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Thermoeconomic Analysis of Geothermal Power Cycles: A Case Study of IDDP-1

Maria Gudjonsdottir, Alberto Mereto, Gudrun Saevarsdottir, Vijay Chauhan

Reykjavik University, Menntavegur 1, 102 Reykjavik, Iceland

msg@ru.is

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ABSTRACT

This paper presents a thermoeconomic analysis of power cycles proposed to utilize geothermal fluid in a superheated state with acid chloride impurities. A case study was performed where utilization models of the fluid from the well IDDP-1 proposing four different viable power cycles. Each cycle includes a technique to overcome or mitigate the chloride present in the superheated steam before it is utilized for power generation. The techniques are based on either an application of a wet scrubbing process or using a binary cycle. In order to perform the thermoeconomic analysis, exergy analysis and cost estimation were done for each component and for the cycle as a whole. The four different cycles for which the thermoeconomic analysis was done include: a single flash power cycle with wet scrubbing, a power cycle with an additional turbine and wet scrubbing, a power cycle with heat recovery and wet scrubbing and a binary cycle without any scrubbing process. The cycle containing heat recovery performs best, having highest power output and lowest unit cost of product exergy. The binary cycle turned out to be the most expensive one in unit cost of product exergy and the cycle with wet scrubbing performed the worst in power output. The study highlights the importance of taking into account exergetic efficiency and exergy cost using thermoeconomic analysis, when comparing power cycle options for geothermal utilization.

1. INTRODUCTION

In geothermal power plants where superheated fluid from high temperature reservoirs is utilized, mitigation of impurities such as acid gases and solid particles is essential since these impurities can lead to corrosion and scaling, thus causing damage to the plant components. The concentration of the impurities varies between reservoirs and the mitigation techniques are chosen considering the viability of the technique in terms of technology and cost. The biggest challenge thus, is to find the most feasible technique for utilizing the resource while minimizing the production cost. Selecting a technology for utilizing geothermal steam requires two important factors to be taken into consideration, that is, the cost of the technology used and the power output obtained. For conventional geothermal steam with limited enthalpy, application of traditional methods of mitigating steam impurities using wet scrubbing and a conventional thermodynamic cycle are an optimal way to utilize the geothermal steam. The selection, however, becomes more complicated when dealing with unconventional high enthalpy geothermal systems with superheated steam. The superheated steam often contains acid gas and other impurities in gaseous phase. Application of conventional techniques would require quenching of steam superheat which cause loss in power output. A case study with such conditions is that of well IDDP-1 drilled in Krafla, Iceland in 2008, which is a part of the Iceland Deep Drilling Project (IDDP). The project aims at investigating utilization of unconventional geothermal systems with high fluid enthalpy. Superheated steam with an enthalpy upto 3200 kJ/kg and wellhead pressure upto 14MPa was extracted (Einarsson et al. 2015). The superheated steam however, contains chloride gas which required mitigation before utilization was feasible.

A comparison study of the thermodynamic performance of various mitigation techniques and methods for utilizing fluid from IDDP-1 was done by Hjartarson et al. (2014). Different combinations in terms of power cycle components and mitigation techniques were studied there. The mitigation techniques proposed in the study include dry scrubbing, wet scrubbing and using a binary cycle. In dry scrubbing, solid or liquid material is injected into the stream, and after the mixing, the flow is driven through an electrostatic precipitator or a bag house filter where the contaminants and chemicals are filtered out. Dry scrubbing is commonly based on either of two mechanisms: absorption where a chemical reaction occurs between the contaminants and the injected material and adsorption where the chemical attaches to the surface of the adsorbate without a direct chemical reaction. Unfortunately, even though it is a method that looks promising it is still under development. Application of dry scrubbing is currently limited to the laboratory scale and was not considered further for this work. The most common technique applied in the industry is wet scrubbing. The technique is also widely used in industries dealing with gases containing harmful substances that must be eliminated from a fluid, as for example in the case of exhaust gases. This technique relies on using a reactant, such as sodium hydroxide, NaOH, dissolved in water which can be injected into the superheated steam.

