Research Journal of

Environmental Sciences

ISSN 1819-3412

Academic
Journals Inc.

www.academicjournals.com

Research Journal of Environmental Sciences 9 (2): 74-87, 2015
ISSN 1819-3412 / DOI: 10.3923/rjes.2015.74.87

Energy and Exergy Analyses of Geothermal Power Plants with and without Re-Injection

S.J. Self, B.V. Reddy and M.A. Rosen
Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000, Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

Corresponding Author: S.J. Self, Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000, Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

ABSTRACT

Growing energy demands and the desire to reduce pollution have increased interest in 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 utilized 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.

Key words: Exergy, geothermal energy, power generation, re-injection

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 effects worldwide (Unverdi and Cerci, 2013). Fossil fuel reserves are also thought, by some, to be finite and that global shortages will occur in the future (Ediger *et al.*, 2007). Hammond (2000) argued fossil fuel depletion and greenhouse gas emissions are the most significant factors when considering sustainable and environmentally benign energy systems.

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 (Bayer *et al.*, 2013; Coskun *et al.*, 2012; Ganjehsarabi *et al.*, 2012). The Earth is a large source of thermal energy which is often contained in geothermal reserves (Bayer *et al.*, 2013; Ganjehsarabi *et al.*, 2012). The thermal energy 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 (Bayer *et al.*, 2013; Barbier, 2002; Gupta and Roy, 2007; Rybach, 2003). As the thermal energy travels towards the surface, it becomes captured and stored within the earth's crust (Gupta and Roy, 2007; Bertani, 2012). Geothermal reserves vary from water filled reservoirs to areas of hot dry rock (Bayer *et al.*, 2013). Utilization of geothermal energy can be categorized into two main methods: electricity generation and direct use (i.e., space heating) (Coskun *et al.*, 2012).

In this study the focus is exclusively on high-enthalpy geothermal energy use for power generation. The use of geothermal energy for power generation has had rapid global utilization recently (Ganjehsarabi *et al.*, 2012). The short-term forecasts indicate that the installed capacity will be approximately 18,500 MWe by 2015 which is a 73% increase since 2010 (Bertani, 2012; Zarrouk and Moon, 2014; Feili *et al.*, 2013; Guzovic *et al.*, 2012). 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 (Aneke *et al.*, 2011). Typically geothermal reserves utilized for power generation are above 120°C (Unverdi and Cerci, 2013; Bayer *et al.*, 2013; Guzovic *et al.*, 2012; Bertani, 2005; Eliasson *et al.*, 2011; Franco and Vaccaro, 2014).

Geothermal power plants are environmentally benign when compared to conventional fossil fuel fired plants. Without burning fossil fuel there are no combustion by-products (Aneke *et al.*, 2011; Eliasson *et al.*, 2011; Chamorro *et al.*, 2012). Geothermal power plants produce emissions through the release of gasses that are dissolved and contained in the geofluid (Rybach, 2003; DiPippo, 2012). The main source of emissions is through direct discharge of the waste geofluids after the plant (Aneke *et al.*, 2011; Pambudi *et al.*, 2014). 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 (Rybach, 2003; Lv *et al.*, 2009). Thermal pollution is also present with direct discharge as the fluid are usually of temperature above the environment. One suitable method 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 (Bayer *et al.*, 2013; Eliasson *et al.*, 2011).

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 geothermal installations is an imbalance of the amount of heat being fed to a reserve and the amount being used for power production. Over time the temperature, pressure and water level in a reservoir may decrease if it is overused which results in reduced plant production and resource life (Gupta and Roy, 2007; DiPippo, 2012; Nagy and Kormendi, 2012; Drozdz, 2003). A good solution that increases short term sustainability is re-injection (Unverdi and Cerci, 2013). 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 (Lv *et al.*, 2009; Drozdz, 2003). Re-injection is considered favorable, but it is still not routine practice (Bayer *et al.*, 2013).

