Life cycle assessment of geothermal power generation

Kathrin Menberg[1,2,3], Philipp Blum[1], Stephan Pfister[4], Ladislaus Rybach[5], Peter Bayer[3]

[1] Karlsruhe Institute of Technology (KIT), Institute of Applied Geosciences (AGW), 76131 Karlsruhe, Germany.
[2] University of Cambridge, Department of Engineering, Cambridge, United Kingdom.
[3] ETH Zurich, Department of Earth Sciences, 8092 Zurich, Switzerland.
[4] ETH Zurich, Institute for Environmental Engineering, Zurich, Switzerland.
[5] ETH Zurich, Institute of Geophysics, Zurich, Switzerland.

Keywords: Geothermal power, Life cycle assessment (LCA), Life cycle inventory (LCI), Environmental impact, Water use.

ABSTRACT

An overview of environmental effects during the life cycle of geothermal power generation including enhanced geothermal systems (EGS) is presented. Until now, only few studies provide quantitative assessments on direct and indirect environmental consequences of such deep geothermal systems. Hence, studies based on life cycle assessment (LCA) for the geothermal electricity production are rare. In addition, the few existing studies are country- and/or site-specific with a clear concentration of geothermal systems in California, USA. A global and universal assessment is therefore still challenging mainly caused by the different nature and maturity of the applied geothermal plant technology, the site-specific characteristics and uncertainty in long-term productivity of the investigated or planned system. Greenhouse gas emissions (GHG), geological hazards, and water and land use effects are extremely variable and also may change during a life cycle. For conventional geothermal energy productions (non-EGS), potential emissions of toxic elements such as mercury, boron and arsenic and their environmental consequences are insufficiently studied and should therefore be investigated in future research.

1. INTRODUCTION

Geothermal resources consist of thermal energy stored within the earth in both rock and trapped steam or liquid water. Utilization of the resource can be distinguished in two main categories: (1) electricity generation and (2) direct use for space heating and balneology. In this study we fully focus on high-enthalpy geothermal energy use for power generation (e.g. Bertani 2012). For direct use and low-enthalpy technologies such as geothermal heat pumps, ground source heat pump (GSHP) and groundwater heat pump (GWHP) systems the reader is referred to recent comprehensive reviews (e.g. Bayer et al. 2012, Saner et al. 2010). Geothermal energy is counted among renewable energies and like all other alternative environmentally favorable power generation options, the life cycle is also associated with environmental impacts.

The objective of this study is to provide a brief review on life cycle environmental effects of geothermal power generation including emissions, energy and resource usage and also social consequences (Figure 1). These environmental impacts are more thoroughly described in the previous study by Bayer et al. (2013). Additionally, findings for conventional systems are compared to those for enhanced geothermal systems (EGS).

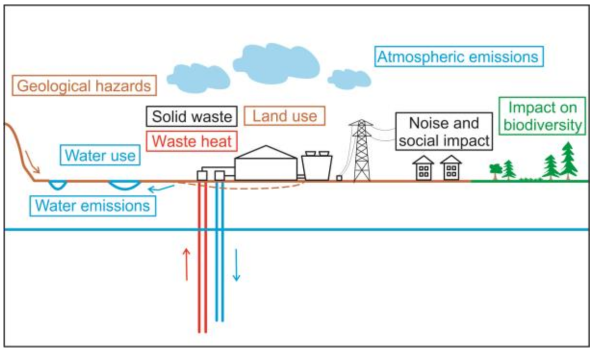

Figure 1: Overview of direct life cycle environmental impacts of geothermal power production (modified from Bayer et al. 2013).

2. METHODS

LCA is performed according to ISO 14040 and ISO 14044, which describe the four main life cycle phases of a product, including supply chain, production, use and final disposal. The assessment requires comprehensive data analysis and data on life cycle inventories considering various impact categories such as global warming, toxicity and resource depletion. The latter is comprehensively described and discussed in the study by Bayer et al. (2013). Thus, the focus of the present study is on the key results stimulating further research on LCA of geothermal power generation.