The other mitigation technique studied in the work of Hjartarson et al. (2014) is the application of binary cycle. The cycle design does not really eliminate the corrosion but limits it to the heat exchangers. The heat exchangers are stationary components and have a wider margin of selection in the material they are made of than more sensitive components like the turbines. The heat exchanger can tolerate the same rate of corrosion longer than the turbine as the turbine is a moving part with more limited choice of construction material.

The study by Hjartarson et al. (2014) shows the effect of application of different mitigation techniques on the overall thermodynamic output from the power cycle. The economic value of the final product, that is the power output, however also depends upon the cost of technology required to extract the output. A better way to analyze a system is to simultaneously take both thermodynamic performance and cost into consideration. Thermoeconomics is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations but which are crucial to the design and operation of a cost effective system (Bejan, and Tsatsaronis, 1996). In the last few decades there has been a great development in the field of thermoeconomics. Lozano and Valero (1993) defined thermoeconomics as the general theory of useful energy saving where conservation is a cornerstone. Thermoeconomic analysis of a system involves exergy analysis of each component of the system and estimating cost of all input and output exergy flow of the component and the system as a whole. The cost of output exergy flow is calculated as a function of input exergy flow cost and the cost of the component. The component cost is usually obtained as a function of thermodynamic efficiency and size. In case where the cost relation is not available, the cost is calculated based on the previous year cost data from the market and taking other factors such as inflation into account.

To demonstrate the application of thermoeconomic analysis to geothermal power plants, a case study is carried out for IDDP-1. The design of the power cycles, for which thermoeconomic analysis is performed in this study, are from the work of Hjartarson et al. (2014). Four different cycles are selected, considering the technical viability of the cycles discussed in the literature work. The cycles are: a) Single flash with wet scrubbing, where superheat is quenched before entering the steam into the turbine. b) Single flash cycle with wet scrubbing and heat recovery, where superheat is recovered after the wet scrubbing process using the application of heat recovery system. c) Single flash cycle with wet scrubbing and an additional turbine, where superheated steam is directly passed into the turbine and keeping the steam superheated to a few degree at the exit and then using wet scrubbing before passing it into the second turbine. d) Binary cycle, which utilizes a series of heat exchangers which allows energy to transfer to the secondary fluid, thus requiring no mitigation. The schematics of the four cycles are shown in Figure 1.

