# Energy and Exergy Analyses of Cerro Prieto I Geothermal Power Plant

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**Abstract** — Growing energy demands and the desire to reduce pollution have increased interest in and research on unconventional power plant technologies. Geothermal power plant technology is an important area being explored as a renewable and environmentally benign alternative to fossil fuel technologies. Geothermal power plants have sources of emissions associated with use, including the use of evaporation ponds. An example of a geothermal power generation unit that utilizes an evaporation pond to manage spent geothermal fluids during its operation is the Cerro Prieto I plant in Mexico. A theoretical model is developed to retrofit the plant with geothermal fluid re-injection. Energy and exergy analyses are performed for the standard plant, using the evaporation pond, as well as a hypothetical system utilizing fluid re-injection. The plant without re-injection is found to have an energy efficiency of 12.6% and an exergy efficiency of 47.5%. With re-injection the energy efficiency is 16.5% and the exergy efficiency is 51.5%. The greatest loss in the standard system is through direct discharge of the geothermal fluids to the evaporation pond.

**Keywords** — Exergy, Geothermal energy, Power Generation, Re-injection

## 1 INTRODUCTION

Global energy demand is increasing quickly. Fossil fuels such as coal, natural gas, furnace oil, gasoline, diesel, and kerosene provide the world with a large portion of the required energy. Burning fossil fuels produce greenhouse gas emissions that have negative affects worldwide. Fossil fuel reserves are also thought, by some, to be finite and that global shortages will occur in the future [1]. Hammond [2] argues fossil fuel depletion and greenhouse gas emissions are the most significant factors when considering sustainable and environmentally benign energy systems. One category of systems that is sustainable and environmentally benign includes geothermal energy.

The Earth is an abundant source of energy extending past the idea that it contains fossil fuel. One sustainable and environmentally benign energy resource directly involves the ground and is referred to as geothermal energy. The Earth's crust stores a large source of thermal energy [3].

One use for geothermal energy is power generation. In geothermal power generation heat from the ground is used to provide energy to a power generating system, similar to conventional fossil fuelled power plants. The thermal energy contained in geothermal reserves originates from the core of the earth and localized radioactive decay of naturally occurring minerals, which is transferred from depth towards the Earth's surface [3], [4], [5]. As the thermal energy travels towards the surface it becomes captured and stored within the earth's crust [4]. Geothermal reserves vary from water filled reservoirs to areas of hot dry rock. Typically geothermal reserves utilized for industrial use are between 100°C and 300°C [3], [6].

Geothermal power plants are environmentally benign when compared to conventional fossil fuel fired plants. Without burning fossil fuel there are no combustion by products. Geothermal power plants produce emissions through the release of gasses that are dissolved and contained in the geofluid [5], [7]. The main source of emissions is through direct discharge of the waste geofluids after the plant. Direct discharge has no restraint on environmental emissions. Minerals and gasses are directly released at ground level where they can have a large effect on the local environment [5], [8]. Thermal pollution is also present with direct discharge as the fluid are usually of temperature above the environment.

One of the best ways to combat emissions from geothermal use is through re-injection. Re-injection involves returning geofluids to the reservoir they were taken from after use. Essentially a closed loop is created, with potentially harmful substances restrained within the loop, where little to no emissions are released to the environment [8].

It can be said that geothermal reserves are sustainable, as energy is continually being fed to geothermal reservoirs through heat transfer from the hot core of the earth. One problem that arises in

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geothermal installations is an imbalance of the amount of heat being fed to a reserve and the amount being used for industry. Over time a reserve may turn cold if the resource is over used [4], [7]. A good solution that increases short term sustainability is re-injection. When performed, the strain on the reservoir is reduced as warm fluids, which would otherwise be wasted, are used to help replenish the energy in the reservoir [8].

The following is a comparison of an operational geothermal power generating station that does not have re-injection to an identical system that is theoretically retrofitted with re-injection through energy and exergy analysis. Energy and exergy efficiencies are calculated, as well as the exergy destruction within each component for each system arrangement.

## 2 SYSTEM DESCRIPTION

The system being examined is the Cerro Prieto I geothermal power generating located East of Cerro Prieto Volcano [7]. The type of geothermal reserve that associated with Cerro Prieto I is a hydrothermal wet steam resource. This resource contains geothermal fluid at high temperature and pressure. It is often referred to as wet steam because the pressure decreases as fluid is extracted from the reservoir and becomes a mixture of vapor and liquid.

