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Improved Energy Utilization in the Cerro Prieto Geothermal Field Fluid Transportation Network

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Keywords

Cerro Prieto, transportation network, thermal performance, heat losses, improved energy utilization

ABSTRACT

The thermal performance and the potential for improving energy utilization at the Cerro Prieto geothermal field (CPGF) were evaluated. The study is based on the premise of no additional producing wells and includes the fluid transportation network only. For the evaluation of the transportation network performance, the mass, energy and exergy flows of the separated steam and water at selected points of the transportation network, the mass and heat losses from the separators, pipelines and fittings, and the partial (transportation sub-processes) and overall (wellhead to power plant inlet) thermal efficiencies were evaluated. The 1st law efficiencies range from 86.8 to 98.1% for the individual fluid transportation sub-processes while those of the 2nd law vary from 78.9 to 95.9%. The overall efficiencies are 67.6% and 75.2%, respectively. The potential for improvement of energy utilization involved the evaluation six areas of opportunity. Four of them involve diverse schemes for energy recovery in the steam transportation pipeline network, one for energy recovery from the separated water, and the other involves reducing heat losses from the pipelines and fittings. The analysis shows a potential for installing 71.6 MWe of additional power which represents an increase of 9.9 % over the field installed capacity of 720 MWe. In addition, it is possible to gain an equivalent of 11.2 MWe by reducing heat losses from the steam transportation pipeline networks and fittings. Hence, by maintaining the same rate of fluid and energy extraction and the same number of producing wells, it is possible to increase the field energy utilization by 82.82 MWe or 11.5 % of the present installed capacity.

1. Introduction

In large geothermal fields, the performance of the pipeline fluid transportation network is affected by the actual physical conditions, complexity, and operating strategies of the network components. In fact, one of the largest problems in analyzing pipeline network behavior is the difficulty in accounting for the actual component features as some conditions change from the designed ones. This occurs, for example, when a turbine is connected to the pipelines. In fact, for these devices, one flow rate corresponds to each pressure value and vice versa. For this reason, the pipeline network operating points depend on both pipe geometry, and the physical behavior of the other components. In the case of the CPGF, the size, complexity, interconnectivity, physical condition of the pipes, thermal insulation and operating philosophy are some of the factors that affect the fluid transportation network thermal performance such that it is possible to improve utilization of the energy extracted from the reservoir without additional wells. Cerro Prieto started generating electricity in 1973 with two-37.5 MWe units in the Cerro Prieto 1 area. Since then, new power plants, wells and pipelines were added to reach the present capacity of 720 MWe in the Cerro Prieto 1-4 areas based on steam turbines only, i.e., the energy of the unflashed water is not utilized. Also, an adequate steam supply was provided through the installation of inter-field pipeline connections while at the same time the physical condition of some network components like pipeline thermal insulations was losing effectiveness and design conditions were changing.

Steam flow modeling and energy-exergy analysis of geothermal fields, often including power plant analysis, appears to have started with the evaluation of a six-well network of Larderello (Marconcini and Neri, 1979). Betaggli and Bidini (1996) carried out an energy-exergy study of the pipeline network in the Larderello-Farinello-Valle Secolo, Italy, area. DiMaria (2000) analyzed the pipeline network of a geothermal power plant operating under design and off-design conditions. White and Morris (2000) performed an energy and efficiency audit of the Wairakei geothermal power station and reported a snapshot of the plant´s operation on 15 February 2000. Quijano (2000) performed an exergy analysis of the Ahuachapan and Berlin geothermal fields. Kwambai (2005) performed an exergy analysis of the Olkaria-I power plant and computed exergy flows and efficiencies of the production and separation processes, the fluid transportation system and the power plant. Exergy waste and destruction were analyzed and improvements to the plant were suggested. Kaplan and Schochet (2005) analyzed ways of improving geothermal power plant performance. Additional generating capacity may be obtained without drilling new wells. Aqui et al. (2005) carried out an exergy assessment of the Palinpinon production field and found that the current power generation can be increased significantly with the existing steam production. Otzurk et al. (2006) analyzed the Kizildere geothermal power plant, Turkey, and determined energy and exergy efficiencies and destructions in the whole plant. García-Gutierrez et al (2009a) carried out a simulation study of the Los Azufres geothermal field which included optimization of some flow cases. Garcia-Gutierrez, et al. (2006) simulated steam flow in the CPGF network. This and a further study (García-Gutierrez et al., 2009b) allowed an overall assessment of the network thermal-hydraulic performance whereby a series of opportunities for improving the network performance and the energy utilization of the produced energy within the field were detected.