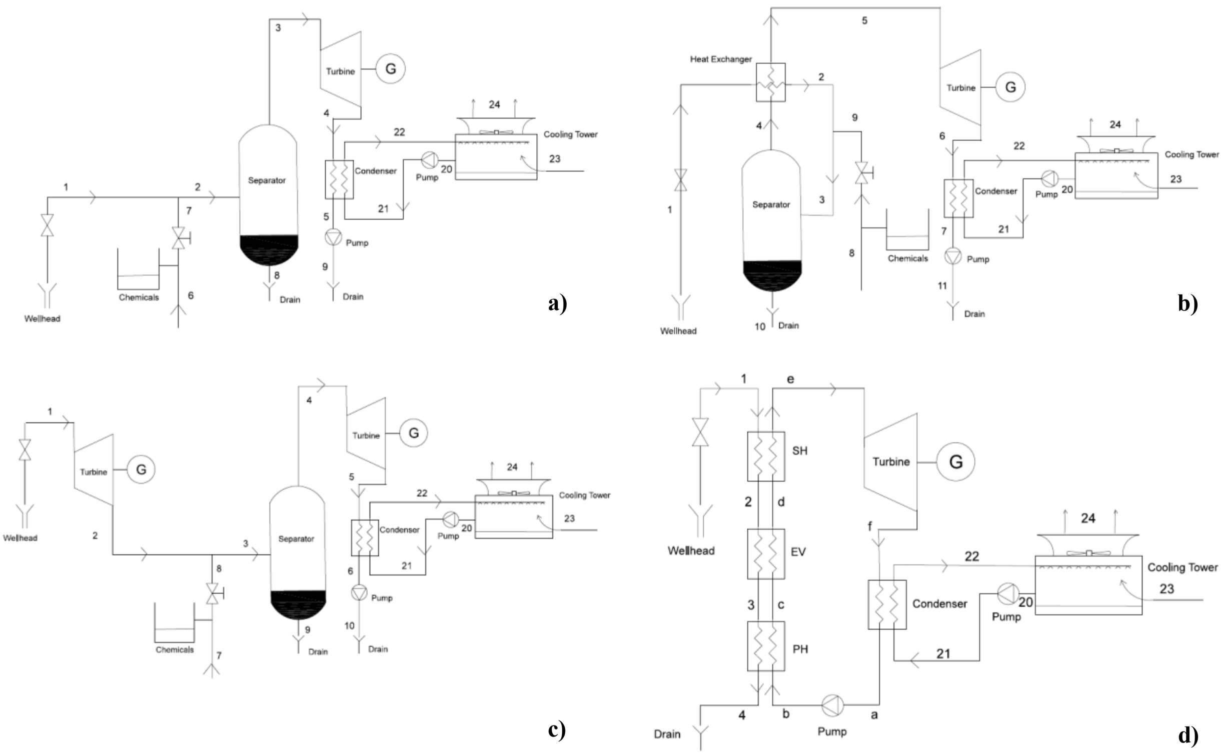


Figure 1: Schematic diagrams of the proposed power cycles for the utilization of IDDP-1. a) Single flash cycle with wet scrubbing. b) Single flash cycle with wet scrubbing and heat recovery. c) Single flash cycle with wet scrubbing and an additional turbine. d) Binary cycle

Each cycle was subject to a thermoeconomic analysis, in order to be able to find an optimum solution based on cost and output exergy. The mass flow rates at different wellhead pressures were presented in the work of Hjartarson et al. (2014). Since the values were only measured at few points, the curve is a modelled curve from the measured points. Figure 2 shows this productivity curve for the well IDDP-1.

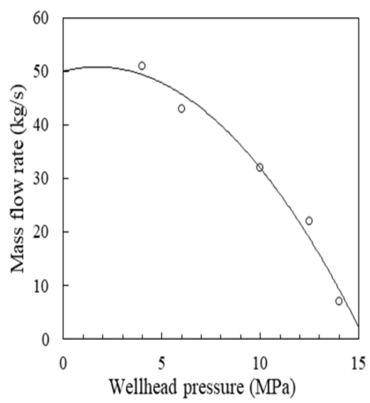


Figure 2: Productivity curve for the well IDDP-1

2. METHODS

Thermoeconomic analysis of a system requires calculating exergy flow rates through each state point in the cycle and then assigning cost to that exergy flow taking into account the component cost and the exergy destroyed. The steps are as follows:

2.1 Exergy Analysis

The method of exergy analysis aims to result in utilizing energy resources more effectively than conventional energy efficiency analysis because it enables to identify the cause, location and actual magnitude of waste and loss (Dincer & Rosen, 2012). Exergy is closely related to Gibbs energy, and is a property representing the energy potential which can be destroyed while energy itself can neither be created nor destroyed, it can only change its form. The total exergy associated with a stream of fluid is expressed on a unit-of-mass basis known as specific exergy (*e*), and is expressed as:

$$e = (h - h_0) - T_0(s - s_0) \tag{1}$$

where *h* and *s* are the specific enthalpy and entropy of the stream respectively, while the subscript 0 represents these properties at the dead state (environment) and T_0 is the environment temperature. When introducing the mass flow $\dot{m}$ of the stream, we obtain the total exergy flow rate $\dot{E}$ of the stream as:

$$\dot{E} = \dot{m}e \tag{2}$$

When the exergetic analysis is used to examine components in an energy process individually, exergy balance can be expressed using the following relation:

$$\dot{E}_{i,k} = \dot{E}_{e,k} + \dot{E}_{D,k} + \dot{E}_{L,k} \tag{3}$$

where $\dot{E}_{i,k}$ represents the exergy rate entering component *k*, while $\dot{E}_{e,k}$ represents the exergy rate exiting the same component. The two exergetic elements remaining with subscripts *D* and *L* are the exergy destruction and loss respectively for the given component. Whether the exergy is lost or destroyed only depends on the choice of the boundary of the system, but the sum $\dot{E}_{D,k} + \dot{E}_{L,k}$ will be constant if both $\dot{E}_{i,k}$ and $\dot{E}_{e,k}$ stay constant (Bejan and Tsatsaronis, 1996).

