Displaced Exergy: The Valuation of Thermal Power

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ABSTRACT

Conventional exergy analysis is a useful tool to compare the relative efficiency of cycles harnessing geothermal fluids of different fluid properties, as well as to assess the power generation potential of production well flows and power plant process side streams. These side streams could be fluid flows re-injected to the reservoir or low enthalpy fluids discharged from the power generation process. Exergy analysis is also a valuable tool to assess the potentials for improvement of a cycle or plant component. However, exergy analysis on power generation projects has the potential to overlook the value of the process streams and the potential contribution that they can make when the same system is analyzed from a more holistic perspective. This paper discusses the concept of "displaced exergy," where improved matching of a stream's utilization to local demands and the prevailing energy resources is shown to result in better conversion efficiencies than conventional exergy analysis would indicate is possible. When viewing projects through this proposed perspective, geothermal plants with flexibility in generating both thermal and electrical energy can achieve much higher effective efficiencies than a conventional exergy analysis would indicate. A higher effective efficiency using displaced exergetic analysis could be possible in geographic locations where fossil fuels are widely used for thermal demands, and where the fossil fuel thermal generation could be substituted by utilizing geothermal fluids.

Introduction

The concept of exergy analysis is a useful tool for comparing the efficiency of cycles that use fuels or fluids with different energy capacities. First law efficiencies of geothermal plants are significantly lower than conventional fossil fuel plants, such as gas turbine combined cycles, largely due to the much lower temperature of the heat source. Exergy analysis assigns a maximum theoretical potential for generating work through a heat engine by a fluid, based on the differences between its properties and assumed "dead state" conditions where it would be at equilibrium. Dr. Ronald DiPippo pioneered the use of exergy as a diagnostic tool for geothermal plants and his many papers and textbooks provide an excellent framework for this analysis.

As an illustration of the perspectives to be presented in this paper, we will draw from an exergy analysis of one stream presented in DiPippo's paper, Exergy Analysis of Geothermal Power Plants (DiPippo R, Marcille D. 1984). This is a low temperature stream from the double flash plant at Krafla, Iceland. It could also be viewed as a stream from a low temperature geothermal well (neglecting the different propensities for scaling the stream might have, in this idealized analysis). The conditions of the stream, the dead state properties and the exergetic analysis are summarized in Table 1.

Conventional exergy analysis would conclude at this point and make the observation that with an assumed second law conversion efficiency of approximately 30% (a reasonable estimate for an actual plant [DiPippo R, Marcille D. 1984]), this stream might produce about 4 MWe of power if a binary power plant were applied. Viewed from this perspective, 4

Table 1. Assumed Steam Conditions and exergy calculation.

Parameter	Value	Notes
Flow Rate	641,000 kg/hr	Flow exiting second flash separator
Temperature	122.8°C	Flow exiting second flash separator
Steam Enthalpy	515.71 kJ/kg	Saturated water at 0.22 MPa
Stream Entropy	1.56 kJ/kg*K	Saturated water at 0.22 MPa
Dead State Temperature	11.1°C	Ambient conditions at equilibrium
Dead State Pressure	1 bara	
Dead State Enthalpy	46.73 kJ/kg	
Dead State Entropy	0.17 kJ/kg*K	
Exergy	$\dot{m}[(h-h_0)-T_0(s-s_0)]$	$78.056\ kg/s * \left[\begin{array}{l}(515.71-46.73\ kJ/kg)-284.25K \\ *(1.56-0.17\ kJ/kg*K)\end{array}\right]$ $=13.2\,MWe$

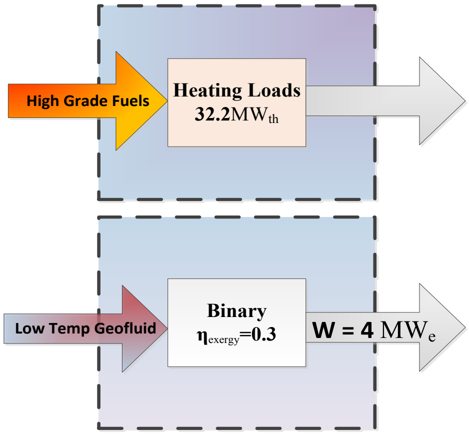

Figure 1. Conventional exergy perspective of a geothermal source.

