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Thermo-Economic Comparison of Different Layouts of a Steam Power Plant Integrated with Geothermal Resource

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A thermo-economic analysis was performed of three different steam power plants, using a main fuel (coal or biomass) integrated with a geothermal resource. The purpose is to limit the use of fossil resources by means of geothermal integration, and to calculate and compare the unit cost of electricity produced by the power plant. Three cases are investigated: a reference 320 MW steam power plant, the same 320 MW unit modified for integration with geothermal resources, and a 160 MW steam power plant integrated with geothermal sources. The study shows that the conventional 320 MW power plant is the most convenient option in the case of a low price of fuel (coal), while, when replacing the fuel with a biomass, the geothermal integration represent a favourable economic solution.

1. Introduction

In 2011, almost 41 % of the 22 TWh of world electricity production was generated by power plants using coal, making it the most used fuel in the world (International Energy Agency, 2013). At present coal, coupled with modern emission control equipment, represents in many countries the most attractive choice for economic development with moderate prices of electricity. However, in many countries (with special reference to those without local coal resources) opposition against the use of coal is rising, considering negative issues on sustainability due to greenhouse as well as pollutant emissions. From this point of view, the combination of geothermal energy and fossil fuels or biomass/biofuels for electricity generation in hybrid power plants provides significant advantages in comparison with a separated approach. Among the different layouts of hybrid geothermal-coal power plants distinguished in literature (DiPippo, 1997), geothermal feed-water preheating in conventional steam power plants (Bruhn, 2002) is the most promising. In this concept, the conventional preheating process (with boiler feed-water preheated by steam extracted from the turbine) is partially replaced with preheating by a geothermal resource at low temperature. In this case study, the focus is set on the maximization of use of the local low-temperature geothermal resource, rather than on power augmentation. The geothermal preheating is first provided by low-temperature hot water resources available at the investigated site; further preheating heat demand is satisfied by two steam wells at higher temperature. The conditions for steam and hot water are corresponding to those available in the Larderello geothermal area (Bettagli and Bidini, 1996). Three different power plant layouts are investigated. The first – representing the reference case - is a conventional 320 MW coal steam power plant, while the other two are coal steam power plants with geothermal feed-water preheating respectively of 320 MW and 160 MW. The cost of electricity in terms of €/kWh produced is calculated through a thermo-economic analysis. The influence of the cost of various fuels and of different percentage of biomass on the final cost of the kWh produced by the power plant is also assessed. The scope of this paper is to compare the three investigated power plants and to provide guidelines to which fuel combination could be more convenient from the economics and sustainability point of view.

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2. Description of Power Plants

The layout of the power plant investigated is shown in Figure 1. The cycle is a typical Hirn cycle with reheat (Manfrida and Fiaschi, 2009). The maximum temperature of the cycle is set at 538 °C (points 12 and 15, Figure 1), while the maximum pressure is 170 bar (point 12, Figure 1). Steam is extracted from the