2.2 Thermoeconomic Analysis of Components

A thermoeconomic analysis requires cost information about the components of the system being analyzed, and is used to compare and include efficiency, capital costs and O&M costs of the component or the overall system. When possible, in order to have the most precise results, the cost balance is formulated for each component individually. To each exergy stream *n*, a cost is therefore attributed as:

$$\dot{C}_n = c_n\dot{E}_n \tag{4}$$

Here, c_n represents the average cost per unit of exergy (e.g. in $/kJ) and therefore $\dot{C}_n$ is the cost rate of the n^{th} stream. When analyzing a component's or system's balance, exiting exergy streams are compared to the entering exergy streams and the total costs, subdivided into capital costs and O&M costs. This is formulated as:

$$\dot{C}_e = \dot{C}_i + \dot{Z}^{CI} + \dot{Z}^{OM} \tag{5}$$

Equation (5) shows that the total cost $\dot{C}_e$ associated with the exiting stream from a component is the sum of the entering stream cost $\dot{C}_i$, capital investment $\dot{Z}^{CI}$ and the other costs related to operation and maintenance $\dot{Z}^{OM}$ of the component generating the product. In this study, the operation and maintenance cost were chosen 5% of the initial investment cost. The exergoeconomic analysis is based on the principle of assigning cost to every flow stream entering and exiting a system. The cost of the particular flow will be proportional to the amount of exergy it contains and hence the amount of work it can produce (Chauhan, 2014). When one wants to understand the cost formation process and cost flow in the system, all exergy loss streams are defined with a cost as if they were to be processed further. In order to give an economic magnitude to the loss, the exergy loss is assumed to be compensated by additional supply of entering exergy, therefore, the exergy loss cost rate in a component k is given as:

$$\dot{C}_{L,k} = c_{i,k}\dot{E}_{L,k} \tag{6}$$

The relation for the k^{th} component is given as:

$$\dot{C}_{e,k} = \dot{C}_{i,k} - \dot{C}_{L,k} + \dot{Z}_k \tag{7}$$

where $\dot{Z}_k$ is the investment or operating cost of the k^{th} component. Nevertheless, in order to give the full burden of the exergy lost to the supplied exergy, the exergy loss cost rate is considered null by setting $\dot{C}_{L,k} = 0$. This only applies to streams finally released to the environment (Bejan & Tsatsaronis, 1996) and not processed further. When the exiting stream needs further processing, the cost of process ($\dot{Z}_{process}$) needs to be accounted for using the following relation:

$$c_e = -\frac{\dot{Z}_{process}}{\dot{E}_e} \tag{8}$$

In this case, the exergy loss is no longer considered but rather an exit stream with a unit cost, even though it is not of any use in the system any more.

The following Table 1 summarizes the equations used for cost estimation of the components used for the thermoeconomic analysis of the four power cycles analyzed in this study. A detailed description of the variables used in the equations is found in (Mereto, 2016). The subscript numbers refer to the state numbers in Figure 1 and the other subscripts indicate the component name.

Table 1: Summary of equations used for estimating cost of the exergy streams from the components of the power cycles used for the thermoeconomic analysis

