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Keywords

Air-cooled binary geothermal power plant, concentrated solar power, hybrid power plant, organic Rankine cycle, geothermal resource productivity decline, solar thermal retrofit

ABSTRACT

Many, if not all, geothermal resources are subject to decreasing productivity manifested in the form of decreasing production fluid temperature, flow rate, or both during the life span of the associated power generation project. The impacts of resource productivity decline on power plant performance can be significant; a reduction in heat input to a power plant not only decreases the thermal energy available for conversion to electrical power, but also adversely impacts the power plant efficienc . The reduction in power generation is directly correlated to a reduction in revenues from power sales. Further, projects with Power Purchase Agreement (PPA) contracts in place may be subject to significant economic penalties if power generation falls below the default level specified

This paper evaluates the retrofit of existing air-cooled binary geothermal power plants with concentrated solar heat input to mitigate the effects of geothermal production fluid temperature decline. The evaluation includes analysis of several declining geothermal production fluid temperature scenarios and identification of the ranges of solar collector capital cost and electrical power sales price where solar thermal retrofit of the base geothermal power plant could improve project economics.

It is concluded that solar thermal retrofit of a geothermal power plant with declining production fluid temperature can increase net power generation, especially during periods of high ambient temperature when air-cooled binary plant output is typically lowest. Power plants with higher production fluid design temperatures can achieve higher efficienc , which allows these plants to generate a greater quantity of power from each unit of solar energy input. The quantity of additional power generation attributed to each unit of solar heat input increases as the production fluid temperature decreases from its design point temperature.

In general, geo-solar hybrid plant retrofit economics are increasingly favorable with higher electricity sales price and lower solar collector array (SCA) cost. For the scenarios evaluated the economic viability of a solar retrofi of the base geothermal power plant increased with production fluid temperature. The presence of a geofluid exit temperature limit decreases the magnitude of the NPV that is associated with a solar hybrid retrofit of the plant.

Introduction and Motivation

Geothermal resource productivity decline is a source of signifi ant risk in geothermal power generation. Many, if not all, geothermal resources are subject to decreasing productivity manifested in the form of decreasing production fluid temperature, flow rate, or both during the life span of the associated power generation project. The impacts of geothermal production fluid temperature decline on power plant performance can be

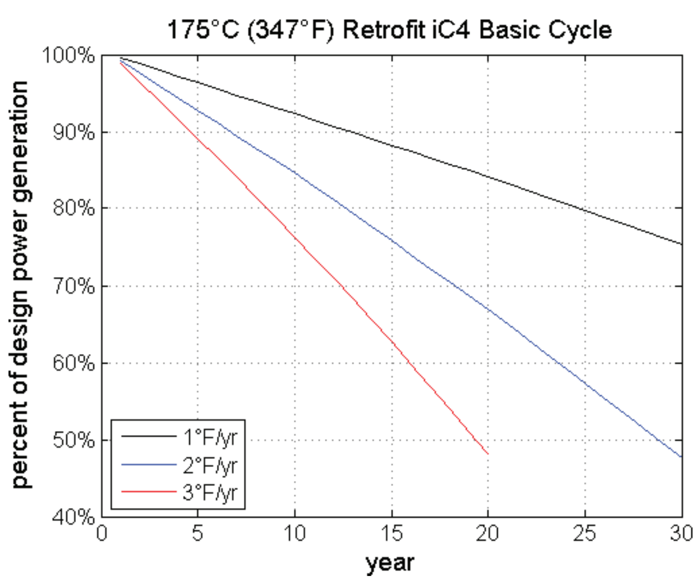


Figure 1. Decrease in power generation of a isobutane basic cycle with 175°C (347°F) production fluid design temperature as function of production fluid temperature decline rate.

significant; a reduction in heat input to a power plant not only decreases the thermal energy available for conversion to electrical power, but also adversely impacts the power plant efficienc . As indicated in Figure 1, a steady unmitigated annual production fluid temperature decline could decrease the power generation of an aging air-cooled binary geothermal power plant to a small fraction of its design point performance.

The impact of resource productivity decline on power generation project economics can be equally detrimental. The reduction in power generation is directly correlated to a reduction in revenues from power sales. Further, projects with Power Purchase Agreement (PPA) contracts in place may be subject to significant economic penalties if power generation falls below the default level specified. While the magnitude of PPA penalties varies on a case-by-case basis, it is not unrealistic for these penalties to be on the order of the value of the deficit power sales such that the utility may purchase the power elsewhere.

Electrical power demand is generally at peak levels during periods of elevated ambient temperature and it is therefore especially important to utilities to be able to provide electrical power during these periods. Unfortunately, the performance of air-cooled binary plants is lowest when ambient temperatures are high due to the decrease in air-cooled binary plant performance that occurs when the working fluid condensing temperature, and consequently the turbine exhaust pressure, increases. As a result, an air-cooled binary plant generating power from a decreased temperature production fluid may be especially vulnerable to not meeting contracted levels of power generation during periods of elevated ambient temperature.

A potential solution to restoring the performance of a power plant operating from a declining productivity geothermal resource involves the use of solar thermal energy to restore the thermal input to the power plant. As indicated in previous analyses [1-5] and demonstrated in field testing [6-10], there are numerous technical merits associated with a renewable geothermal-solar hybrid plant concept. The time periods in which air-cooled binary geothermal power plant performance is lowest generally correspond to periods of high solar insolation, which improves the correlation with electrical power demands. Shared use of the geothermal power block eliminates the requirement for solar thermal storage for operation during times of low or no solar insolation. This analysis examines the use of geo-solar hybrid retrofit technology for mitigation of resource productivity decline, which has not been a primary topic of investigation in previous analyses in the open literature.