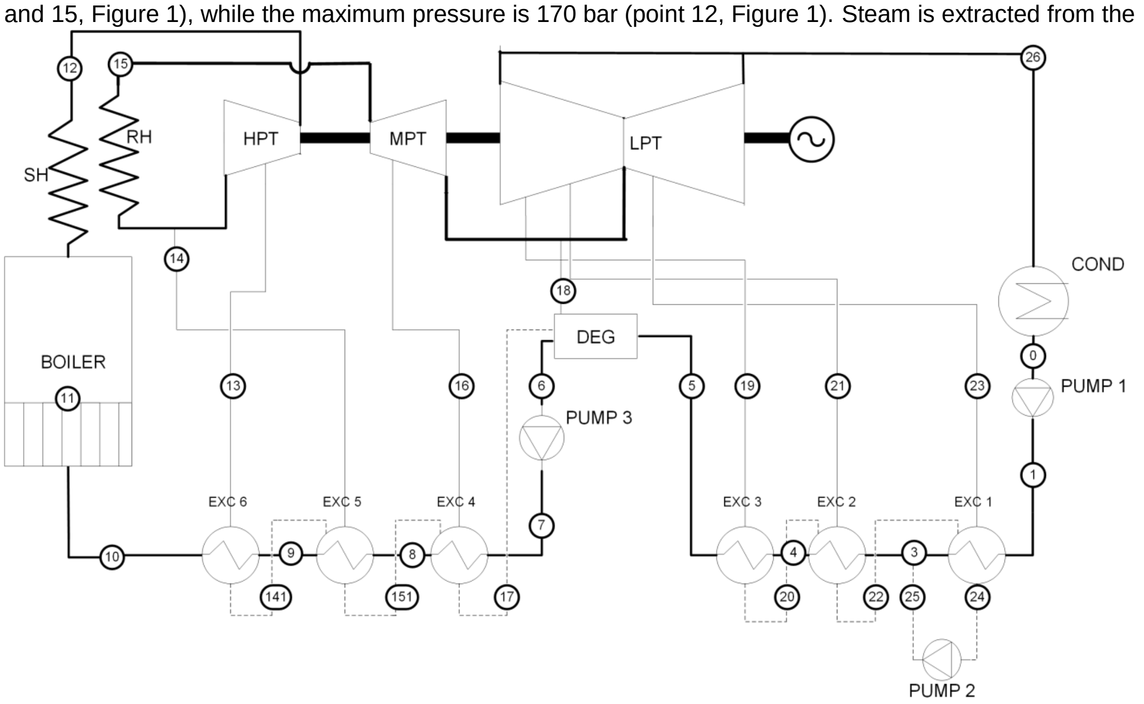

Figure 1: 320 MW Steam power plant with reheating

turbines at various pressures to pre-heat the liquid water coming from the condenser and flowing to the boiler, as is typical in order to increase the efficiency of the system. Furthermore, a mixing feed-water heater/deareator (DEG) is used to extract the incondensable gases. The operating parameters of the steam power plant are reported in Table 1.

The integration with a geothermal resource is shown in Figure 2 in the case of the 320 MW power plant. The 160 MW power plant with integration of geothermal resource is similar, except that there is no extraction from the MPT. In the geothermal-integrated configurations, almost all the extractions from the steam turbines are substituted by heat provided by the geothermal resource. In the present case (Manfrida and Fiaschi, 2009) priority is given to the two low temperature geothermal wells (at 85 °C and 50 °C respectively), while using the remaining heat from two hot water geothermal wells at medium temperature (at 185 °C and 160 °C). The cycle maximum temperature and pressure remain set, respectively, at 538 °C and at 170 bar (Table 1).

Table 1: Main operating parameters

		320 MW	160 MW +geo	320 MW+geo
Turbine efficiency	HP	0.88	0.88	0.88
	MP	0.89	0.89	0.89
	LP	0.9	0.9	0.9
Pump efficiency		0.8	0.8	0.8
Boiler efficiency		0.94	0.94	0.94
T Max cycle [K]		811.16	811.16	811.16
T Ambient [K]		288.16	288.16	288.16
Geothermal mass	well 1 (185 °C, 6.5 bar)	-	1.32	5.09
flow rate [kg/s]	well 2 (160 °C, 4.5 bar)	-	12.07	21.34
	well 3 (85 °C, water)	-	84.72	111.1
	well 4 (50 °C, water)	-	11.11	83.33
Condenser Pressure [bar]		0.05	0.05	0.05