	Cost balance equation			
Component	Single flash wet scrubbing	Single flash with wet scrubbing and additional heat recover	Single flash cycle with wet scrubbing and additional turbine	Binary cycle
well	$\dot{C}_1 = \dot{Z}_{well}$			
salt injection	$\dot{C}_7 = \dot{C}_{NaOH}$	$\dot{C}_9 = \dot{C}_{NaOH}$	$\dot{C}_8 = \dot{C}_{NaOH}$	-----------
mixing	$\dot{C}_2 = \dot{C}_7 + \dot{C}_1$	$\dot{C}_3 = \dot{C}_9 + \dot{C}_2$	$\dot{C}_3 = \dot{C}_8 + \dot{C}_2$	-----------
separator	$\dot{C}_3 = \dot{C}_2 - \dot{C}_8 + \dot{Z}_{separator}$ $c_8 = -\frac{\dot{Z}_{reinjection}}{\dot{E}_8}$	$\dot{C}_4 = \dot{C}_3 - \dot{C}_{10} + \dot{Z}_{separator}$ $c_{10} = -\frac{\dot{Z}_{reinjection}}{\dot{E}_{10}}$	$\dot{C}_4 = \dot{C}_3 - \dot{C}_9 + \dot{Z}_{separator}$ $c_9 = -\frac{\dot{Z}_{reinjection}}{\dot{E}_9}$	----------
turbine	$\dot{C}_{\dot{W},turb} = \dot{C}_3 - \dot{C}_4 + \dot{Z}_{turbine}$ $c_4 = c_3$ $c_{\dot{W},turb} = \frac{\dot{C}_{\dot{W},turb}}{\dot{W}_{turb}}$	$\dot{C}_{\dot{W},turb} = \dot{C}_5 - \dot{C}_6 + \dot{Z}_{turbine}$ $c_6 = c_5$ $c_{\dot{W},turb} = \frac{\dot{C}_{\dot{W},turb}}{\dot{W}_{turb}}$	$\dot{C}_{\dot{W},turb\_1} = \dot{C}_1 - \dot{C}_2 + \dot{Z}_{turbine\_1}$ $c_2 = c_1$ $c_{\dot{W},turb\_1} = \frac{\dot{C}_{\dot{W},turb\_1}}{\dot{W}_{turb\_1}}$	$\dot{C}_{\dot{W},turb} = \dot{C}_e - \dot{C}_f + \dot{Z}_{turbine}$ $c_f = 0$ $c_{\dot{W},turb} = \frac{\dot{C}_{\dot{W},turb}}{\dot{W}_{turb}}$
additional turbine	-----------	----------	$\dot{C}_{\dot{W},turb\_2} = \dot{C}_4 - \dot{C}_5 + \dot{Z}_{turbine\_2}$ $c_5 = c_4$ $c_{\dot{W},turb\_2} = \frac{\dot{C}_{\dot{W},turb\_2}}{\dot{W}_{turb\_2}}$	-----------
cooling tower	$\dot{C}_{20} - \dot{C}_{22} = \dot{C}_{23} - \dot{C}_{24} + \dot{Z}_{CoolingTower}$, $c_{24} = 0$ $c_{23} = c_{\dot{W},fan} = 0$, $\dot{C}_{20} = \dot{Z}_{CoolingTower}$ $\dot{C}_{21} = \dot{C}_{20} + \dot{Z}_{CoolingPump} + \dot{Z}_{CoolingPiping}$, $c_{22} = 0$			
condenser	$\dot{C}_5 - \dot{C}_4 = \dot{C}_{21} - \dot{C}_{22} + \dot{Z}_{condenser}$	$\dot{C}_7 - \dot{C}_6 = \dot{C}_{21} - \dot{C}_{22} + \dot{Z}_{Condenser}$	$\dot{C}_6 - \dot{C}_5 = \dot{C}_{21} - \dot{C}_{22} + \dot{Z}_{Condenser}$	$\dot{C}_a - \dot{C}_f = \dot{C}_{21} - \dot{C}_{22} + \dot{Z}_{Condenser}$
reinjection	$\dot{C}_9 = \dot{C}_5 + \dot{Z}_{DrainPump}$	$\dot{C}_{11} = \dot{C}_7 + \dot{Z}_{DrainPump}$	$\dot{C}_{10} = \dot{C}_6 + \dot{Z}_{DrainPump}$	
heat recuperator	-----------	$\dot{C}_5 - \dot{C}_4 = \dot{C}_1 - \dot{C}_2 + \dot{Z}_{HX}$ $\dot{C}_2 = c_1\dot{E}_2$	----------	-----------
binary heat exchanger and pump assembly	------------	------------	-----------	$\dot{C}_b = \dot{C}_a + \dot{Z}_{PumpBinary}$ $c_2 = c_1 = c_3$ $\dot{C}_4 = \dot{Z}_{well}$ $\dot{C}_c - \dot{C}_b = \dot{C}_3 - \dot{C}_4 + \dot{Z}_{PH}$ $\dot{C}_d - \dot{C}_c = \dot{C}_2 - \dot{C}_3 + \dot{Z}_{EV}$ $\dot{C}_e - \dot{C}_d = \dot{C}_1 - \dot{C}_2 + \dot{Z}_{SH}$
total plant	$\dot{C}_{total} = \dot{C}_9 + \dot{C}_{\dot{W},turb} + \dot{C}_{other}$	$\dot{C}_{total} = \dot{C}_{11} + \dot{C}_{\dot{W},turb} + \dot{C}_{other}$	$\dot{C}_{total} = \dot{C}_{10} + \dot{C}_{\dot{W},turb\_1} + \dot{C}_{\dot{W},turb\_2} + \dot{C}_{other}$	$\dot{C}_{total} = \dot{C}_{\dot{W},turb} + \dot{C}_{other}$

