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Holistic Design Approach for Geothermal Binary Power Plants with Optimized Net Electricity Provision

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ABSTRACT

The contribution of geothermal binary power plants to the energy system is based on the provision of net electricity. That is defined by the produced gross electricity from which the auxiliary power to run power consuming components in the different parts of the plant must be deduced. In contrast to other thermal power plants the ratio of auxiliary power to gross electricity can significantly vary in geothermal binary power plants depending on site-specific conditions. It typically lies between 30 to 50 % but can be also higher depending on the site-specific energetic effort to deliver the geothermal fluid from the reservoir or the effort for the recooling of the conversion cycle. In order to optimize the provision of net electricity at a specific site it is hence important to consider the different characteristics of gross electricity production and auxiliary power consumption. The paper will therefore introduce a geothermal-specific, holistic design approach in which not only parameters, which characterize the quality of single plant components, but also site-specific reservoir and ambient conditions are considered. A case study will show that maximizing the installed electrical capacity, which is typical in other power plant applications, does not result in an optimum net electricity output. With the presented methodology, in contrast, it is possible to realize geothermal binary power plants with a higher net electricity output based on existing technology.

1. INTRODUCTION

Binary power plants are used to produce power from low to medium temperature heat sources. Since the predominant part of the world wide geothermal potential is based on a temperature level between 100 and 200 °C, binary power plants will play a more and more important role for geothermal power generation in the future. The role which different power plant technologies or energy sources play in the electricity mix is typically measured by the total installed power capacity. However, the real contribution of power plants is their net electricity output which is defined by the produced gross electricity from which the auxiliary power to run the power consuming components in a plant must be deduced.

Geothermal binary power plants contain not only the power unit on the surface but also the geothermal fluid loop to deliver the fluid from the reservoir (Figure 1). Therefore, the power consuming components of such plants are in the geothermal fluid loop (such as the downhole pump), in the binary power unit (such as the feed pump), and the recooling system (such as cooling pumps and fans). Existing experiences show that, in contrast to other thermal power plants, the auxiliary power demand in geothermal binary power plants can significantly vary depending on site-specific conditions.

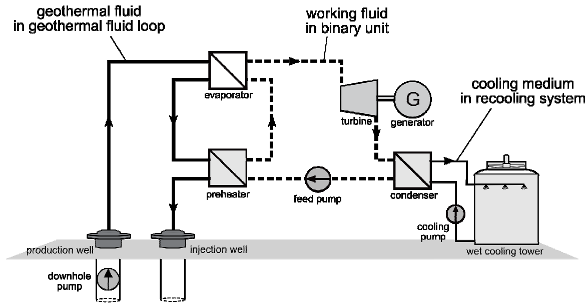

Figure 1: Schematic set-up of a geothermal binary power plant showing the different subsystems

The power demand for the geothermal fluid production, for example, is determined by the reservoir characteristics and the delivered flow rate, e.g. Heidinger et al. (2006), Sanyal et al. (2005), Legarth (2003). When dimensioning the geothermal fluid flow from a specific reservoir, technical restrictions, such as the maximum installation depth and maximum pump capacity, must be considered. Another important aspect is the over-proportional increase of the pumping effort with increasing fluid flow rate. Since a higher flow rate results in a larger draw down of the fluid level in the production well, the production effort shows a quadratic dependence with respect to the flow rate. The increase of the fluid production effort with increasing geothermal fluid flow rate is stronger for lower reservoir productivities (Figure 2).

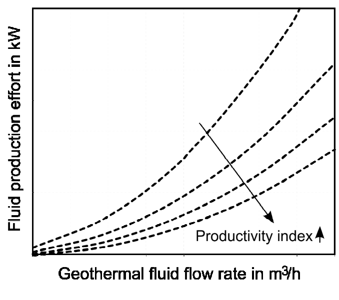

Figure 2: Example of fluid production effort as a function of geothermal fluid flow for different reservoir productivities

The auxiliary power consumed by the recooling system - which has a considerable influence on the net power output due to relatively large waste heat amounts - is significantly influenced by site preconditions and ambient conditions, e.g. Moya and DiPippo (2007), Kröger (2004), IPPC (2001), Klenke (1970). The relative amount of waste heat thereby increases with decreasing conversion efficiencies (Figure 3). For removing the waste heat from the binary cycle, a suitable heat sink, such as surface water, water from groundwater wells or ambient air is necessary. In conventional power plant engineering, water cooling is usually preferred to air cooling due to the ability to realize lower condensing temperatures and therefore a larger power output. However, the precondition of sufficient supply of cooling water can at many sites, if any, only be met with additional technical and energetic effort. The design of the recooling system in geothermal binary power plants will therefore oftentimes be a compromise between technical realization and energetic aspects.