Currently, there is very limited work on the advantages and disadvantages of implementing re-injection processes in geothermal power generating plants, in terms of overall system and reservoir performance. Coskun *et al.* (2012), Jalilinasrabadya *et al.* (2012) and Ganjehsarabi *et al.* (2012) have conducted energy and exergy analyses of various geothermal power plants with re-injection. In their studies, exergy analyses are conducted according to available energy and exergy after the wellhead, without considering the subsurface conditions and the reservoir. In doing so the energy and exergy contents of the plant at the point of re-injection are treated as total losses which provides the same efficiency values as systems without re-injection. It is also found that re-injection pumps are omitted from the studies. The inclusion of re-injection pumps is required in the energy and exergy analyses as they may potentially affect the overall system efficiency. Franco and Vaccaro (2014) state that in order to develop a complete understanding of the benefits of re-injection on the overall system efficiency and the reservoir feasibility, the energy and exergy contents of the re-injected fluid and the energy requirements of the re-injection process must be considered.

The objective of this study is to investigate the advantages and disadvantages of utilizing re-injection in a dual flashed steam condensing system, connected to high-enthalpy hydrothermal wet steam reservoir, through energy and exergy analysis. Energy and exergy efficiencies are calculated, as well as the exergy destructions within each component, for system arrangements with and without re-injection. The study aims to further expand the knowledge of re-injection associated with geothermal power production and provide recommendations for system improvements.

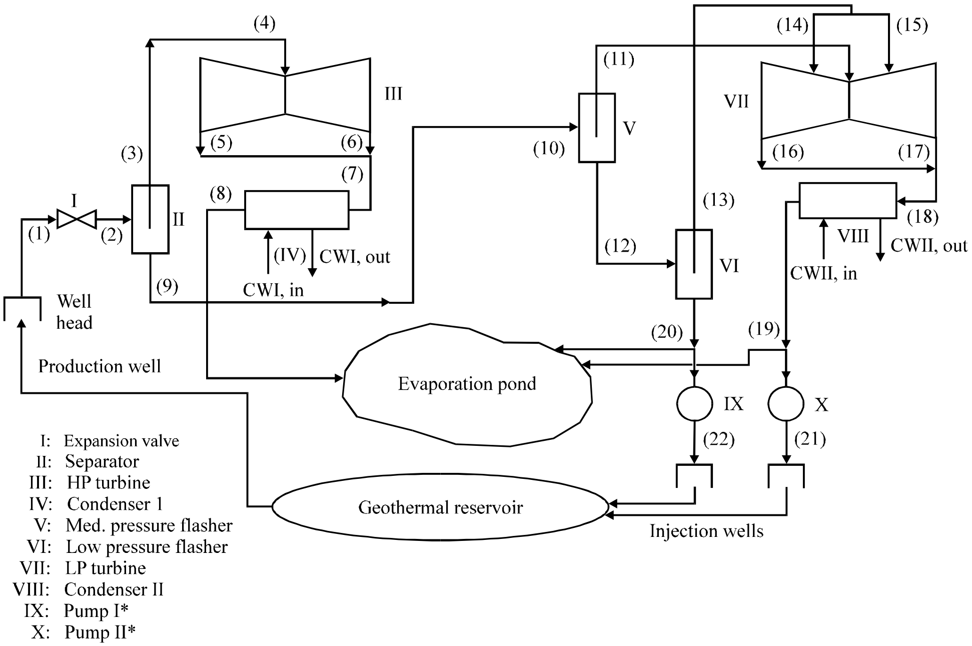
MATERIALS AND METHODS

System description: The system being examined is based on the Cerro Prieto I geothermal power generating plant formerly located East of Cerro Prieto Volcano (Bertani, 2012; DiPippo, 2012). Cerro Prieto I utilized a hydrothermal wet steam resource. This type of 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 consisted of five units. Units one through four were single flash units (Bertani, 2012). In single flash units, the pressure is reduced at the well head, allowing the liquid to become a vapour/liquid mixture that can be separated (DiPippo, 2012). 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 (DiPippo, 2012).

