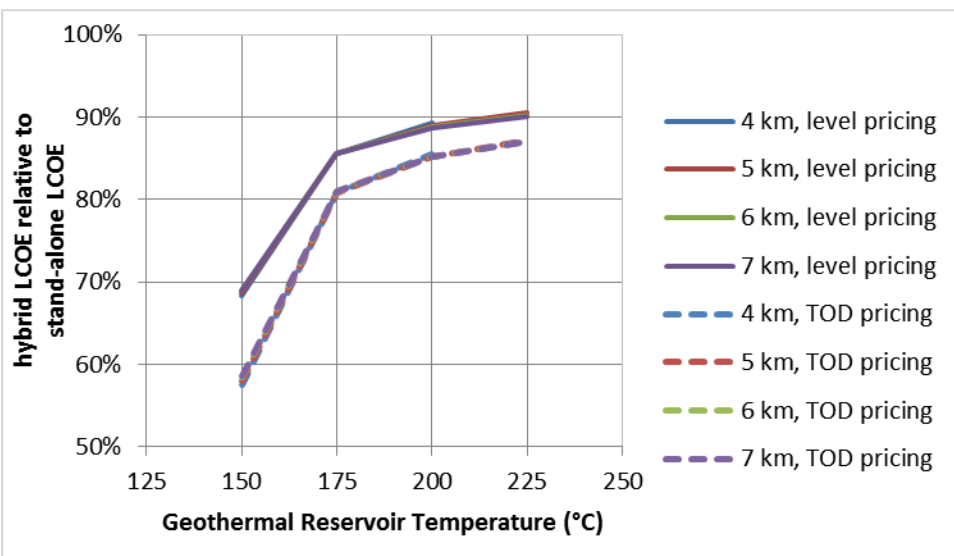

Figure 14. Deep EGS hybrid geo-solar LCOE as percentage of stand-alone geothermal LCOE for Business-As-Usual Scenario. Largest LCOE reductions result from using hybrid geo-solar technology with lower temperature geothermal resources.

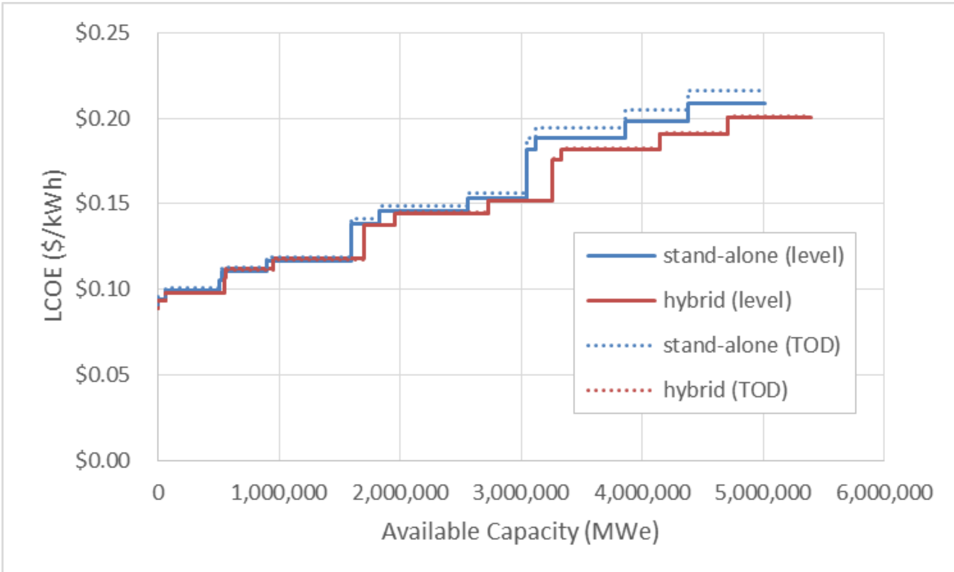

Figure 15. Deep EGS Supply Curve (Technology Transfer Scenario)

