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Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy

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ABSTRACT

Greenhouse gas emissions, climate change and the rising energy demand are currently seen as most crucial environmental concerns. With the exploration of renewable energy sources to meet the challenges of energy security and climate change, geothermal energy is expected to play an important role.

In this study a LCA (Life Cycle Assessment) and an EMA (Emergy Assessment) of a 20 MW dry steam geothermal power plant located in the Tuscany Region (Italy) are performed and discussed. The plant is able to produce electricity by utilizing locally available renewable resources together with a moderate support by non-renewable resources. This makes the geothermal source eligible to produce renewable electricity. However, the direct utilization of the geothermal fluid generates the release into the atmosphere of carbon dioxide, hydrogen sulfide, mercury, arsenic and other chemicals that highly contribute to climate change, acidification potential, eutrophication potential, human toxicity and photochemical oxidation.

The study aims to understand to what extent the geothermal power plant is environmentally sound, in spite of claims by local populations, and if there are steps and/or components that require further attention. The application of the Emergy Synthesis method provides a complementary perspective to LCA, by highlighting the direct and indirect contribution in terms of natural capital and ecosystem services to the power plant construction and operation.

The environmental impacts of the geothermal power plant are also compared to those of renewable and fossil-based power plants. The release of CO_2-eq calculated for the investigated geothermal plant (248 g kWh^{-1}) is lower than fossil fuel based power plants but still higher than renewable technologies like solar photovoltaic and hydropower plant. Moreover, the SO_2-eq release associated to the geothermal power plant (3.37 g kWh^{-1}) is comparable with fossil fuel based power plants.

Results suggest the need for further investigation of other geothermal options (e.g. binary systems) in order to reduce the environmental impacts while taking the maximum advantage of the geothermal resource.

1. Introduction

Greenhouse gas emissions, climate change and the rising energy demand are currently seen as most crucial environmental concerns. Renewable energy use is claimed to be at least a partial solution in order to reduce fossil energy consumption and related environmental impact as well as capital and operating and maintenance costs [1–4].

The discontinuous nature of most renewable resources calls for storage devices [5–8] and smart grids [9] capable to constantly manage electricity supply and demand.

With the exploration of renewable energy sources to meet the challenges of energy security and climate change, geothermal energy is expected to play an important role [10,11].

Over the past ten years geothermal uses increased in many parts of the world, both in countries that have traditional interests in conventional geothermal resources and countries without historical interests in geothermal energy [12].

Geothermal resources have been identified in approximately 90 countries, and their use was quantified in 72 countries, with 24

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Nomenclature

ISO	international organization for standardization
ILCD	international reference life cycle data system
CED	cumulative energy demand
CML	centre of environmental sciences of the Leiden University
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
EMA	emergy assessment
R	locally renewable emergy flows
N	locally nonrenewable or slow-renewable emergy flows
F	emergy flows imported from outside (purchased) or supplied as feedback
U	total emergy supporting the process or system under investigation.
seJ	solar equivalent Joule: unit used to quantify emergy flows
ELR	environmental loading ratio
ESI	emergy sustainability index
EYR	emergy yield ratio
UEV	unit emergy value
EROEI	energy returned on energy invested
ORC	organic rankine cycle

countries relying on geothermal power for electricity generation [13,14].

Significant geothermal energy capacity is being developed across Europe. The total installed capacity for geothermal energy in Europe is 1600 MW, producing 10,900,000 MWh of electric power through 59 geothermal power plants, 47 of which are in European Union (EU) member states. In addition, in EU member states there are 109 new power plants under construction or under investigation. By 2015, Europe is expected to have about 2600 MW of installed geothermal energy capacity, with an additional 800 MW to be under development or investigation by 2018 [15].

Within Europe, Italy has installed over 50 percent of the European capacity. Geothermal electricity generation only occurs in the Tuscany region (central Italy), while direct uses are spread all along the country, mainly for bathing and district heating purposes. The total installed capacity is about 882 MW, with 35 plants and a production of 5315 GWh yr^{-1}.

