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A combined energetic and economic approach for the sustainable design of geothermal plants

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ABSTRACT

The perspectives of future development of geothermal power plants, mainly of small size for the exploitation of medium–low temperature reservoirs, are discussed and analyzed in the present paper. Even if there is a general interest in new power plants and investments in this sector are recognized, the new installations are reduced; the apparent advantage of null cost of the energy source is negatively balanced by the high drilling and installation costs. A key element for the design of a geothermal plant for medium temperature geothermal source is the definition of the power of the plant (size): this is important in order to define not only the economic plan but also the durability of the reservoir. Considering that it is not possible that the development of geothermal industry could be driven only by an economic perspective, the authors propose a method for joining energetic and economic approaches. The result of the combined energetic and economic analysis is interesting particularly in case of Organic Rankine Cycle (ORC) power plants in order to define a suitable and optimal size and to maximize the resource durability. The method is illustrated with reference to some particular case studies, showing that the sustainability of small size geothermal plants will be approached only if the research for more economic solutions will be combined with efforts in direction of efficiency increase.

1. Introduction

Nowadays geothermal plants represent only a marginal part of the worldwide energy mix but a growing interest from industry and national institutions has been observed in the last five years concerning the possible increase of the use of geothermal energy. The development of new geothermal power plants is strongly dependent on the availability and geographical distribution of the resources. The overall conversion efficiency of those plants is affected by many parameters, like the chemical composition of geothermal fluid, parasitic loads, reinjection temperature, environmental conditions [1,2]. The power plant size affects the overall efficiency of the plant and the durability of the geothermal reservoir, being usually the result of merely economic decision making processes.

For example the chemical composition of geothermal fluid is important in order to define the minimum value of reinjection temperature while the environmental temperature has a direct influence on the condensation temperature. The low efficiency level can be related to the important impact of the cooling systems on the overall performances. Unfortunately the high investment costs of geothermal plants, mainly in case of size below 1 MW, represents a serious limit for the possible future development of new installations. The growth of installed power plant in the last 10 years, analyzed in [3] appears to be not particularly meaningful in comparison with the growth of the whole renewable energy sector. The typical approach to the geothermal potential assessment has always been quite conservative from the point of view of sizing and optimum design, so that a lot of installed plants shows relatively low First Law Efficiency (often below 10%) but quite high Second Law Efficiency (sometimes higher than 30–40%); but they are often designed based on an overexploitation of the reservoir. Reservoir and power plant should be considered as a global "geothermal system", together with the environment. The reservoir temperature decline is in fact a complex function of the exploitation (mass flow rate extraction), reinjection strategy (mass flow rate and position of reinjection wells) and the power generated with the plant (size of the plant), that is linked to the net power capacity of the reservoir.

It is well known that the development of geothermal energy is influenced by the high installation costs. Some quantitative analysis on this problem are exposed both in the textbook about geothermal power systems, like [1] and in scientific papers

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Nomenclature

C_{aux}	auxiliary costs sustained for the operation of the plant (€/year)
C_{fuel}	cost of fuel (€/year)
C_{in}	total cost sustained for the plant (€/year)
C^{*}_{in}	total cost sustained for the plant of increased power (€/year)
c_I	specific cost of exergy losses (€/kW h)
C_I	cost of the irreversibilities (€/year)
C_{max}	maximum sustainable (or affordable) cost (€/year)
C_{MW}	make up well cost (€/year)
$C_{O\&M}$	specific cost of the operation and management costs (€/year)
C_{PP}	cost of the components of the power plant (€/year)
c_{en}	specific energy cost (€/kW h)
c_p	specific heat capacity (J/kg K)
e	specific exergy (J/kg)
e_Q	specific exergy of the input geothermal source (J/kg)
E_Q	inlet exergy flow (W)
$e_{Q,av}$	specific exergy flow of the input geothermal source available for energy conversion (J/kg)
$E_{Q,av}$	exergy flow of the input geothermal source available for energy conversion (W)
f_g	gain function (€/year)
h	specific enthalpy (J/kg)
h_o	reference value of enthalpy (J/kg)
h_{geo}	specific enthalpy of the geothermal fluid (J/kg)
I	total exergy losses (W)
I^{*}	exergy losses in the modified power plant (W)
m_{geo}	mass flow rate of the geothermal fluid (kg/s)
m^{*}_{geo}	modified geothermal fluid extraction rate (kg/s)
p_0	reference pressure (bar)
p_{en}	specific reference price of electricity (€/kW h)
s	specific entropy (J/kg K)
s_o	reference value of entropy (J/kg K)
s_{geo}	specific entropy of the geothermal fluid (J/kg K)
T_{cond}	condensation temperature (°C)
T_{geo}	temperature of the geothermal source (°C)
T_{rein}	reinjection temperature (°C)
T_0	reference temperature (K)
t	number of operating hours in a year (h/year)
W	power output (W)
W_{net}	net power produced by the plant (W)
W_{ref}	reference value for the definition of the cost (W)
W^{*}	modified power (W)
z_{geo}	depth of the geothermal reservoir (m)
α	scaling exponent of Eq. (14)
β	specific consumption of geothermal fluid (kg/J)
η_I	First Law Efficiency (%)
η_{II}	Second Law Efficiency (%)