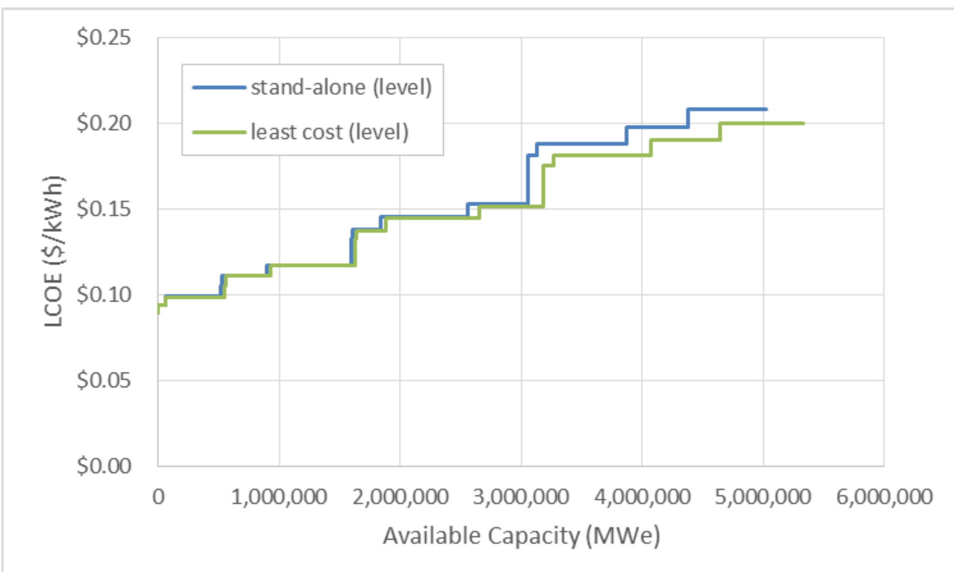

Figure 16. Merged stand-alone and hybrid geo-solar Deep EGS supply curve (Technology Transfer Scenario, level pricing)

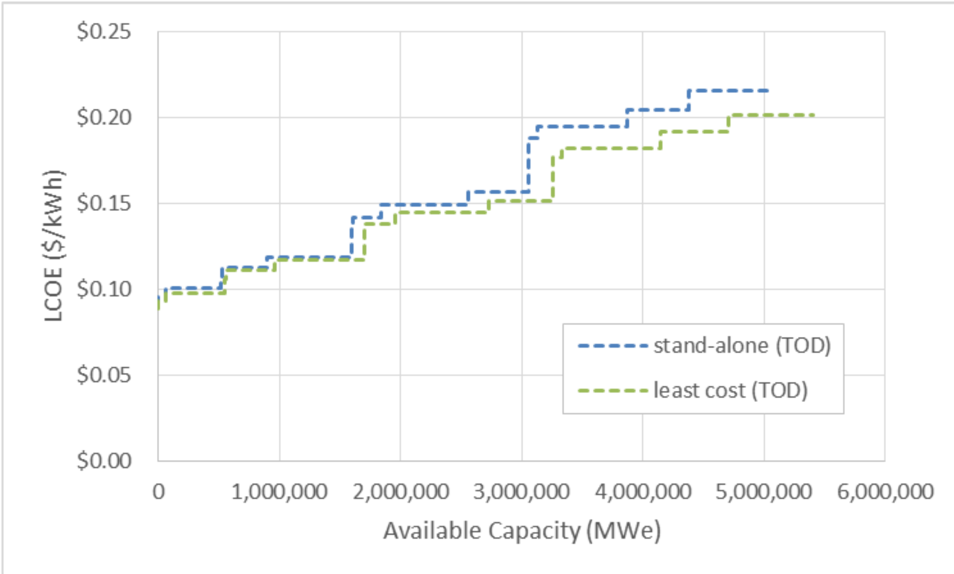

Figure 17. Merged stand-alone and hybrid geo-solar Deep EGS supply curve (Technology Transfer Scenario, TOD pricing)