The present study presents the evaluation of the thermal performance of the CPGF fluid transportation network and six areas of opportunity with potential for improving utilization of the energy extracted from the reservoir. The study is a snapshot of the plant´s operation on June 2009 while operating on a typical steady-state mode and covers only the fluid production and transportation system, composed of the production wells and the pipeline network for steam transportation to the power plants, and the residual energy of the separated water. It excludes the existing power plants (García-Gutierrez et al., 2009b).

2. Description of the Fluid Transportation Network

The Cerro Prieto geothermal field is the largest liquid-dominated geothermal field in the world with an installed capacity of 720 MWe. It is composed of four field areas named progressively from Cerro Prieto One (CP1) to Cerro Prieto Four (CP4). The field has thirteen condensing power plants (Gutiérrez-Negrín et al., 2010) which are fed with separated steam from 165 producing wells through a complex pipeline system that includes high- and low-pressure networks, as well as a pipeline network for transporting two-phase mixtures of water and steam. These networks have lengths of 92.1 km, 47.6 km and 26 km, respectively, totaling 165.72 km. The pipelines have diameters between 8” and 48″ and are thermally insulated with a 2″ layer of mineral wool or glass fiber, and an exterior metallic cover of aluminum or wrought iron.

In the CPGF the steam is separated at each production well and individual pipelines transport steam to the main collecting ducts, called branches. The network is highly complex and has several arrangements for steam separation. CP1 has high-pressure steam separation only, whereas CP2, CP3 and CP4 have both high- and low-pressure separation. In CP2 and CP3 there also exist several “sites” for steam separation. In such a “site” the high-pressure steam is separated first and the separated water is sent to the low-pressure separator together with the brine from other neighboring wells. In CP4 there are “separation islands”, which are square areas, divided into four modules. Each module has four high-pressure separators that receive the two-phase flow from a well to separate the high-pressure steam. Then, the separated water of the four streams is mixed and fed to a single separator to obtain low-pressure steam. There also exist some auxiliary wells, which do not actually produce water or steam, but their facilities are used to separate the steam from the mixture produced by a neighbor well. The large majority of the separated water is finally sent to an evaporative pond via open channels, however some of the separated water is reinjected either hot or cold. CP1 has eight high-pressure branches, while CP2, CP3 and CP4 have both high- and low-pressure parallel branches, two per field area. The steam transportation network also has several interconnections among the different field areas to ensure an adequate steam supply to the power plants. Figure 1 shows the steam pipeline network of the entire geothermal field. Thus, the CPGF steam network is complex and the operating conditions have changed through the years while at the same time the physical conditions of the thermal insulation have also changed.

