Energy 45 (2012) 908–923

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Environomic optimal configurations of geothermal energy conversion systems: Application to the future construction of Enhanced Geothermal Systems in Switzerland

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ARTICLE INFO

Article history:
Received 23 April 2012
Received in revised form
13 June 2012
Accepted 25 June 2012
Available online 21 July 2012

Keywords:
Geothermal energy
Energy conversion systems
Combined heat and power
Multi-objective optimization
Life Cycle Assessment
Enhanced Geothermal Systems

ABSTRACT

The development of Enhanced Geothermal Systems (EGS) for the cogeneration of electricity and district heating is expected to be important in the future. The criteria to be accounted for in the energy conversion system design are the economic profitability, the thermodynamic efficiency in the usage of the resource, and the generated life-cycle environmental impacts, which are as well a key point for the public acceptance of geothermal energy. This paper presents a systematic methodology for the optimal design and configuration of geothermal systems considering environomic criteria. Process design and process integration techniques are used in combination with Life Cycle Assessment (LCA) and multi-objective optimization techniques, using a multi-period strategy to account for the seasonal variations in the district heating demand. It is illustrated by an application to the future EGS construction for cogeneration in the context of Switzerland. Different conversion cycles are considered: single and double-flash systems, organic Rankine cycles (ORC), and Kalina cycles. The optimal configuration is determined at each construction depth for the EGS from 3000 down to 10,000 m and at each district heating network installed capacity from 0 to 60 MW_{th}. Results show that in the shallowest range of depths (3500–6000 m), the optimal configurations for all considered performance indicators are EGS between 5500 and 6000 m with a Kalina cycle for cogeneration, and a district heating network with an installed capacity between 20 and 35 MW_{th}. In the deepest range (7500–9500 m), when compared with the single electricity production, the cogeneration of district heating is less favorable from an economic and exergetic perspective (11% and 17% of relative penalty, respectively, for a district heating network with an installed capacity of 60 MW_{th}) but more favorable in terms of environmental performance (37% of relative improvement for avoided CO_2 emissions).

1. Introduction

In the perspective of increasing the share of renewable energy to mitigate global warming issues and to respond to fossil resources depletion, the use of geothermal energy has gained interest. Major applications of geothermal energy include electricity production (67,246 GWh_e/yr in 2010) and direct use for heating (117,740 GWh_{th}/yr in 2010) [1]. As stated by the International Energy Agency in its roadmap for geothermal energy [2], by 2050 the geothermal power production should be increased to 1400 TWh_e/yr, and the direct heating use to 1600 TWh_{th}/yr. These objectives have to be reached by developing both conventional resources like hydrothermal aquifers and emerging ones like Enhanced Geothermal Systems (EGS). Hence, geothermal Combined Heat and Power (CHP) production from EGS is expected to know an important development in the future. Moreover, several countries including Switzerland have recently taken the political decision to abandon progressively nuclear power, which supposes to develop alternatives energy sources for power production.

However, the economic competitiveness of geothermal energy is still a critical point [2], and several methodologies have been developed to increase its cost-effectiveness by an optimal system design. Important aspects to be accounted for are the geothermal resources characteristics [3], the design of the conversion cycle, which has to be optimized to maximize its efficiency [3–5], the choice of the working fluid for binary cycles [6–9], and the district heating parameters for CHP applications [8,9]. The thermodynamic performance is as well critical to ensure an efficient use of the

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http://dx.doi.org/10.1016/j.energy.2012.06.068