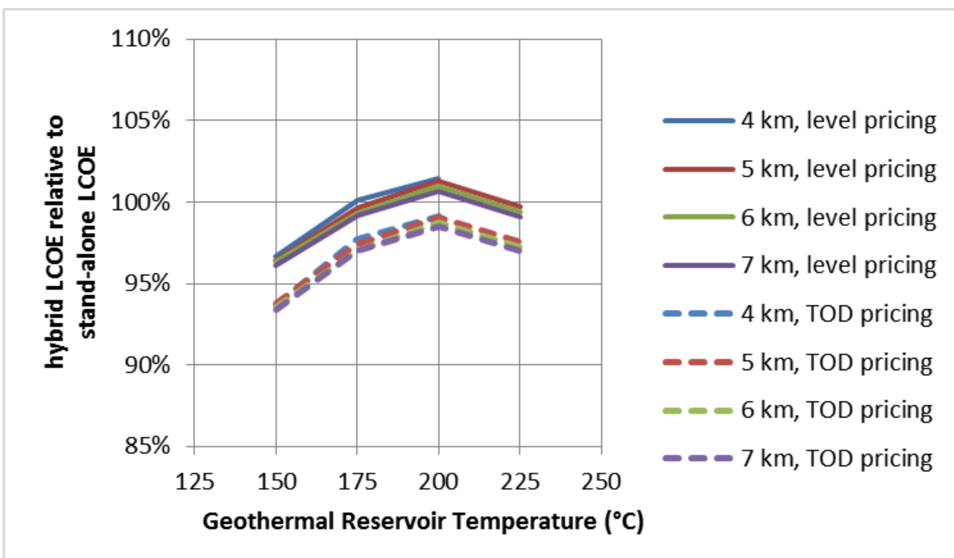

Figure 18. Deep EGS hybrid geo-solar LCOE as percentage of stand-alone geothermal LCOE for Technology Transfer Scenario.

4. Summary

The performance characteristics of hybrid geo-solar power plants are generally considered superior to those of stand-alone air-cooled geothermal power plants (i.e. the hybrid plant power generation profile is more closely matched to the electrical grid load). Evidence for the improved correlation between hybrid geo-solar plant output with the electrical load is provided through evaluation of a TOD electrical pricing scenario (where greater electricity sales prices are assigned to times when electrical demand is greatest). In the TOD pricing scenario, greater LCOE reductions are realized through use of the hybrid geo-solar plant due to the hybrid plant being able to provide increased revenues during periods when more revenue is available from increased electrical sales pricing.

Table 2. LCOE of hybrid geo-solar relative to stand-alone geothermal (hybrid plant LCOE as percentage of stand-alone LCOE, reported as a capacity-weighted average)

	Business-as-Usual		Technology Transfer	
	Level pricing	TOD pricing	Level pricing	TOD pricing
Identified hydro	104.8%	102.1%	101.8%	99.1%
Undiscovered hydro	103.9%	101.2%	100.6%	98.0%
Near-Field EGS	85.9%*	81.9%*	100.2%	97.5%
Deep EGS	89.5%*	86.2%*	98.4%	96.0%

*Sites with stand-alone geothermal plant LCOE > $1.00/kWh excluded from calculation

The reduction in LCOE provided by hybrid ORC plants is generally smaller in magnitude for the Tech Transfer Scenario than for the BAU Scenario. This is primarily due to the significant reduction in geothermal resource development costs associated with the Tech Transfer Scenario. While decreased solar hardware costs are also used in the evaluation of the Tech Transfer Scenarios, the hybrid plant LCOE is driven mainly by the geothermal costs (the majority of the heat input in the hybrid ORC configuration comes from geothermal energy) such that there is less opportunity for LCOE reduction from incorporating low cost solar energy. Nonetheless, several significant opportunities for hybrid technology to lower LCOE and increase the deployment of plants that utilize geothermal energy were identified. Applicable conditions for each resource type and scenario are summarized below:

4.1 Business-As-Usual (level and TOD pricing)

In the Business-As-Usual Scenario with level pricing identified hydrothermal stand-alone and hybrid plant LCOE are similar; variability in geothermal resource development costs results in a site-by-site determination as to which plant type will result in the lower LCOE. In this scenario, hybrid technology may be deployed on a site-by-site basis and be utilized primarily for mitigating geothermal resource development risks or impacts associated with geothermal resource productivity decline.