dedicated to this specific argument [4,5]. The problem is particularly evident in case of exploitation of medium to low enthalpy geothermal sources by means of Organic Rankine Cycle (ORC): the cost is variable between 2000 and 5000 €/kW and in some cases it could be also higher. This aspect is strictly connected with the lack of standardization of the ORC machinery [6] that requires a specific design for each case and to the high drilling costs [7].

Under a purely economic perspective a further development of plants based on the exploitation of geothermal energy appears to be very difficult if compared with other renewable energy sources. It is clear that the economic variables cannot be neglected; in a large number of cases a purely economic analysis can negatively influence the design process causing an overestimation of the plant size (particularly in case of medium-small size ORC power plants). This can lead to both a low efficiency of the plant and to a low durability of the resource and in the majority of the cases, to the end of the activity before the drilling phase.

An appropriate design method (particularly for the definition of the size of the power plant) is then necessary, in order to find a compromise between profitability, energy performances and sustainable utilization of the resource. Unfortunately, the connection between the energy efficiency and the economic variables is not well developed and new players in the energy market and the institutions often neglect the "complexity" of the problem.

On the other hand the energy market is continuously in progress. Boundary conditions can change in terms of resources availability (price of fossil-fuel supplies) and economic scenario (market liberalization, reduction of components costs, subsides and financial incentives). This dynamic behaviour of energy market does not encourage the activity in the geothermal field, where the mining and design risks are particularly high.

The attempt of obtaining a compromise between energetic and economic optimization objectives is well known in the literature since the early 1990s being the object of important textbooks, like [8] and it is still considered in scientific papers like [9,10]. Under a general perspective a combined energetic and economic analysis is interesting for the prior feasibility assessment of a geothermal plant. The same analysis can be used to define the size and the optimal operating parameters of the plant. Only a few applications are connected to geothermal energy both for direct use and district heating systems, as in [11,12] and for geothermal power as in [13–16].

Thermoeconomic analysis takes into account both the physical environment (geothermal source and the reference state) and the economic scenario (manufacturing and operative costs, taxes, interest rates). A particular and simplified thermoeconomic approach that seems suitable to the geothermal energy systems has been developed by Franco and co-authors in [17–19]. The aim of this particular thermoeconomic optimization is the minimization of a cost function, which is the sum of the cost of exergy inefficiencies and the structural cost of the plant. The method has been applied to power plants in general [17], to some specific components [18], and also to renewable energy sources [19], is here taken into account for a sustainable and optimal design of a geothermal plant, considering Thermodynamics (efficiency increase), Economics (reduction of specific costs with size increase) and Reservoir Engineering elements (sustainable extraction rate, reinjection strategy). The particular approach is applied to analyze the performance of existing plants and the results are then discussed. The interesting element of the method is the definition of a preliminary size of the plant; this permits to define the mass flow rate of geothermal fluid that will be extracted from the reservoir. The method can be proposed as first step of a comprehensive methodology for the sustainable design of geothermal plants. The focus of the present paper is about power production, but it could be applied to the systems for the direct use of thermal energy too.

2. The sustainable design of geothermal plants

Geothermal energy has a relatively reduced number of power installations worldwide. Since the early stage of industrial