The pressure is reduced further allowing the liquid to flash producing steam that can be separated and used in a conventional steam turbine.

The Cerro Prieto I station consists of five units.

Units one through four are single flash units. Water from the well head has its pressure reduced, allowing the liquid to become a vapour/liquid mixture that can be separated [7]. Flashing and separation for units one through four occur at the well head. The steam is transported to the power houses for each respective unit, for use in turbines. After expansion the used fluid is condensed and sent to an onsite evaporation pond. The liquid separated at the well heads of units one through four is combined into a single stream and transported a distance to unit five. For this analysis units one through four will be considered as one larger unit, as they are of similar design and utilize the same flow conditions at the well head [7].

Unit five is a double flash unit involving a two stage flash process. The medium pressure water from the first four units is flashed and separated in a single unit called the medium pressure flasher (MPF). The liquid separated from the MPF is fed into a low pressure flasher (LPF). Steam extracted from the MPF and LPF is fed into a dual-admission turbine to produce work. The turbine exhaust fluid is condensed.

The actually arrangement of Cerro Prieto I has



I: Expansion Valve
II: Separator
III: HP Turbine
IV: Condenser I
V: Med. Pressure Flasher
VI: Low Pressure Flasher
VII: LP Turbine
VIII: Condenser II
IX: Pump I*
X: Pump II*
*Included in the re-injection arrangement, otherwise streams at states 19 and 20 are directed to the evaporation pond
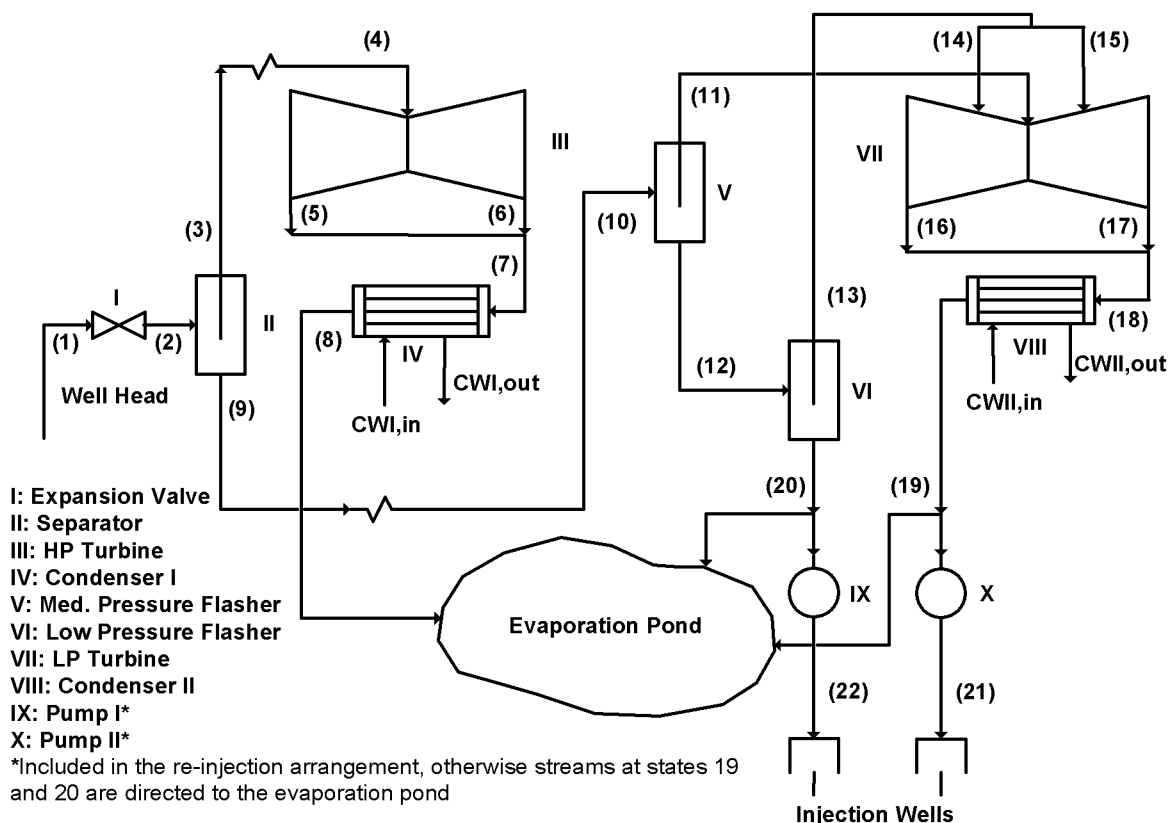
Fig. 1. State diagram for the Cerro Prieto I geothermal power plant. Modified from Reference [7].

the exhaust streams from unit five's LPF and condenser directed to an evaporation pond [7].