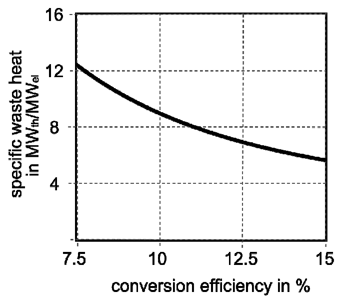

Figure 3: Specific waste heat as a function of the conversion efficiency

Based on the considerations above, geothermal binary power plant design must focus on net electricity provision and integrate site-specific reservoir characteristics, ambient conditions and operation characteristics in a holistic design approach. In the following, such an approach will be introduced and applied in a theoretical case study. It will be shown that the presented methodology leads to geothermal binary power plants with a higher net electricity output based on existing and proven technology.

2. HOLISTIC DESIGN APPROACH – THEORETICAL CONSIDERATIONS

The design of the subsystems in geothermal binary power plants depends on different site-specific influences and parameters. In order to design reliable and efficient geothermal binary power plants it is therefore important to integrate these different characteristics in an overall or holistic design approach. The most important aspects or differences of a holistic design approach compared to the separate design of each subsystem are:

- an optimum geothermal fluid flow rate*:* The gross power which can be generated from a geothermal resource linearly increases with increasing geothermal fluid flow rate. However, the considerations above have shown that increasing the flow rate at a site also results in an over-proportional increase in power consumption of the fluid production system (Figure 2). This means that an optimum geothermal fluid flow rate exists for which the net power provision of a geothermal binary power plant reaches its maximum. Assuming a specific plant set-up on the surface, the optimum flow rate for a site with lower reservoir productivity is therefore lower. Referring to different surface plants set-ups, the optimum flow rate is increasing with a more efficient and better utilization of the geothermal heat such as with more efficient (and reliable) binary units or the supply of the residual heat in the geothermal fluid after the heat transfer to the binary unit.

- an optimum working fluid: The selection of the working fluid enables the adaptation of the binary conversion cycle to the characteristics of the geothermal heat source. This is due to different shapes of the dew-point curve and different evaporation characteristics which can be realized with different media and mixtures. The choice of a suitable working fluid is therefore an important aspect in designing geothermal binary power plants. A suitable working fluid must allow reliable operation (e.g. thermally stable in the long-term, compatible with other materials used in the binary cycle), a high conversion efficiency and a good utilization (i.e. the cooling of the geothermal fluid) of the geothermal heat. Due to the relatively large waste heat amount in geothermal binary power plants, also a selection of the working fluid according to the heat sink and operation characteristics must be considered.

- an optimum evaporation temperature: The evaporation temperature contrarily influences the conversion cycle efficiency and the utilization of the geothermal heat. Hence, an optimum evaporation temperature exists for which the power output reaches a maximum. Regarding the design of the evaporation also annually varying ambient conditions which might influence the condensation temperature must be considered. If a geothermal binary power plant should also supply heat in serial connection to the binary power unit, the evaporation temperature also depends on the temperature which is required at the outlet of the binary unit in order to provide a certain supply temperature. The outlet temperature of the geothermal fluid can be increased with higher evaporation temperatures. Another possibility is internal heat recuperation in case a dry working fluid is used.

- an optimum condensation temperature: The gross power output of a binary unit is increasing for decreasing condensation temperatures due to the increasing enthalpy difference in the expansion machine. However, also the requirements for the recooling are increasing with decreasing condensation temperatures. This is because lower temperatures must either be realized by lower cooling sink temperatures such as in case of once-through cooling systems. At many sites, where once-through cooling is not an option, lower condensation temperatures can only be realized by a larger auxiliary power input to the fans of wet cooling towers or air coolers. The correlation between condensation temperature and auxiliary power demand is determined by the recooling system, its performance and the ambient conditions. Therefore, regarding the net electricity production, also an optimum condensation temperature does exist. It must be considered that the ambient conditions can significantly vary during the year. Regarding the relatively large waste heat amounts in geothermal binary power plants, the technical use of the waste heat (e.g. conventional cogeneration) can also reduce the demand for recooling.