Nomenclature

$\dot{E}_p^{-}$	net electrical power produced by system at the operating conditions of period p, in MW_e
$\dot{E}_t^{-}$	electrical power produced by the turbines of the cycle, in MW_e
$\dot{fu}_p$	quantity of functional unit involved during period p
$\dot{I}_O$	impact due to the operation phase
$\dot{m}_{ext}$	extracted mass flow rate from EGS, in kg/s
$\dot{m}_f$	mass flow rate of geothermal steam passing through the flash system turbine, in kg/s
$\dot{m}_{inj}$	injected mass flow rate in EGS, in kg/s
$\dot{m}_i$	mass flow rate of emission of substance i from flash system condensers, in kg-i/kg-geofluid
$\dot{m}_{mkup}$	mass flow rate of make-up water for EGS, in kg/
$\dot{m}_{scal}$	quantity of scaling and residues from EGS to be disposed, in kg/s
$\dot{Q}_{max}^{-}$	district heating network installed capacity, in MW_{th}
$\dot{Q}_p$	district heating requirement during period p, in MW_{th}
η	exergy efficiency of the conversion system, in %
c_e^{-}	selling price of electricity, in USD/kWh_e
$C_{inv,an}$	annualized total investment costs, in USD/yr
$C_{inv,DH}$	investment costs associated with the district heating network, in USD
$C_{inv,EGS}$	investment costs associated with the EGS construction
$C_{inv,tot}$	total investment costs of EGS, conversion system and district heating network, in USD
$C_{inv,w}$	investment costs associated with equipment w, in USD
$c_{o,EGS}$	specific operating costs of EGS, in USD/h
$c_{o,t}$	specific operating costs of conversion technology t, in USD/h
c_q^{-}	selling price of district heating, in USD/kWh_{th}
e_i	emission factor of substance i from the flash system condensers, in kg-i/kg-geofluid
$e_{CO_2,NGCC}$	specific CO_2 emissions of electricity production from NGCC, in kg CO_2-eq/kWh_e
$e_{CO_2,NGCC}$	specific CO_2 emissions of heating production from natural gas boiler, in kg CO_2-eq/kWh_{th}
$E_{CO_2,av}$	yearly avoided life-cycle CO_2-equivalent emissions, in kg CO_2-eq/yr
I_C	impact due to the construction phase
I_E	impact due to the end-of-life phase
I_{FU}	final impacts per functional unit
I_{wat}	water losses in EGS, in %
L_{wf}	losses and required make-up of working fluid in binary cycles, in kg/yr
l_{wf}	yearly losses of working fluid in binary cycles, in %
M_k	required quantity of auxiliary material k
M_{wf}	initial quantity of working fluid in binary cycles, in kg
n_w	number of wells
n_{ec}	number of LCI elements associated with construction phase
n_{ee}	number of LCI elements associated with end-of-life phase
n_{eo}	number of LCI elements associated with operation phase
R_{an}	annual revenue, in USD/yr
s	success factor in achieving the EGS sub-surface plant construction, in %
T_{out}	outlet temperature at which hot source is cooled, in °K
t_p	duration of period p, in h
T_a	ambient temperature, in °K
T_{in}	inlet temperature of the hot source, in °K
T_{lm}	logarithmic mean temperature, in °K
t_{pb}	payback period, in yr
t_{yr}	expected lifetime of the EGS reservoir, in yr
υ_k	reference quantity of auxiliary material k
υ_{scal}	quantity of scaling and residues per mass unit of geothermal water, in kg-residues/kg-geofluid
x_d	decision variables of the non-linear MOO problem
y_{wf}	thermodynamic properties of working fluid in binary cycles
z	EGS construction depth, in m
CHP	Combined Heat and Power
EGS	Enhanced Geothermal Systems
IPCC	Intergovernmental Panel on Climate Change
Kalina	Kalina cycle based on the KCS-11 design
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MILP	Mixed Integer Linear Programming
MINIP	Mixed Integer Non-Linear Programming
MOO	Multi-Objective Optimization
NGCC	Natural Gas Combined Cycle
ORC	Organic Rankine Cycle
ORC-2	ORC with two evaporation levels
ORC-d	ORC with an intermediate draw-off at the turbine
ORC-s	supercritical ORC

resource, and it can be assessed using the exergy efficiency [10–13]. Accounting for the two criteria, the thermo-economic approach has been applied to the analysis of geothermal systems in several studies [14–17]. Recently, Lazzaretto et al. [18] have demonstrated its validity to design geothermal power plants. In a previous work [19], we have developed a methodology integrating all the above aspects in a multi-objective optimization framework, using a multi-period approach and process integration techniques to identify the thermo-economic optimal configurations of geothermal systems in areas where the geothermal resource potential has been assessed.

A third aspect, relevant for the public acceptance, is the environmental dimension. Indeed, Evans et al. [20] demonstrated that geothermal energy may have higher impacts on the environment when compared with other renewable energy sources such as hydro, wind and solar, though their study was mostly based on existing hydrothermal systems for power generation and not on EGS. Thus, this aspect should be as well integrated in the design of geothermal energy conversion systems. Regarding the evaluation of renewable energy systems, Life Cycle Assessment (LCA) is the most appropriate methodology, since it accounts for a wide range of environmental impacts and considers the overall life cycle in a quantitative way [21,22]. Though many previous studies discuss the environmental impacts of geothermal systems [23–26], very few use a quantitative life cycle perspective. Among them, Saner et al. [27] performed an LCA for shallow geothermal systems, and Santoyo-Castelazo et al. [28] for electricity generation from hydrothermal systems in Mexico. To our knowledge, Frick et al. [29] are the only authors who performed an environmental analysis by LCA specifically for power generation from EGS, considering the use of binary cycles. They demonstrate the relevance of using a life cycle approach for the environmental evaluation of EGS and found that the efficiency of the conversion cycle is a critical parameter. However, they use a scenario approach based on average technologies, and do not consider systematically the thermo-economic optimal configurations of geothermal systems in the impact assessment. In a previous study [30], we have developed such