A case involving re-injection of these two streams is investigated, where flows from the LPF and condenser would be pumped back into the reservoir at the pressure it was extracted. Fig. 1 illustrates the system being analyzed and includes the layout of the system with and without re-injection. For the case without re-injection pumps one and two are removed and flow is directed towards the evaporation pond.

## 3 ANALYSIS

### 3.1 Assumptions Made

The following assumptions are made for the energy and exergy analyses:

a) System operates as a steady state, steady flow process.
b) Effects of minerals within the geofluid are neglected.
c) Thermodynamic properties of the geothermal fluid are taken as those of water.
d) Heat loss occurs along the distances between the separator and high pressure turbine as well as the MPF.
e) Parasitic losses accompanied with the condensing system are negligible.
f) Processes are adiabatic.
g) Negligible pressure drop.
h) Turbine and pump efficiencies are 0.80 and 0.95, respectively.

### 3.2 Balance Equations, and Energy and Exergy Efficiencies

For a general steady-state, steady-flow process, the three balance equations, namely mass, energy and exergy balance equations are employed to find the energy and exergy flow rate, rate of exergy destruction as well as energy and exergy efficiencies

Generally, mass balance equations can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where $\dot{m}$ is the mass flow rate and the subscripts indicate inlet and outlet.

The general energy balance equation can be represented as the total energy input equal to the total energy output, where $\dot{E}_{in} = \dot{E}_{out}$. Including all energy terms the general energy balance becomes

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \tag{2}$$

where $\dot{Q}$ is the rate of net heat input, $\dot{W}$ is the rate of net work output and $h$ is the specific enthalpy.

The general exergy balance equation is expressed as

$$\dot{Ex}_{in} = \dot{Ex}_{out} + \dot{Ex}_{des} \tag{3a}$$

where $\dot{Ex}_{in}$ and $\dot{Ex}_{out}$ are the rate of exergy transfer by heat, work, and mass. $\dot{Ex}_{des}$ is the rate of exergy destruction. Eq. 3a can be expanded to

$$\dot{Ex}_{heat} + \dot{Ex}_{mass,in}$$
$$= \dot{Ex}_{mass,out} + \dot{Ex}_{work} + \dot{Ex}_{des} \tag{3b}$$

Eq. 3b can also be written as

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k + \sum (\dot{m}e_x)_{in}$$
$$= \sum (\dot{m}e_x)_{out} + \dot{W} + \dot{Ex}_{des} \tag{3c}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature $T_k$ at location $k$, $\dot{W}$ is the rate of work, $e_x$ is the specific flow exergy and $T_0$ is the temperature of the reference state.

The specific exergy for each state is obtained as follows:

$$e_{xi} = (h_i - h_0) - T_0(s_i - s_0) \tag{4}$$

where $h$ an $s$ are specific enthalpy and entropy respectively, the subscript $i$ indicates the state number and subscript 0 represents properties at the reference state of $P_0$ and $T_0$.

The exergy rate with regard to mass is calculated by

$$\dot{Ex}_i = \dot{m}e_{xi} \tag{5}$$

The mass, energy and exergy balance equations, respectively, for each component illustrated in Fig. 1 are listed as follows:

Expansion valve (I)

$$\dot{m}_1 = \dot{m}_2 \tag{6a}$$

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 \tag{6b}$$

$$\dot{m}_1 e_{x1} = \dot{m}_2 e_{x2} + \dot{Ex}_{des,EV} \tag{6c}$$

Separator (II)

$$\dot{m}_2 = \dot{m}_3 + \dot{m}_9 \tag{7a}$$

$$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_9 h_9 \tag{7b}$$

$$\dot{m}_2 e_{x2} = \dot{m}_3 e_{x3} + \dot{m}_9 e_{x9} + \dot{Ex}_{des,Separator} \tag{7c}$$

### High pressure turbine (III)

$$\dot{m}_4 = \dot{m}_5 + \dot{m}_6 \tag{8a}$$

$$\dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{m}_6 h_6 + \dot{W}_{\text{HP Turbine}} \tag{8b}$$

$$\dot{m}_4 e_{x4} = \dot{m}_5 e_{x5} + \dot{m}_6 e_{x6}$$
$$+ \dot{W}_{\text{HP Turbine}} + \dot{E}x_{\text{des,HP Turbine}} \tag{8c}$$