Unit five is a double flash unit involving a two stage flash process (Bertani, 2012). 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.

Figure 1 illustrates the system being analyzed and includes the layout of the system with and without re-injection. The actually arrangement of Cerro Prieto I directs the exhaust streams from the LPF and condenser, of unit five, to an evaporation pond (DiPippo, 2012). A case involving re-injection of these two streams is investigated, where flows from the LPF and condenser two would be pumped back into the reservoir at the pressure it was extracted. For the arrangement without re-injection pumps one and two are removed and flow is directed towards the evaporation pond. Ideally, the re-injected geothermal fluids would absorb thermal energy from the ground while traveling from the injection well to the production well and retune the fluid to its original state for use in the power plant. In reality, reservoir modelling is complex and it is still hard to predict reservoir heat and mass transfer characteristics, but research in the area is ongoing (Porkhial *et al*., 2015; Jeanne *et al*., 2014; Jing *et al*., 2014). In order to perform a comparison of systems with and without re-injection simplified assumptions have been made.



*Include in the re-injection arrangement, otherwise streams at states 19 and 20 are directed to the evaporation pond

Fig. 1: State diagram for the geothermal power plant being analyzed

Analysis

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

- Steady state and flow conditions are assumed
- Negligible pressure drop between components
- Effects of minerals within the geofluid are neglected
- Thermodynamic properties of the geothermal fluid are taken as those of water (Borsukiewicz-Gozdur, 2013; Yildirim and Ozgener, 2012)
- Heat loss occurs along the distances between the separator and high pressure turbine as well as the MPF. All other processes are considered adiabatic
- Parasitic losses accompanied with the condensing system are negligible; energy consumption is said to equivalent between systems with and without re-injection and allows for reasonable comparison. In industry pump efficiencies range approximately from 30-95% and medium to large industrial pumps offer efficiencies 75-95% (Volk, 2005; Bloch and Budris, 2010). A pump efficiency of 95% is utilized in this study
- Turbine efficiency is taken as 80%
- Energy and exergy content of fluids, being directed to evaporation ponds, is considered a loss to the environment
- The entirety of the re-injected geothermal fluid flows from the re-injection wells to the production well and no mass transfer between the reservoir and the surroundings occurs
- Sufficient thermal energy is transferred to the re-injected fluid to return its energy and exergy content to that of state 1

Balance equations and energy and exergy efficiencies: For a general steady-state, steady-flow process 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.

The specific exergy for each state is obtained as follows:

$$e_{xi} = (h_i - h_o) - T_o(s_i - s_o) \tag{1}$$

where, h and 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:

$$\dot{E}x_i = \dot{m}e_{xi} \tag{2}$$

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

Expansion valve (I):

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 \tag{3}$$

$$\dot{m}_1 e_{x1} = \dot{m}_2 e_{x2} + \dot{E}x_{des\ EV} \tag{4}$$

Separator (II):

$$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_9 h_9 \tag{5}$$

$$\dot{m}_2 e_{x2} = \dot{m}_3 e_{x3} + \dot{m}_9 e_{x9} + \dot{E}x_{des,\ Separator} \tag{6}$$

High pressure turbine (III):

$$\dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{m}_6 h_6 + \dot{W}_{HP\ Turbine} \tag{7}$$

$$\dot{m}_4 e_{x4} = \dot{m}_3 e_{x3} + \dot{m}_6 e_{x6} + \dot{W}_{HP\ Turbine} + \dot{E}x_{des,\ HP\ Turbine} \tag{8}$$

Condenser I (IV):

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

$$\dot{m}_7 e_{x7} = \dot{m}_8 e_{x8} + \dot{Q}_{Condenser\ I} \cdot \left(1 - \frac{T_o}{T_{Condenser\ I}}\right) + \dot{E}x_{des,\ Condenser\ I} \tag{10}$$

Medium pressure flasher (V):

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

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

Low pressure flasher (VI):