The heat delivered to direct uses is around 3500 GWh from 1000 MW_{th} plants, 50% of this installed capacity being used by heat pumps [16].

Geothermal energy is mainly utilized in three technological categories: (i) heating and cooling of buildings via geothermal heat pumps that utilize shallow sources, (ii) heating structures with direct-use devices, and (iii) generating electricity through indirect use [17].

The basic types of geothermal power plants operating today are steam condensing turbines and binary cycle units. Steam condensing turbines can be used in flash or dry-steam plants operating at sites with intermediate and high temperature resources (generally higher than 150 °C) while binary-cycle plants, typically ORC (Organic Rankine Cycle) units, are commonly installed to extract heat from low and intermediate temperature geothermal fluids (generally from 70 to 170 °C).

The environmental impacts of geothermal uses differ depending on the technology. As for other renewable technologies, the environmental burden of geothermal energy use must be assessed based on a life cycle approach [18,19]. LCA (Life Cycle Assessment) investigates environmental impacts of systems or products from cradle to grave throughout the full life cycle, from the exploration and supply of materials and fuels, through the production and operation of the investigated objects, to their final disposal or recycling [20].

LCA has been widely used to investigate renewable energy technologies and it has already been used in various applications to reveal the directions for future greenhouse emission reduction [21–24]. For geothermal power plants, all the impacts directly and indirectly related to the construction, operation and decommissioning of the plant need to be considered in LCA. Geothermal power plants consist of numerous components such as production and reinjection boreholes, pipelines, intermediate equipment, turbines, generators, and cooling towers and each of them has environmental effects and adds to life cycle contributions.

The distinction between open-loop and closed-loop systems is important with respect to air emissions. In closed-loop systems, gases from the well are not released to the atmosphere and are injected back into the ground after releasing their heat, so that air emissions are minimal. In contrast, open-loop systems release into the atmosphere emissions as hydrogen sulfide, carbon dioxide, ammonia, methane, among others. As a consequence, direct and indirect emissions from geothermal sources use and their contribution to environmental impact categories need to be assessed.

LCA has already been used in a few papers to evaluate the environmental impact of geothermal power plants. Some studies focused on conventional flash or dry-steam plants [25–27] while others investigated binary power plants [18,28,29].

Bayer et al. [30] published a review on LCA of geothermal electricity production. They found that LCA studies on geothermal electricity production are scarce and often focused on a more qualitative description or analysis of environmental burdens and benefits. According to these authors, some studies are focused only on a specific aspect of LCA, such as a global warming potential, water use, or on a selected life cycle stage and in some cases transparent reporting and assessment of local and regional environmental consequences are lacking.

More recently, Martín-Gamboa et al. [31] addressed the LCA of power generation in a binary-cycle power plant using high-enthalpy geothermal resources, and heat generation in a closed-loop geothermal heat pump system using low-enthalpy resources. Bravi and Basosi [32] evaluated the environmental impact of selected geothermal power plants in Italy with a special focus on emissions of non-condensable gases of geothermal fluids, pointing out non-negligible emissions of CO_2, H_2S, NH_3, and CH_4. However, only the power production phase of the investigated geothermal power plants has been considered in this paper while the consumption of material and energy resources associated with the drilling, construction, and operation of geothermal plants were not included.

The aim of this study is to present and discuss the environmental performance of a geothermal power plant located in the Tuscany region of Italy from a cradle to grave perspective, applying the LCA methodology. In addition, the Emergy Synthesis method is used to expand the perspective of LCA and provide the added value of a comprehensive donor-side assessment, namely an estimate of the total environmental support to the investigated process.

2. Materials and methods

2.1. LCA mechanism and characteristics

LCA is a methodological framework to assess the potential environmental impacts and resources used throughout a product's