3. CASE STUDY

The relevance of a holistic design approach will be presented in the following in a simplified case study. The objective of this case study is to maximize the net power output of a geothermal binary power plant at a specific site. Two different approaches are thereby compared. Based on the implementation of existing and reliable technology for both approaches, one approach is aiming at the maximization of the installed capacity or gross power and the other one is directly maximizing the net power by means of holistic plant design.

3.1 Reference Case

The case study is based on an average geothermal low temperature site referring to reservoir and site pre-conditions. The geothermal reservoir is assessed with a doublet. On the surface, the heat of the produced geothermal fluid is used in a binary unit. The conversion unit is based on a Rankine Cycle with pure working fluid and is cooled by a forced-draught cooling tower. The reservoir and the geothermal fluid are defined as follows:

reservoir / fluid temperature	150 °C
reservoir depth	4,000 m
productivity index	30 m^3/(h MPa)
injectivity index	30 m^3/(h MPa)
pore pressure gradient	10.7 bar/100 m
specific heat capacity fluid	3.5 kJ/kg K
fluid density	1.147 kg/m^3

The design will be made for two different ambient conditions:

ambient temperature 15 °C, relative air humidity 75 %
ambient temperature 20 °C, relative air humidity 66 %

The parameters which are varied in the following in order to derive the optimum plant design for the two different design approaches are: the working fluid, the evaporation temperature T_V (corresponding to a certain reinjection temperature of the geothermal fluid $T_{TW,out}$), the condensation temperature T_C, and the geothermal fluid flow rate $\dot{m}_{TW}$.

General considerations in plant design also refer to component-specific parameters, such as efficiencies of turbines and pumps, temperature differences in heat exchangers or cooling tower characteristics. For the comparison of the different design approaches, these general design considerations will not be explicitly addressed. Following parameters are therefore assumed for both design approaches:

Geothermal fluid loop	
efficiency downhole pump	0.75
well head pressure production well	10 bar
intake pressure downhole pump	10 bar
relative roughness riser tube	0.003
relative roughness casing	0.008
diameter riser tube	5’’
diameter casing	8 ½’’
Binary conversion cycle	
heat exchanger temperature differences	5 K
pressure loss per heat exchanger	0.1 bar
efficiency feed pump	0.8
isentropic efficiency turbine	0.75
mechanical efficiency turbine	0.95
mechanical efficiency generator	0.95
Wet cooling tower	
approach (to wet bulb temperature)	3 K
cooling range	6 K
cooling tower constant	0.8
specific heat capacity water	4.2 kJ/kg K
installation height cooling tower fill	1.5 m
water-sided pressure losses	1 bar
pressures increase fans	0.002 bar
cooling pump efficiency	0.8
cooling fan efficiency	0.8

3.2 Net Power Calculation

The net power P_{net} is calculated based on the gross power P_{gr} from which the auxiliary power P_{aux} of the subsystems is deduced.

$$P_{net} = P_{gr} - P_{aux} \tag{1}$$

3.2.1 Gross Power

In order to calculate the gross power of the binary power unit the evaporation and condensation temperature need to be defined for a specific working fluid and according to the temperature profile of the heat source. The live vapor is assumed to be saturated vapor, unless the exhaust steam wetness in the turbine does not exceed an allowed limit. The working fluid mass flow can be calculated from the energy balance around the heat input:

$$\dot{m}_{TW}\ c_{p,TW}\ (T_{TW,in} - T_{TW,out}) = \dot{m}_{WF}\,(h_{WF,pC} - h_{WF,V}) \tag{2}$$

where $\dot{m}_{TW}$, $c_{p,TW}$, $T_{TW,in}$, $T_{TW,out}$ are mass flow, specific heat capacity, inlet temperature and reinjection temperature of the geothermal fluid, and $\dot{m}_{WF}$, $h_{WF,pC}$ and $h_{WF,V}$ are working fluid mass flow, enthalpy of the pressurized condensate and live vapor enthalpy, respectively.