Insufficient resource data were available for rigorous site-by-site evaluation of hybrid plants at undiscovered hydrothermal sites; this analysis does not suggest that hybrid plants would significantly reduce LCOE at undiscovered hydrothermal sites, but as with identified hydrothermal sites this determination would likely be made based on site-specific considerations.

In the BAU Scenario with level pricing significant reductions in LCOE result from the use of hybrid geo-solar technology with near-field EGS and deep EGS resource types. Near-field EGS hybrid plant LCOE is lower than stand-alone plant LCOE at every site evaluated. Deep EGS hybrid plant LCOE is lower than stand-alone plant LCOE at every temperature and depth combination evaluated (assuming a minimum average solar resource of 6.0 $kWh/m^2/day$). However, the LCOE associated with hybrid plant power generation are likely still too high to realize significant deployment.

4.2 Technology Transfer Scenario (level pricing)

Technology Transfer Scenario (level pricing) results are similar to those from the BAU Scenario for the identified hydrothermal and undiscovered hydrothermal resource type, i.e. variability in geothermal resource development costs and other site-specific considerations result in a site-by-site determination of whether to utilize hybrid technology.

The near field EGS supply curve for the Technology Transfer Scenario with level pricing (Figure 10) indicates that hybrid technology provides the least-cost LCOE option for deployment of capacity greater than 585 MW from the sites evaluated (geothermal resource 150°C < T < 225°C; solar resource > 4.8 kWh/m^2/day), which corresponds to LCOE values of $0.111/kWh or greater.

The deep EGS supply curve for the Technology Transfer Scenario with level pricing (Figure 16) indicates that hybrid technology provides the least-cost LCOE option for deployment of capacity greater than 1,600,000 MW from deep EGS resources in the temperature range of 150°C to 225°C with a minimum average solar resource of 6.0 kWh/m^2/day, which corresponds to LCOE values of $0.138/kWh or greater.

4.3 Technology Transfer Scenario (TOD pricing)

Hybrid plant configurations are predicted to provide a lower capacity-weighted average LCOE (the average LCOE of all available capacity; see Table 2) than stand-alone geothermal plants for all resource types (identified hydrothermal, undiscovered hydrothermal, and near-field EGS with geothermal resource 150°C < T < 225°C and solar resource > 4.8 kWh/m^2/day; deep EGS with geothermal resource 150°C < T < 225°C, depth of 4 km to 7 km, and solar resource of 6.0 kWh/m^2/day) in the Technology Transfer Scenario with TOD pricing. Therefore, a geothermal power industry comprised completely of hybrid plants would, on average, result in lower pricing than a market comprised completely of stand-alone geothermal plants in the Technology Transfer Scenario with TOD pricing.

The identified hydrothermal supply curve for the Technology Transfer Scenario with TOD pricing (Figure 6) indicates that hybrid technology provides the least-cost LCOE option for deployment of capacity greater than 880 MW from the sites evaluated (geothermal resource 150°C < T < 225°C; solar resource >4.8 kWh/m^2/day), which corresponds to LCOE values of $0.087/kWh or greater. Utilization of hybrid technology increases the available capacity from the identified hydrothermal resource sites evaluated from 1680 MW to 1775 MW.

Near-field EGS hybrid plant LCOE is lower than stand-alone plant LCOE at all sites evaluated (geothermal resource 150°C < T < 225°C; solar resource >4.8 kWh/m^2/day). Deep EGS hybrid plant LCOE is lower than stand-alone plant LCOE for all temperature and depth combinations evaluated (geothermal resource 150°C < T < 225°C; depth of 4 km to 7 km; solar resource of 6.0 kWh/m^2/day). The deployment of predominantly hybrid plants would therefore be expected at near field EGS and deep EGS sites in the Technology Transfer Scenario with TOD pricing.