			387
Steam Generator Pressure [bar]	170	170	170
e_{fuel} (coal) [kJ/kg]	34,000	34,000	34,000

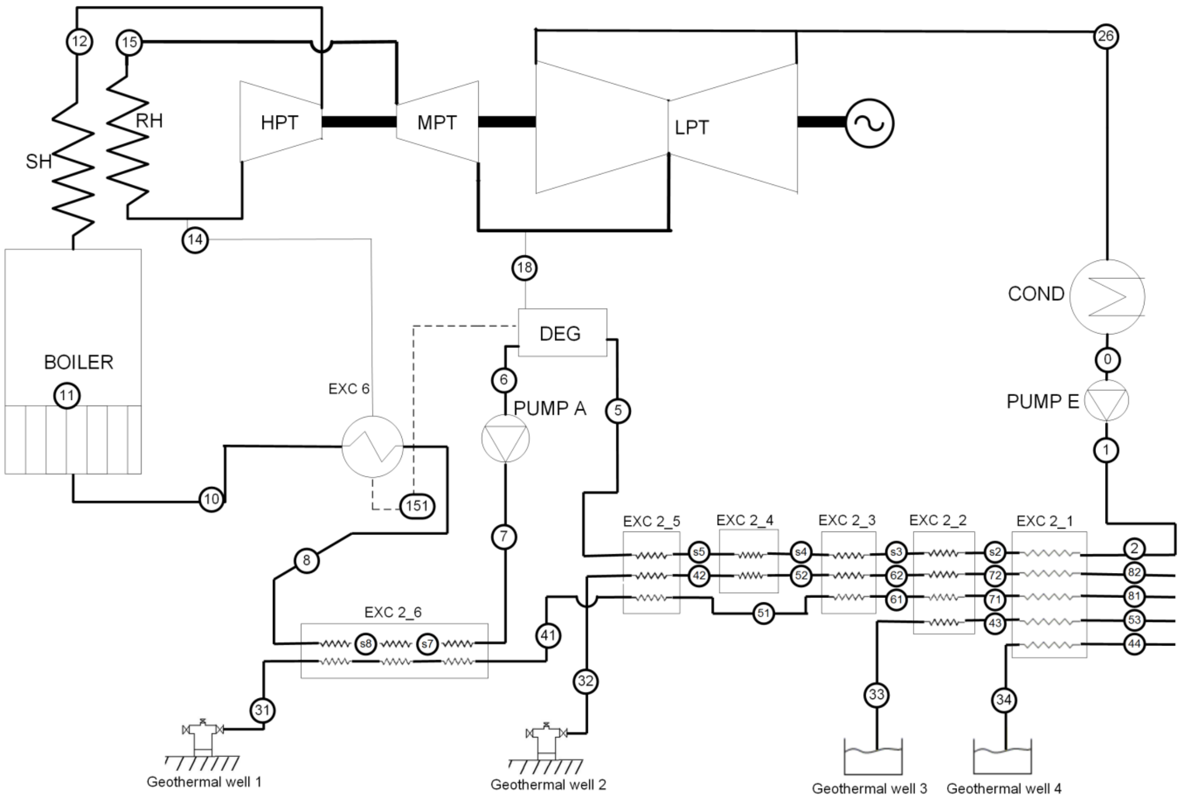

Figure 2: 320 MW Steam power plant with geothermal feed-water preheating (320MW+geo)

3. Methods

3.1 Energy Analysis

The three systems were modelled using the Engineering Equation Solver simulator (EES). The system efficiency is calculated by:

$$\eta_{system} = \frac{W_{net}}{Q_{geo} + Q_{fuel}} \quad (1)$$

where W_{net} is the net power output of the cycle, Q_{geo} is the heat rate supplied by the geothermal resource and Q_{coal} is that provided by the fuel. Table 2 summarizes the main results of the energy analysis. The geothermal feed-water preheating allows to decrease the coal consumption of about 10 to 12 kg/MWh, corresponding to the substitution of more than 4 % of the fossil fuel resource in terms of sustainability.

Table 2: Results of Energy Analysis

		320 MW	160 MW+geo	320 MW + geo
First law efficiency		0.44	0.43	0.43
Net Power output [kW]		327,304	164,603	302,122
Steam flow rate [kg/s]		290.6	125	222
Fuel consumption [kg/MWh]	coal	243.13	231.35	233.43
Fuel Power input [kW]		738,311	353,306	654,296
Geothermal reinjection temperature [K]		-	311.08	311.08
Geothermal power input [kW]		-	52,287	95,364

3.2 Exergy Analysis

The exergy analysis of the three power plants was performed following the reference literature (Bejan et al., 1996). The exergy input to the system comes from fuel or from the combination of the fuel and of the geothermal resource. The exergy of the fuel is approximated by Eq(2), where e_{fuel} is the chemical exergy of the fuel (Table 1), while the exergy input from the geothermal resource is calculated by Eq(2).

$$E_{fuel} = m_{fuel} \cdot e_{fuel} \tag{2}$$

$$E_{geo} = m_{geo} \cdot \left(e_{geoin} - e_{geoout}\right) \tag{3}$$

The exergy analysis of the system is used as basis for the subsequent thermo-economic analysis.

