Integration of a Concentrating Solar Steam Topping Turbine to an Existing Geothermal Binary Power Plant

Cooperative Research and Development Final Report

CRADA Number: CRD-17-700

NREL Technical Contact: Guangdong Zhu

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Technical Report
NREL/TP-5500-76726
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Cooperative Research and Development Final Report

Report Date: 3/30/20

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: US Geothermal, Inc.

CRADA number: CRD-17-700

CRADA Title: Integration of a Concentrating Solar Steam Topping Turbine to an Existing Geothermal Binary Power Plant

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$75,000.00
TOTALS	$75,000.00

Abstract of CRADA Work:

U.S. Geothermal Inc. is a publicly traded leading renewable energy company focused on the development, production, and sale of electricity from geothermal energy with operating generation facilities at Raft River, Idaho; San Emidio, Nevada; and Neal Hot Springs, Oregon. (U.S. Geothermal was acquired by Ormat Technologies, Inc. since the execution of this project). This project will evaluate the integration of a concentrating solar steam topping cycle with a geothermal bottoming binary cycle. This hybrid plant configuration will enable high efficiency conversion of the solar heat to electrical power, while simultaneously increasing the power output of the bottoming cycle. Such a design has the potential to reduce the cost of electrical power from concentrating solar power (CSP) and geothermal plants, and a viable design could be deployed at existing geothermal plants that have experienced resource productivity decline as well as in greenfield projects. This analysis will examine US Geothermal’s Raft River power plant for implementation of this concept. INL and NREL have previously collaborated in the analysis of geo-solar hybrid power plants. These two labs will again work together to model the solar field, steam-topping, and geothermal bottoming cycles in order to investigate the performance of the proposed cycle. This analysis will provide US Geothermal with technical information including equipment specifications and estimated power generation necessary to advance the concept toward implementation.

A successful project outcome has two parts: One would be for USGeothermal to have a process flow diagram (heat and mass balance), and performance parameters for the major pieces of equipment. USGeo could then use this information evaluate the techno-economic feasibility of the hybrid power cycle, and serve as the basis for subsequent detailed equipment design, purchase, and installation of the cycle. The second would be for the developed solution to be published by DOE for use by other geothermal developers both to retrofit underperforming plants and to lower the LCOE of new developments.

<u>Summary of Research Results</u>:

We have successfully completed all four tasks. The detail work regarding the tasks were summarized in the 68-page technical report [1]. In addition, one short article was published on the GRC bulletin [2] and one journal article [3] was just published on the high-impact journal: Applied Thermal Energy.

In this project, a geothermal binary cycle is retrofitted with a solar topping steam cycle. The waste heat from the steam cycle is used to return the binary cycle to its design point. We develop design and off-design models of the geothermal plant (and verify against operational data), solar field, and topping cycle. These models account for variations in ambient temperatures and solar resource. We undertake annual simulations to evaluate the additional electricity generated and levelized cost of electricity (LCOE).

Task 1. Assemble data on existing Raft River power plant and identify performance metric targets for hybrid plant.

The Raft River geothermal power plant uses a dual-pressure-level binary cycle (organic Rankine cycle) that was designed and constructed by Ormat, as illustrated in Fig. 1. A high pressure (HP) and low-pressure (LP) turbine are connected on either side of a common generator, and the design point conditions are shown in Table 1. Geothermal brine flows into the HP and LP vaporizers in series, and then the brine splits to feed the preheaters of both systems.