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

$$\dot{m}_{12}e_{x12} = \dot{m}_{13}e_{x13} + \dot{m}_{20}e_{x20} + \dot{E}x_{des,\ LPF} \tag{14}$$

Low pressure turbine (VII):

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

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

Condenser II (VIII):

$$\dot{m}_{18}h_{18} = \dot{m}_{19}h_{19} + \dot{Q}_{Condenser\ II} \tag{17}$$

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

Pump I (IX):

$$\dot{m}_{20}h_{20} + \dot{W}_{Pump\ I} = \dot{m}_{22}h_{22} \tag{19}$$

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

Pump II (X):

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

$$\dot{m}_{19}e_{x19} + \dot{W}_{Pump\ II} = \dot{m}_{21}e_{x21} + \dot{E}x_{des,\ Pump\ II} \tag{22}$$

The net-work output of the geothermal systems with and without re-injection is calculated as follows.

Geothermal system with re-injection:

$$\dot{W}_{net,w} = (\dot{W}_{HP\ Turbine} + \dot{W}_{LP\ Turbine}) - (\dot{W}_{Pump\ I} + \dot{W}_{Pump\ II}) \tag{23}$$

Geothermal system without re-injection:

$$\dot{W}_{net,w/o} = (\dot{W}_{HP\ Turbine} + \dot{W}_{LP\ Turbine}) \tag{24}$$

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.

The system illustrated in Fig. 1 has geothermal fluid rejected to the evaporation pond for the plant with and without re-injection. The arrangement with re-injection cannot be considered a closed system as there is still a portion of geothermal fluids being rejected to the evaporation pond from condenser one. With the evaporation pond, there may be a change in the mass available to absorb and carry thermal energy within the reservoir over time. This reduction in mass is not considered as steady state and flow conditions are assumed.

The energy content of the re-injected geothermal fluid is assumed to partially recharge that of the reservoir and does not consider it a loss. The instantaneous energy efficiency of the geothermal power plant with re-injection is calculated as follows:

$$\eta_{\text{plant},\text{w}} = \frac{\dot{W}_{\text{net,w}}}{\dot{m}_1 h_1 (\dot{m}_{21} h_{21} + \dot{m}_{22} h_{22})} \tag{25}$$

The geothermal plant without re-injection has the entirety of the geothermal fluid sent to evaporation ponds after use and no geothermal fluid are used to recharge the reservoir. As a result the instantaneous efficiency is calculated using the energy content of the geothermal fluid at the well head:

$$\eta_{\text{plant},\text{w/o}} = \frac{\dot{W}_{\text{net,w/o}}}{\dot{m}_1 h_1} \tag{26}$$

The exergy efficiency of the geothermal power system and its components is calculated as follows:

Geothermal plant with re-injection:

$$\psi_{\text{plant,w}} = \frac{\dot{W}_{\text{net,w}}}{\dot{E}x_1 - (\dot{E}x_{21} + \dot{E}x_{22})} \tag{27}$$

Geothermal plant without re-injection:

$$\psi_{\text{plant,w/o}} = \frac{\dot{W}_{\text{net,w/o}}}{\dot{E}x_1} \tag{28}$$

Evaporation valve (I):

$$\psi_{\text{EV}} = \frac{\dot{E}x_2}{\dot{E}x_1} \tag{29}$$

Separator (II):

$$\psi_{\text{Separator}} = \frac{\dot{E}x_3 + \dot{E}x_9}{\dot{E}x_2} \tag{30}$$

High pressure turbine (III):

$$\psi_{\text{HP Turbine}} = \frac{\dot{W}_{\text{HP Turbine}}}{\dot{E}x4 - (\dot{E}x_5 + \dot{E}x_6)} \tag{31}$$

Condenser I (IV):

$$\psi_{\text{Condenser I}} = \frac{\dot{Q}_{\text{Condenser I}}\left(1 - \frac{T_o}{T_{\text{Condenser I}}}\right)}{\dot{E}x_7 - \dot{E}x_8} \tag{32}$$