Solving the cost balance equations given in Table 1 requires calculation of the cost of each component ($Z_{component}$). When attributing cost to plant components, many assumptions have to be made when comparing options. The major components rarely have a price list available, therefore cost estimation formulas are required. For the main components of a geothermal power plant the cost estimating equations are described in Table 2. A more detailed explanation of the nomenclature can be found in (Mereto 2016). The formulas in question initially come from El-Sayed and Frangopoulos (1983), but were updated various times until the versions used here by Xiong et al. (2012), Roosen and Dincer (2003) and Uhlenbruck and Lucas (2004).

Table 2: Summary of equations used for estimating cost of components for the thermoeconomic analysis.

Component	Cost relation
turbine	$C_{turb} = 3880.5\left[1 + 5e^{\left(\frac{T_{in}-866}{10.42}\right)}\right]\left[1 + \left(\frac{1-0.85}{1-\eta_{T,i}}\right)^3\right] W_T^{0.7}$
condenser	$C_{cond} = 280.74\,\frac{\dot{Q}_{cond}}{U_{cond}\,LMTD} + 746\,\dot{m}_{CW} + 70.5\,\dot{Q}_{cond}\,(-06936\ln(T_{CW} - T_{WB}) + 2.1898)$
pump	$C_{pump} = 378\left[1 + \left(\frac{1-0.808}{1-\eta_{p,is}}\right)^3\right]\dot{E}_{out}^{0.71}$
salt solution	$\dot{Cost}_{NaOH} = 0.33\dot{m}_{NaOH}$ $C_{NaOH} = CRF \times \dot{Cost}_{NaOH}$
other components	$C_{PE,Y} = C_{PE,W}\left(\frac{X_Y}{X_W}\right)^{\alpha}$

The equation for the Capital Recovery Factor (CRF), used for calculating the cost of salt solution is expressed as:

$$CRF = \frac{i(1+i)^n}{1+i^n-1} \tag{9}$$

where i is the interest rate, assumed here to be 8% and n is the power plant life, here assumed to be 25 years.

The last equation in Table 2 shows the economies of scale and relates the cost $C_{PE,Y}$ of component Y of size X_Y to the known cost $C_{PE,W}$ of component of size X_w and α represents the scaling factor, which is assumed here to be 0.6.