### Condenser I (IV)

$$\dot{m}_8 = \dot{m}_7 = \dot{m}_5 + \dot{m}_6 \tag{9a}$$

$$\dot{m}_7 h_7 = \dot{m}_8 h_8 + \dot{Q}_{\text{Condenser I}} \tag{9b}$$

The heat transfer rate from the geothermal fluid is equal to the heat absorbed by the cooling water in the condenser as follows:

$$\dot{Q}_{\text{Condenser I}} = \dot{m}_{CI} c_{p,CW}(T_{out,CI} - T_{in,CI}) \tag{9c}$$

where $\dot{m}_{CI}$ is the the coling water flow rate, $c_{p,CW}$ is the specific heat, and $T_{out,CI}$ and $T_{in,CI}$ are the outlet and inlet temperatures for condenser one.

$$\dot{m}_7 e_{x7} = \dot{m}_8 e_{x8} + \dot{Q}_{\text{Condenser I}}$$
$$\cdot \left(1 - \frac{T_0}{T_{\text{Condenser I}}}\right) + \dot{E}x_{\text{des,Condenser I}} \tag{9d}$$

### Medium pressure flasher (V)

$$\dot{m}_{10} = \dot{m}_{11} + \dot{m}_{12} \tag{10a}$$

$$\dot{m}_{10} h_{10} = \dot{m}_{11} h_{11} + \dot{m}_{12} h_{12} \tag{10b}$$

$$\dot{m}_{10} e_{x10} = \dot{m}_{11} e_{x11} + \dot{m}_{12} e_{x12} + \dot{E}x_{\text{des,MPF}} \tag{10c}$$

### Low pressure flasher (VI)

$$\dot{m}_{12} = \dot{m}_{13} + \dot{m}_{20} \tag{11a}$$

$$\dot{m}_{12} h_{12} = \dot{m}_{13} h_{13} + \dot{m}_{20} h_{20} \tag{11b}$$

$$\dot{m}_{12} e_{x12} = \dot{m}_{13} e_{x13} + \dot{m}_{20} e_{x20} + \dot{E}x_{\text{des,LPF}} \tag{11c}$$

### Low pressure turbine (VII)

$$\dot{m}_{11} + \dot{m}_{14} + \dot{m}_{15} = \dot{m}_{16} + \dot{m}_{17} \tag{12a}$$

$$\dot{m}_{11} h_{11} + \dot{m}_{14} h_{14} + \dot{m}_{15} h_{15}$$
$$= \dot{m}_{16} h_{16} + \dot{m}_{17} h_{17} + \dot{W}_{\text{LP Turbine}} \tag{12b}$$

$$\dot{m}_{11} e_{x11} + \dot{m}_{14} e_{x14} + \dot{m}_{15} e_{x15}$$
$$= \dot{m}_{16} e_{x16} + \dot{m}_{17} e_{x17} + \dot{W}_{\text{LP Turbine}}$$
$$+ \dot{E}x_{\text{des,LPTurbine}}. \tag{12c}$$

### Condenser II (VIII)

$$\dot{m}_{18} = \dot{m}_{19} = \dot{m}_{16} + \dot{m}_{17} \tag{13a}$$

$$\dot{m}_{18} h_{18} = \dot{m}_{19} h_{19} + \dot{Q}_{\text{Condenser II}} \tag{13b}$$

The heat transfer rate from the geothermal fluid is equal to the heat absorbed by the cooling water in the condenser as follows:

$$\dot{Q}_{\text{Condenser I}} = \dot{m}_{CII} c_{p,CW}(T_{out,CII} - T_{in,CII}) \tag{13c}$$

where $\dot{m}_{CII}$ is the the coling water flow rate, $c_{p,cw}$ is the specific heat, and $T_{out,CII}$ and $T_{in,CII}$ are the outlet and inlet temperatures for condenser one.

$$\dot{m}_{18} e_{x18} = \dot{m}_{19} e_{x19} + \dot{Q}_{\text{Condenser II}}$$
$$\cdot \left(1 - \frac{T_0}{T_{\text{Condenser II}}}\right) + \dot{E}x_{\text{des,Condenser II}} \tag{13d}$$