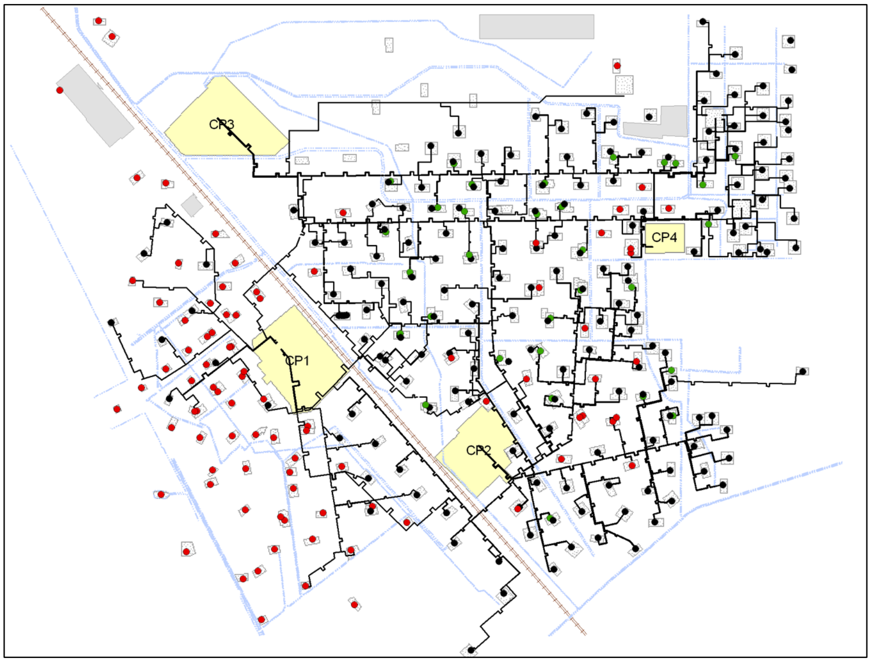

Figure 1. The Cerro Prieto geothermal field steam transportation network.

3. Theoretical Aspects

Energy and exergy are defined (e.g., DiPippo, 2005) as

$$e_n = \dot{m}h \tag{1}$$

$$e_x = \dot{m}\left[\left(h_i - h_0\right) - T_0\left(s_i - s_0\right) \right] \tag{2}$$

where e_n denotes energy, e_x is exergy, h enthalpy, $\dot{m}$ mass flow rate, s entropy and T temperature, the index *0* denotes the reference state or ambient conditions and index *i* indicates the system conditions at point i.

Energy and exergy efficiencies are given by:

$$\eta_{e_n} = e_{n\,out} / e_{n\,in} \tag{3}$$

$$\eta_{e_x} = e_{x\,out} / e_{x\,in} \tag{4}$$

where η denotes efficiency and the indexes in and out denote inlet and outlet.

The power obtained by steam expansion in a turbine is given by

$$P = \dot{m}_s \eta_t (h_1 - h_{2s}) \tag{5}$$

where P is power, $\dot{m}$ is steam mass flow rate, η_t *is* turbine isentropic efficiency, h_1 is the steam enthalpy at the turbine inlet and h_{2s} is the steam enthalpy after the isentropic expansion process.

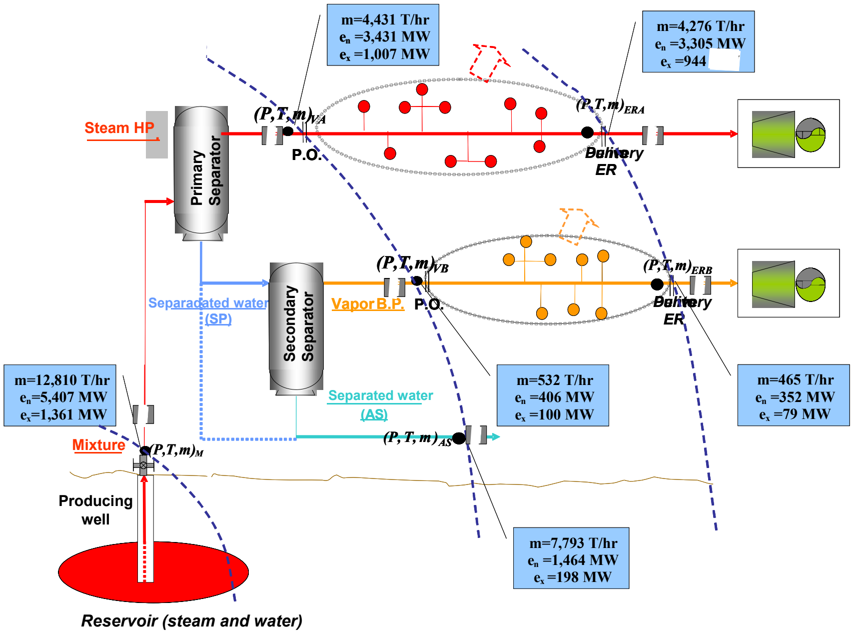

Figure 2. Overall mass, energy and exergy flows at selected points of the CPGF fluid transportation network.