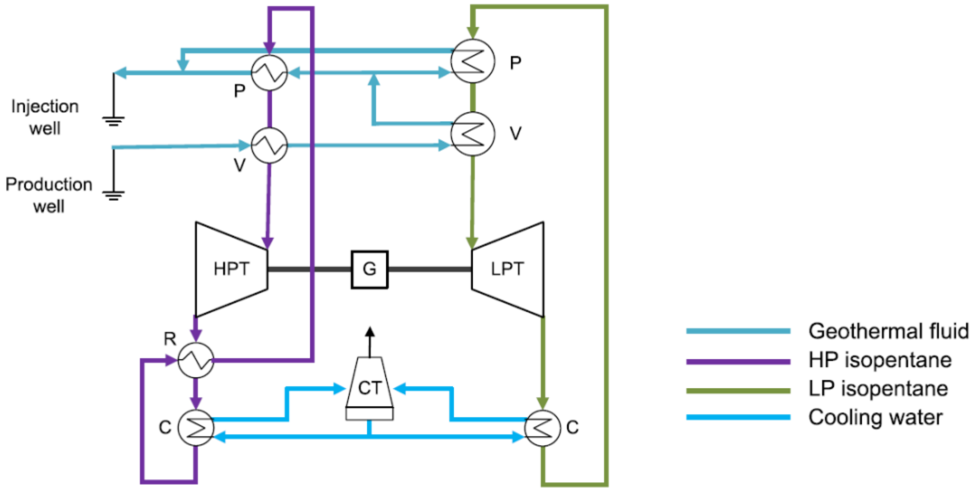


Fig. 1. Raft River geothermal power plant process flow diagram. Key: HPT: High-pressure turbine; LPT: Low-pressure turbine; G: Generator; C: Condenser; CT: Cooling tower; P: Preheater; V: Vaporizer. Some pumps and other equipment are not shown for clarity.

	P, bar	T, °C	$\dot{m}$, kg/s	x	Phase
High-pressure loop					
Turbine inlet	9.6	113.5	139.3	1	(slight SH)
Turbine exhaust	0.9	62.4	139.3	1	(high SH)
Condensate	0.9	19.9	139.3	0	(saturated)
Low-pressure loop					
Turbine inlet	5.1	84.7	128.9	1	(slight SH)
Turbine exhaust	0.9	48.2	128.9	1	(mod SH)
Condensate	0.9	19.4	128.9	0	(saturated)

Table 1. Selected isopentane design state points on Fig. 1 (SH = superheated).

Description	Modelled design point		Modelled current operation	
	Flow, kg/s	T, °C	Flow, kg/s	T, °C
Geothermal production fluid	396.9	137.8	340.2	133.3
Geothermal injection fluid	396.9	65.6	340.2	60.4
	Gross	Net	Gross	Net
Power output, MW_e	16.8	14.6	13.7	11.6

Table 2. Comparison of design and actual operating conditions and generation. (Power output does not include geothermal fluid pumping).

The cooled brine is then injected into the geothermal reservoir. The Raft River geothermal resource has a lower mass flow rate and temperature than originally anticipated when the system was designed.

The power block therefore operates at part-load and the plant produces less energy, as indicated in Table 2. The design point may be restored by adding solar heat to the system, and solar resource data is shown in Table 3. The solar resource in Idaho is lower than what is typically suitable for CSP plants. However, hybridizing solar heat with geothermal may enable CSP technologies to be deployed in new regions. Various hybridization options for the Raft River plants were examined, which suggested that a topping steam cycle was the most effective approach. Here, steam from the turbine exhaust is added to the high-pressure binary loop. After the existing high-pressure geothermal preheater, the binary fluid is split. A fraction continues on the original path and is vaporized by geothermal heat. The

Annual average	Unit	Burley, ID
Direct normal irradiance	$kWh/m^2/day$	5.71
Global horizontal irradiance	$kWh/m^2/day$	4.63
Wet-bulb temperature	°C	5.1
Wind speed	m/s	3.8
Elevation	m	1,267
Latitude	°N	42.533
Longitude	°E	−113.767