3. RESULTS

A comparison of the exergy flow rates and the total exergy destructions for four different cycles utilizing fluid from IDDP-1 is shown in Figure 3. E_i in Figure 3 refers to the exergy flow rate at point i, corresponding to the state points shown in Figure 1. As shown in the figure, the exergy flow rate at the turbine inlet first increases and then decreases with wellhead pressure for all cycles irrespective

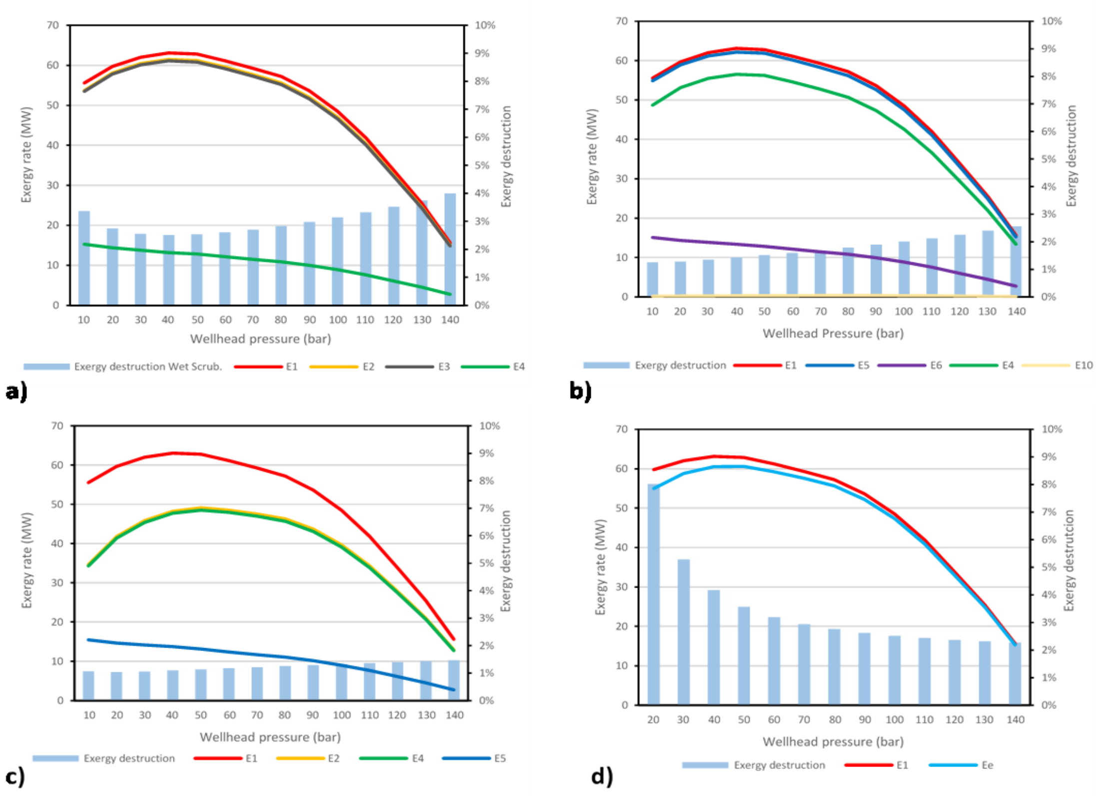
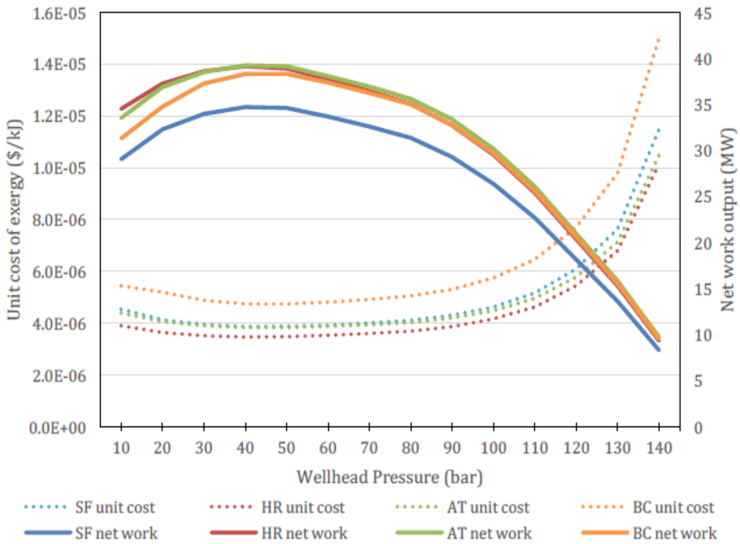