### Pump I (IX)

$$\dot{m}_{20} = \dot{m}_{22} \tag{14a}$$

$$\dot{m}_{20} h_{20} + \dot{W}_{\text{Pump I}} = \dot{m}_{22} h_{22} \tag{14b}$$

$$\dot{m}_{20} e_{x20} + \dot{W}_{\text{Pump I}} = \dot{m}_{22} e_{x22} + \dot{E}x_{\text{des,Pump I}} \tag{14c}$$

### Pump II (X)

$$\dot{m}_{19} = \dot{m}_{21} \tag{15a}$$

$$\dot{m}_{19} h_{19} + \dot{W}_{\text{Pump II}} = \dot{m}_{21} h_{21} \tag{15b}$$

$$\dot{m}_{19} e_{x19} + \dot{W}_{\text{Pump II}} = \dot{m}_{21} e_{x21} + \dot{E}x_{\text{des,Pump II}} \tag{15c}$$

The net work output of the geothermal systems with and withough re-injection is calculated as follows:

Geothermal system with re-injection

$$\dot{W}_{net,w} = \left(\dot{W}_{\text{HP Turbine}} + \dot{W}_{\text{LP Turbine}}\right)$$
$$- \left(\dot{W}_{\text{Pump I}} + \dot{W}_{\text{Pump II}}\right) \tag{16a}$$

where $\dot{W}_{\text{HP Turbine}}$ and $\dot{W}_{\text{LP Turbine}}$ are the power output of the high pressure and low pressure turbine respectively. $\dot{W}_{\text{Pump I}}$ and $\dot{W}_{\text{Pump II}}$ are the work input required by pump one and two respectively.

Geothermal system without re-injection

$$\dot{W}_{net,w/o} = \left(\dot{W}_{\text{HP Turbine}} + \dot{W}_{\text{LP Turbine}}\right) \tag{16b}$$

The energy efficiency of the geothermal system with and without re-injection is calculated as follows:

Geothermal plant with re-injection

$$\eta_{\text{plant,w}} = \frac{\dot{W}_{net,w}}{\dot{m}_1 h_1 - (\dot{m}_{21} h_{21} + \dot{m}_{22} h_{22})} \tag{17a}$$

Geothermal plant without re-injection

$$\eta_{\text{plant,w/o}} = \frac{\dot{W}_{net,w/o}}{\dot{m}_1 h_1} \qquad (17a)$$

The exergy efficiency of the geothermal power system and its components are calculated as follows:
Geothermal plant with re-injection

$$\psi_{\text{plant,w}} = \frac{\dot{W}_{net,w}}{\dot{E}x_1 - (\dot{E}x_{21} + \dot{E}x_{22})} \qquad (18a)$$

Geothermal plant without re-injection

$$\psi_{\text{plant,w/o}} = \frac{\dot{W}_{net,w/o}}{\dot{E}x_1} \qquad (18b)$$

Evaporation valve (I)

$$\psi_{\text{EV}} = \frac{\dot{E}x_2}{\dot{E}x_1} \qquad (19)$$

Separator (II)

$$\psi_{\text{Separator}} = \frac{\dot{E}x_3 + \dot{E}x_9}{\dot{E}x_2} \qquad (20)$$

High pressure turbine (III)

$$\psi_{\text{HP Turbine}} = \frac{\dot{W}_{\text{HP Turbine}}}{\dot{E}x_4 - (\dot{E}x_5 + \dot{E}x_6)} \qquad (21)$$

Condenser I (IV)

$$\psi_{\text{Condenser I}} = \frac{\dot{Q}_{\text{Condenser I}}\left(1 - \frac{T_0}{T_{\text{Condenser I}}}\right)}{\dot{E}x_7 - \dot{E}x_8} \qquad (22)$$

Medium pressure flasher (V)

$$\psi_{\text{MPF}} = \frac{\dot{E}x_{11} + \dot{E}x_{12}}{\dot{E}x_{10}} \qquad (23)$$

Low pressure flasher (VI)

$$\psi_{\text{MPF}} = \frac{\dot{E}x_{11} + \dot{E}x_{12}}{\dot{E}x_{10}} \cdot \qquad (24)$$

Low pressure turbine (VII)

$$\psi_{\text{HP Turbine}}$$
$$= \frac{\dot{W}_{\text{LP Turbine}}}{(\dot{E}x_{11} + \dot{E}x_{14} + \dot{E}x_{15}) - (\dot{E}x_{16} + \dot{E}x_{17})} \qquad (25)$$