3.3 Cost and Thermo-economic Analysis

3.3.1 Cost Analysis

The costs of turbines and boilers were taken from Pauschert (2009), while costs for heat exchangers, including the condenser, and pumps were calculated using the software Capcost® (Turton et al., 2009). The component cost was divided in three separate parts: a 30 % of fixed cost, a 35 % related to the cost of energy for production and a 35 % related to the cost of raw material. Then, the component cost was actualized assuming an increase of 15.75 % of the cost of energy and an increase of 3.7 % of the cost of raw material. The O&M cost was fixed at 15 % of the actualized component cost (Liszka and Ziebik, 2009). Finally, the cost for well drilling was taken from US Department of Energy (2004).

3.3.2 Thermo-economic Analysis

The thermo-economic balance for any unit is performed integrating the exergy and the cost balances (Bejan et al., 1996):

$$\sum_{in} C = \sum_{out} C + Z \tag{4}$$

where *C* is the cost rate according to inlet and outlet streams, and *Z* is the capital investment and operating & maintenance (O&M) costs. In exergy costing, a cost is associated with each exergy stream. Thus, for inlet and outlet streams of matter with associated rates of exergy transfer E_i, E_o and power W, we can write as follows (Bejan et al., 1996):

$$C = c_{i,o} \cdot E_{i,o} \tag{5}$$

Assuming 8,000 hyearly working h, the specific cost of the electricity (€/MWh) produced by each turbine section and by the system is calculated. In addition, three relevant thermo-economic parameters are calculated:

- The Cost rate associated with exergy destruction:

$$C_{D,k} = c_{F,k} \cdot E_{D,k} \tag{6}$$

- The relative cost difference between product and fuel of the component is given by:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{7}$$

- The exergoeconomic factor is defined as:

$$f_k = \frac{Z_k}{Z_k + C_{D,k}} \tag{8}$$

Table 3: Cost of electricity produced by the power plant

		320 MW	160 MW+geo	320 MW + geo
Coal	[€/MWh]	13.1	14.3	13.1
Biomass	[€/MWh]	131.6	126	125.8

4. Results - Coal or biomass integration with geothermal pre-heating

The unit cost of the MWh produced from the three power plants does not vary much, as shown in Table 3. These results are obtained with a coal price of 46 €/ton (USA Energy Information Administration 2014). Running a sensitivity analysis with variable coal price, the 320MW+geo power plant remains more convenient than the coal power plant until a value of the coal cost of 43 €/t, while the 160 MW+geo power plant remains less convenient even for a coal cost of 113 €/t.

Since an interesting option to reduce the use of coal – thereby realizing a completely “green” hybrid biomass/geothermal power plant - could be to substitute it with biomass (Ryabov and Dolgushin, 2013), the cost of the energy produced by the same power plants using a mix of sunflower oil (LHV: 37.7 MJ/kg; cost: 0.66 €/kg) and sunflower oil cake (LHV: 22.7 MJ/kg; cost: 0.37 €/kg), is investigated (Enama, 2014). The results are shown in Table 3: switching to biomass integration, the power plants with geothermal integration show similar cost in terms of €/MWh. Finally, Table 4 reports the main results of the thermo-economic analysis. It should be remarked that a higher exergoeconomic factor means higher impact of the cost of the component over the exergy destruction (this applies for example for the first and second heat exchanger in both power plants with geothermal integration). Instead, a high value of “r” means that the component produces a large cost increase (this applies, in the specific case, for the boilers).

