



Cite this: *Energy Environ. Sci.*, 2016, 9, 2720

A matter of meters: state of the art in the life cycle assessment of enhanced geothermal systems†

Kathrin Menberg,^{a,abc} Stephan Pfister,^d Philipp Blum^b and Peter Bayer^e

This work presents a review of the studies applying life-cycle assessment (LCA) methodologies to evaluate the environmental performance of enhanced geothermal systems (EGSs). Due to the scarcity of commercially installed EGS power plants such studies are rare and usually represent very site-specific conditions and plant characteristics. A detailed inspection of the outcome of these studies shows that the major environmental impacts of the investigated EGS plants are caused by the drilling of geothermal wells during construction. However, recent developments in environmentally friendly drilling technologies, which up to now have only marginally been considered in LCA studies, will provide opportunities to reduce the impact by drilling. Our analysis reveals that the use of electricity from a grid instead of diesel to drive the drilling rigs can improve the environmental performance of EGS plants significantly, provided that the employed electricity is supplied by environmentally friendly technologies. The largest share of uncertainty in the LCA of EGS plants is consequently linked to the incalculable number of boreholes that need to be drilled during the life-time of the plant in order to sustain efficient power production. From the LCA perspective, however, the power needed to drill these additional boreholes can be subtracted directly from the power production of the EGS plant. Under this presumption the examination of greenhouse gas emissions of EGS plants as a function of drilled borehole meters shows that even EGS plants with a large number of deep wells can be competitive in terms of environmental effects compared to conventional energy technologies. When predictions of technological improvements in geothermal drilling and plant design are taken into account, future EGS power plants are prone to have the potential to perform environmentally better than most other renewable energy technologies.

Received 8th April 2016,
Accepted 26th July 2016

DOI: 10.1039/c6ee01043a

www.rsc.org/ees

Broader context

Enhanced Geothermal Systems (EGSs) are considered as one of the most promising options for utilizing the vast energy resources stored in the interior of the earth to generate electricity. With the operation of a few field scale applications so far, not only could the viability of this technology be demonstrated but also, a more reliable assessment of the environmental performance is now possible. This study reviews the state-of-the art in the life cycle assessment (LCA) of EGSs, and compares the carbon footprints of past, present and future technologies. Based mainly on central European case studies, it is revealed that through improvements in the drilling technique, modern EGSs are among the most environmentally favourable power generation technologies. This work also highlights the difficulty when defining a general EGS design and the high uncertainty in performance prediction. By taking the total borehole meters drilled (the most relevant uncertain parameter) as an unknown, a transparent environmental assessment is facilitated. This approach demonstrates that with the technologies available now, several tenths of borehole kilometres could be drilled, but the GHG generated from geothermal power would still not reach the environmental impacts associated with the electricity mix of countries such as Switzerland, Germany or the USA.

^a Department of Earth Sciences, Swiss Federal Institute of Technology, Sonneggstrasse 5, 8092 Zurich, Switzerland. E-mail: kcm30@cam.ac.uk, bayer@erdw.ethz.ch

^b Institute for Applied Geosciences, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany. E-mail: philipp.blum@kit.edu

^c Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK

^d Institute for Environmental Engineering, Swiss Federal Institute of Technology, John-von-Neumann-Weg 9, 8093 Zurich, Switzerland.
E-mail: stephan.pfister@ifu.baug.ethz.ch

^e Institute of New Energy Systems, Ingolstadt University of Applied Sciences, Esplanade 10, 85049 Ingolstadt, Germany. E-mail: Peter.Bayer@thi.de

† Electronic supplementary information (ESI) available: Tables SI1–SI3, Fig. SI1 and SI2. See DOI: 10.1039/c6ee01043a

Introduction

The utilization of the energy stored in the ground for the generation of electricity is receiving growing interest among the currently available renewables.^{1–3} The worldwide installed capacity for the production of geothermal power in 2015 is 12.6 GW_{el} electricity. This capacity has increased only moderately (by 16%) during the last five years; growth rates of around 70% are predicted by 2020.⁴ By 2050, a supply of 8.3% of the world's total electricity production is deemed to be possible and is associated with annual CO₂ savings of around 1000 Mio. tons.^{5,6}

These numbers reflect that so far only a very small fraction of the enormous amount of thermal energy in the Earth's crust is being extracted. One crucial aspect is that under average geological conditions, the shallow ground temperature is low.⁷ It increases with depth, but usually only by 25–30 °C km⁻¹. This means temperatures of 150 °C and higher are found at depths of at least 5 km, and these regions can only be accessed by costly boreholes. Harnessing geothermal energy at those few geologically young places in the world is economically more attractive, often where volcanism exists and geothermal gradients are exceptionally high. Accordingly, the western USA, Philippines, Indonesia, Mexico and New Zealand dominate the currently installed worldwide capacity.⁴

