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Evaluation of the Impact of Off-Design Operation on an Air-Cooled Binary Power Plant

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Key Words: binary power plants, air-cooled condenser, off-design operation, available energy analysis

Abstract

Geothermal power plants are designed and constructed to provide a rated power output at specific resource and ambient conditions. Due to both diurnal and seasonal changes in the ambient air temperature, as well as a decline in resource productivity over time, plants seldom operate at these “design” conditions. This paper examines the impact of “off-design” operation of an air-cooled binary geothermal power plant. An available energy analysis is used to evaluate operation at these conditions. This evaluation identifies those portions of the power cycle that are most sensitive to changing resource and ambient conditions, as well as where improvements in cycle component or system performance would have the largest impact in increasing power output.

Background

This paper summarizes the results of a recently completed study that examined the effects of operating an air-cooled binary power plant at off-design resource and ambient conditions.¹ The impact of operating at off-design conditions is particularly significant in binary geothermal power plants because of both the temperature and energy content of the geothermal fluids used. This sensitivity can be illustrated by examining the thermal efficiency of an ideal (reversible) power cycle. For this ideal cycle, the thermal efficiency is equivalent to the Carnot efficiency,

$$\eta_c = 1 - (T_C / T_H),$$

where T is the absolute temperature at the sink (C) and source (H).

The ideal thermal efficiency of geothermal power cycle operating with a 330°F resource and 45°F ambient would be ~36%; which implies that an idealized cycle operating between these resource and ambient temperatures could convert 35% of the heat input into power. (In contrast if the source temperature were 1000°F, the ideal thermal efficiency would be ~65%.) The performance limit defined by the Carnot efficiency assumes that work and heat are equivalent and interchangeable. The Second Law of Thermodynamics states heat can not be completely converted to work in a cyclic process. A Second Law analysis identifies the ideal work that can be done between a heat source and a heat sink, and provides a basis for determining where in a power cycle this ideal work is lost (irreversibility).

Available energy is a measure of the ability to do work. It is defined as “that portion of energy which could be converted into work by ideal processes which reduce the system to a dead state – a state in equilibrium with the earth and its atmosphere.”² (In this study, the dead state condition is taken to be the ambient.) Figure 1 is a plot of the available energy of a liquid, geothermal resource as a function of both resource temperature and the ambient air temperature.

This figure illustrates the sensitivity of the ideal power output from a plant to both the

resource and ambient temperatures. Although the magnitude of the change is larger at the higher temperature resource, the relative impact of the ambient temperature on the available energy is larger as the resource temperature decreases (the available energy of the 400°F resource decreases ~40% over this range of ambient temperatures; the available energy of the 250°F resource decreases by ~60%).

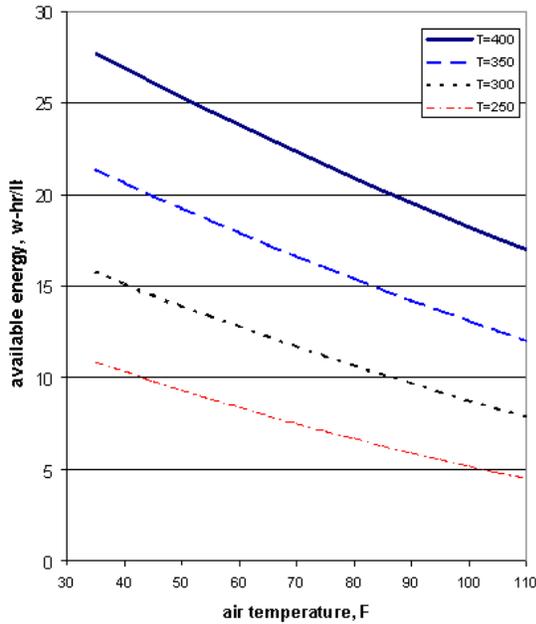


Figure 1: Impact of resource and ambient temperatures on available energy of a liquid dominated geothermal resource

The Second-Law efficiency is the measure of the ability of a heat engine, or power cycle, to convert the available energy to power. It is defined as

$$\eta_{2nd} = W_{net} / AE,$$

where W_{net} is the net work and AE is the available energy.

If the Second-Law efficiency were constant at all operating conditions the power output from the plant would follow the available energy trends indicated in Figure 1. Maintaining this constant conversion rate

requires that all conversion system components operate at a constant efficiency or performance level for all operating conditions. If their performance degrades (as typically occurs in an operating plant), then the Second-Law efficiency will decrease, and the plant power output will degrade by more than indicated by the available energy trends in Figure 1.