Additional attributes providing incentive for use of solar heat to restore defi it thermal energy unavailable to a geothermal power plant as a result of resource productivity decline include the low risk associated with identifying and characterizing solar thermal resources and the possibility of matching the thermal capacity of the solar collector array (SCA) with the decline in geothermal resource productivity through modular expansion of the solar collector array. It is likely that the risk associated with characterizing the solar resource at a given power plant location is less than that associated with expansion of an existing geothermal well field, which may or may not produce geofluid having the desired temperature and flow properties; an additional risk associated with wellfield expansion is the possibility that additional production capacity may accelerate the rate of resource productivity decline [11].

Despite the compelling argument for development of geothermal-solar hybrid plants, there are several technical and economic factors that must be evaluated prior to proceeding with such a project. Typical geofluid production temperatures are low relative to the temperatures typical of the heat transfer fluid exiting a concentrated solar trough collector (where temperatures of 500°C are possible). In order to integrate the geothermal and solar heat sources, the temperature of the combined heat sources must be in a range that is compatible and beneficial for power generation via the existing geothermal power conversion equipment. Since the efficiency of the conversion of solar heat to power will be limited to that allowed by the existing geothermal power plant equipment, the benefits of a relatively low efficiency conversion of the high grade solar heat to electrical power must be weighed against the cost savings realized by not installing dedicated solar power generation and thermal storage as required for a stand-alone CSP plant.

Power plant thermal integration must also be considered. While retrofit scenarios would be more likely to use the solar thermal energy to increase the temperature of the production fluid prior to the working fluid heat exchange, Greenfield scenarios (which are not considered in this analysis) would have the additional flexibility to utilize direct working fluid heating. In either case, the inclusion of the additional heat exchange equipment and any associated operational impacts must be considered. Finally, the electric generator in any installation will have finite capacity and addition of excessive solar heat could potentially lead to failure of this critical power block component.

Since concentrated solar heat is expensive relative to geothermal heat, one of the primary obstacles facing deployment of retrofit geothermal-solar hybrid plants is economic viability. While SCA cost reductions may be possible through improved collector manufacturing techniques, development of lower temperature collectors, and/or use of less costly heat transfer fluids, the cost reductions associated with retrofit application specific collector designs are unknown and this analysis therefore considers a range of possible collector costs. This paper analyzes several declining production fluid temperature scenarios and identifies the range of solar collector capital costs and electrical power sales prices where solar thermal retrofit of the base geothermal power plant could improve project economics.

Retrofit Hybrid Plant Configuration

Numerous geothermal-solar hybrid plant configurations are possible. These include configurations with dedicated solar and geothermal power cycles with some transfer of heat between the two otherwise separate cycles, as well as configurations in which the solar and geothermal heat sources are both utilized by a single power cycle. The focus of this analysis is the retrofit of an existing air-cooled binary power plant to mitigate production flui temperature decline and therefore a configuration in which the solar heat is input to the base geothermal power plant is required.

Although it would be possible to use the high temperature concentrated solar thermal (CST) heat transfer flu d (HTF) to provide direct heating of the power plant working fluid, this configuration would result in significantly increased plant integration design and analysis. The direct working fluid heating configuratio is therefore less likely to be implemented in retrofit applications than in Greenfield applications where the power cycle would be designed to accept heat input from a CST array (although not necessarily upon initial plant start-up).

The most basic implementation of the hybrid geothermal-solar power plant entails utilization of the solar thermal energy to increase the temperature of the geothermal production fluid en route to a geothermal power plant capable of stand-alone operation without input from a CST heat source. This hybrid plant confi uration could be installed as a retrofi to an existing geothermal plant, which would be especially appealing for mitigating a decline in geothermal resource productivity.

Depending on the nature of the geothermal resource productivity decline, there are two possibilities for the location of the heat exchanger used to transfer heat from the CST system HTF to the production fluid. If the geothermal resource productivity decline is primarily due to a decrease in production fluid flow rate, a "post-heat" CST heat exchanger may be configured to heat a portion of the geofluid exiting the power cycle preheater such that this fluid can be recycled to the vaporizer inlet, resulting in vaporizer inlet stream temperature and flow rate closer to design. If the geothermal resource productivity decline has manifested primarily as a decline in production fluid temperature, positioning a "pre-heat" CST system heat exchanger in the production fluid piping en route to the power cycle vaporizer can result in operating conditions similar to those for which the plant was designed (which also correspond to the highest plant efficiency); the analysis presented in this report is based on the pre-heat hybrid plant configuration. The solar collectors were assumed to use a dedicated heat transfer fluid as opposed to circulation of geofluid through the solar field

Technical Approach

Solar hybrid retrofit scenarios of air-cooled binary geothermal power plants with production fluid design temperatures of 150, 175, and 200°C are evaluated. The 200°C production fluid temperature was evaluated in scenarios with and without a geofluid exit temperature limit for minimization of heat exchanger fouling. The production fluid temperature in each scenario is assumed to decline at a rate such that the annual power generation decreases by approximately 50% following 30 years of base power plant operation (see Table 1). Each scenario was assumed to have a constant production fluid flow rate of 378 kg/s (3 million lb/hr) for the duration of the power plant operation. Each of the power plant designs utilizes a basic organic Rankine cycle (no recuperation) configuration with isobutane working flui

Table 1. Assumed annual production fluid temperature decline rates.

