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On the environmental suitability of high- and low-enthalpy geothermal systems

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ABSTRACT

This article addresses the life cycle assessment of (i) power generation in a binary-cycle power plant using high-enthalpy geothermal resources, and (ii) heat generation in a closed-loop geothermal heat pump system using low-enthalpy resources. For the geothermal power system, production and injection wells show a high contribution to the environmental impacts, mainly due to activities such as drilling and casing. Power plant operation is also identified as an important source of impact because of working fluid losses. A favourable life-cycle energy balance is estimated for this system. Furthermore, when compared to fossil electricity, geothermal electricity is generally found to be a promising alternative. For the geothermal heat system, the electricity demands for heat generation and use are the main sources of impact. An unfavourable life-cycle energy performance is predicted for this system. When compared to fossil heat, the environmental suitability of geothermal heat highly depends on the availability of eco-friendly electrical grids.

1. Introduction

The use and development of renewable energy systems is gaining worldwide interest as a sustainable solution to current energy concerns such as the depletion of conventional fossil resources, the subsequent increase in the price of fuels, energy supply insecurity, the accomplishment of global warming policies, and the growing social awareness of environmental issues (Chiavetta et al., 2011; Huenges, 2010; International Energy Agency, 2011). In particular, geothermal energy (GE) is one of the most abundant sources of energy, and it is often presented as a key option to mitigate the energy and environmental problems of the current fossil-based energy system (Llopis and Rodrigo, 2008). GE is considered to be cost-effective, with an initial investment offset by low maintenance costs and high energy rates; its continuous nature, independent of climatic, seasonal and geographical conditions, provides GE with a distinguishing feature when compared to other renewable energies (Llopis and Rodrigo, 2008; O'Sullivan et al., 2010).

The most common classification of geothermal resources is based on the temperature of the water taken from the reservoir, which is called geothermal fluid (GF) (Agemar et al., 2012). Temperatures above 150 °C characterize high-enthalpy resources, which involve a GF suitable for power generation (Barbier, 2002). Low-enthalpy resources typically present temperatures below 150 °C, and their geothermal potential is still underexploited, being heat generation the main current application (e.g., building heating) (Barbier, 2002).

Power generation from high-enthalpy geothermal resources generally involves a thermodynamic cycle similar to that of conventional thermal power plants, using a steam generator, a steam turbine, and a condenser (Chamorro et al., 2012; Pous and Jutglar, 2004). There are different geothermal power technologies depending on the specific conditions of the geothermal resource (Sonney and Vuataz, 2008). The most common layouts are shown in Fig. 1.

When the GF is already available as a vapour from the production well, dry-steam power plants (Fig. 1a) are used. In this type of plants, the GF is directly fed to the turbine-generator unit after conditioning (Chamorro et al., 2012; Pous and Jutglar, 2004). On the other hand, when the GF reaches the surface as a vapour–liquid mixture, single-flash power plants (Fig. 1b) are used since the GF cannot be directly fed to the turbine. In these plants, the mixture is separated so that the vapour fraction can be fed to the turbine, while the liquid phase is returned to the geothermal reservoir through an injection well (Chamorro et al., 2012; Huenges, 2010; Pous and Jutglar, 2004). When the pressure of the fluid at the well head is high, the power-generation capacity can be increased in double-flash power plants (Fig. 1c), which have an additional flash process

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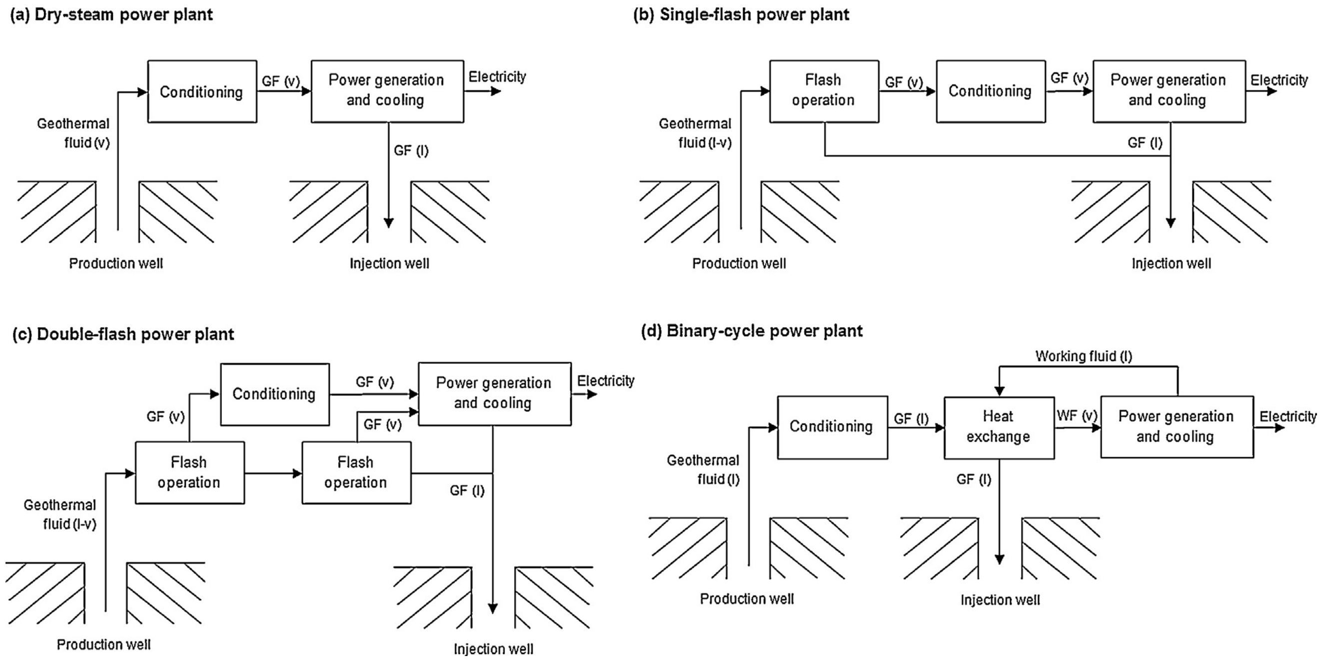