Medium pressure flasher (V):

$$\psi_{\text{MPF}} = \frac{\dot{E}x_{11} + \dot{E}x_{12}}{\dot{E}x_{10}} \tag{33}$$

Low pressure flasher (VI):

$$\psi_{\text{MPF}} = \frac{\dot{E}x_{11} + \dot{E}x_{12}}{\dot{E}x_{10}} \tag{34}$$

Low pressure turbine (VII):

$$\psi_{\text{HP Turbine}} = \frac{\dot{W}_{\text{LP Turbune}}}{(\dot{E}x_{11} + \dot{E}x_{14} + \dot{E}x_{15}) - (\dot{E}x_{16} + \dot{E}x_{17})} \tag{35}$$

Condenser II (VIII):

$$\psi_{\text{Condenser II}} = \frac{\dot{Q}_{\text{Condenser II}}\left(1 - \frac{T_o}{T_{\text{Condenser II}}}\right)}{\dot{E}x_{18} - \dot{E}x_{19}} \tag{36}$$

Pump I (IX):

$$\psi_{\text{Pump I}} = \frac{\dot{E}x_{22} - \dot{E}x_{20}}{\dot{W}_{\text{Pump I}}} \tag{37}$$

Pump II (X):

$$\psi_{\text{Pump II}} = \frac{\dot{E}x_{21} - \dot{E}x_{19}}{\dot{W}_{\text{Pump II}}} \tag{38}$$

RESULTS AND DISCUSSION

System operating conditions for Cerro Prieto I are taken from DiPippo (2012) and Tempesti *et al.* (2012). 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 (2012) 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 which is a decrease of 2% compared to the system without re-injection. 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. Table 1 shows that the pumps in the re-injection system produces an increase in specific exergy due to work input.

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

State	Temp. (°C)	Pressure (kPa)	Specific enthalpy (kJ kg^{-1})	Specific entropy (kJ kg^{-1} K)	Quality	Mass flow rate (kg sec^{-1})	Energy rate (kW)	Specific exergy (kJ kg^{-1})	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

*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

Table 2: Energy and exergy efficiencies of geothermal power plant

Plant arrangement	Energy efficiency, η_{plant} (%)	Exergy efficiency, ψ_{plant} (%)
Without re-injection	12.6	47.6
With re-injection	16.5	51.5

The separation processes actual cause an increase and decrease in the specific exergy content at each of the exits. 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 than 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 MPF and LPF are lower than the liquid. The mass flow rates seen by each stream differ substantially which is a result of low mixture quality at the inlet of the MPF and LPF, resulting in a large 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 nor 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 minuscule and accounts for less than 1% of the total exergy flow in the system.

The energy and exergy efficiencies for the case without re-injection are 12.6 and 47.6%, respectively as seen in Table 2. DiPippo (2012) 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% whereas, the energy efficiency is 12.6%. The difference appears in the definition of energy and exergy efficiency (Eq. 25-28). The energy and exergy equations have the same net

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

			Relative irreversibility (%)		
Device No.	Device	Exergy destruction rate, Ex_{des} (kW)	Without re-injection	With re-injection	Exergy efficiency (ψ %)
1	Expansion valve	52,457.0	54.9	54.7	86.4
2	Separator	0.0	0	0	100.0
3	HP turbine	35,203.0	36.8	36.7	85.1
4	Condenser I	23.7	0.0248	0.0247	99.8
5	Med. pressure flasher	1947.0	2.04	2.03	97.7
6	Low pressure flasher	462.0	0.484	0.482	99.2
7	LP turbine	5427.0	5.68	5.66	81.2
8	Condenser II	23.6	0.0247	0.0246	99.8
9	*Pump I	280.0	-	0.293	91.6
10	*Pump II	32.3	-	0.0337	90.6
-	Plant w/o re-injection	95,542.0	100	-	47.6
-	Plant with re-injection	95,855.0	-	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

work output specific to each system arrangement. The exergy flow into the system is considerably less than 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 increased the energy efficiency by 31% and the exergy efficiency by 8.2% while only encountering a 2% decrease in plant output. 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.