Condenser II (VIII)

$$\psi_{\text{Condenser II}} = \frac{\dot{Q}_{\text{Condenser II}}\left(1 - \frac{T_0}{T_{\text{Condenser II}}}\right)}{\dot{E}x_{18} - \dot{E}x_{19}} \qquad (26)$$

Pump I (IX)

$$\psi_{\text{Pump I}} = \frac{\dot{E}x_{22} - \dot{E}x_{20}}{\dot{W}_{\text{Pump I}}} \qquad (27)$$

Pump II(X)

$$\psi_{\text{PumpII}} = \frac{\dot{E}x_{21} - \dot{E}x_{19}}{\dot{W}_{\text{Pump II}}} \qquad (28)$$

## 4  RESULTS AND DISCUSSION

System operating conditions for Cerro Prieto I are taken from DiPippo [7]. Thermodynamic properties of water are found using Engineering Equation Solver (EES) software package program.

The system without re-injection is the standard arrangement found at Cerro Prieto I. The calculated net power output for the standard system is 183.2 MW. The actual net power output stated by DiPippo [7] for the system is 180 MW, which leads to an error of 1.7% between the actual system and the model utilized in the present analysis. Differences in fluid characteristics between the actual and theoretical systems, assuming adiabatic processes, and neglecting pressure losses are some sources of error.

The net power output for the system including re-injection is 179.5 MW. Reduction in power output compared to the system without re-injection arises through the introduction of re-injection pumps.

Temperature, pressure, and flow rate data for the working fluid, are given in Table 1 following the state numbers specified in Fig. 1 for both the systems with and without re-injection. Table 1 shows that and the separation processes and the pumps in the re-injection system produces an increase in ex. The pumps in the re-injection system create an increase in ex due to their work input. The separation processes actual cause an increase and decrease in the ex at each of their exits respectively. When a vapor liquid mixture is separated it can be considered two separate fluids. The steam leaving has a higher enthalpy and entropy than the mixed fluid entering a separator, and alternatively the enthalpy and entropy of the liquid leaving is lower that the fluid entering. The overall result is a higher specific exergy leaving through steam and lower specific exergy leaving in liquid compared to the specific exergy entering a separator.

The exergy flow rates of the steam leaving the separators are lower than the liquid leaving the separators. The mass flow rates seen by each stream differ substantially, which is a result of low mixture quality within the separators, resulting in a large

Table 1. Exergy analysis results for each state of the geothermal power station

| State | Temp. (°C) | Pressure (kPa) | Specific Enthalpy (kJ/kg) | Specific Entropy (kJ/kg·K) | Quality | Mass Flow Rate (kg/s) | Energy Rate (kW) | Specific Exergy (kJ/kg) | Exergy Rate (kW) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 25 | 101.3 | 104.8 | 0.3669 | - | - | - | - | - |
| 1 | 250 | 3974 | 1269 | 3.144 | 0.1073 | 1145 | 1,453,000 | 336.5 | 385,283 |
| 2 | 165 | 700 | 1269 | 3.298 | 0.2769 | 1145 | 1,453,000 | 290.7 | 332,826 |
| 3 | 165 | 700 | 2763 | 6.708 | 1 | 317 | 875,967 | 768.2 | 243,505 |
| 4 | 160.1 | 620 | 2758 | 6.749 | 1 | 317 | 874,315 | 750.7 | 237,973 |
| 5 | 49.15 | 11.85 | 2278 | 7.122 | 0.8692 | 158.5 | 361,037 | 159.4 | 25,264 |
| 6 | 49.15 | 11.85 | 2278 | 7.122 | 0.8692 | 158.5 | 361,037 | 159.4 | 25,264 |
| 7 | 49.15 | 11.85 | 2278 | 7.122 | 0.8692 | 317 | 722,074 | 159.4 | 50,529 |
| 8 | 49.15 | 11.85 | 1756 | 5.503 | 0.6504 | 317 | 556,737 | 120.2 | 38,114 |
| 9 | 165 | 700 | 697.3 | 1.992 | 0 | 827.9 | 577,266 | 107.9 | 89,320 |
| 10 | 160 | 617.7 | 675.7 | 1.943 | 0 | 827.9 | 559,371 | 101 | 83,620 |
| 11 | 136.1 | 322.7 | 2729 | 6.968 | 1 | 39.7 | 108,330 | 656.1 | 26,047 |
| 12 | 136 | 322.7 | 572.2 | 1.698 | 0 | 788.2 | 451,041 | 70.57 | 55,626 |
| 13 | 121 | 205 | 2708 | 7.119 | 1 | 37.8 | 102,349 | 589.9 | 22,300 |
| 14 | 121 | 205 | 2708 | 7.119 | 1 | 18.9 | 51,175 | 589.9 | 11,150 |
| 15 | 121 | 205 | 2708 | 7.119 | 1 | 18.9 | 51,175 | 589.9 | 11,150 |
| 16 | 47.85 | 11.1 | 2319 | 7.277 | 0.8876 | 38.75 | 89,868 | 154.5 | 5989 |
| 17 | 47.85 | 11.1 | 2319 | 7.277 | 0.8876 | 38.75 | 89,868 | 154.5 | 5989 |
| 18 | 47.85 | 11.1 | 2319 | 7.277 | 0.8876 | 77.5 | 179,736 | 154.5 | 11,977 |
| 19 | 47.27 | 11.1 | 197.9 | 0.6682 | 0 | 77.5 | 15,336 | 3.238 | 250.9 |
| 20 | 121 | 205 | 464.7 | 1.427 | 0 | 750.4 | 348,692 | 43.79 | 32,864 |
| *21 | 47.51 | 3974 | 202.3 | 0.6696 | 0 | 77.5 | 15,678 | 7.272 | 563.6 |
| *22 | 122.1 | 3974 | 469.1 | 1.428 | 0 | 750.4 | 352,012 | 47.86 | 35918 |