Design Temperature	AnnualTemperature Decline
150°C (302°F)	1.0°C (1.8°F)
175°C (347°F)	1.1°C (2.0°F)
200°C (392°F)	1.5°C (2.7°F)

Typical meteorological year (TMY) data for Reno, Nevada were assumed for each year of power plant operation. Reno is a candidate location for hybrid geothermal-solar power plants due to the availability of both geothermal and solar resources. TMY ambient temperature and direct normal irradiation (DNI) data for Reno were obtained from the NREL System Advisor model (SAM) [12]. This data is plotted in Figure 2 and Figure 3, respectively. Based on the Reno TMY data, an ambient design temperature of 10°C (50°F) was selected for each of the plant designs.

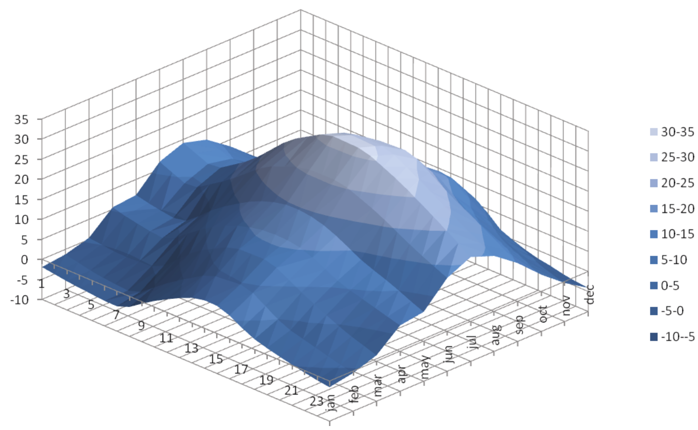


Figure 2. Monthly-averaged hourly TMY ambient temperature for Reno, Nevada (°C).

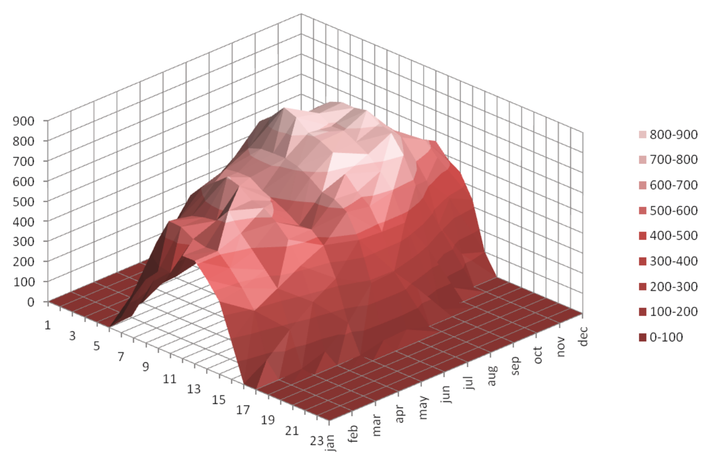


Figure 3. Monthly-averaged hourly TMY DNI data for Reno, Nevada (W/m^2).

Aspen Plus power plant design and rating models were used to determine equipment specifications and performance of these power plants [13]. The equipment specifications of each power plant were determined using the set of common design parameters

Table 2. Plant equipment design parameters.

Equipment Type	Design Specification
heat exchanger minimum temperature approach	preheater/vaporizer: 10°F air-cooled condenser: 15°F
rotational equipment efficiencies (isentropic/mechanical)	pump: 80%/98% fan: 55%/90% turbine: 83%/94%
piping and equipment fluid frictional losses	liquid piping: 10 psi vapor piping: 4 psi preheater/vaporizer: 38 psi condenser: 1 psi control valve: 2 psi

specified in Table 2. The plants were assumed to be equipped with variable geometry turbine nozzles and working fluid pumps with variable frequency drive (VFD) motor speed control. Table 3 summarizes the design point operating performance of the power plants associated with each of the production fluid temperature scenarios.

Table 3. Base power plant design point operation for selected geothermal production fluid temperature scenarios.

Production Fluid Design Temperature	Geofluid Exit Temp Limit Constraint	Base Plant Design Point Heat Input (Mw_t)	Base Plant Design Point Power Output (Mw_e)	Base Plant Design Point Thermal Efficiency	Base Plant Turbine Inlet Conditions (Subcritical or Supercritical)
150°C	no	135.7	13.6	10.0%	subcritical
175°C	no	199.2	24.2	12.1%	supercritical
200°C	no	249.6	33.3	13.3%	supercritical
200°C	yes	197.8	28.2	14.3%	supercritical

The off-design performance of the solar hybrid retrofit of each air-cooled binary geothermal power plant is determined by simulating plant performance over a range of production fluid and ambient temperatures with varying levels of solar heat input to the production fluid entering the base power plant. The resulting map of power plant performance is used in combination with hourly production fluid temperature, ambient temperature, and DNI data to determine base and hybrid plant performance over the designated plant operating period.