Even if modern techniques facilitate drilling deep boreholes, there typically exists a great uncertainty about the settings at such depths.^{8,9} This uncertainty refers to the *in situ* thermal conditions as well as to the (hydro)geology of the target reservoir. Ideally, hot groundwater or geofluid can be extracted and circulated,

but such productive deep hydrothermal reservoirs are only locally present. As an alternative, so-called Enhanced or Engineered Geothermal Systems (EGSs) have been suggested.^{3,10–12} The main principle is to inject cold water into the hot and dry rock of the crystalline basement; this way the water serves as an artificial heat carrier. The heat transported by the circulating water can be converted into electrical power aboveground in a binary conversion cycle containing a working fluid with a low boiling point. Due to the typically low temperature of the heat source, direct use of the geothermal fluid in a power conversion cycle is not efficient from a thermodynamic perspective. If the encountered reservoir temperatures are sufficiently high, direct utilization with flash technology would also be feasible for EGS power plants.

In order to create sufficient permeability and a contact surface for heat exchange in the deep underground, different ways of rock mass stimulation are discussed.^{13–15} Stimulation is essential for enhancing the accessibility to a sufficient volume of



Kathrin Menberg

modelling of geoenery, and energy and exergy performance simulation of renewable energy systems.

Kathrin Menberg (born in 1985) is a postdoctoral research associate at the Engineering Department at the University of Cambridge. From January to June 2014 she worked as a postdoctoral researcher at the Department of Earth Sciences at ETH Zurich. She received her doctoral degree from Karlsruhe Institute of Technology in 2014, where she had graduated in 2010 at the Institute for Applied Geosciences. Her research interests are in environmental aspects and



Stephan Pfister

one-year post-doc at UC Santa Barbara in 2011 and has published more than 40 scientific original research papers.

Stephan Pfister (born 1980) is a senior research associate at ETH Zurich in the group of Ecological Systems Design (since 2012). His methodological focus is on the impact assessment of water consumption and land use in Life cycle Assessment (LCA) with applications to agriculture and power production. In this context, he advanced water footprint concepts, including future assessments and international trade. He obtained his PhD in 2011 from ETH Zurich, did a



Philipp Blum

assistant professor. Since 2010 he has headed the engineering geology research group at the KIT. He has published more than 100 scientific papers on various topics in applied geology.

Philipp Blum (born in 1972) is a professor of Engineering Geology at Karlsruhe Institute of Technology (KIT), Germany. In 2000 he received his MSc degree in Applied Geology at the former University of Karlsruhe (now KIT). In 2003 he obtained his PhD in Earth Sciences at the University of Birmingham, UK. Afterwards he worked for an engineering consultancy. In 2006 he joined the University of Tübingen (Germany) as an



Peter Bayer

published widely in these areas and has authored more than 100 scientific papers and a text book on the thermal use of shallow aquifers.

Peter Bayer (born in 1972) is a professor in Geothermics at the Ingolstadt University of Applied Sciences, Germany. He graduated in 1999 at the University of Tübingen (Germany) and earned his PhD from the same institution in 2003. By early 2016 he was a senior research associate at the Department of Earth Sciences at ETH Zürich. The focus of his research is on multifaceted aspects in geoenery, groundwater and environmental sciences. He has

a reservoir, but is also the most critical step due to the risk of inducing seismic events.^{16,17} Published induced seismic magnitudes range between -1 (Groß Schönebeck) up to 4.4 (Berlin, El Salvador).¹⁸ Their mitigation and control represents a major challenge in research and development. This sensitive aspect, together with little experience in geothermal stimulation and typically high investment costs, explain why the development of EGSs is still at an early stage and why mainly pilot plants are operated and planned. Additionally, the long term consequences on the environment of such innovative geothermal utilizations are still not completely known.¹⁹

Currently, generating electricity by EGSs is promoted as a renewable variant with high potential in the future.^{3,20,21} EGSs are favourable over conventional geothermal power production due to the minor site-specific requirements. EGSs can conceivably provide reliable and continuous base load energy for decades. In contrast to wind and solar energy, EGSs are independent of weather and seasons. Due to the progression from a premature to an economically attractive and environmentally friendly technology, several countries have installed or plan to install test facilities, such as the USA, Canada, France, Iceland, Germany, China, Australia.^{4,22–27} The geological environments and thermal ground conditions for these EGS installations are diverse, therefore the technologies' configurations, borehole numbers and depths, capacities and performance are as well. This, however, makes it difficult to define a representative reference case for a generalized technological assessment and for an economic or environmental comparison to alternative power production technologies.