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 (2012) and assumptions utilized, the separator is entropic in this study for simplification. 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. 1, 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 different expansion processes or devices are employed to lower the pressure instead of expansion valves, the exergy destruction can be reduced. Cerro Prieto II and III utilized a double-flash configuration which helps to reduce the losses associated with flashing processes while increasing steam production (Glassley, 2014). The flashing process is done in two steps at different pressures (Zarrouk and Purnanto, 2015). Steam is produced in a high pressure separator and the exiting liquid is directed to a low pressure separator generating additional steam (Glassley, 2014; Zarrouk and Purnanto, 2015). Both high and low pressure steam flows are directed to a dual pressure turbine producing power (Glassley, 2014).

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 (DiPippo, 2012). 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.

CONCLUSION

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. Although the power output is reduced the possible gains in overall system efficiency may allow for enhanced system feasibility.

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.

To fully understand the impact of re-injection on geothermal power generation and resource conservation, transient investigations should be performed with accurate models of reservoir dynamics and the effects of re-injection. Appropriate combinations of modern reservoir models and plant designs will allow greatly improve understanding of re-injection on performance, environmental and economic aspects of geothermal power generation design.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Aneke, M., B. Agnew and C. Underwood, 2011. Performance analysis of the Chena binary geothermal power plant. Applied Thermal Eng., 31: 1825-1832.

Barbier, E., 2002. Geothermal energy technology and current status: An overview. Renew. Sustain. Energy Rev., 6: 3-65.

Bayer, P., L. Rybach, P. Blum and R. Brauchler, 2013. Review on life cycle environmental effects of geothermal power generation. Renew. Sustain. Energy Rev., 26: 446-463.

Bertani, R., 2005. World geothermal power generation in the period 2001-2005. Geothermics, 34: 651-690.

Bertani, R., 2012. Geothermal power generation in the world 2005-2010 update report. Geothermics, 4: 1-29.

Bloch, H.P. and A.R. Budris, 2010. Pump User's Handbook: Life Extension. 3rd Edn., Fairmont Press, India, ISBN: 13-9780881734539, Pages: 429.

Borsukiewicz-Gozdur, A., 2013. Exergy analysis for maximizing power of organic Rankine cycle power plant driven by open type energy source. Energy, 62: 73-81.

Chamorro, C.R., M.E. Mondejar, R. Ramos, J.J. Segovia, M.C. Martin and M.A. Villamanan, 2012. World geothermal power production status: Energy, environmental and economic study of high enthalpy technologies. Energy, 42: 10-18.

Coskun, C., Z. Oktay and I. Dincer, 2012. Thermodynamic analyses and case studies of geothermal based multi-generation systems. J. Cleaner Prod., 32: 71-80.

DiPippo, R., 2012. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact. 3rd Edn., Elsevier, USA., ISBN: 13-9780123947871, Pages: 624.

Drozdz, M., 2003. An optimisation model of geothermal-energy conversion. Applied Energy, 74: 75-84.

Ediger, V.S., E. Hosgor, A.N. Surmeli and H. Tatlidil, 2007. Fossil fuel sustainability index: An application of resource management. Energy Policy, 35: 2969-2977.

Eliasson, E.T., S. Thorhallsson and B. Steingrimsson, 2011. Short course on geothermal drilling, resource development and power plants. UNU-GTP and LaGeo in Santa Tecla, El Salvador, January 16-22, 2011.

Feili, H.R., N. Akar, H. Lotfizadeh, M. Bairampour and S. Nasiri, 2013. Risk analysis of geothermal power plants using Failure Modes and Effects Analysis (FMEA) technique. Energy Conv. Manage., 72: 69-76.