CST array performance was obtained from SAM for the Solargenix SGX-1 physical trough SCAs using the default configuratio settings; the performance specifications of this trough design are based on stand-alone solar thermal power plant operation and are not optimized for geo-solar hybrid plant applications. The quantity of solar heat input was limited to 50% of the base plant design point input. This quantity results in hybrid plant maximum summer generator output values that are approximately equal to base plant maximum winter generator output values (which occur during periods of minimum ambient temperature). Due to the similar power generation levels at low ambient temperature and high ambient temperature with the specified levels of solar heat input, simulation results do not include a generator capacity constraint. In practice, the generator capacity of a given power plant must be considered prior to determining the amount of solar heat addition possible (the extent of geothermal production fluid temperature decline will also factor into the quantity of solar heat that can be added without changes to the base plant electrical generation equipment).

Additional production fluid pumping is included to prevent vaporization for hybrid plant operating points where the production fluid is heated above the design temperature. Solar heat addition to the production fluid entering a geothermal power plant is limited by the heat exchanger temperature and pressure ratings; this analysis assumes the base power plant heat exchanger ratings are sufficient to allow addition of the solar heat quantities specified in each of the scenarios investigated.

To evaluate the economic viability of retrofitting the base geothermal plant with concentrated solar thermal collectors, a discounted cash flow analysis was performed to determine the net present value (NPV) of the retrofit project. The cash flow analysis revenue stream included the additional power sales revenue associated with the hybrid plant configuration assuming a power plant utilization factor of 95%. Expenses included the installed capital costs of the solar collectors and ancillary equipment (minus depreciation calculated using the 5 year MACRS cost recovery schedule with an assumed 35% tax rate). A discount rate of 7% was applied to the expenses and revenue streams associated with the solar thermal retrofit project

The NPV was evaluated for a range of electricity sales prices and SCA capital equipment costs to provide results that would be generally applicable and as widely useful as possible. The solar retrofit equipment specifications were determined by using the MATLAB optimization toolbox to vary the SCA size and installation date to maximize the retrofit project NPV. Expenses and/or credits associated with O&M, insurance, royalties, taxes, renewable energy credits, and the offset of PPA penalties as a result of the solar retrofit were deemed project specific and therefore not incorporated into this analysis. No contingency factor was applied to the SCA capital costs for the same reason.

The NPV computed for the hybrid retrofit was independent of the base plant economics, i.e. if the hybrid retrofit were being considered to improve the economics of a geothermal power plant whose production fluid temperature was significantly below design/expected conditions, the NPV of the solar retrofit would have to be added to the NPV of the base plant to determine the overall project NPV. The NPV of a base geothermal power plant with a production fluid temperature decline rate that significantly exceeds the design basis is likely to be highly negative if this rate of temperature decline was not factored into the original project assumptions. It is therefore possible that the NPV of the base plant plus hybrid retrofit could be negative even if the hybrid retrofit NPV is positive for a given scenario; in this case the addition of the hybrid retrofit would increase the economics of the overall project, but not fully restore the economics to those of a design basis that did not account for unplanned production fluid temperature decline.

Results and Discussion

Sample plots of base and hybrid plant performance for the 175°C production fluid design temperature scenario over daily, monthly, and annual time scales are included in Figure 4 to Figure 6. These plots illustrate the performance characteristics of the hybrid plant relative to the base plant for a case in which the solar collector array is sized such that the maximum solar heat input is equal to 25% of the base geothermal plant design heat input (solar heat input arbitrarily selected for purposes of illustration).

Figure 4 illustrates the increased mid-day power generation of the hybrid plant for a date in mid-June with various levels of production fluid temperature decline. The additional mid-day power generation of the geo-solar hybrid plant results in a power generation profile that is more closely matched to a typical power demand profile than that from a stand-alone air-cooled binary geothermal power plant. It can additionally be seen from Figure 4 that, provided sufficient solar collector area is installed, it is possible for

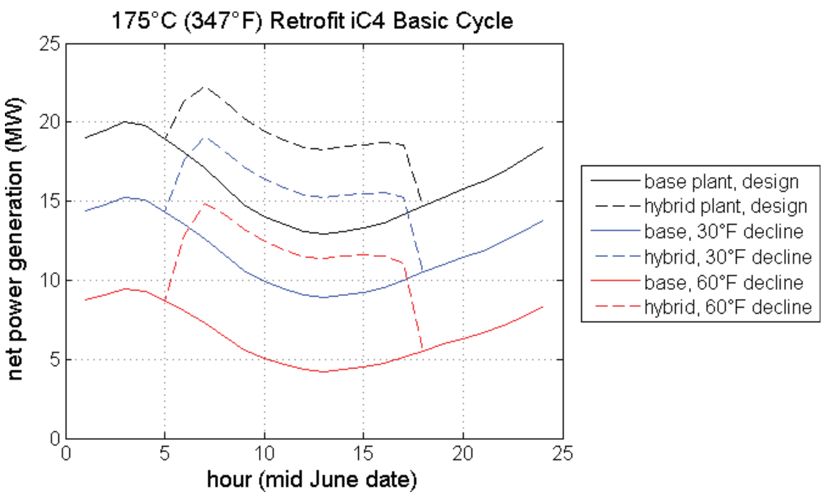


Figure 4. Simulated mid-June iC4 base and 18-SCA loop hybrid plant performance with 347, 317, and 287°F production fluid temperature (347°F design temperature).

