Green-field Geothermal/Solar Designs

Cooperative Research and Development Final Report

CRADA Number: CRD-18-00763

NREL Technical Contact: Guangdong Zhu

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-92228
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Suggested Citation
Zhu, Guangdong. 2024. *Green-field Geothermal/Solar Designs: Cooperative Research and Development Final Report, CRADA Number CRD-18-00763.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-92228. https://www.nrel.gov/docs/fy25osti/92228.pdf.

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Cooperative Research and Development Final Report

Report Date: November 14, 2024

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

Parties to the Agreement: Hyperlight Energy (formerly Combined Power, LLC)

CRADA Number: CRD-18-00763

CRADA Title: Green-field Geothermal/Solar Designs

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office and Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$100,000.00
Modification #1	$0.00
Modification #2	$0.00
TOTALS	$100,000.00

Executive Summary of CRADA Work:

Geothermal power (GEO) and concentrating solar power (CSP) can be integrated to obtain the best aspects of both systems. The green-field design will utilize the full potential of the higher-temperature CSP sector by having a topping solar steam turbine and a bottoming geothermal cycle. In the proposed hybrid cycle, geothermal energy can be converted into electricity at a higher cycle efficiency because of the high-temperature topping cycle during the daytime. CSP benefits from lower-cost solar collectors, a less expensive topping turbine, and virtual elimination of the heat rejection system cost.

The green-field case study will be focused on a geothermal resource site which will deliver the 160 - 220 °C pressurized brine at the inlet of power block. While the case study will look at a single case study, the tools to be developed as part of the project will be available to model annual performance of

GEO/CSP hybrids for new greenfield projects (may also be applied to certain types of brown-field retrofits). The evaluation tools will also calculate important economic parameters such as the levelized cost of energy (LCOE) and the internal rate of return (IRR).

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope,
- Adds new capability to the laboratory's core competencies,
- Enhances the laboratory's core competencies,
- Uses the laboratory's core competencies, and/or
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.

Summary of Research Results:

TASK DESCRIPTIONS:

This project will mainly study on the general green-field geothermal/solar designs.

The integrated model will be able to take a weather file as input and predict power generation variation of the hybrid plant with varying amounts of solar power addition depending on sun intensity and availability. The power generation will be simulated as a function of time and, with an electricity price schedule, a cash flow can be generated as well. Combined with an installed plant cost and maintenance & operating cost, the internal rate of return (IRR) and levelized cost of energy (LCOE) can be calculated.

The integrated model will be applied to a low-temperature geothermal resource with a temperature of 160 - 220 °C as a case study. NREL will work with Hyperlight Energy to develop a model and conduct the feasibility study.

The proposed green-field model will integrate the following (tasks):

1. A geothermal power system with an equipment configuration tailored to the integrated design, a range of production fluid temperatures, power block performance, and potential changing reservoir conditions.
2. A solar thermal power system with a collector field which may be one type of line-focus CSP collectors: parabolic trough or linear Fresnel, and a topping cycle for higher temperature solar heat. A topping cycle will admit a higher temperature steam and generate electricity at a higher cycle efficiency. The exhausted steam will be directed to the bottom geothermal power cycle. This has a well-proven analogue in Ormat's existing "combined cycle" geothermal systems in which geothermal steam expands through a backpressure steam turbine to heat the working fluid of a geothermal ORC.
3. Solar heat storage to smooth solar intermittency, and to provide economical energy storage.
4. An operating strategy coordinating operations of solar and geothermal sectors.
5. An economic model to predict economic performance of a hybrid power plant.

Task 1: *A geothermal power system with an equipment configuration tailored to the integrated design, a range of production fluid temperatures, power block performance, and potential changing reservoir conditions.*

Task 1 Results:

The software model developed for this project was designed to be able to assess and compare any geothermal-solar hybrid system, given that the necessary data is provided. Amongst weather data, solar field performance, thermal storage sizing, and economic parameters, a required data component for running this software is performance curves for the power system. The overview of the model flow is shown below in Figure 1.