Franco, A. and M. Vaccaro, 2014. Numerical simulation of geothermal reservoirs for the sustainable design of energy plants: A review. Renew. Sustain. Energy Rev., 30: 987-1002.

Ganjehsarabi, H., A. Gungor and I. Dincer, 2012. Exergetic performance analysis of *Dora II* geothermal power plant in Turkey. Energy, 46: 101-108.

Glassley, W.E., 2014. Geothermal Energy: Renewable Energy and the Environment. 2nd Edn., CRC Press, Boca Raton, FL., ISBN: 13-9781482221749, Pages: 423.

Gupta, H. and S. Roy, 2007. Geothermal Energy: An Alternative Resources for the 21st Century. Elsevier, USA., ISBN: 13-9780080465647 Pages: 292.

Guzovic, Z., B. Majcen and S. Cvetkovic, 2012. Possibilities of electricity generation in the Republic of Croatia from medium-temperature geothermal sources. Applied Energy, 98: 404-414.

Hammond, G.P., 2000. Energy, environment and sustainable development: A UK perspective. Trans. Inst. Chem. Eng. Part B: Proc. Safety Environ. Protect., 78: 304-323.

Jalilinasrabady, S., R. Itoi, P. Valdimarsson, G. Saevarsdottir and H. Fujii, 2012. Flash cycle optimization of *Sabalan geothermal* power plant employing exergy concept. Geothermics, 43: 75-82.

Jeanne, P., J. Rutqvist, P.F. Dobson, M. Walters, C. Hartline and J. Garcia, 2014. The impacts of mechanical stress transfers caused by hydromechanical and thermal processes on fault stability during hydraulic stimulation in a deep geothermal reservoir. Int. J. Rock Mech. Mining Sci., 72: 149-163.

Jing, Y., Z. Jing, J. Willis-Richards and T. Hashida, 2014. A simple 3-D thermoelastic model for assessment of the long-term performance of the *Hijiori deep* geothermal reservoir. J. Volcanol. Geothermal Res., 269: 14-22.

Lv, T., Q.C. Zhu, H.B. Lu and X.G. Li, 2009. Geothermal reinjection technology and its application in geothermal power plant. Proceedings of the 9 International Conference on Energy and Environment Technology, Volume 1, October 16-18, 2009, Guilin, Guangxi, pp: 683-686.

Nagy, K. and K. Kormendi, 2012. Use of renewable energy sources in light of the "New Energy Strategy for Europe 2011-2020 Applied Energy, 96: 393-399.

Pambudi, N.A., R. Itoi, S. Jalilinasrabady and K. Jaelani, 2014. Exergy analysis and optimization of dieng single-flash geothermal power plant. Energy Conver. Manage., 78: 405-411.

Porkhial, S., M. Salehpour, H. Ashraf and A. Jamali, 2015. Modeling and prediction of geothermal reservoir temperature behavior using evolutionary design of neural networks. Geothermics, 53: 320-327.

Rybach, L., 2003. Geothermal energy: Sustainability and the environment. Geothermics, 32: 463-470.

Tempesti, D., G. Manfrida and D. Fiaschi, 2012. Thermodynamic analysis of two micro CHP systems operating with geothermal and solar energy. Applied Energy, 97: 609-617.

Unverdi, M. and Y. Cerci, 2013. Performance analysis of *Germencik geothermal* power plant. Energy, 52: 192-200.

Volk, M., 2005. Pump Characteristics and Applications. 2nd Edn., CRC Press, Boca Raton, FL., ISBN-13: 978-0824727550, Pages: 568.

Yildirim, D. and L. Ozgener, 2012. Thermodynamics and exergoeconomic analysis of geothermal power plants. Renew. Sustain. Energy Rev., 16: 6438-6454.

Zarrouk, S.J. and H. Moon, 2014. Efficiency of geothermal power plants: A worldwide review. Geothermics, 51: 142-153.

Zarrouk, S.J. and M.H. Purnanto, 2015. Geothermal steam-water separators: Design overview. Geothermics, 53: 236-254.