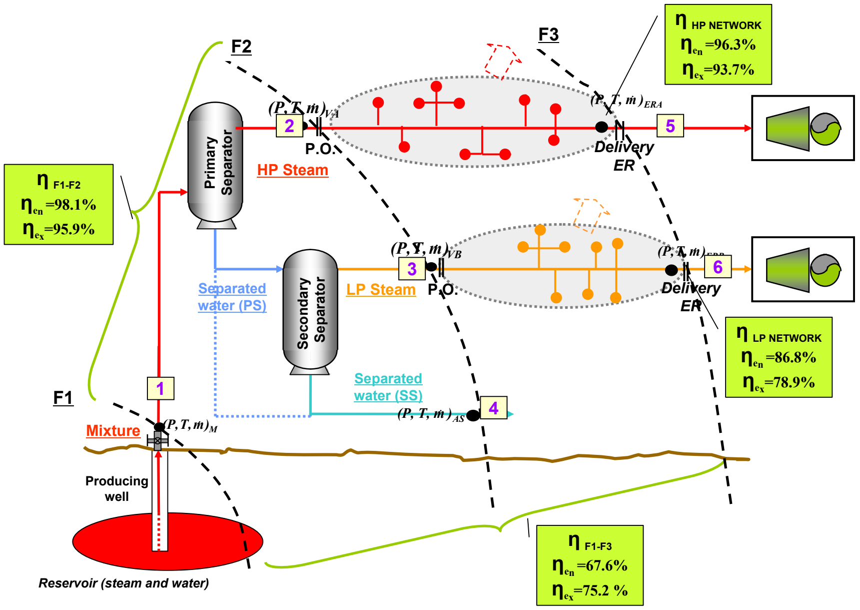

Figure 3. Energy and exergy efficiencies of the CPGF fluid transportation network.

4. Network Performance

Mass, energy and exergy flows were estimated using operating and environmental data of June 2009 to evaluate the fluid transportation network performance. These quantities were evaluated at three boundaries: F1 (wellhead), F2 (the outlet of steam and water from the high- and low pressure separators), and F3 (the power plant steam delivery points from the steam field). Once these quantities were known, the partial and overall efficiencies were estimated. This evaluation was complemented by an evaluation of the heat losses from the pipelines and fittings (Ovando-Castelar et al., 2011). Fig. 2 shows schematically these boundaries and the corresponding mass, energy and exergy flows; F2 and F3 have been subdivided to show the individual flows of the high- and low-pressure steam and the separated water. Fig. 3 shows the energy and exergy efficiencies for the individual stages and overall process.

Fig. 2 shows that about 61% of the produced fluids is liquid water, which carries about 27% of the thermal energy produced and about 14.5% of the exergy produced. The high-pressure steam after separation carries 63.5 and 74 % of the produced energy and exergy, respectively, whereas the low-pressure steam after separation carries 7.5 and 7.3% of the produced energy and exergy, respectively. Fig. 3 shows that the separation process (boundaries F1 and F2) has energy and exergy efficiencies of 98.1 and 95.9%, respectively, whereas the overall transportation process boundaries (F1 and F3) has energy and exergy efficiencies of 67.6 and 75.2 %, respectively. The corresponding individual efficiencies are 96.3 and 93.7% for the high- pressure network and 86.8 and 78.9% for the low-pressure network (boundaries F2 and F3). The energy balance of the produced fluids is shown in Fig. 4.

The energy losses from the separation process amount to 106 MWt or 2%.The thermal losses from the pipelines are subdivided into losses through insulation materials, fittings and friction, plus condensate drains. The losses from the insulation and pipeline fittings were determined experimentally, and these losses were subtracted from the total losses obtained from the operational conditions (points 2 and 5 of Fig. 2 for the high-pressure steam network, and points 3 and 6 for the low-pressure steam network). The thermal losses of the high-pressure network are higher than those of the low-pressure network since it is a much longer network, but actually represent a smaller percentage of the total network losses: 3.7 vs 13.3%, respectively.