3. RESULTS AND DISCUSSION

3.1. Previous LCA studies

LCA studies on geothermal power production are scarce and for EGS even less frequent (e.g. Frick et al. 2010, Lacirignola and Blanc 2013, Sullivan et al. 2010, Treyer et al. 2015; Table 1). In most of the LCA studies only few environmental impact categories have been studied, due to the fact that environmental impacts from certain power plants are often local and case specific, and therefore general conclusions are difficult to make.

Table 1: Overview of performed LCA studies on geothermal power generation.

Technology			Country
Dry steam	Flash steam	Binary-cycle	
	×	×	USA
	×	×	USA
×	×	N/A	USA
	×		Japan
	×		USA
		×	New Zealand
	×		Iceland
		× (EGS)	Germany
		× (EGS)	Germany
		× (EGS)	France
		× (EGS)	Switzerland

Karlsdottir et al. (2010), however, who performed a LCA study of the Hellisheidi geothermal power plant on Iceland, investigated eleven environmental impact categories, mainly calculating primary energy and CO_2 factors. The determined primary energy factor in this plant is within the range of 2.7 – 9 kWh primary energy per kWh produced electricity. The calculated CO_2 emission factor is between 35-45 kg CO_2 equivalents per MWh of produced electricity, and the drilling phase contributes here with 24% of the total emissions during the technical lifetime of 30 years.

Typical geothermal power plants require anomalous geological conditions, which exist only in few places worldwide, e.g. triple junction of the Reykjanes Peninsula on Iceland. These conditions are typically a high geothermal gradient, which are found in geologically young and/or active volcanic areas, and the existence of a substantial and accessible reservoir of geothermal fluid and heat beneath. The case-specific characteristics complicate the formulation of generally valid LCA frameworks, and available environmental assessments often refer to a local conditions. It therefore remains challenging, if not impossible, to develop a universal assessment of environmental impacts as common in LCA studies on other more industrial based renewable energy technologies (Bayer et al. 2013).

A general conclusion from the initial assessment of previous LCA studies is that, environmental effects are commonly related with emissions at the site and not with plant components of the manufacturing process and/or associated drilling activities. Atmospheric emissions, especially of fugitive greenhouse gases (GHG) via steam release, are reported from many case studies. Furthermore, other aquatic and atmospheric emissions such as mercury, boron and arsenic, which may carry toxic concentration levels, are not thoroughly studied and assessed. Despite the often only local effects in the vicinity of the plant, accidental or permanent release can also represent a significant threat to the environment. Hence, more research and surveys are required to gain an improved depiction on worldwide average emission rates and environmental consequences of geothermal power generation.

3.2. LCA study for EGS

The environmental impact from EGS power plants obtained by LCA studies listed in Table 1 is also illustrated in Figure 2 as average GHG emissions per produced kWh electricity for the assessed countries. The proportion of emissions caused during the individual life cycle stages are presented. The error bars in Figure 2 indicate that there is a considerable variability in GHG emissions arising from the different scenarios investigated in the individual studies. These scenarios cover different site-specific assumptions about reservoir temperature and depth, as well as flow rate, which lead to different power capacities and life time electricity outputs.

Differences between the average values of individual studies occur on the one hand due to varying assumptions in the life-cycle inventories, such as the amount of steel and concrete needed for borehole casing. More significant, on the other hand, is the variation caused by the type and in particular the amount of fuel consumed for drilling one borehole meter. As indicated by the red markers in Figure 2, the amount of consumed diesel is directly reflected in the amount of GHG emissions occurring during drilling operations.