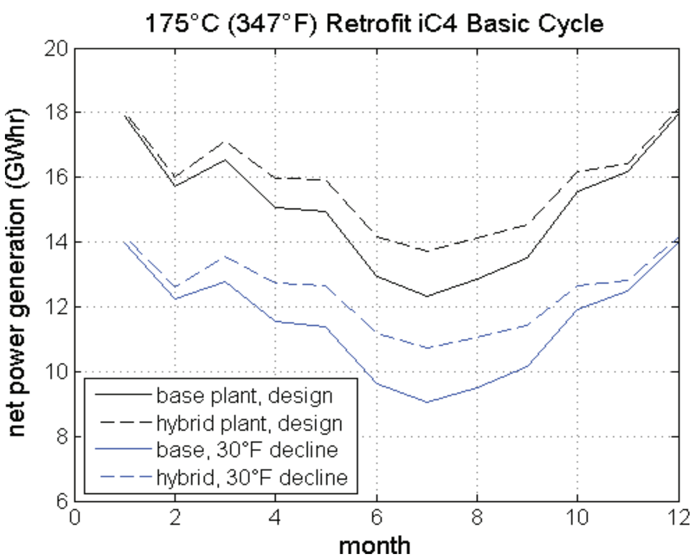
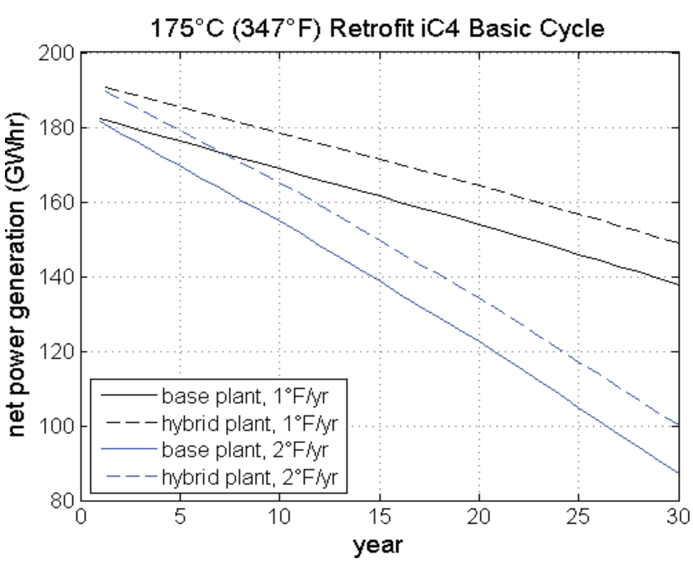


Figure 5. Base and hybrid plant monthly power generation.



the hybrid plant mid-day power generation to exceed that of the base power plant even after a significant decrease in production fluid temperature

Monthly and annual power generation for the 175°C production fl id design temperature scenario is plotted in Figure 5 and Figure 6, respectively. More power generation is realized from each unit area of CST array during summer months when solar insolation is the greatest (despite the increased dry-bulb ambient temperatures).

Additional power generation resulting from various levels of solar heat input in each of the production fluid temperature scenarios investigated is presented in Figure 7, where solar heat input is presented as a percentage of the base plant design point heat addition for each production fluid temperature scenario (base plant design point heat input values are provided in Table 3). Figure 7 indicates that the power generation from a constant quantity of solar heat addition results in increasing power generation as the production fluid temperature decreases. As can be inferred from Figure 1 and Figure 6, a constant decrease in the production fluid temperature results in an accelerating decrease in the base plant power generation due to the decrease in power plant efficiency as the operating point progressively deviates from the design point. The additional power generation from each unit of solar heat input therefore increases as the production fluid temperature decreases due to the solar heat addition elevating the production fluid temperature to achieve greater increases in thermal efficienc (the increases in efficiency are greater for degraded production fluid temperature).

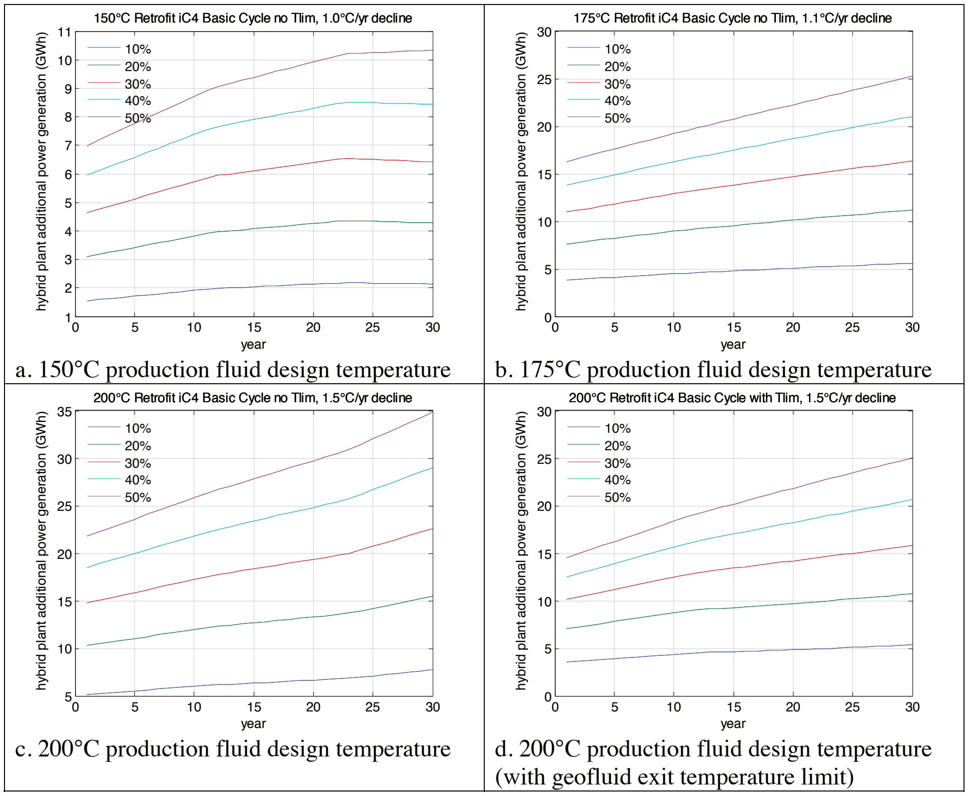
The thermal efficiency of power conversion from solar heat addition equal to 25% of base plant design point heat input as a function of production fluid and ambient temperature is presented in Figure 8. This thermal effi iency value corresponds to the difference between the base and hybrid plant power generation divided by the quantity of solar heat input for each combination of production fluid and ambient temperatures:

The efficiency trends illustrated Figure 8 are consistent with the discussion in the preceding paragraph, i.e. the power conversion thermal efficiency associated with the solar heat input is greater as the production fluid temperature decreases from the design point value.

NREL recently performed a survey of solar collector array costs that have been reported for recent concentrated solar power projects [14]. This analysis bracketed current solar collector array costs to a range of values from approximately \$300 to \$600 per square meter for large trough and linear Fresnel collectors. The range of SCA costs evaluated in this analysis was selected so as to generally correspond to the range of SCA cost values identifie in the NREL analysis. It is expected that advances in collector manufacturing and increased mass production of collectors would lead to further cost decreases.

A sensitivity analysis of NPV vs SCA cost and electricity sales price was performed for each of the power plants designed for the specified geothermal production fluid temperatures. The

Figure 6. Base and hybrid plant annual power generation with 1 and 2°F/year annual production fluid temperature decline.



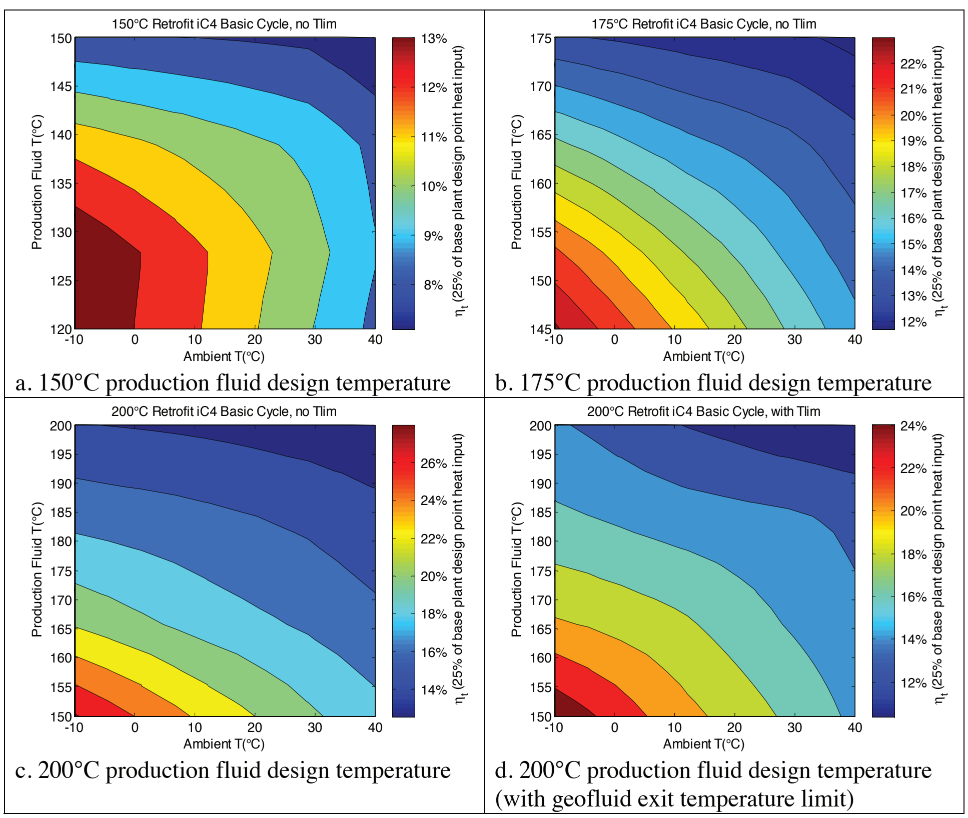
a. 150°C production fluid design temperature

b. 175°C production fluid design temperature

c. 200°C production fluid design temperature

d. 200°C production fluid design temperature (with geofluid exit temperature limit)

Figure 7. Additional annual power generation from solar retrofit of base plant as function of solar heat addition (percentage of base plant design point heat input).



a. 150°C production fluid design temperature

b. 175°C production fluid design temperature

c. 200°C production fluid design temperature

d. 200°C production fluid design temperature (with geofluid exit temperature limit)