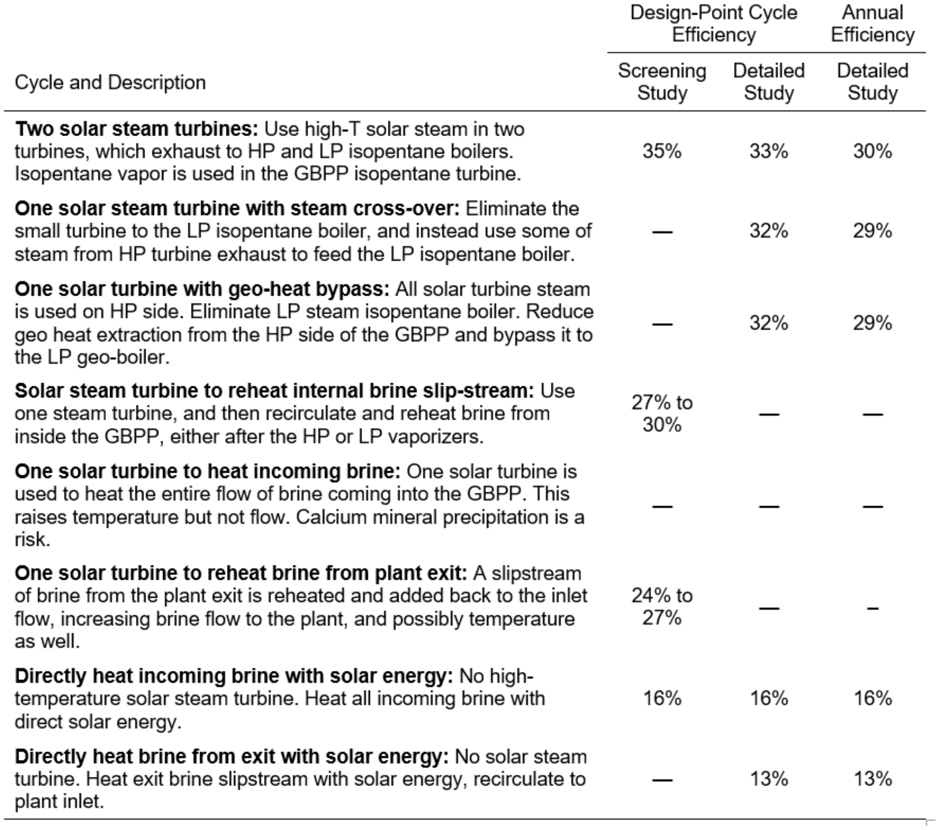
Table 3. Typical solar irradiance, weather and geographical conditions at the Raft River geothermal power plant.

remainder is vaporized and then superheated by the exhaust from the steam turbine. The two high-pressure binary flows are then mixed and drive the high-pressure binary turbine. The hybrid plant includes thermal storage in the form of two liquid tanks that contain the solar field heat transfer fluid (HTF). This type of storage is comparatively straight-forward technologically and has been previously deployed at CSP plants. It is assumed that the tanks are sufficiently insulated so that heat leakage losses are negligible over the storage duration which may be several hours. In this article, several modes of operation are considered depending on the state-of-charge of storage and the available solar energy. Excess solar heat is stored in the tanks. In the event that the tanks are full, and the steam turbine is at maximum capacity, steam can be bypassed around the turbine and added directly to the geothermal system.

Task 2. Perform design point analysis of U.S. Geothermal proposed retrofit geo-solar steam-topping binary-bottoming cycle.

The initial screening study was performed on a large number of different cycle configurations at a single operating condition. Subsequently, a more detailed study investigated annual cost and performance. Both the screening study, using one set of modeling software, and the detailed analysis using another software package were calibrated against one or more aspects of the Raft River operating condition. The combined results of the screening and detailed study are shown in Table 4 (although the results from one model should not be compared to those of the other).

As the study progressed, additional steam-topping cycle configurations were compared with the aim of simplifying the cycle and reducing the capital cost. The most promising involves using a single steam turbine whose exit flow vaporizes the binary cycle working fluid. This cycle achieves a conversion efficiency of solar thermal power to electricity of 32.0 % at the design point, and 29 % over the year. The advantages of this cycle were that it reduced the number of equipment components added to the cycle, made use of the existing brine bypass to transfer heat to the low-pressure turbine, and retained the advantage of lowering the brine exit temperature when the solar turbine was operating.