Table 4: Thermo-economic results of the power plants

	320 MW				160 MW + geo				320 MW + geo			
	$\dot{E}_d$ [MW]	$\dot{Z}$ [€/h]	r [%]	f [%]	$\dot{E}_d$ [MW]	$\dot{Z}$ [€/h]	r [%]	f [%]	$\dot{E}_d$ [MW]	$\dot{Z}$ [€/h]	r [%]	f [%]
Boiler	305.3	683.4	0.89	0.24	199.6	437.14	1.03	0.24	318	606.21	1.05	0.26
Turbine HP	4.7	54.4	0.12	0.50	2.37	35.10	0.16	0.55	5.58	63.38	0.13	0.50
Turbine MP	6.83	75.9	0.11	0.49	4.46	57.40	0.15	0.52	6.92	77.56	0.14	0.50
Turbine LP	15.3	104.5	0.16	0.37	7.09	62.86	0.18	0.42	12.9	94.11	0.17	0.39
Pump 1 / Pump E	0.04	0.5	0.33	0.50	0.01	0.23	0.28	0.59	0.02	0.30	0.24	0.58
Pump 2	0.03	0.17	0.07	0.31	-	-	-	-	-	-	-	-
Pump 3 / Pump A	1.31	7.5	0.04	0.31	0.38	5.14	0.06	0.49	0.68	7.75	0.07	0.47
Exc1 / Exc2_1	4.88	0.07	0.01	0.00	0.07	1.54	1.16	0.86	0.12	2.37	1.33	0.89
Exc 2 / Exc2_2	0.93	0.08	0.10	0.01	0.18	2.63	0.59	0.85	0.37	2.48	0.51	0.76
Exc 3 / Exc2_3	0.99	0.05	0.04	0.00	0.24	0.56	0.01	0.25	0.57	0.65	0.08	0.21
Exc 4 / Exc2_4	1.87	0.08	0.04	0.00	1.43	1.79	0.18	0.16	3.04	1.90	0.22	0.14
Exc 5 / Exc2_5	2.26	0.08	0.03	0.00	0.00	0.00	0.04	0.00	0.02	0.44	0.10	0.84
Exc 6	1.00	0.07	0.01	0.01	3.54	1.18	0.10	0.03	4.03	2.56	0.06	0.06
Exc2_6	-	-	-	-	0.02	0.00	0.00	0.00	0.14	1.12	0.00	0.47
Deareator	2.35	0.36	0.06	0.01	0.10	0.16	0.01	0.15	0.16	0.28	0.01	0.22
ReHeather	45.7	93.54	0.15	0.17	24.15	68.28	0.17	0.22	48.8	95.15	0.22	0.17

5. Conclusions

Three different steam power plants (a 320 MW conventional steam power plant, a 320 MW and a 160 MWe unit with geothermal feed-water preheating); two different fuels (coal and a mix of sunflower oil and sunflower oil cake) have been investigated in this paper through a thermo-economic analysis.

The substitution of a fossil fuel (coal) with a renewable resource is clearly beneficial in tems of sustainability. Form the economics point of view, this study shows that the geothermal feed-water preheating in the 320 MW power plant is convenient down to a coal cost of 43 €/t, while the 160 MW+geo power plant is less convenient even considering an escalation in the coal price (113 €/t). Considering a mix of biomass (sunflower oil and sunflower oil cake) in place of coal, the cost of electricity is much larger for both power plants with geothermal integration; however, the smaller size unit becomes more interesting because the cost of electricity is similar in the two cases.

Nomenclature

C:	Cost [€/s]
c_p	Cost of product per unit exergy [€/MWh]
c_f:	Cost of fuel per unit exergy [€/MWh]
c_d:	Cost of exergy destruction [€/MWh]
e	Specific Exergy [kJ/kg]
E:	Exergy [kW]
E_d:	Destroyed Exergy [MW]
η:	Efficiency
h:	Enthalpy [kJ/kg]
m:	Mass flow rate [kg/s]
p:	Pressure [bar]
Q:	Heat rate [kW]
T:	Temperature [K]
W:	Work [kW]
Z:	Component cost (capital investment + levelized operating & maintenance) [€]

Suffixes and Acronyms

Boiler	Steam Generator
Fuel:	Fuel (coal or biomass)
geoin:	Geothermal inlet to the system
geoout:	Geothermal reinjection into the well
geo:	Geothermal
i, o :	Component inlet/outlet
L/M/HPT	Low/Medium/High pressure turbine

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