Approach

Because of the impact of the ambient temperature on its performance, an air-cooled binary plant was selected for evaluation. In this plant type, heat is rejected directly to the ambient air (dry-bulb) temperature, which represents the “sink” temperature. Plants utilizing evaporative heat rejection systems also reject directly to the ambient, however their “sink” condition is represented by ambient wet-bulb temperature. Because ambient dry-bulb temperature is higher than the wet-bulb temperature, the performance of a plant using air-cooled condensers is more sensitive to changes in the ambient air temperature.

An air-cooled binary plant model was developed using ASPEN Plus software. The modeled plant size (15 MWe, net) and configuration were similar to those of existing commercial binary plants. Component performance was modeled around existing plant component specifications and/or plant operating data. The modeled plant used an isobutane working fluid. The plant and components were sized to produce the desired power output for specified resource and ambient conditions. This fixed configuration plant was then used to evaluate performance at off-design resource and ambient scenarios. Individual component performance was modeled to vary with changes in flow rates,

so that the modeled plant's response to changes in resource and ambient conditions would be indicative of an actual plant's response. The turbine was modeled assuming it had variable geometry nozzles. Deviation in its efficiency was determined using corrections obtained from Balje³ for both throttling with the turbine nozzles, and for deviation from the design velocity ratio (ratio of the rotor tip speed to the spouting velocity). Friction losses were calculated using representative pipe diameters, estimated piping lengths, and process data.

For a given resource and ambient scenario, the turbine inlet pressure and temperature were varied until the maximum net power output was achieved. Achieving this optimum output is limited by the pump (deliver flow at the desired pressure), by the brine heat exchanger (bring flow to the required turbine inlet temperature), or the turbine (expand the flow). The turbine can limit operation because the vapor flow through the turbine nozzles is "choked". Using a turbine with a variable nozzle geometry offers an additional degree of freedom in operating the plant (and optimizing output) by allowing the turbine nozzle flow area to be varied. This allows the vapor flow rate to be varied for specific turbine inlet conditions.

The available energy analysis of the power cycle is based upon the conservation of available energy. For steady flow, the conservation of the available energy in a binary plant can be expressed as:

$$AE, gf-in = AE, gf-out + AE, air-out + P_{net} + \Sigma(Irreversibility)_{component/process},$$

where $AE, gf-in$ is the available energy of the brine entering the plant, $AE, gf-out$ is the available energy of the brine leaving the plant, $AE, air-out$ is the available energy of the air leaving the plant, P_{net} is the net plant power, and $\Sigma(Irreversibility)_{component/process}$ is

the sum of the plant component and process irreversibilities.

For a steady state flow, the available energy of a stream is

$$AE = m [(h - h_o) - T_o(s_{in} - s_o)],$$

where m is the mass flow rate, h is enthalpy, T is the absolute temperature, s is entropy, and subscript o refers to "dead" state condition (ambient conditions).

The irreversibility (I) for a process or component at steady state can be shown to be

$$I = -T_o \Sigma m_{nth} (s_{in} - s_{out})_{nth},$$

where the subscript nth represents the different streams in and out of the process/component.

The air entering the plant is at the defined dead state condition, thus its available energy is zero and it is not included as an inlet available energy stream. The terms to the right side of the available energy conservation equation represent the consumption or dissipation of the available energy of the brine entering the plant.

Model Results

The modeled plant produced 15 MWe at a resource temperature of 330°F and an ambient temperature of 45°F. The optimum power output was achieved by varying the turbine inlet conditions. In Figure 2, the dissipation of the available energy of the brine entering the plant is shown as a function of the turbine inlet pressure (for the design resource and ambient conditions). This available energy analysis indicates that the optimum power output (P_{net}) occurs at an inlet pressure of ~470 psi in the modeled plant. (The P_{net} curve is equivalent to the Second-Law efficiency).

P_{net} , or Second-Law efficiency, is optimized by minimizing the remaining factors associated with the dissipation of the inlet brine's available energy. The available energy of the brine leaving the plant is the largest of these factors. Both it and the turbine irreversibility increase with increasing turbine inlet pressure. The other factors remain relatively constant or decrease as the inlet pressure increases. Similar analyses at other resource and ambient conditions showed that the optimum power output (maximum Second-Law efficiency) tends to occur at the point where the turbine irreversibility is minimized.