Fig. 1. Simplified representation of different types of geothermal power plants. *Abbreviations*: GF (geothermal fluid) and WF (working fluid).

and a two-stage turbine (Chamorro et al., 2012; Pous and Jutglar, 2004).

A common situation, different to the previous cases, is the availability of a GF with inadequate temperature or a high salt content. In order to deal with this inconvenience, binary-cycle power plants (Fig. 1d) avoid the direct use of the GF by using a working fluid for power generation (Chamorro et al., 2012; Frick et al., 2010; Huenges, 2010; Pous and Jutglar, 2004).

The systems based on geothermal heat pumps (GHP), which can use low-enthalpy resources typical of shallow depths (below 400 m), claim to be clean and efficient technologies for, among other uses, building heating/cooling (Saner et al., 2010). The heat pump extracts energy from a heat carrier fluid by compressing and evaporating a refrigerant. This heat carrier fluid can operate in either groundwater heat pump (GWHP) systems or ground-source heat pump (GSHP) systems, also known as open and closed systems, respectively. Open-loop systems (Fig. 2a) use the groundwater itself as the heat carrier through production and injection wells, while closed-loop systems (which are more commonly used; Fig. 2b) are provided with U-shaped borehole heat exchangers that use a synthetic heat carrier fluid (Saner et al., 2010).

Despite the high geothermal potential for power and heat generation, the current use of geothermal resources is low (Axelsson, 2010). In 2010 the total installed capacity worldwide was 10,700 MW for indirect geothermal utilization in power plants, and 20,583 MW for direct geothermal utilization in heat generation facilities (Guzović et al., 2012). Many countries with a high geothermal potential have low GE generation levels due to technological and/or political barriers. For instance, Spain accounted for a contribution below 1% to the European GE production in 2008, even though it is an area of interest for the development and promotion of GE systems (Bayer et al., 2012).

Unfortunately, the use of a renewable resource does not guarantee an energy system with an environmentally friendly performance. In this respect, comprehensive analyses are needed to evaluate the environmental suitability of energy systems. Life cycle assessment (LCA) is a well-defined methodology to assess the environmental aspects and potential impacts associated with a product (ISO, 2006a,b). Because of its holistic nature, the use of LCA is appropriate to thoroughly evaluate energy systems.

2. Materials and methods

The LCA methodology assesses the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study (ISO, 2006a). LCA studies involve four stages (ISO, 2006a,b):

- *Goal and scope definition*: This step includes the definition of the objectives and potential uses of the study as well as of other key aspects such as the functional unit (FU), the system boundaries, assumptions and restrictions.
- *Life cycle inventory analysis*: This stage demands an inventory of the input and output data for the system under study, thus involving data collection.
- *Life cycle impact assessment*: This stage comprises three mandatory steps: (i) selection of impact categories, indicators and characterization models, (ii) classification, and (iii) characterization. Classification involves the association of the inventory data with the selected impact categories, while characterization deals with the calculation of the results of each category indicator through the conversion of the life cycle inventory elements to common units (using characterization factors) and the aggregation of the converted results within the same impact category.
- *Interpretation*: According to the goal and scope defined for the LCA study, the results from the previous steps are summarized and discussed in order to identify relevant issues and provide conclusions, recommendations and information for decision-making purposes.

2.1. Goal and scope definition

The goal of this study is to determine the life-cycle environmental and energy performance of (i) power generation in a geothermal