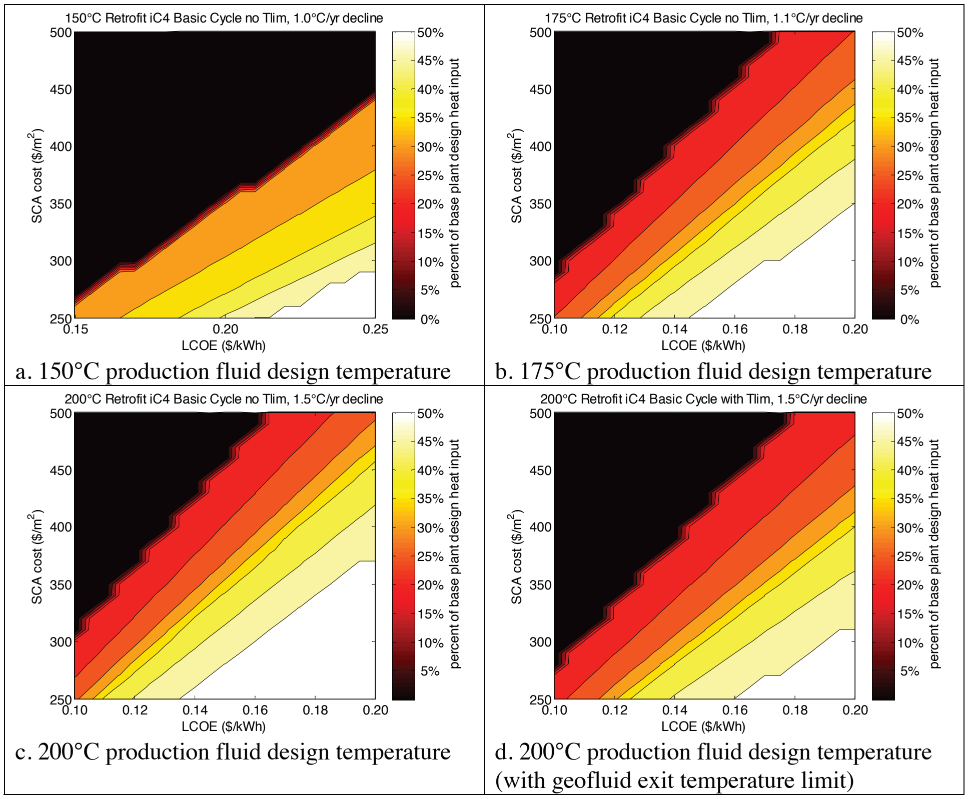
Figure 8. Thermal efficiency of power conversion from solar heat addition equal to 25% of base plant design point heat input.

electricity sales price was varied in the range from \$0.10 to \$0.20/kWh except for in the case of the 150°C production fluid design temperature for which more informative results were obtained when the electricity sales price was varied in the range from \$0.15 to \$0.25/kWh. The SCA costs, which include site improvements, solar field, and heat transfer system, were varied in the range from \$250 to \$500/m^2. The number of SCA loops and SCA installation year was optimized at each point in the sensitivity analysis with the goal of optimizing retrofit installation NPV. The optimal quantity of solar heat addition for each combination of SCA cost and electricity sales price is presented in Figure 9.

If the geo-solar hybrid plant economics were unfavorable for a given combination of electricity sales price and SCA cost the optimization routine would drive the number of SCA loops selected to zero; this condition is indicative that proceeding with installation of the solar collectors with the specified electricity sales price and SCA cost would result in a negative NPV. Therefore, for the conditions specified and assumed in this analysis, favorable conditions for installation of a geo-solar hybrid plant retrofi are indicated by a positive NPV result; greater NPVs correspond to increasingly favorable hybrid retrofit economics. Optimized NPV results for each combination of SCA cost and electricity sales price are presented in Figure 10.

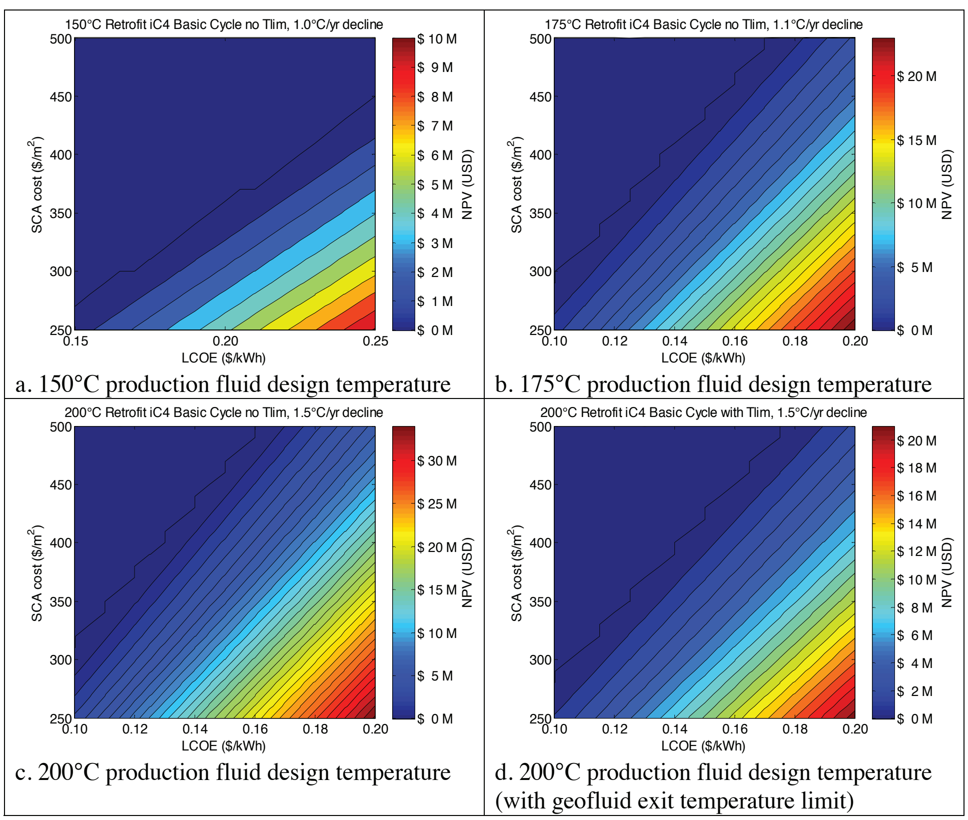
It should be reiterated that the NPV presented in this analysis only applies to the cost of the solar retrofit installation and the resulting increase in power generation and power sales revenue for the specified economic assumptions. The base project NPV may be highly negative if production fluid temperature decline is higher than planned and therefore the base plant and solar thermal retrofit NPV have to be summed to evaluate the overall project economics. There may be cases where the base plant economics are sufficiently poor that additional revenue generation from an economically favorable solar retrofit would still result in overall project economics that were not viable.