*State only exist within system with re-injection

mass exiting in the form of liquid and a small mass leaving in the form of steam. Even though the specific exergy for the liquid stream is substantially lower than that of the steam the flow exergy for the liquid is high because of its high flow rate. Overall the separation processes in this analysis do not result in an increase or decrease in $\dot{E}x$ since the processes are taken as reversible, rather the exergy flow streams entering these components are split into two streams for which the sum of $\dot{E}x$ leaving is equal to $\dot{E}x$ entering.

Within the arrangement without re-injection the greatest loss is created by natural direct discharge to an evaporation pond. About 63.4% of the initial energy and 18.5% of the initial exergy is discharged to the pond. The water released to the open environment to sit and evaporate constitutes as waste, since fluid being introduced to the evaporation pond still contains energy and exergy. The initial flashing is the next wasteful process in terms of consuming or destroying exergy in the system, by reducing the exergy entering the system by 14.2%. Exergy flashing losses are followed by turbine losses (10.5%), and heat loss/removed from the system (9.2%).

For the re-injection arrangement the highest consumer of the energy is still the evaporation pond, but the percentage is reduced to 38.3%. The

remaining 25.1% of the energy flow is re-injected into the reservoir. With re-injection the source of waste exergy is no longer the evaporation pond but rather the flashing processes with the same reduction in initial exergy of 14.2%. Re-injection has taken approximately half of the exergy flow away from the evaporation pond. Exergy flow through re-injection is neither consumed or wasted and is fed into the original reservoir allowing for the reduction in waste, and higher exergy efficiency as mentioned above. The parasitic exergy loss with regard to the pumps is miniscule and accounts for less than 1% of the total exergy flow in the system.

The energy and exergy efficiences for the case without re-injection are 12.6% and 47.6% respectively as seen in Table 2. DiPippo [7] states that the exergy efficiency of Cerro Prieto I is 41.4%; the difference in exergy efficiencies can be attributed to the assumptions made in the analyses.

It is found that the exergy efficiency is higher than the energy efficiency for the geothermal plant arrangements. As seen in Table 2, for the standard case without re-injection the exergy efficiency is 47.6% where as the energy efficiency is 12.6%. The difference appears in the definition of energy and exergy efficiency (Eq. 17a, b and 18a, b). The energy and exergy equations have the same net work output specific to each system arrangement. The

exergy flow into the system is considerably less then energy, creating the situation where it takes less to get the same amount of work in terms of exergy supplied, allowing for higher exergy efficiency.

The same result was found when the system was equipped with re-injection. Table 2 shows that re-injection resulted in an increase in both exergy and energy efficiency, but the exergy efficiency, 51.5%, is still much greater than the energy efficiency, 16.5%, for the same reason given for the system without re-injection. Out fitting the system with re-injection allowed for an increase of 4% for exergy and energy efficiency. The increase in efficiency arises from the fact that the energy and exergy flow rates being re-injected is subtracted from the rate of energy and exergy being fed into the system.