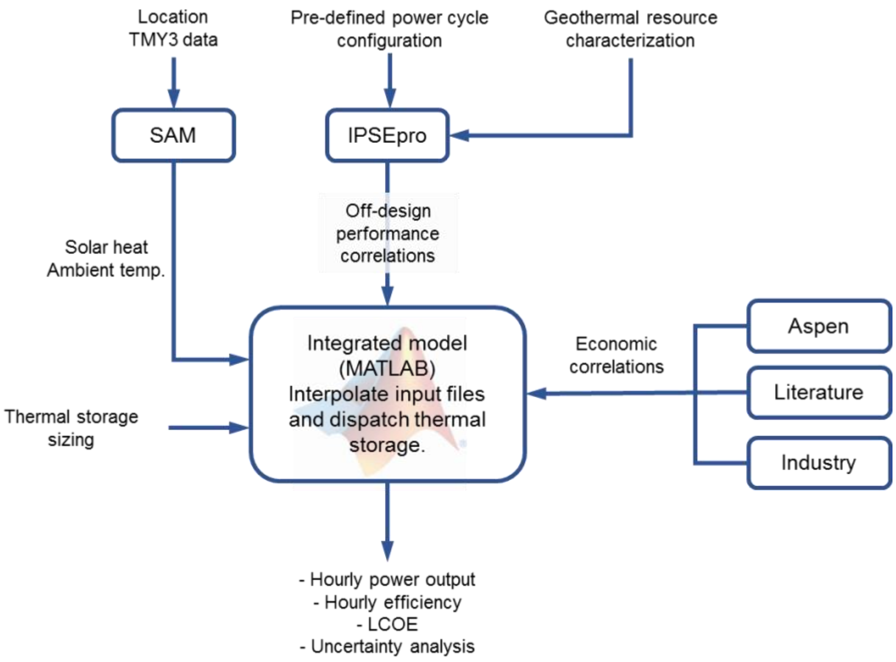

Figure 1. Integrated Model Overview

For our work, the performance data for our hybrid plant configurations were generated via IPSEpro [1]. A flow-sheeting software that can make predictions for both design and off-design systems, IPSEpro can be used to flexibly model the configuration of geothermal plants with varying conditions, such as production fluid temperatures, power block performance, and changing reservoir conditions. It can also be used to model integrated configurations. Figure 2 shows an example of a geothermal-solar hybrid plant modelled in IPSEpro.

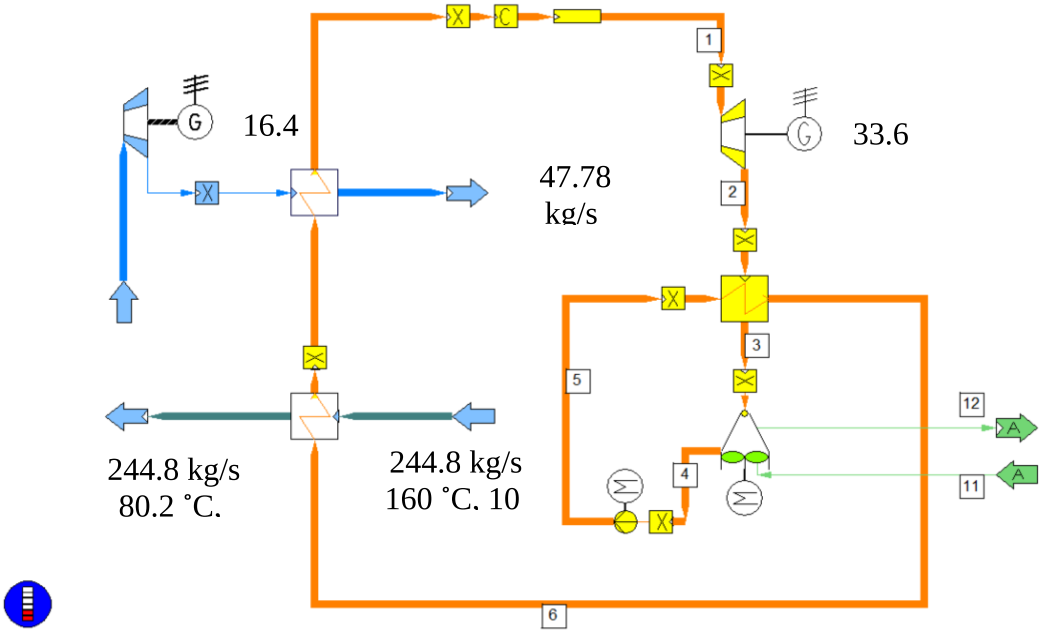

Figure 2. Example schematic of a geothermal-solar hybrid plant as modelled in IPSEpro

The data generated by IPSEpro is then input into our integrated model. As our model only requires this data input, users may model the power cycles of their plant configurations in any software of their choice, given that it generates the necessary performance curves.