MWe is the realistic "worth" of this stream and 13.2 MW would be the maximum theoretical power generation. Figure 1 shows a binary plant operating to produce 4 MWe from the geofluid. Incidentally, there may be residential or industrial users of thermal energy (e.g. heating loads) in the same area. This thermal energy may be generated using fossil fuels. We will envision in the following section that the process stream previously analyzed could be used instead to deliver generate 32.2 MWth, potentially replacing the fossil fuels used.

In this paper, we modify our perspective of the project to be broader and illustrate how this perspective radically changes the maximum realistic "value" of this low temperature geothermal stream.

Displaced Exergy

Assume the low temperature geofluid stream discussed above is used instead to deliver thermal power to a local process, such that the geofluid enters at 122.8°C and exits the process at 80°C for a change in temperature of 42.8°C. At a flow rate of 641,000 kg/hr, this results in 32.2 MW$_{th}$ of thermal energy delivered. This process stream could substitute for the thermal energy produced from the combustion of a high grade fuel source. 32.2 MW$_{th}$ is equivalent to 109,785,668 Btu/hr or 3108 m^3/hr of natural gas that would be required to deliver this quantity of thermal energy. Using geothermal energy instead "displaces" this quantity of natural gas, which can be used to generate electricity.

An industrial process or community could harness the natural gas in an alternative manner. A combined cycle H class power plant has a heat rate of less than 6000 Btu/kWh$_{net}$ (GE Power and Water, 2014). This amount of displaced natural gas could be used to generate an estimated 18 MW$_e$ (net) of electric power. Table 2 summarizes this analysis.

Table 2. Displaced Exergy analysis summary.

Geofluid Stream	$\dot{m}(h_{in}-h_{out})$ $\frac{641000}{3600}*\left(\frac{515.71kJ}{kg}-\frac{334kJ}{kg}\right)$	32.2MWth
Natural Gas	3108m3/hr ≈ 32.2 MWth	3108m3/hr ≡ 109.7MBtu/hr
Natural Gas Combined Cycle	6000 Btu/kWhnet	$\frac{109.7\text{MBtu / hr}}{6000\text{ Btu / kWhnet}}=18\ \boldsymbol{MWe-net}$

Applying a different perspective towards energy application by combining energy sources, the collective output has increased even beyond what conventional exergy analysis would indicate is possible

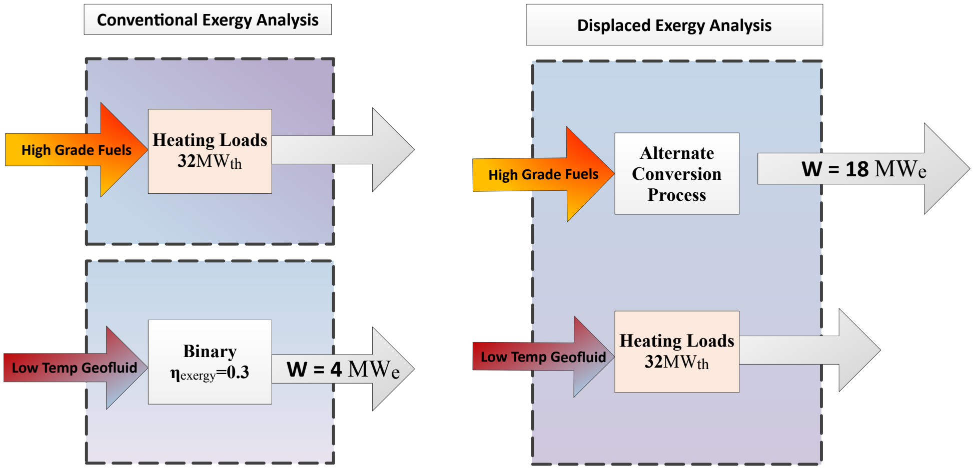

Figure 2. Comparison of conventional and displaced exergy analysis.

theoretically. Using the new perspective and harnessing the streams more appropriately, the net output increased from 4 MW_e to 18 MW_e. It seems that conventional exergetic analysis potentially undervalues the stream in this setting. Figure 2 illustrates this comparison of conventional exergy and displaced exergy methods and perspectives. Applying displaced exergy analysis, two separate processes have been combined into a single cogeneration process, illustrated by the dashed area in the figure.