The gross power is then calculated with the working fluid mass flow, the difference of live vapor and exhaust steam enthalpy $(h_{WF,V} - h_{WF,E})$, which accounts the isentropic turbine efficiency, and the turbine and generator efficiency η_T and η_G , respectively:

$$P_{gr} = \dot{m}_{WF}\,(h_{WF,V} - h_{WF,E})\,\eta_T\ \eta_G \tag{3}$$

3.2.2 Auxiliary Power

The auxiliary power demand is the sum of the auxiliary power demand in the geothermal fluid loop $P_{aux,TW}$, in the binary unit $P_{aux,bin}$ and in the recooling system $P_{aux,cool}$:

$$P_{aux} = P_{aux,TW} + P_{aux,bin} + P_{aux,cool} \tag{4}$$

For the estimation of the auxiliary power consumption in the geothermal fluid loop, the dynamic fluid level is calculated referring to top ground surface:

$$h_{DFL} = h_{SFL} + \frac{\dot{V}_{TW}}{\rho_{TW}\, g\ PI}\ , \tag{5}$$

where h_{DFL}, h_{SFL}, $\dot{V}_{TW}$, ρ_{TW}, g and PI are dynamic fluid level, static fluid level (depending on the pore pressure gradient, the reservoir depth and the geothermal fluid flow rate and density), gravity constant and productivity index of the reservoir.

Assuming that the pressure at the bottom of the injection well, resulting from the water head in the injection well and its wellhead pressure are sufficient to overcome the reservoir pressure, the auxiliary power demand of the geothermal fluid loop can be calculated as follows:

$$P_{aux,TW} = \dot{V}_{TW}\,(-(\rho_{TW}\, g\ h_{DFL}) + \Delta p_{fr} + p_{wh})\frac{1}{\eta_{DP}} \tag{6}$$

where Δp_{fr}, p_{wh} and η_{DP} are friction losses in the production well calculated according to Legarth (2005), well head pressure and downhole-pump efficiency, respectively.

The auxiliary power to run the feed pump in the binary unit depends on the working fluid flow rate and density ρ_{WF}, the pressure increase from the condensation to the evaporation pressure, p_C and p_V, respectively, and the efficiency of the feed pump η_{FP}

$$P_{aux,bin} = \frac{\dot{m}_{WF}}{\rho_{WF}} (p_V - p_C) \frac{1}{\eta_{FP}} \quad (7)$$

The auxiliary power demand of the open wet cooling tower results from the operation of the cooling water pump and the fans to generate the forced draught:

$$P_{aux,cool} = P_{aux,CP} + P_{aux,fan} \quad (8)$$

where $P_{aux,CP}$ and $P_{aux,fan}$ are the power consumption of cooling water pump and fans respectively.

The auxiliary power demand of the cooling water pump is:

$$P_{aux,CP} = \frac{\dot{m}_{CW}}{\rho_{CW}} (\Delta p_{CW} + \rho_{CW}\ g\ h_{fill}) \frac{1}{\eta_{CP}} \quad (9)$$

where $\dot{m}_{CW}$, $\Delta p_{CW}, \rho_{CW}$, h_{fill} and η_{CP} are cooling water flow rate, friction losses, cooling water density, height of cooling tower fill and cooling pump efficiency.

The cooling water mass flow is derived from the energy balance around the condenser:

$$\dot{m}_{CW}\ c_{p,CW}\ (T_{CW,w} - T_{CW,c}) = \dot{m}_{WF}\ (h_{WF,E} - h_{WF,C}) \quad (10)$$

where $c_{p,CW}$, $T_{CW,w}$, $T_{CW,c}$ and $h_{WF,C}$ are the specific heat capacity of the cooling water, temperature of the heated and cold cooling water, and enthalpy of the working fluid condensate at the feed pump inlet. The temperature difference ($T_{CW,w}$ - $T_{CW,c}$) is referred to as cooling range which depends on the cooling tower design.