5. Conclusion

This analysis evaluated a hybrid geo-solar air-cooled supercritical binary cycle power plant configuration. Other hybrid geo-solar plant configurations, including geothermal boiler feedwater heating, flash plant configurations, and/or combined cycle configurations were not included in the supply curve analysis; however, a case study analysis of hybrid CSP power plants using geothermal boiler feedwater heating is included in Appendix A.

General benefits of hybrid geo-solar technology include the ability to decrease the risks and mitigate impacts associated with geothermal resource productivity decline. The hybrid plant therefore will better utilize the power block equipment (a "sunk cost") as a function of time and decreasing geothermal resource. Although this analysis does not incorporate the use of a lower discount rate for the hardware associated with the solar resource, hybrid geo-solar power generation costs would improve relative to stand-alone geothermal if lower discount rates were used for these components.

Hybrid geo-solar power plants also improve the temporal correlation between generation and load (as demonstrated through the increased favorability of hybrid geo-solar LCOE relative to stand-alone geothermal power in a time-of-delivery pricing scenario). Use of geo-solar hybrid plants could therefore largely defend against the economic penalties that would otherwise be associated with air-cooled geothermal power generation in a time-of-delivery electricity pricing market.

This analysis suggests that if the costs of solar collectors can be reduced to the targets set by DOE and the concentrating solar power industry, hybrid geo-solar technology will allow LCOE reductions in locations with good solar resource and where stand-alone geothermal power generation costs are moderate (~\$0.10/kWh) to high ($\gg$\$0.15/kWh), i.e. when the cost of solar heat is low, hybrid geo-solar technology provides a means by which to reduce the LCOE of geothermal power generation. This analysis indicates that hybrid geo-solar technology generally provides the greatest reductions in LCOE when paired with low-temperature geothermal resources (where costs of stand-alone geothermal power generation tend to be highest).

Although the ReEDS market analysis model is not currently able to evaluate market penetration for hybrid technologies, the supply curves generated in this analysis suggest that for all geothermal resource types evaluated, there exists a threshold LCOE where a geothermal industry that utilizes hybrid geo-solar plants would be able to provide increased capacity at an equal or lower LCOE than a geothermal industry comprised solely of stand-alone geothermal plants. The supply curve capacity ranges where hybrid plants provide increased capacity at equal or lower LCOE to stand-alone plants represent the market conditions where the use of hybrid plants could significantly impact the deployment of power plants that utilize geothermal energy. Further analysis using ReEDS is necessary to quantify the impact of hybrid geo-solar plant availability on the utilization of geothermal energy as a source of power generation.

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REFERENCES

Loh, H. P., Lyons, J. and White, C. W. (2002) *Process Equipment Cost Estimation, Final Report*: National Energy Technology Lab (DOE/NETL-2002/1169.

National Renewable Energy Laboratory *National Solar Radiation Database*. Available at: https://nsrdb.nrel.gov/ (Accessed: September 2016.

National Renewable Energy Laboratory *Solar Data: Summary spreadsheet of annual 10-kilometer solar data by state and zip code*. Available at: http://www.nrel.gov/gis/docs/SolarSummaries.xlsx.

National Renewable Energy Laboratory (2017) *System Advisor Model*. Available at: https://sam.nrel.gov/.

Turchi, C. (2010) *Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model (SAM)*: National Renewable Energy Laboratory (NREL/TP-550-47605.

U.S. Department of Energy (2012) *SunShot Vision Study*. Available at: https://energy.gov/eere/sunshot/sunshot-vision-study.

Wendt, D., Mines, G., Turchi, C. and Zhu, G. (2015a) *Geothermal Risk Reduction via Geothermal/Solar Hybrid Power Plants: Final Report*: Idaho National Laboratory (INL/EXT-15-37307.

Wendt, D., Mines, G., Turchi, C., Zhu, G., Cohan, S., Angelini, L., Bizzarri, F., Consoli, D. and De Marzo, A. 'Stillwater Hybrid Geo-Solar Power Plant Optimization Analysis'. *GRC Transactions*, Reno, NV, 891-900.