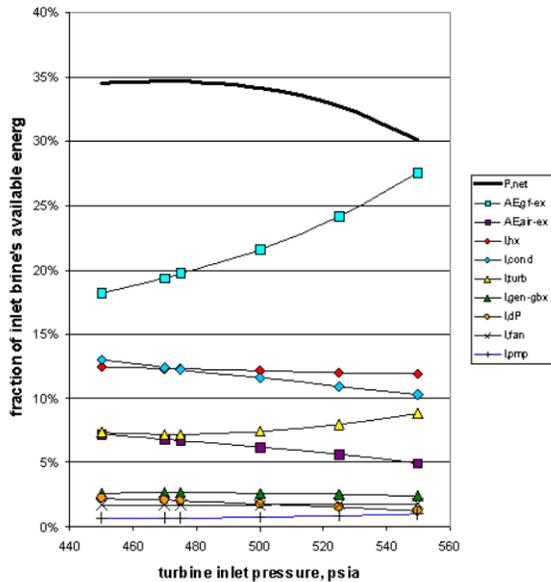


Figure 2: Available energy dissipation as function of turbine inlet pressure

The first off-design condition evaluated was the effect of the ambient air temperature on performance. With the brine inlet temperature and flow at their design conditions, plant performance was optimized for ambient air temperatures between 40° and 100°F. At each optimized condition, an available energy evaluation was made to determine how the available energy of the brine entering the plant was being dissipated, or consumed. This

dissipation of the inlet brine's available energy is shown in Figure 3 as a function of the ambient air temperature. The major contributors to the dissipation of the inlet brine's available energy are the effluent brine's available energy, the irreversibilities associated with both heat exchange process, the turbine irreversibility, and the available energy of the air leaving the plant. The results show that the Second-Law efficiency, or available energy conversion rate, declines as the ambient air temperature rises. This indicates that the degradation in plant performance with ambient temperature will be greater than would be indicated by considering just the change in available energy (as indicated in Figure 1).

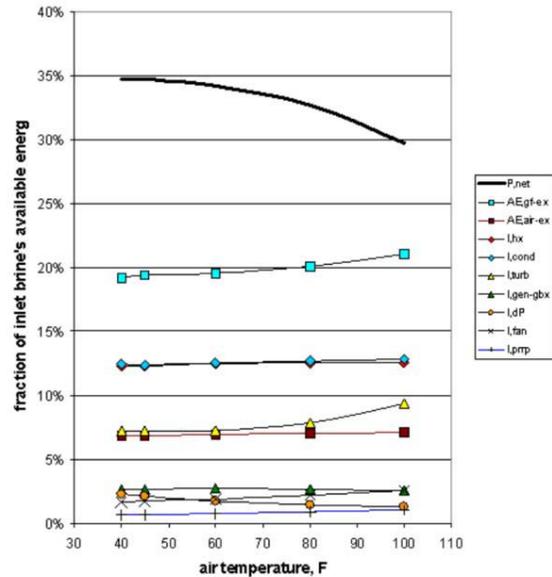


Figure 3: Impact of ambient air temperature on available energy dissipation at design brine conditions

A similar analysis was used to evaluate the effect of a decline in resource productivity on plant performance over the same ambient temperature range. Five scenarios for resource decline were evaluated; declines in brine flow of 10% and 20% (at the design temperature of 330°F), brine inlet temperatures of 320°F and 310°F (at design flow), and a 310°F brine inlet temperature

with a 20% decline in brine flow. An example of this analysis is shown in Figure 4, which shows the impact of the brine inlet temperature on performance at an ambient temperature of 80°F. These results show how plant performance declines as the resource temperature decreases. This decline occurs largely because of the increasing significance of the effluent brine's available energy with the lower resource temperatures. The results suggest the turbine irreversibility also tends to increase as the resource temperature decreases. These undesired increases in the available energy dissipation are partially offset by decreases in both the available energy of the air leaving the plant and irreversibility associated with the condenser (both decreases are due to less heat is being rejected). The report on the study of the impact of off-design resource and ambient conditions on binary plant performance contains the complete available energy evaluation for each of the five off-design resource scenarios, as well as the available energy analysis for the design conditions.¹