EGS power plants with binary cycles for power conversion represent closed systems and are often considered environmentally friendly or nearly CO₂-neutral.^{3,28,29} This is in contrast to conventional geothermal power plants using other conversion technologies, such as single- or double-flash plants. For many conventional applications, release of CO₂ and other non-condensable gases (NCGs) from geothermal boreholes has been reported.^{30,31} These direct emissions may dominate the overall environmental impact of a power plant. In the case of the absence of direct release, overall environmental impacts are smaller. Indirect emissions and resource use, like those associated with materials and processes used for construction, may become more important. For holistic and combined analysis of often miscellaneous environmental effects, life cycle assessment (LCA) based frameworks are most suitable. They follow internationally standardized procedures for quantifying the environmental impact during the full life cycle of products or services. While the focus is often set on greenhouse gas (GHG) emissions and carbon footprints, LCA facilitates a concerted view on a broad range of environmental effects and impact categories.

Existing LCA studies on EGSs show significant differences that exhibit large variations in estimated environmental impacts in terms of GHG emissions and cumulative energy demand per kW_{el} produced.^{32–37} A major reason for these differences is that no unique and valid EGS reference case exists. Each analysis is based on different case-specific assumptions or idealized conditions.

For example, Frick *et al.* and Lacirignola and Blanc develop their scenarios based on data from an exhaustive survey of both German geothermal projects and the plant at Soultz-sous-Forêts.^{32,33} The report by Treyer *et al.* refers to Switzerland and is oriented toward deep drilling projects in Basel and St. Gallen, and the analysis of Sullivan *et al.* is based on the conditions in the USA.^{34,35} In some studies, modified approaches are presented. Gerber and Maréchal evaluate optimal EGS design with respect to environmental and economic criteria, while Pehnt and Lacirignola *et al.* propose streamlined LCA models.^{36–39} Finally, a major reason for the inconsistency and diversity of the available environmental assessments is the limited long-term experience with EGSs. Thus, LCA can only be prospective, which results in substantial uncertainty from predictions done on long-term system performance.

Our work represents a review of the findings from existing LCA studies. The objective is to provide an overview and a comprehensive explanation of the differences in the quantified environmental impacts. For this, we scrutinize the environmentally relevant plant components and characteristics identified by previous studies. This covers the technological and geological assumptions for the different EGSs, the assembled life cycle inventories and the selected impact categories. The review of previous work is complemented with an analysis of the environmental impacts of EGSs under consideration of current developments and innovations such as environmentally friendly drilling technologies. While past studies consider diesel-driven drilling rigs and some present studies assume the use of electricity from a grid, the prospective LCA for the future scenarios in our study takes into account evolving drilling technologies, such as hydrothermal spallation and electro pulse drilling. Our ultimate goal is to use the compiled insight for a more robust and generally applicable assessment. This is tackled by threshold-based analysis including uncertainty assessment, rather than diverse scenario analyses.

Within the generated framework, comparison of EGSs to other non-renewable and renewable energy generation technologies is facilitated.

Enhanced geothermal systems

Enhanced geothermal systems (EGSs) are engineered heat exchangers in deep rock formations (>500 m) with high temperatures (>150 °C). In these formations initial permeabilities are generally low and therefore have to be artificially enhanced by hydraulic fracturing, high flow rate injections and/or chemical stimulation.^{40–42} After the successful enhancement of the reservoir (*i.e.* increased permeability), geothermal water is circulated in the newly engineered heat exchanger, providing heat for power generation and/or heat supply. In 1973 the first EGS experiments were performed in Fenton Hill (USA) and followed by various feasibility studies in Japan. DiPippo and Breede *et al.* give overviews of both worldwide EGS projects at various stages and installed geothermal power plants.^{18,43} A selection of ongoing electricity generating EGSs, including their key characteristics, is provided in Table 1.