The type of the condenser is assumed to be cross flow so that the temperature of the heated cooling water depends on the condensing temperature in the binary cycle T_C and the pinch point or temperature difference ΔT_C in the condenser:

$$T_{CW,w} = T_C - \Delta T_C \quad (11)$$

The auxiliary power demand of the fan in the cooling tower depends on the air flow $\dot{m}_a$, the pressure increase in the fan Δp_{fan} and the fan efficiency η_{fan}:

$$P_{azx,fan} = \frac{\dot{m}_a}{\rho_a} \Delta p_{fan} \frac{1}{\eta_{fan}} \quad (12)$$

where ρ_a is the air density at ambient pressure.

The air flow rate is determined according to Klenke (1970) by the cooling water mass flow, the air ratio λ and the theoretical minimum air flow l_{min}, which are both calculated from the ambient conditions, such as air temperature and relative humidity and the cooling tower performance (e.g. approach and cooling tower constant) for a specific mode of operation:

$$\dot{m}_a = \lambda\ \dot{m}_{CW}\ l_{min} \quad (13)$$

3.3 Results

The results of the case study are shown in Figure 4. It can be seen that under the conditions assumed for the example site, the net power varies between 0.9 and 1.3 MW and that geothermal fluid production and recooling have a significant auxiliary power demand which ranges from 39 to 47 % and 9 to 18 %, respectively. Comparing the two design approaches, the maximization of the net power results in a 12 % or 14 % higher net power output compared to the plants which would be realized based on maximizing the gross power. The installed capacity or gross power (i.e. sum of net power and auxiliary power in Figure 4) referring to the plants with optimized net power is in contrast 15 % or 21 % lower. With net power maximization the ratio of net power output to gross power is therefore increased by 33 and 43 %, respectively. These improvements are based on the differently chosen design parameters which especially result in a decrease of the auxiliary power demand for recooling and geothermal fluid production. From the following table it can be seen that all design criteria except the working fluid depend on the design objective.

	Gross power maximization		Net power maximization	
Ambient conditions	15 °C, 75 %	20 °C, 66 %	15 °C, 75 %	20 °C, 66 %
Working fluid	isobutane		isobutane	
T_V [°C]	100	100.5	100.5	101
$T_{TW,out}$ [°C]	63	65.5	64.5	67
T_C [°C]	25.7	29.4	28	31.6
$\dot{m}_{TW}$ [kg/s]	100	100	88	82

The optimum evaporation temperature T_V varies only by little between gross and net power maximization and between the assumed ambient scenarios.

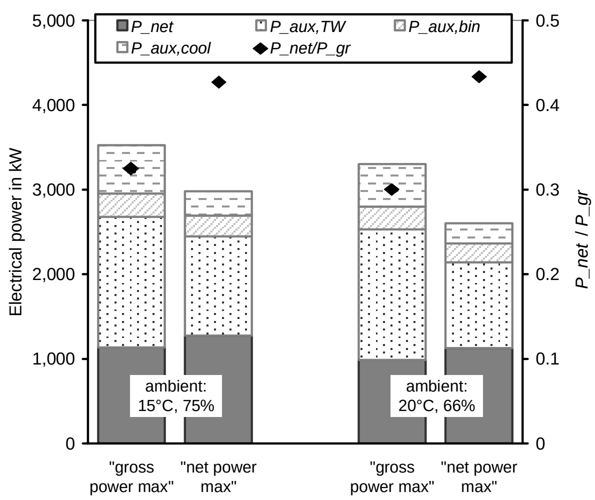

Figure 4: Comparison of net power output, auxiliary power consumption and ratio of net power to gross power for different design approaches and ambient conditions

Regarding the optimum condensation temperature, in contrast, the design approach and the ambient scenario have a significant influence. The working fluid in the binary cycle of the plant designed for maximum gross power is condensed at the minimum condensation temperature depending on the ambient conditions. This results in a specific auxiliary power demand for recooling of 17 to 19 kW_{el}/MW_{th}. When maximizing the net power in contrast, a higher condensation temperature is chosen so that the specific recooling effort is reduced to 10 to 11 kW_{el}/MW_{th} which results in a decrease of the auxiliary power demand for recooling by 50 and 53 %.