5. Areas for Improving Energy Utilization

Six areas of opportunity were evaluated to estimate the potential of increasing the utilization of the energy extracted from the reservoir keeping constant the rate of fluid and energy extraction. Four areas involve diverse schemes for energy recovery in the

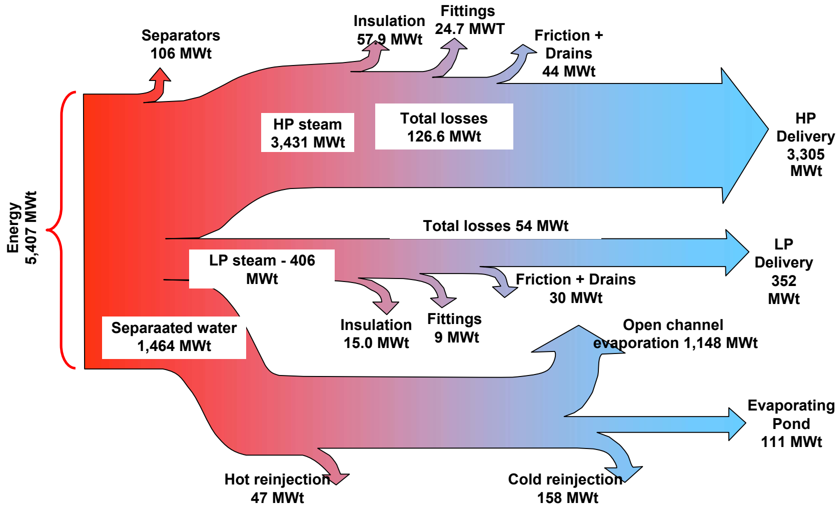

Figure 4. Energy balance of the produced fluids at the CPGF.

steam transportation pipeline network, one for energy recovery from the separated water, and one by reducing heat losses from the pipelines and fittings.

(1) Use of a total-flow turbine or a very high-pressure separator-steam turbine system at wells with wellhead pressures at 600 psig or more. Ten wells met these conditions: two 3-well groups from CP2 and a 4-well group from CP4. This grouping was done according to their location in the field and to make an optimum use of existing installations. The turbine inlet pressure was assumed to be 500 psi (to provide for pressure decline with time) with expansion to 230 psi, so that the resulting fluid could be processed as is normally done in the field: the present high-pressure separation process occurs at 200-230 psi. The power from these wells was computed using Eq. (5) and the mass flow rate of each well, along with turbine efficiencies which were obtained directly from turbine manufacturers. A rotary separator turbine, a steam turbine and a turboexpander were considered in this study.

(2) Use of the residual energy contained in the separated water. In the CPGF only steam turbines are installed so that binary cycle power plants could be used to take advantage of the residual energy of the unflashed fluids. Only wells producing 30 tons/h or more of separated water at 145°C were considered. Eighty-one wells met these conditions and were grouped into nine clusters or groups of wells according to their location in the field, and after a pipeline length optimization process was performed for each cluster. Each cluster was equipped with a power plant, and hot water at 140°C was delivered to the power plant, except for CP1 where water was delivered at 120°C, and cooled to 100°C. The conversion of thermal to electric power was computed using a graph of efficiency vs. the temperature of the geothermal fluid (Tester et al., 2006). Scaling due to cooling the separated water was not considered.

(3) Replacement of the regulation valves located just before the inlet to the CP4 power plant by steam turbines in order to take advantage of the pressure drop occurring at these valves. The power plants of the CP4 area are fed with about 800 tons/h of steam at 145 psi at the delivery point from the steam field. However, just before this point, there are regulating valves that receive the steam at ~180 psi and reduce it to ~150 psi. This study consists of replacing those valves with steam turbines and estimating the power that would be generated using Eq. (5). The net power takes into account the steam reduction that would be sent to the present power plants after expansion since some condensation will occur. This steam reduction is accounted for by considering the specific steam consumption of the power plants.