Cycle and Description	Design-Point Cycle Efficiency		Annual Efficiency
	Screening Study	Detailed Study	Detailed Study
Two solar steam turbines: Use high-T solar steam in two turbines, which exhaust to HP and LP isopentane boilers. Isopentane vapor is used in the GBPP isopentane turbine.	35%	33%	30%
One solar steam turbine with steam cross-over: Eliminate the small turbine to the LP isopentane boiler, and instead use some of steam from HP turbine exhaust to feed the LP isopentane boiler.	—	32%	29%
One solar turbine with geo-heat bypass: All solar turbine steam is used on HP side. Eliminate LP steam isopentane boiler. Reduce geo heat extraction from the HP side of the GBPP and bypass it to the LP geo-boiler.	—	32%	29%
Solar steam turbine to reheat internal brine slip-stream: Use one steam turbine, and then recirculate and reheat brine from inside the GBPP, either after the HP or LP vaporizers.	27% to 30%	—	—
One solar turbine to heat incoming brine: One solar turbine is used to heat the entire flow of brine coming into the GBPP. This raises temperature but not flow. Calcium mineral precipitation is a risk.	—	—	—
One solar turbine to reheat brine from plant exit: A slipstream of brine from the plant exit is reheated and added back to the inlet flow, increasing brine flow to the plant, and possibly temperature as well.	24% to 27%	—	–
Directly heat incoming brine with solar energy: No high-temperature solar steam turbine. Heat all incoming brine with direct solar energy.	16%	16%	16%
Directly heat brine from exit with solar energy: No solar steam turbine. Heat exit brine slipstream with solar energy, recirculate to plant inlet.	—	13%	13%

Table 4. Comparison of different hybrid plant configurations from the screening study and detailed study. '—' indicates the configuration was not studied

Task 3. Estimate annual hybrid plant power generation.

The sizing of the solar field is investigated, and it is found that the LCOE is minimized at solar multiples of 1.25. In a hybrid system, excess solar heat does not have to be curtailed but can be bypassed around the turbine and added directly to the geothermal plant. This reduces the quantity of energy that is curtailed, increases the optimal solar multiple to be around 1.5, and slightly decreases the LCOE.

However, this mode of operation is less efficient than extracting work at high temperatures in the solar field. Installing thermal storage allows power to be extracted at higher efficiencies at later times, and also improves the dispatchability of the plant and may enable it to take advantage of fluctuating prices. The hybrid system with the storage of 4 hours is calculated to have an optimal solar multiple of 1.75, and the system with the storage of eight hours has an optimal value of 2.0. We find that storage should cost less than \$30/kWh$_{th}$ in order for the minimum LCOE to be lower than that of a hybrid plant with no storage. Further details can be found in the referenced published papers below.

Task 4. Techno-Economic analysis

The LCOE is calculated for hybrid plants located in Burley, Idaho; Reno, Nevada; and Imperial, California. The annual average ambient temperature significantly affects the performance of the geothermal plant (which uses an evaporative cooling tower), with the California plant generating the least electricity due to higher wet-bulb temperatures. However, the solar resource is greater in Imperial, CA than at the other two locations, leading to a higher quantity of additional electricity produced due to the solar field. Consequently, the LCOE, without tax incentives, of a hybrid plant in California is lower (0.118 $ / kWh$_e$) than the other two locations (0.126 $ / kWh$_e$ at Burley, ID and 0.122 $ / kWh$_e$ at Reno, NV).

With an added thermal energy storage, the hybrid system has a better economic than PV with battery even under the current pricing structure. When the future grid with high renewable energy penetration starts to appreciate the value of energy dispatchability, the hybrid system with energy storage will have an increasing advantage over PV with battery. Further details can be found in the referenced published papers below.

References:

1. McTigue, J.D., Kitz, K., D. Wendt, G. Zhu*, N. Kincaid, J. Gunderson, "Solar Driven Steam Topping Cycle for a Binary Geothermal Power Plant," NREL, Golden CO: 2015, Technical Report No.: NREL/ TP-5500-71793. (https://www.nrel.gov/docs/fy19osti/71793.pdf)
2. Kitz, K.*, J.D. McTigue, D. Wendt, G. Zhu, N. Kincaid, J. Gunderson, "Solar thermal and geothermal hybrid power plant study," *Geothermal Resources Council Bulletin,* vol. 47, 2018.
3. McTigue, J.D., D. Wendt, Kitz, K., J. Gunderson, N. Kincaid, G. Zhu*, "Assessing geothermal/solar hybridization – integrating a solar thermal topping cycle into a geothermal bottoming cycle with energy storage," Applied Thermal Energy, Vol 171, May 2020. (https://doi.org/10.1016/j.applthermaleng.2020.115121)

Subject Inventions Listing:

None

ROI #:

None

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