Figure 3: Exergy flow rates and exergy destruction for the four power cycles utilizing fluid from IDDP-1. a) Single flash cycle with wet scrubbing. b) Single flash cycle with wet scrubbing and heat recovery. c) Single flash cycle with wet scrubbing and an additional turbine. d) Binary cycle.

of the mitigation technique used. This can be explained based on the mass flow rate variation with respect to the wellhead pressure in Figure 2, showing an almost constant mass flow value in the initial pressure range and then a decrease in mass flow with increasing wellhead pressure. The variation of exergy destruction with wellhead pressure however shows different trends for different cycles. For the cycle with single flash and wet scrubbing, exergy destruction decreases and then increases with wellhead pressure. This is due to limit of turbine exit pressure for which vapour quality first decreases and then increases, which first causes decrease in exergy loss due to fluid exiting and then increase. This variation is however buffered in the other two cycles containing the heat recovery system or an additional turbine. The total exergy destruction curve shown for the binary cycle includes exergy loss due to the fluid injected back to the ground and exergy destruction in the components. The total exergy destruction is therefore proportional to the total inlet exergy entering the system, which decreases with increase in wellhead pressure due to decreasing mass flow rate.

Figure 4 shows the net-work output and the unit cost of product exergy for four different cycles shown in Figure 1, utilizing the fluid from IDDP-1. As seen from the figure, the net-work output first increases and then decreases with the wellhead pressure for all four cycles. The variation is proportional to the inlet exergy to the cycles, denoted by E_1 in Figure 3. The single flash cycle with wet scrubbing shows the lowest net-work output due to maximum loss in exergy due to quenching of superheat in the wet scrubbing process. The unit cost of produced exergy shows a different trend as compared to the trend of net-work output. The results shows the cycle with heat recovery system as having the lowest unit product exergy cost. This can be explained on the basis of component costs. As seen from Figure 4, although the cycle with heat recovery and the cycle utilizing additional turbine shows comparable net-work output, the cost of adding a heat recovery system is far smaller compared to a turbine, thus making low cost of the final product exergy. Among the single turbine cycles, the addition of a heat exchanger for the binary cycle adds significant cost compared to that of single flash with wet scrubbing, resulting in a high cost of final product exergy. The results from the thermoeconomic analysis show a completely different choice of the cycle obtained from the thermodynamic analysis only.



a) **b)** **c)** **d)**

Figure 4: Net work output and unit cost of exergy of the proposed power cycles. SF: Single Flash; HR: Heat Recovery; AT: Additional Turbine; BC: Binary Cycle. The letters a)-d) refer to the schematic diagrams of the four processes shown in Figure 1.

5. CONCLUSIONS

A thermoeconomic analysis of a full geothermal cycle is composed of both an exergetic analysis and an economic analysis where each component in the cycle is analyzed. In this work, the analyses were based on important data such as mass flow rates and wellhead pressures, which might involve some uncertainties from the flow tests. In this study, four cycles have been analyzed, where the cycles were designed for chloride mitigation. The results of the thermoeconomic analyses of all the cycles aiming at chloride mitigation in IDDP-1 came to the conclusion that the best cycle to use for this purpose is the single flash system with heat recovery. This cycle is able to produce the greatest amount of power among all cycles, and the wellhead pressure at which it produces the highest output is also the point with the lowest unit cost for producing the electricity.

It is important to consider the fact that these cycles are focused only on the chloride mitigation, not on other elements present in the geothermal fluid, such as for example, silica, responsible for scaling. These cycles could not be applied directly as proposed because technical limitations that were not considered would incur. The cycle that seems best suited is the heat recovery cycle and therefore should be chosen for further analysis and technical design considering more aspects of the circumstances. Even though the cycles studied were simplified and would need to be modified before using for real circumstances, this analysis still represents a useful and important work for the purpose of thermoeconomic analysis of geothermal power plants with the goal of finding the most suitable power cycle for utilization of a chloride rich superheated steam.

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