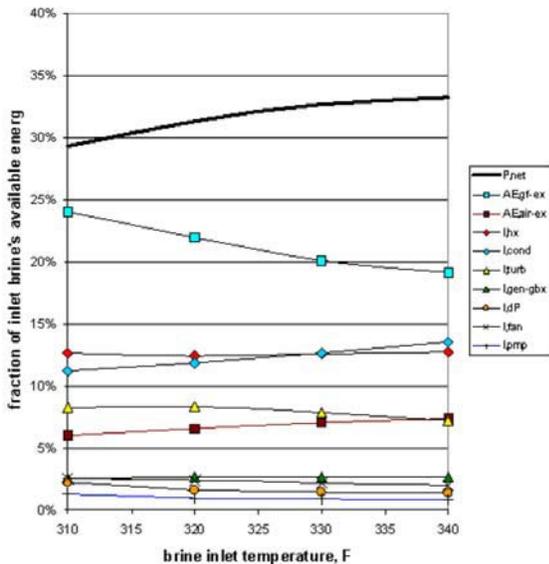


Figure 4: Impact of brine temperature on available energy dissipation at 80°F ambient

Performance Improvements

The available energy analysis revealed that available energy of the brine and air streams leaving the plant, the irreversibilities associated with both heat exchange processes, and the turbine irreversibility have significant adverse impacts on the available energy dissipation. Because results presented represent optimized power output operation, no additional performance gain can be achieved by adjusting plant operating conditions. Further increases in plant performance will be achieved by removing any imposed operating constraints or by modifying plant components. The following is a brief summary of some of the evaluated methods of mitigating the adverse impact of off-design operation on performance. Again, a more detailed discussion of the evaluation of these methods is provided in the detailed report of these studies.

Remove turbine inlet superheat constraint

Plant performance as initially modeled assuming a minimum superheat level had to be maintained at the turbine inlet. By removing this constraint and allowing superheat levels down to 0.5°F, the plant performance increased by up to ~3%. Performance increases were largest at the cooler ambient temperatures and for resource scenarios corresponding to a decline in fluid flow rate (the benefit was smaller with a resource temperature decline). The benefit decreased with increasing ambient air temperatures, and at the design brine conditions there was no benefit.

Spraying excess pump flow into turbine exhaust

When there is excess pump capacity (corresponding to a decline in resource productivity), excess flow could be

sprayed into the turbine exhaust piping to reduce the amount of superheat entering the condenser. Heat transfer coefficients for de-superheating are lower than those for condensing, thus condenser performance should be improved. However, the modeled plant results indicate there is no benefit in using the excess pump capacity in this manner. Increases in heat transfer coefficients due to reduced de-superheating were partially off-set by the decrease in condensing heat transfer coefficients due to the additional flow. The resulting predicted increase in the overall heat transfer coefficient was small enough to be offset by the effect of the additional condenser heat load due to the heat added by the working fluid pump.

Increasing heat exchanger performance/size

– The impact of increasing the size or performance of both the condenser and brine heaters was evaluated by assuming there was an increase in the product of the overall heat transfer coefficient and the heat exchanger surface area (UA). A 25% increase in the brine heat exchanger UA increased power production from ~3.2% at the design ambient temperature (45°F) to 5.5% at 100°F. A similar 25% increase in the condenser UA would increase plant power production by ~3% and ~4.6% for the same ambient temperatures.

Management of plant parasitics – The potential benefit of using variable frequency drives (VFD's) to manage the plant parasitics or “house loads” was evaluated. These devices were applied to the working fluid pump and fan motors, allowing the working fluid and air flow rates to be varied to meet plant requirements. Modeling results indicate that because these devices consume power (~3%) there is minimal benefit from using them unless there is a decline in resource productivity. Using the

VFD's on the working fluid pumps produces an increasing benefit as the resource productivity declines. When used on the pump motors with a 20% decline in brine flow, these devices allowed 2 to 3% more power to be produced over the ambient temperature range of 40° to 100°F. If the resource temperature declined to 310°F, their use allowed 4 to 8% more power to be produced over this air temperature range. The benefits of using the VFD's with the condenser fans were not as large. For the decline in brine flow, the increase in plant power varied from 3.5% at 40°F to 1% 100°F. With a 310°F resource, using the VFD,s on the condenser fans increased power by 2.5% (40°F) to 1% (100°F). In most, if not all, of the cases evaluated, optimum net plant power occurred when the VFD's were used to reduce the pump or fan power.