In general, power plants designed for higher temperature production fluids result in solar retrofit hybrid plants having greater NPV for a given set of economic conditions. This is primarily



a. 150°C production fluid design temperature
b. 175°C production fluid design temperature
c. 200°C production fluid design temperature
d. 200°C production fluid design temperature (with geofluid exit temperature limit)

Figure 9. Optimized solar hybrid retrofit heat input (percentage of base plant design point heat input) to base plant.



a. 150°C production fluid design temperature
b. 175°C production fluid design temperature
c. 200°C production fluid design temperature
d. 200°C production fluid design temperature (with geofluid exit temperature limit)

Figure 10. Optimized NPV for solar hybrid retrofit of base plant.

due to the increased efficiency of power plants designed for higher production flu d temperatures. While combinations of electricity sales price and SCA cost for which solar hybrid retrofit results in a positive NPV do exist for the plant with the geofluid exit temperature limit, the NPV is generally lower than for the case without the temperature limit.

When installation of concentrated solar collectors results in a positive NPV, the NPV was found to be maximized by installation of the collectors in year 1 for the "single upgrade" installation strategy (all solar collectors are installed at the same time) evaluated in this analysis. An "on-demand" installation strategy (in which more collectors are added as the production flui temperature decreases) was not examined as part of this analysis due to complexities in presenting generalized results for this strategy. The "on-demand" strategy may be useful in a scenario where installation of solar collectors is only economically favorable for generating sufficient power to avoid PPA penalties. In this case, the solar collectors could be added in response to production fluid temperature decline to provide thermal energy for generating the required quantity of electrical power.

The hybrid geo-solar power plants evaluated provided increased ability to generate power during the months in which ambient temperature is greatest. Geothermal power plants with declining production fluid temperature and PPA terms that require a fixed level of monthly power generation (not seasonally adjusted to account for the decrease in air-cooled binary plant performance at higher ambient temperatures) could utilize solar thermal retrofi technology to meet PPA power generation requirements and avoid or offset PPA penalties. However, the hybrid plant configuration provides additional power generation capacity that can assist with meeting PPA contract obligations on annual, monthly, or even daily reporting periods.

In cases where resource productivity decline is not an issue, an ideal PPA contract for a geo-solar hybrid plant may be one that involves separate contracts for the power generation associated with the separate geothermal and solar heat sources. The geothermal heat source is likely to be best suited to sale of power through a fixed rate base load power contract, while the solar heat source would be best suited for power sales using a time-of-delivery pricing contract. The existence of dual contracts that apply to the power generated from a single power block would most certainly involve a rigorous and likely complicated contract; the details of such a contract are not addressed here other than to note that the contract structure would require the relatively simple requirement that the power plant instrumentation accurately measure and record the quantity of heat utilized from each of the heat sources.

Conclusions

Solar thermal retrofit of a geothermal power plant with declining production fluid temperature can increase net power generation, especially during periods of high ambient temperature when air-cooled binary plant output is typically lowest. The quantity of additional power generation attributed to each unit of solar heat input increases as the production fluid temperature decreases since the solar heat input offsets the progressive degradation in power plant efficiency that occurs as the plant operating point deviates from the design point. This results in greater thermal efficiency of the power conversion of solar heat input as the production fluid temperature decreases from the design point value.

The NPV sensitivity analysis presented in this analysis identifies the combinations of electricity sales price and SCA cost where a retrofit installation can improve project economics. The NPV presented is only for the concentrated solar thermal collector array retrofit and does not account for the economics of the base power plant. In general, geo-solar hybrid plant retrofit strategy is increasingly favorable with higher electricity sales price and lower SCA cost. Of the scenarios evaluated, the power plants with the higher production fluid design temperatures had higher design point thermal efficiencies, which permitted these plants to generate a greater quantity of power from each unit of solar energy input. The presence of a geofluid exit temperature limit decreases the magnitude of the NPV that is associated with a solar hybrid retrofit of the plant

A scenario in which production fluid temperature decline has resulted in the imposition of PPA penalties for deficient base geothermal plant power generation is likely to realize additive benefit from a solar retrofit if the additional power generation can be used to prevent the project from being in default of the PPA contract.

Nomenclature

CST	Concentrated Solar Thermal
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
HTF	Heat Transfer Fluid
MACRS	Modified Accelerated Cost Recovery System
NPV	Net Present Value
PPA	Power Purchse Agreement
SAM	System Advisor Model
SCA	Solar Collector Array
TMY	Typical Meteorological Year
VFD	Variable Frequency Drive

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