Task 2: *A solar thermal power system with a collector field which may be one type of line-focus CSP collectors: parabolic trough or linear Fresnel, and a topping cycle for higher temperature solar heat. A topping cycle will admit a higher temperature steam and generate electricity at a higher cycle efficiency. The exhausted steam will be directed to the bottom geothermal power cycle. This has a well-proven analogue in Ormat's existing "combined cycle" geothermal systems in which geothermal steam expands through a backpressure steam turbine to heat the working fluid of a geothermal ORC.*

Task 2 Results:

As mentioned in Task 1, our integrated model takes in weather data and solar field performance as inputs. Using the System Advisor Model (SAM [2]), weather data can be generated for a required location, along with performance data for a selected concentrating solar collector field (e.g. parabolic troughs or linear Fresnel mirrors). As illustrated in Figure 1 (introduced in Task 1), SAM takes in the location data, and with the configurations set within SAM, returns the solar ambient temperature and thermal power per unit of mirror area for each hour of the year. This information is then read into our integrated model.

Hybrid power plants with configurations supporting a solar topping cycle can be modeled in IPSEpro, as described in Task 1. Figure 2 in Task 1 depicts a configuration of a hybrid plant with a geothermal heat input and a solar steam topping cycle. The effect of solar heat input and ambient temperature on net power is then output as a performance curve our integrated model reads in. The data generated for the example in Figure 2 is shown below in Figure 3.

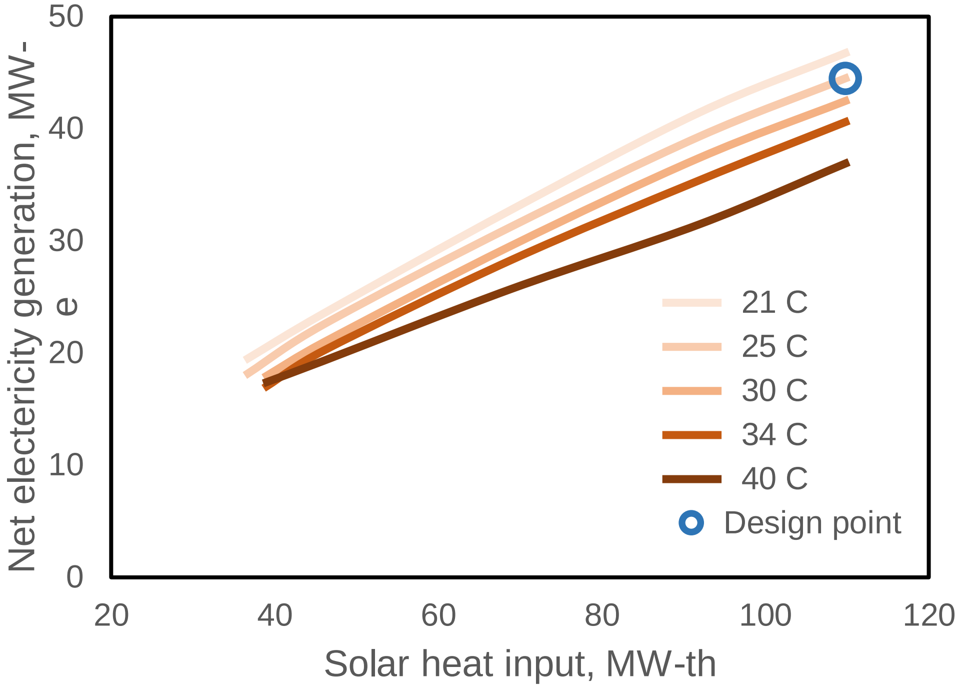

Figure 3. Net power output of a hybrid geothermal-solar power plant as a function of solar heat input and ambient temperature. Data is generated by IPSEpro.

Task 3: *Solar heat storage to smooth solar intermittency, and to provide economical energy storage.*

Task 3 Results:

As mentioned in Task 1, a parameter of our model is thermal storage sizing. When there is an excess of solar thermal power available, our model charges storage. When the solar thermal power decreases below the design point, our model discharges the storage. Storage sizing and cost were varied in our model to see the effect on LCOE. The results are presented below in Figure 4.

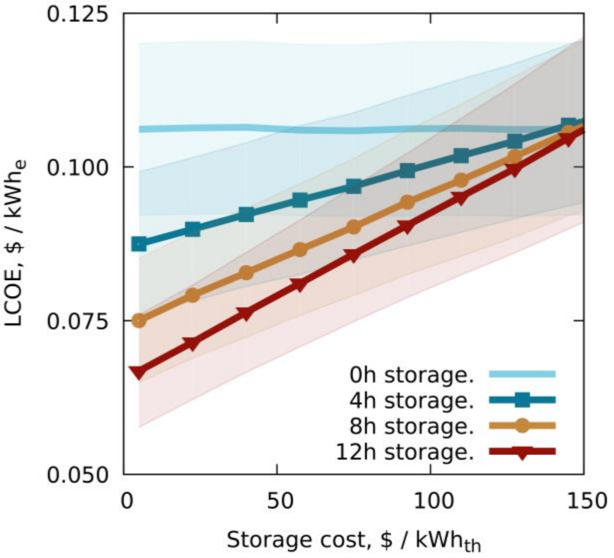

Figure 4. Impact of thermal storage cost and size on the LCOE. Shaded bands indicate the uncertainty of the LCOE and are given by the mean value plus/minus the standard deviation of the LCOE probability distribution.