Evaporative pre-cooling air entering the condenser -

The scheme evaluated passes the air through an evaporative cooling device before it enters the air-cooled condensers. As the air comes in contact with the water in this cooler, a portion of the water evaporates and cools the air stream. Model results indicate this concept has potential to substantially improve performance. The improvement is contingent upon the pressure drop through the evaporative cooler, the relative humidity of the ambient air, and the availability of water (in this study, no attempt was made to examine the effectiveness of the evaporative cooler). One case study assumed that the pressure drop through the evaporative cooler was equivalent to the design value for the air-cooled condenser bundle, that the air had a relative humidity of 30% and that there was excess water for the evaporative cooler. The resulting increase in the modeled plant performance varied from 7 to 30% over an ambient temperature range of 60° to 100°F

(with the largest benefit at the higher ambient temperature).

Hybrid heat rejection system - Hudson Products Corp. includes in its product line a hybrid system that incorporates an evaporative cooler for the air entering the air-cooled condenser, with a water-cooled condenser. A similar combined wet-dry heat rejection system was evaluated where it was assumed that the water-cooled condenser was in series with the air-cooled condensers. Working fluid vapor leaving the turbine first entering the air-cooled condenser and then passed to the water-cooled condenser where the condensation was completed. The scenario used for this study was a resource temperature of 310°F and air at a temperature of 80°F with a 30% relative humidity. If 25% of the condenser heat load was handled by the water cooled condenser, the hybrid system produced ~29% more power than the modeled baseline plant (no performance augmentation), and 8% more power than obtained by only pre-cooling the air entering the air-cooled condenser. The performance advantage increases as the fraction of the heat rejected in the water-cooled condenser increases; this also increases the size and cost of this condenser. No attempt was made in this study to determine the added cost associated with this performance gain, nor was any attempt made to optimize the hybrid heat rejection system configuration to achieve a maximum power benefit for a given water-cooled condenser size and cooling water flow rate.

Improve turbine performance - The modeled turbine efficiency varied with the velocity ratio and the degree of throttling done with the variable nozzles. The velocity ratio is the ratio the turbine rotor tip speed to the spouting velocity; the spouting velocity is determined from the isentropic enthalpy

change of the expanded working fluid vapor. The variable geometry nozzles allow the turbine inlet conditions to be varied to adjust this isentropic enthalpy change and approach the optimum velocity ratio. Because these adjustments are usually associated with throttling vapor flow, the optimum efficiency may not correspond to the maximum power (which is the product of the mass flow rate, isentropic enthalpy change, and turbine efficiency). One could also approach the optimum velocity ratio by varying the turbine rotor tip speed. By varying (and controlling) the turbine speed, the velocity ratio producing the maximum power output could be achieved without throttling flow. The modeled binary plant was used to determine the performance improvement that would be realized if it were possible to vary the turbine speed. The analysis indicates there is minimal benefit at the lower ambient temperatures. However, the benefit increases as the ambient temperature increases (at 100°F, ~6% more power could be produced). This improvement in performance would require the turbine speed be reduced to ~85% of its design value at this higher ambient temperature. Wind turbines utilize devices that are analogous in design and operation to motor VFD's to vary turbine speed. If these devices have a power consumption similar to the motor VFD's, they would consume ~3% of the turbine power. This power consumption is on the same order of magnitude as the projected benefit. Because the potential benefit is relatively small, no work was done in this study to examine the practicality of varying the turbine speed.

Summary

An available energy analysis was used to evaluate the impact of off-design operation of an air-cooled binary power plant. This type of analysis can be a valuable method of

identifying inefficiencies in the plant operation, and in evaluating how improvements to the component performance impact plant performance. This evaluation indicates that as plant operation deviates from the design resource and ambient scenario, its ability to convert the available energy in the inlet brine degrades. Both the inlet brine's available energy and the plant conversion rate are particularly sensitive to changes in the ambient temperature, which compound the impact of the ambient temperature on plant performance. The available energy of the brine leaving the plant represents a major fraction of the inlet brine's available energy, though the optimum power production tends to occur at operating conditions that minimize the turbine irreversibility. The concepts evaluated that had the most potential to mitigate the impact of off-design operation were the evaporative pre-cooling of the air, the hybrid heat rejection system, and the use of variable frequency drives on plant motors to optimally manage parasitic loads.

Acknowledgements

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