Table 1 Selected enhanced geothermal systems (EGSs) generating electricity and key characteristics (data taken from Breede *et al.*)¹⁸

Country	Project	Maximum depth (m)	Maximum temperature (°C)	Temperature gradient (°C km ⁻¹)	Number of wells	Drilled borehole meters (m)	Production flow rate ^a (m ³ s ⁻¹)	Installed plant type	Installed electrical capacity (MW _{el})
USA	Desert Peak	1062	196	178	> 3	> 3300	0.1	Binary	1.5 ^f
USA	Coso	2956 ^h	298	85–120 ⁱ	~ 100 ^h	~ 200 000 ^j	—	Double flash	270
France	Soultz-sous-Forêts	5093	203	40	5	21 260 ^b	0.02–0.035	Binary	1.5 ^g
France	Bouillante	2500 ^k	260 ^k	250	3	4700 ^k	0.17 ^l	Double/single flash	15 ^k
Germany	Landau	3300	159	48	2	6470	0.055	Binary	1.8 ^d
Germany	Bruchsal	2535	131	52	2	4474 ^m	0.025	Binary (Kalina)	0.55
Japan	Hijiori	1910	270	117	3 ^c	6811 ^c	0.017	Binary	0.13
Italy	Larderello	4000	350	88	> 500 ⁿ	—	0.1	Dry steam	700
El Salvador	Berlin	2380	183	77	34 ^o	—	0.13 ^p	Flash and binary ^b	109 ^o
Australia	Cooper basin	4421	278	63	6 ^e	25 895 ^e	0.03	Binary (Kalina)	1

^a After enhancement. ^b Five wells (EPS1, GPK1–4).²⁶ ^c Deep reservoir only. ^d Average (2008–2012).⁴⁵ ^e Bendall *et al.*⁴⁶ ^f Chabora *et al.*⁴⁷ ^g Feng *et al.*¹¹ ^h Julian *et al.*⁴⁸ ⁱ Monastero and Unruh.⁴⁹ ^j Estimated with an average drilling depth of 2000 m. ^k Sanjuan *et al.*⁵⁰ ^l From which 0.03 m³ s⁻¹ are steam. ^m Meixner *et al.*⁵¹ ⁿ Minissale.⁵² ^o Reyes,⁵³ including 2 monitoring wells. ^p Based on 14 productions wells and an average production rate of 33.1 t h⁻¹ per well provided by Herrera *et al.*⁵⁴

Usually a minimum of two deep wells (an injection and a production well) is required. Typical well depths are > 3 km, resulting in total drilled borehole lengths of at least 6 km or even up to about 200 km (the Coso geothermal field in the USA). According to Jung, economic flow rates for an EGS doublet system should be between 0.05 and 0.1 m³ s⁻¹ and produce 3 to 10 MW_{el} over a life time of at least 25 years.⁴⁴ The installed electrical capacity of most EGSs shown in Table 1 is however still rather low, indicating the low economic efficiency of the currently installed systems. In addition, recent projects have been suspended due to induced seismicity during hydraulic stimulation. In Basel and St. Gallen (Switzerland) for example, both planned EGS projects were suspended due to seismic events and low flow rates. In St. Gallen, the maximum achieved flow rate was only 0.012 m³ s⁻¹ and therefore too low for economic operation.

Nevertheless, when flow rates and temperatures are sufficient, several energy conversion technologies such as dry steam, flash steam and binary cycles are typically available.⁴³ For EGS projects two types of binary systems are currently installed: (1) the organic Rankine cycle (ORC) and (2) the Kalina cycle (Table 1). Most EGS projects are, however, operated with ORC power plants, which use organic working fluids such as propane (C₃H₈), isopentane (C₅H₁₂) or isobutene (C₄H₁₀). In contrast, few Kalina cycle power plants, which commonly use a mixture of 5–30% water and 70–95% ammonia (NH₃) as a working fluid, are in operation. The typical system components of binary cycle power plants are a heat exchanger, turbine, generator, condenser, cooling tower and grid connection.

Methodology of life cycle assessment

LCA is a methodology according to ISO 14040 and ISO 14044 for describing all life cycle phases of a product or service, including supply chain activities, production, and use and disposal, and for assessing related emissions and resource uses.^{55,56} It requires comprehensive data analysis, and it facilitates the simultaneous consideration of different environmental safeguard subjects or impact categories, such as global warming, toxicity

and resource depletion. LCA studies are diverse, since the scope and system boundaries are flexible and adjusted to the specific study case. A broad range of spatially and temporally different data types are combined, and environmental burdens may be computed and interpreted in different ways. Comparability is facilitated by following a standardized four stage procedure and by sharing common data inventories.

The first stage defines the goal and scope. For an EGS this means that the objective of the environmental assessment has to be pre-defined and system boundaries delineated. For example, the objective here is to examine geothermal power and heat generation from low temperature reservoirs, while including construction, reservoir enhancement, plant operation and decommissioning.