(4) Use of parallel steam pipelines to transport high-pressure steam from the CP2 and CP3 to the CP1 area and use of turbines before entering the CP1 power plant in order to take advantage of the excess steam pressure. At present, the CP1 power plants are fed with steam from the CP2 and CP3 areas using an interconnection in each case. However the steam flow rate in these interconnections is very high and a large pressure drop occurs along the pipelines so that the arrival pressure at CP1 is low. In this study, it is proposed to add a parallel steam pipeline to each interconnection so that the pressure drop is much lower and the pressure of the steam arriving at CP1 is higher. This higher pressure at the inlet of the CP1 power plants can be fed into steam turbines to generate additional electricity by reducing the steam pressure to the value required by the present power plants. As in the previous case, the net power takes into account the steam reduction that would be sent to the present power plants after expansion since some condensation will occur. This steam reduction is accounted for by considering the specific steam consumption of the power plants. The CP2-CP1 interconnection carries 375 tons/h of steam at 170 psi. This steam arrives at CP1 at 149 psi in one pipeline or at 159 psi in parallel pipelines. The CP3-CP1 interconnection also carries 375 tons/h of steam at 175 psi. This steam arrives at CP1 at 149.4 psi in one pipeline or at 169.2 psi in parallel pipelines. In each interconnection, a steam turbine is used to expand the steam from the arrival pressure to 110 psi (as required by the actual power plants).

(5) Reduction of heat losses from the entire steam and two-phase pipeline networks and fittings. In the CPGF, the high- and low-pressure steam pipeline networks have lengths of 92.1 km and 47.6 km, respectively, while the two-phase pipelines account for 26 km, totaling 165.72 km. The pipelines have diameters between 8" and 48" and were originally insulated with a 2" layer of mineral wool or glass fiber, and an exterior metallic cover of aluminum or wrought iron. The pipeline fittings are not thermally insulated. Nevertheless, due to the impact of the weather conditions during the time of the field operation, in some parts of the network the thermal insulation has changed compared to its original state and presents varying degrees of weathering or fatigue, including geometric distortion, loss of the outer cover or replacement by a different insulation, or even the absence of its insulation. In a companion paper (Ovando-Castelar, 2012), it is shown that 18-20% of the thermal insulation of the three pipeline networks is deteriorated, damaged or absent, and the estimated heat loss for all the pipelines that make up the steam transportation network amounted to 72.9 MWt or 17.6 MWe of electric power which represents about 2.5% of the current CPGF installed capacity. In this study, the heat loss reduction due the addition of an extra layer of thermal insulation is analyzed such that each pipeline reaches a total insulation thickness of 2″, 3″ and 4″, considering the diameter of each pipeline and the operating conditions of the field. It is also considered to add a 2″ layer of thermal insulation to the pipeline fittings. The analysis considered three commercial insulation materials: mineral fiber metal mesh blanket-RW-4600, semi-rigid glass fiber board -SCR-fiberglass and tensed glass fiber flexible plate. The thermal conductivities of these materials were obtained from the manufacturer. Semi-rigid glass fiber showed the largest heat losses (or the smallest loss reduction) while the other two materials showed similar heat losses. Due to cost considerations, the third material was chosen for the final calculations. It was found that a 1/2″ thick layer of this insulation reduced heat losses by about 50% but this thickness is impractical so that a 1″ layer of insulation was finally considered.

(6) Use of a third main collector to transport steam to the CP2 power plant to re-distribute steam flow and to reduce steam separation pressure at the beginning of the steam collectors. Currently**,** two steam collectors feed the power plants of the CP2 area. The collectors deliver 1,648.8 tons/h of steam at 165.4 psi to the power plants (downstream pressure) and in order to do this job, they are fed by a number of wells whose separation pressures range from 190 to 200 psi (upstream pressures). This study considers the addition of a third collector in parallel with the present collectors to transport steam from some of the wells presently connected to the existing collectors so that the three collectors approximately balance steam flow and separation pressure. In this way, the collectors would require a lower feed pressure, that is, the wells connected to each collector would operate at lower separation pressures and this could result in a larger volume of separated steam. The additional steam would result in a given amount of extra power generation. The original steam flowrates for collectors 1 and 2 were 715.4 and 933.4 tons/h, respectively (total steam production of 1648.8 ton/h). Using three collectors and according to the spatial distribution of the wells, the flowrates would now be 573.2, 551.2 and 524.4 tons/h for collectors 1, 2 and 3, respectively. However, since each steam collector now transports about 1/3 of the total original steam production, the separation pressure of the wells feeding the collectors may be now somewhat lower. The results show that the new separation pressure of the wells would range between 170 and 175 psi, instead of the original separation pressures of 190-200 psi when using two steam collectors. In this way, the total steam production would increase from 1648.8 to 1669.1 tons/h, a net steam gain of 18.1 t/h.