Table 2. Energy and Exergy Efficiencies of Cerro Prieto I Plant

| Plant Arrangement | Energy Efficiency $\eta_{plant}$, (%) | Exergy Efficiency $\psi_{plant}$, (%) |
|---|---|---|
| Without re-injection | 12.6 | 47.6 |
| With re-injection | 16.5 | 51.5 |

A summary of the exergy efficiency, exergy destruction and relative irreversibility of each component is found in Table 3. Overall the component efficiencies appear to be high, which is due to the assumptions made within model. The LP turbine has the lowest exergy efficiency of all the components with 81.2% and the separator has the highest with 100%. A 100% efficiency is unreasonable since there is always entropy generation associated with processes, but given the

technical specifications of the plant specified by DiPippo [7] and assumptions utilized, the separator is isentropic in this study. The MPF and LPF include exergy destruction as they incorporate both expansion and separation within a single unit.

Of all the devices in the system the initial flashing, using an expansion valve, at the well head experiences the most exergy destruction, and relative irreversibilities for in both system arrangements. The initial flashing accounts for 54.9% and 54.7% of all the exergy destruction attributed to system components for non re-injection and re-injection systems respectively. This is understandable through the dynamics of the device, where enthalpy remains constant and entropy increases; upon review of Eq. 4, it visible that this would result in a decrease in exergy flow after the valve. Since this is a single input single output device the change in flow exergy directly contributes to exergy destruction with the valve. The expansion valve is subject to the largest flow rate in the system, which also contributes to the high exergy destruction.

If a different expansion device was used to lower the pressure instead of expansion valves the destruction could be reduced. One possibility would be to place the expansion valve with a total flow turbine. A total flow turbine is one that can accommodate both liquid and vapor in the turbine at once, without it being damaged, to produce work [7]. The fluid leaving the turbine would be at lower pressure allowing for vapor and liquid to be separated similar to a conventional geothermal power production system.

Table 3. Table comparing exergy destruction and exergy efficiency of system components

| Device Number | Device | Exergy Destruction Rate, $\dot{Ex}_{des}$ (kW) | Relative Irreversibility (%) | | Exergy Efficiency, $\psi$ (%) |
|---|---|---|---|---|---|
| | | | w/o Re-injection | With Re-injection | |
| I | Expansion valve | 52,457 | 54.9 | 54.7 | 86.4 |
| II | Separator | 0 | 0 | 0 | 100 |
| III | HP turbine | 35,203 | 36.8 | 36.7 | 85.1 |
| IV | Condenser I | 23.7 | 0.0248 | 0.0247 | 99.8 |
| V | Med. pressure flasher | 1947 | 2.04 | 2.03 | 97.7 |
| VI | Low pressure flasher | 462 | 0.484 | 0.482 | 99.2 |
| VII | LP turbine | 5427 | 5.68 | 5.66 | 81.2 |
| VIII | Condenser II | 23.6 | 0.0247 | 0.0246 | 99.8 |
| IX | *Pump I | 280 | - | 0.293 | 91.6 |
| X | *Pump II | 32.3 | - | 0.0337 | 90.6 |
| - | Plant w/o re-injection | 95,542 | 100 | - | 47.6 |
| - | Plant with re-injection | 95,855 | - | 100 | 51.5 |

*Components are only incorporated into the case including re-injection
Relative Irreversibility is the fraction percent of exergy destruction within a specific component compared to the total exergy destruction in the system

## 5 CONCLUSIONS

Cerro Prieto I is a geothermal power plant with a standard calculated 183.2 MW output. The standard system had an energy and exergy efficiency of 12.6% and 47.5% respectively. The plant output is reduced to 179.5 MW for the re-injection arrangement, but the efficiency increased to 16.5% and 51.5% for energy and exergy efficiency. In the standard system most of the energy and exergy was being wasted through the use of direct discharge to. With re-injection that amount is almost cut in half and the main source of exergy waste or destruction is the evaporation valve at the well head.

Even though only part of the fluid would be re-injected the amount of reduced discharge over a large span of time would be great. Increased efficiency goes hand in hand with this concept. The overall efficiency of the system increases with re-injection, meaning essentially less waste, leading to lowered environmental impact. It is thought that most appropriate improvement would be to re-inject the entirety of the condensed fluid. The result would be a greater increase in both energy and exergy efficiency within this system.

One of the greatest losses within both systems involved the flashing and it is thought that the use of other devices, such as total flow turbines, would help to decrease the losses and improve efficiency.

Re-injection improves efficiency, increases reserve life and reduces emissions. When the power is available and favourable economics exist geothermal power plants should include re-injection within their design.

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