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Review on life cycle environmental effects of geothermal power generation

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ABSTRACT

A comprehensive overview of potential environmental effects during the life cycle of geothermal power plants is presented using widely scattered available information from diverse literature sources. It is shown that so far only few studies provide quantitative estimates on both direct and indirect environmental consequences. Life cycle assessment (LCA) studies on geothermal electricity production are scarce and typically country- or site-specific with a focus on the geothermal fields in the western USA. In fact a general assessment is challenging due to the dissimilar nature and maturity of currently applied geothermal power plants, the influence of site-specific characteristics, and uncertainty in long-term productivity. Especially life cycle fugitive emissions, the thread from geological hazards, and water and land use effects are highly variable and may even change with time. Based on our survey, ranges are provided for emissions and resource uses of current worldwide geothermal power generation. We also define an approximate universal case that represents an expected average. The collected data is suitable to feed life cycle inventories, but is still incomplete. Potential emissions of critical toxic substances such as mercury, boron and arsenic and their local and regional environmental consequences are particularly inadequately addressed on the global scale.

Contents

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1. Introduction

Geothermal energy is thermal energy generated and stored in the earth. Ninety-nine percent of the earth's volume has temperatures $>1000\,^{\circ}C$, with only 0.1% at temperatures $<100\,^{\circ}C$. The total heat content of the earth is estimated to be about 10^{13} EJ and is therefore immense. The main sources of geothermal energy come from the residual energy available from planet formation and the energy continuously generated from radionuclide decay. Planet earth can afford to give away heat to the atmosphere, with a thermal power of 40 million MW_t (equivalent to the thermal power of about 13,000 nuclear power plants of the 1 GW_e class) without any cooling. Thus, the geothermal resource base is sufficiently large and basically ubiquitous. Geothermal resources consist of thermal energy stored within the earth in both rock and trapped steam or liquid water. Utilization is in two main categories: electricity generation and direct use (for space heating, balneology, greenhouses, etc.). In our contribution we exclusively focus on high-enthalpy geothermal energy use for power generation [1–3]. For direct use and low-enthalpy technologies such as ground source heat pump (GSHP) and groundwater heat pump (GWHP) systems the reader is referred to recent comprehensive reviews [4–8].

Geothermal energy is counted among renewable energies, with a long tradition, experience and great potential for the future [9–14]. As for all other alternative environmentally favorable power generation options, the life cycle of such technology is also associated with environmental impacts. The objective of this study is to provide a structured review on life cycle environmental effects of geothermal power generation. These include emissions, energy and resource usage, as well as social consequences. The compiled information is intended as a basis for a life cycle assessment (LCA), which is a standard and normed procedure to reflect and assess all environmental effects during the life cycle of a service or product.

In the following, first the standard geothermal plant types are shortly described. Then, in a comprehensive review of heterogeneous available information sources, environmental consequences during the life cycle of geothermal power generation are categorized with a qualitative and when possible quantitative discussion. These consequences include land use, geological hazards, noise, emissions to atmosphere, soil and water, energy and water use. Then the findings from the few available life cycle assessment studies are compared, and as far as possible a state-of-the art data inventory is consolidated.

2. Technology description

Geothermal power plants take hot geothermal fluid (or steam) from depth and convert their heat to electricity; the conversion efficiency depends mainly on the fluid's heat content/temperature. The temperature commonly decreases with depth, and is different between geologically active and young areas, in comparison to older and “cooler” regions. Thus, most attractive for this technology are those few geologically young areas worldwide, where very high geothermal gradients are found. This means that in a few hundreds or even thousands meters depth abnormally high temperatures are present, and ideally productive reservoirs with high volumes of stored geothermal fluids and/or steam exist. In contrast to these hydrothermal geothermal reservoirs, petrothermal production is focused on geothermal reservoirs with no or marginal water (hot dry rock, HDR). The latter are typically created through mechanical or chemical stimulation and counted among engineered geothermal systems (EGS). These represent a category of rather new plant types that generate electricity from greater depth and thus can also be applied in other areas of normal geothermal gradient. For example, at the scientific pilot EGS project at Soultz-sous-Forêts (France), the installed capacity is now 1.5 MW. However, EGS still have only a marginal share in the worldwide installed capacity with 10.9 MW in 2010 [2] and accordingly are not further discussed in the present study.

Geothermal power plants consist of numerous components such as production/reinjection boreholes, connecting/delivery pipelines, intermediate equipment like silencers/separators, power house (including turbines/generators, controls) and cooling towers. Each of them has environmental effects and adds to life cycle contributions, some of them only temporary (e.g. during construction), some of them lasting (e.g. silencer noise). These effects and contributions are treated in subsequent chapters “Direct environmental impacts” and “Review of Life Cycle Assessments”; here the various power plant components are briefly described.

Since it is not practical to transmit high-temperature steam over long distances by pipeline due to heat loss, most geothermal plants are built close to the resource. Given the required minimum spacing of wells to avoid interference (typically 200–300 m) and the usual capacity of a single geothermal well of 4–10 MW_e (with some rare, spectacular exceptions), geothermal power plants tend to be in the 20–60 MW_e range, even those associated with large reservoirs. The current (2012) largest geothermal power plant operates with a capacity of 140 MW_e at Nga Awa Purua, Rotokawa geothermal field, New Zealand and is fed by only six production wells. Much smaller plants, in the range of 0.5–10 MW_e, are common as binary-type plants. Below the main geothermal power plant types are briefly described, mainly after DiPippo [1,15], where more details can be found. We can distinguish different technologies, with a current worldwide share in electricity produced as shown in Fig. 1. Average capacity and energy produced

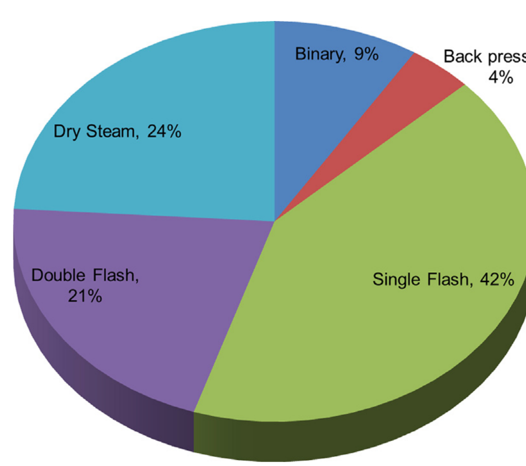

Fig. 1. Share of different geothermal plant technologies in global electricity production (after Bertani [2]).