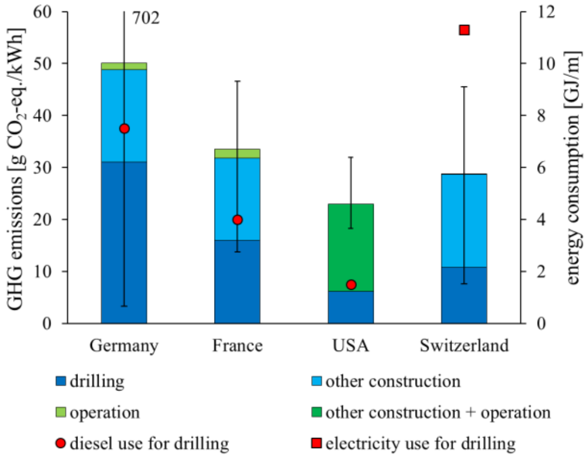

Figure 2: Environmental impact of EGS projects as GHG emissions per produced electricity obtained by previous LCA studies (Frick et al. 2010, Lacirignola and Blanc 2013, Sullivan et al. 2010, Treyer et al. 2015).

While most previous studies consider diesel-driven drilling rigs, most recent deep geothermal drilling projects, such as in St. Gallen and Basel, Switzerland, used electricity from grid as the main energy supply and diesel-generators were only kept as back-ups. However, there are also significant environmental burdens embedded in electricity from grid, which may vary considerably depending on the national electricity mix and the proportion of renewable and fossil fuel-based energy generation. The LCA study from Switzerland, which considers use of electricity from grid for drilling operations, still exhibits higher GHG emissions than the study from the USA, due to the high energy demand per borehole meter in Switzerland (Figure 2).

Beside the change from diesel-driven drilling rigs to electricity from grid, recent years have also seen new advanced drilling technologies emerging, such as hydrothermal spallation and electro-pulse drilling (Ndeda et al. 2015). These technologies also offer a potential improvement of the environmental impact from geothermal drilling in the future. However, the depth and number of boreholes needed to achieve the required reservoir temperatures and flow rates remain difficult to predict, despite recent progress in reservoir modelling and forecasting. In addition, an unknown number of additional boreholes or additional hydraulic and chemical stimulation processes might be required to maintain sufficient heat output throughout the projected life time of the EGS power plant. This uncertainty regarding drilling operations throughout the life time of an EGS plant inflicts the problem of how to consider this uncertainty in the LCA framework. Thus, a different approach to include the uncertain number and depth of boreholes is presented here, which evaluates the environmental impact of EGS power plants as a function of drilled borehole meters (Menberg et al. 2016). The resulting life time GHG emissions for different existing, projected and future EGS plants are depicted in Figure 3.

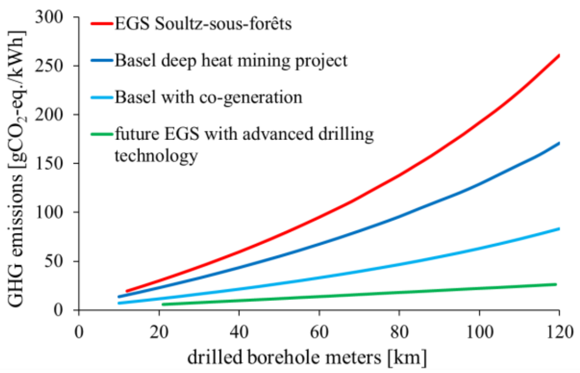

Figure 3: Life time GHG emissions from a selection of existing, projected and future EGS power plants as a function of drilled borehole meters (adopted from Menberg et al. 2016).

LCA results in Figure 3 show that though GHG emissions are increasing significantly with the number of drilled borehole meters, this trend can be reduced, for instance by applying environmental friendly drilling technologies. Compared to the EGS in Soultz-sous-Forêts (France), which represents a test site with boreholes drilled by diesel-driven rigs, the more recent, commercial EGS project in Basel, where electricity from grid was used for drilling, would yield considerably lower life time GHG emissions (assuming it would be in operation). An even better environmental improvement can be achieved when EGS plants are designed for co-generation of heat, e.g. to supply district heating. In the case of co-generation the environmental burden of the EGS plant is allocated between the produced electricity and heat leading to overall lower GHG emission per generated power and heat.