Task 4: *An operating strategy coordinating operations of solar and geothermal sectors.*

Task 4 Results:

Through our work, we found several guiding principles regarding the operation of geothermal-solar hybrid plants, as listed below:

- Work should always be extracted at the highest temperatures (exergies) possible.
- Plant operations should not lead to an increase in brine injection temperature.
- Best cycles result in vaporized ORC fluid; worst cycles result in heated geothermal fluid.
- Heating the incoming geo-fluid is more effective than recirculating it.
- Scaling (mineral deposition) should be avoided.
- Wells and turbines should be operated continuously and at their design points, if possible.

Task 5: *An economic model to predict economic performance of a hybrid power plant.*

Task 5 Results:

As part of the necessary input parameters, economic data are needed to estimate the total capital cost and operations and maintenance cost. This data includes capital cost estimates for the solar mirrors, receivers, land clearance cost, solar-thermal-oil-to-steam generator, geothermal wells, thermal storage, and the power block. For these components, the model has default estimates developed from sources including Aspen [3] and EconExpert [4]. These default estimates are shown below in Table 1.

Table 1. Default estimates of component costs for a geothermal-solar hybrid system.

Component cost		
Solar field mirror	$ / m2	96
Solar field receiver	$ / m2	20
Land management	$ / m2	5
HTF-to-steam generator	$ / kWth	281
Storage	$ / kWhth	50
Geothermal wells	$ / kWe (geothermal only)	2500
Hybrid power block	$ / kWe (total power)	2000
Hybrid plant O&M	$ / MWhe	24.2

Using the other input parameters previously mentioned, our model calculates hourly system performance. This performance, compiled annually, is used along with the economic parameters to calculate LCOE via the Fixed Charge Rate (FCR) method. With the FCR method, additional economic input data besides the above mentioned are required, such as the plant lifetime, discount rate, tax rate, etc. For more information on the FCR method, its parameters, and how it is applied to a hybridized system, please see Refs. [5, 6].

To analyze the uncertainty of these economic metrics, Monte Carlo simulation is used. The capital cost of each component is assumed to have a normal distribution, and the user can provide standard deviation as well as upper and lower limits to augment this distribution. Using this information, the model calculates the probability distributions of the total capital cost and LCOE.

Figure 4 in Task 3 provides an example of our model's calculation results for LCOE and its uncertainty as a function of changing storage cost. Figure 5, below, provides an example of our model's calculation results for LCOE as a function of changing solar field collector and power block cost.

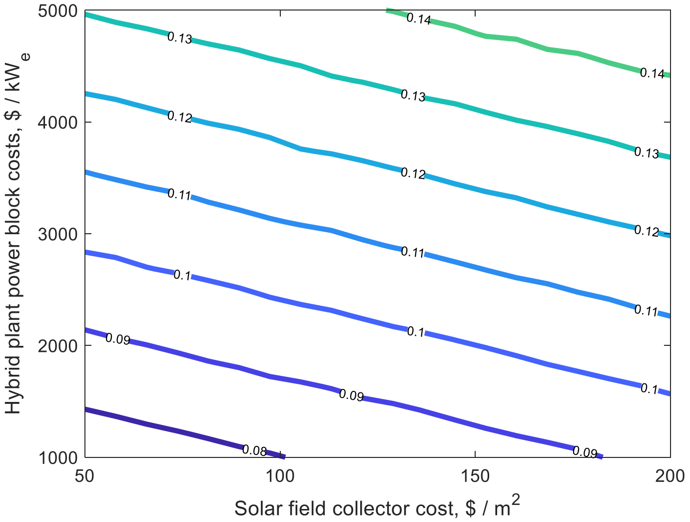

Figure 5. Contours of levelized cost of electricity (LCOE) in $/kWhe.

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[5] W. Short, D.J. Packey, *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*, NREL Tech. Rep. NREL/TP-462-5173. (1995).

[6] J.D. McTigue, J. Castro, G. Mungas, N. Kramer, J. King, C. Turchi, G. Zhu, *Hybridizing a geothermal power plant with concentrating solar power and thermal storage to increase power generation and dispatchability*, Appl. Energy. 228 (2018) 1837–1852. doi:10.1016/j.apenergy.2018.07.064.

Subject Inventions Listing:

None.

ROI #:

None.