Perspectives

The astute reader may raise several points with this simplified analysis. In calculating the stream exergy, it assumes an idealized process that results in the geofluid being brought to equilibrium with the dead state temperature. This is unrealistic for geofluids because troublesome scaling would occur before that point, however these factors are usually neglected to limit subjectivity and allow level comparisons in such calculations.

Conversely, the assumption of return temperature for the thermal power case at 80^{o}C is reasonable and perhaps even high for what might actually be possible, therefore the conclusion is conservative. More aggressive use of thermal energy from the geofluid would result in even higher values for the work that could be produced from the displaced exergy.

It may be uncommon for thermal demands to remain fixed throughout the year, thus some capacity factor would need to be applied that would reduce the perceived benefits of the thermal system. One could envision mixed modes where the plant contributes more thermal power when needed and more electrical power when thermal loads are low. Geothermal cogeneration plants in Iceland and Bavaria are good illustrations of this flexibility. Further research could further explore the relative economics such as district heating versus power generation, or the fungibility and ease of transmission of electrical power versus the site-specific challenges of thermal utilization.

These simple calculations assume a relatively modern gas turbine combined cycle plant efficiency. The way fuels are used in the location around a geothermal resource strongly affects the value of the displaced exergy. If low exergetic value fuels are currently being used to meet thermal loads (e.g. solar water heating), then there is limited benefit in displacing them with geothermal energy. In the other extreme, if electric resistance heaters are being used to meet low temperature thermal loads that could otherwise be met with geofluid, using the geofluid for electrical generation may challenge one's sanity.

All streams entering and leaving our process black box or "resource park" have value, including low quality thermal energy. The concept of a resource park is establishing value for all process streams entering or leaving a region and can incorporate multiple industries. The perception of thermal fluids leaving a geothermal plant should not be that they are waste or that the most effective use is direct electric generation. Many industrial processes use thermal energy. Uses for thermal energy could include district heating, aquaculture, algae biofuel, and other industrial processes. In some cases a bottoming binary power plant may not be the most efficient way to utilize leftover thermal energy. Applying concepts such as industrial symbiosis could create a collaboration of processes suggested in the meaning of a resource park. An industrial symbiosis is an assembly of multiple processes or industries utilizing each other's product streams. Such collaboration requires innovation on an interdisciplinary level, to create more effective ways to utilize value streams, create multiple sources of revenue, and reduce economic risks (Albertsson and Jonsson, 2010).

While it may be perceived through using conventional exergy analysis there is an advantage thermodynamically if low temperature resources are used directly for power generation, displaced exergy analysis could challenge this in particular situations. As DiPippo notes, the resource location and conditions will stipulate technical and financial assessments where economics of resource streams will be a major deciding factor (DiPippo, 1987).

Conclusions

There are several conclusions that emerge from the use of the displaced exergy perspective:

1. Conventional exergy analysis may systematically undervalue the contribution that a low temperature geofluid stream can make to an overall resource park, if the stream can still be used for thermal energy. This distortion is increased as:
   a) Resource temperatures are lower.
   b) The exergetic value of the fuels otherwise used to supply thermal energy is higher.
2. Unlike other renewable sources such as wind, hydro or solar PV, geothermal (with both electrical and thermal power generation potential) may have more context specific value, and needs to be evaluated as such.
3. In locations where high grade fuels are used for thermal power and there is the potential for heating systems with high capacity factors, flexible geothermal cogeneration plant designs that can shift between their

electrical and thermal power modes may significantly improve the overall exergetic efficiency and economic performance of the resource park.

4. The concept of displacement may also be used when communities are considering how to best reduce overall greenhouse gas emissions.

The intent of this paper is not to modify the principles of conventional cycle exergy analysis, which remains an excellent comparison tool for plants operating with different grade resources. Rather, the concept of displaced exergy suggests that when drawing the system boundaries, if wider boundaries of the resource park or region are used, it may better highlight appealing operating configurations, as shown in Figure 2. For future work, a possible useful enhancement and capstone to conventional exergy analysis of projects would be to provide commentary on the plant in the context of the prevailing thermal and electrical generation of the region and examine the potential wider impact a cogeneration geothermal resource park may have in improving regional efficiency or emissions.

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