The future EGS scenario for advanced drilling technologies in Figure 3 also considers a learning effect for additional boreholes drilled in the same reservoir and accounts for more efficient EGS plant technology (Limberger et al. 2014). The low emissions and the almost linear trend with increasing number of borehole meters in this scenario highlight the potentially favorable environmental performance of future EGS power plants. The environmental impact with regard to GHG emissions of this future scenario is in the same range as the impact by nuclear power plants, which typically accounts up to about 20 gCO_2-eq./kWh. Hence, mature EGS power plants are expected to be environmentally competitive with nuclear power in terms of GHG emissions without having the unsolved issue of nuclear waste and serves as an alternative to out-phase fossil fuels for baseload power production.

3. CONCLUSIONS

Until now, only few LCA studies on geothermal power production exist with a clear concentration in California, USA. Studies specifically on EGS are even scarcer. Due to the fact that the results are site- and country-specific a global and universal assessment is still challenging. Nevertheless, this study provides an overview of major findings from existing LCA studies. In addition, existing, projected and future LCA scenarios for EGS are presented. The results clearly demonstrate the importance of total drilled borehole meters and applied drilling technologies. Using advanced drilling technologies such as hydrothermal spallation, flame jet thermal spallation and electro pulse drilling would result in similar GHG emissions as from nuclear power plants. However, as these technologies are still in testing and prototype phase, no standardized LCI assessment are available yet and therefore assessment of different environmental impact categories still have to be obtained for more comprehensive future perspectives.

REFERENCES

Bayer P, Rybach L, Blum P., Brauchler, R. Review on life cycle environmental effects of geothermal power generation, *Renewable and Sustainable Energy Reviews*, 26, (2013), 446-436.

Bayer P, Saner D, Bolay S, Rybach L, Blum P. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review, *Renewable and Sustainable Energy Reviews*, 16, (2012), 1256-67.

Bertani R. Geothermal power generation in the world 2005–2010 update report, *Geothermics*, 41, (2012), 1-29.

Frick, S, Kaltschmitt, M, Schröder, G. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs, *Energy*, 35, (2010), 2281-2294.

James R. Comparing life cycle costs and environmental performance of alternative energy, LCA XII conference presentation. Washington 2012.

Karlsdottir MR, Palsson OP, Palsson H. Factors for Primary Energy Efficiency and CO_2 Emission of Geothermal Power Production. Proceedings World Geothermal Congress 2010 Bali, Indonesia 2010. p. 7.

Lacirignola M, Blanc, I. Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment, *Renewable Energy*, 50, (2013), 901-914.

Limberger J, Calcagno P, Manzella A, Trumpy E, Boxem T, Pluymaekers M, van Wees, J-D. Assessing the prospective resource base for enhanced geothermal systems in Europe, *Geothermal Energy Sciences*, 2, (2014), 55-71.

Menberg K, Pfister S, Blum P, Bayer P. A matter of meters: state of the art in life cycle assessment of enhanced geothermal systems, *Energy & Environmental Sciences* (in review).

Ndeda R, Sebusang E, Marumo R, Ogur E. Review of Thermal Surface Drilling Technologies. Proceedings of Sustainable Research and Innovation Conference 2015, Juja-Thika, Kenya.

Saner, D, Juraske, R, Kübert, M, Blum, P, Hellweg, S, Bayer, P. Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems. *Renewable and Sustainable Energy Reviews*, 14(7), (2010), 1798-1813.

Sullivan, JL, Clark, CE, Han, MWJ. Life-cycle analysis results of geothermal systems in comparison to other power systems, Argonne National Laboratory, Energy Systems Division, US Department of Energy, 2010.

Treyer, K, Oshikawa, H, Bauer, C, Miotti, M. In Energy from the Earth - Deep Geothermal as a Resource for the Future, Eds. Hirschberg, S, Wiemer, S, Burgherr, P. Centre for Technology Assessment Zurich, Switzerland, 2015, vol. TA-SWISS 62/2015, p. 524.

Acknowledgements

The authors acknowledge the financial support by the Competence Center Energy and Mobility and the Competence Center for Environment and Sustainability of the ETH-Domain for the GEOTHERM-2 Project.