A significant influence of the design approaches can also be seen for the optimum flow rate. Maximizing the power plant for gross power, the maximum flow rate with respect to technical restrictions (e.g. installation depth, volume flow, pump capacity) is produced from the reservoir. For the assumed reservoir conditions the maximum flow rate is limited to 100 kg/s. Applying the holistic design approach, a lower flow rate of 82 and 88 kg/s is produced. Figure 5 shows that the optimum flow rate for a specific reservoir depends on the gross power output but also on the auxiliary power demand for recooling. Under more favorable ambient conditions more gross power is produced and less auxiliary power consumed for recooling so that the optimum flow rate reaches a higher value. Producing a net power optimized flow rate, the auxiliary power consumption of the downhole pump is reduced by 24 and 34 %, respectively.

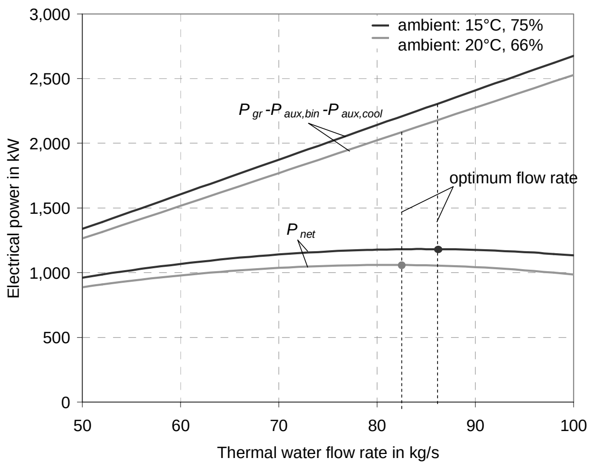

Figure 5: Influence of ambient conditions on optimum geothermal fluid flow rate and maximized net power output

In contrast to the downhole pump, the reduction of the auxiliary power consumption of the feed pump in the binary cycle is lower and lies at 12 and 17 %, respectively. This improvement is based on a lower pressure increase in the feed pump due to the higher condensing pressure and the lower working fluid flow rate.

4. CONCLUSION AND OUTLOOK

Based on general considerations and by means of a case study it could be shown that geothermal binary power plants are, at typical sites, characterized by a considerable auxiliary power demand. This is especially due to the energetic effort for the production of the geothermal fluid and the recooling of the binary unit. In order to realize geothermal binary power plants with optimized net electricity provision, also resulting in an optimized contribution to the energy mix, a holistic design approach has been presented. This approach has its focus on a reliable overall system and defines plant efficiency based on net instead of gross power output.

The results of the case study could show that a holistic design approach can lead to a considerable improvement of the net power output based on existing technology. From an economic viewpoint it is also relevant that this improvement is achieved with a smaller installed plant capacity. Holistic geothermal plant design therefore cannot only increase revenues but also decrease capital investments.

For ongoing studies on holistic design of geothermal binary power plants, further aspects, along with the design parameters discussed in this paper, must be considered. A very important aspect regarding net electricity provision is the plant availability. In this context experience has shown that especially the reliability of the geothermal fluid loop must be considered very carefully in the design of geothermal binary power plants. Problems such as scaling and corrosion can significantly impair the plant performance or may even result in temporal shut down of operation. Also the reliability of the binary power unit on the surface is a crucial aspect in geothermal binary plant design.

Another aspect is that in many cases, binary power units will not always be operated at their design point so that operation characteristics and part load behavior must be considered in plant design. Regarding an annual operation period, part load operation can result from varying ambient conditions and therefore a varying recooling performance. Also the additional provision of district heat can lead to part load operation of the binary unit because combined energy supply, for example power and heat, from low to medium temperature geothermal resources is typically realized in parallel or serial connection. Regarding the design of the binary unit with district heat supply in serial, the cooling of the geothermal fluid might be limited at times of heat demand. In case of a parallel connection, the binary unit might be fed with a variable mass flow during the year. Regarding the lifetime operation of a binary power unit changes in the reservoir productivity or cooling of the reservoir can have an influence on the plant operation.

Apart from technical considerations, also non-technical aspects, such as availability of cooling water, cooling water treatment, noise emission thresholds or land use, are issues which can be integrated in a holistic approach.

In general it can be concluded that holistic power plant design must be a site specific approach because reservoir and site preconditions but also operational characteristics vary from site to site. It is important to note that the success of holistic project development is based on interdisciplinary collaboration.

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