5.1 Results

Table 1 shows the results of the actual heat losses from pipelines and fittings, heat loss reduction due to adding thermal insulation and obtainable electrical power.

The heat losses from the pipelines and fittings are 17.6 and 1.5 MWe, and these can be reduced to 7.82 MWe by adding a 1″ thick extra layer of thermal insulation to the pipelines and a 2″ thick layer to the fittings, resulting in a net power gain of 11.22 MWe. The use of the very high pressure wells (expansion from 500 to 230 psi) results in 15.1 MWe if a total flow machine is used, 19. 8MWe if steam turbines are used, and 20.7 MWe is turboexpanders are used. It is evident that using turboexpanders is more beneficial. Using binary cycle power plants to recover energy from the separated water shows a power recovery of 32.3 MWe of which 1.5MWe are from CP1 (T=120°C, η=8.95%) and 30.8 MWe are from CP3, CP3 and CP4 ((T=140°C, η=10.77%). The substitution of the regulating valves at the inlet of the CP4 area permits recovery of 4.7 MWe if steam turbines are used, and 5.1MWe if turboexpanders are considered. Again, the use of turboexpanders allows for more power generation. The use of parallel steam ducts to transport steam from CP2 and CP3 to CP1 shows a power generation of 10.2 MWe if steam turbines are considered and 11.0 MWe using turboexpanders. The latter option allows more power generation. The use of a third steam collector in CP2 allows better balance of steam flow and pressure in the collectors, with a reduced separation pressure at the upstream wells and a gain of 2.4 MWe. Hence, the total potential for improved energy utilization in the CPGF is 84.4 MWe: 73.2 MWe of additional power generation within the steam field and 11.2 MWe of equivalent power due to reducing heat losses from the pipelines and fittings. The potential for energy recovery from the pipeline supporting legs is not included.

Table 1. Equivalent power due to heat losses and loss reduction using an extra layer of insulation in the HP and LP pipeline network and net obtainable electric power.

RECOVERABLE ENERGY, MWe						
Case	Heat losses from pipeline insulation fittings and legs	Binary Cycle	Biphase Turbine	Steam Turbine	Turbo - expanders	Additional steam
Heat losses due to fluid transport	17.6 + 1.46 + 6.17 *					
Case1: Expansion from 500 to 230 psig			15.1	19.8	20.7	
Case2: Residual energy of separated water		32.3				
Case3: Substitution of valves at CP4 inlet				4.7	5.1	
Case4: Parallel Ducts CP2 & CP3 to CP1				10.2	11.0	
Case5: Extra layer of insulation	7.1 + 0.72 + 0.0 **					
Case6: Third branch in CP2						2.4
SUM	10.5 + 0.72 ***	32.3	15.1	34.7	36.9	2.4
TOTAL POTENTIAL	82.82 (71.6+11.22)					

Notes: *Heat loss from pipelines, fittings and supporting legs; **It is assumed that heat losses from fittings are reduced by 50% when covered with a 2” layer of thermal insulation. Pipeline legs not insulated due to technical and practical reasons; ***Difference of actual heat losses from insulation and fittings and losses using a 1” extra layer of insulation on pipelines and 2” on fittings

6. Conclusions

The CPGF fluid transportation network has steam-water separation 1st and 2nd law efficiencies of 98.1% and 95.9%, respectively. The corresponding overall efficiencies (wellhead to power plant inlet) are 67.6% and 75.2 %, whereas the high-pressure steam transportation network has efficiencies of 96.3% and 93.7%, while the low-pressure steam transportation network has efficiencies of 86.8% and 78.9%. Opportunities for improving thermal performance are in the low-pressure steam network, the separation process and the high-pressure network.

Most of the energy of the separated water is lost during transport in open canals to an evaporation pond. Reinjection is effective in terms of mass. The potential for energy recovery is 82.8 MWe of electrical power in the fluid production and transportation system: 71.6 MWe of additional power generation within the steam field and 11.2 MWe of equivalent power due to reducing heat losses from the pipelines and fittings. The potential for energy recovery from the pipeline supporting legs is not included. This potential is equivalent to improving energy utilization by 11.5% over the present installed capacity of the field.

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