In previous LCA studies the major EGS power plant components are included, but the grid connection is not explicitly considered.^{32–35} This system boundary is also included in our study. The so-called functional unit serves as a reference for comparisons, which, in this case, is the generation of 1 kW h_{el} of net power at the plant and co-generation of 1 MJ_{th} heat. Since this share is different for each study case, allocation for plants with heat co-generation is needed. All system inputs and outputs can be evaluated with regard to 1 kW h_{el} net power or to 1 MJ_{th} produced heat. Existing allocation schemes for co-generation are mostly based on the exergy content of the generated electric and thermal energy.⁵⁷ This is also done in our work, where we follow the same allocation procedure as Frick *et al.*³²

The second stage is the life cycle inventory analysis (LCI), where all mass and energy flows are collected. This is often accomplished by utilizing existing databases, especially for background processes (*e.g.* the production of bentonite used for borehole construction). Among the most commonly used data sets are those provided by Ecoinvent, and these are also employed in our study.^{58–60} The next stage, life cycle impact assessment (LCIA), is conducted for the quantification of environmental effects. This is accomplished by applying characterization factors to emissions and resource consumption (environmental exchanges) quantified in the LCI and aggregation of the characterized results to different impact categories. For example, greenhouse gas emissions of all life cycle stages

are expressed in CO₂-equivalents and summed to estimate the global warming potential. LCIA utilizes methodologies with comprehensive sets of characterization factors such as ReCiPe and IMPACT 2002+.^{61,62} Finally, the last stage follows the interpretation dedicated to the discussion of environmental effects while reflecting on the assumptions made in the previous LCA stages. This might lead to revisions in the other three stages; therefore LCA typically is an iterative process.

Review of LCA studies on enhanced geothermal systems

Methodological and technological aspects of previous studies

In order to facilitate a comprehensive discussion and interpretation of the varying results given by existing LCA studies on EGSs, the methodological and technological differences among the latter have to be assessed in detail. These aspects are scrutinized in this chapter with a focus on the differences in scope, analysed scenarios and applied LCA techniques. The compiled LCIs and investigated scenarios of these studies are essential for the comparative interpretation and will be discussed in the following section. Among the existing LCAs, there are four studies which stand out regarding the level of detail in methodology, the availability of data used, and comprehensive presentation of the results.^{32–35} These four studies cover a variety of geographical settings and therefore differ significantly in the assumed conditions of the geothermal reservoir and the proposed EGS power plant design (Table 2).

The first extensive study using a LCA approach to quantify the environmental impact of EGS was performed by Frick *et al.*³² The two base case scenarios that are presented are distinguished by reservoir and plant design parameters, and refer to the average expected geothermal conditions in Central Europe. The plant design parameters, such as power capacity and conversion efficiency, are specified through thermo-physical models based on the assigned geothermal reservoir characteristics.⁶³ Best and worst case scenarios are defined by varying the geothermal and plant parameter values of the base case according to conditions under which the utilization of geothermal energy is still deemed possible by technological means. Besides dedicated power production, all scenarios are also examined for plant scenarios with co-generation of heat, which is assumed to feed into a district heating network. The study by Frick *et al.* and most other LCA studies on deep geothermal energy follow a “cradle-to-grave” approach and thus also take into account the environmental emissions caused by decommissioning and demolition of the power plants.³²

The LCI for EGS elaborated by Frick *et al.* is based on parameter values from a detailed literature survey.³² In particular, technical reports from existing and operating deep geothermal projects were used, *e.g.* hydrothermal power plants in the German Molasse Basin, as data for EGSs were very scarce in 2010.⁶⁴ For this report, the environmental burden of background processes, such as the transportation and utilization of construction equipment, and used materials, such as steel and diesel, are taken from the Ecoinvent database 2.0.⁵⁸

Although there are no direct environmental impacts, such as emissions of greenhouse gases (GHG), during the operation phase of an EGS power plant, indirect environmental burdens are embedded in the materials and processes needed during plant operation. Several sources of indirect environmental impacts, such as exchange of downhole pumps, make-up water for the geothermal cycle and exchange and disposal of filters, are included in the LCI by Frick *et al.*³² Also the electricity consumption by the downhole pumps, as a function of the geothermal flow rate, and additional energy needs for cooling during operation are accounted for in the LCI. This electricity consumption is allocated with the electricity produced by the binary cycle leading to an offset between the gross power output and the net power output that is supplied to the grid. If not stated otherwise, energy and electricity production values in this study refer to the lifetime net energy generation of the power plants.

Uncertainties in the values of these processes and materials are included in the LCI, and these are taken for assessing different EGS variants in a scenario analysis. The LCI and plant designs are also adopted for two European case studies in a book chapter by Frick *et al.*⁶⁵

Similar to Frick *et al.*, the second comprehensive LCA presented by Lacirignola and Blanc compares the results for different scenarios in order to account for the substantial uncertainty in crucial design parameters (Table 2).^{32,33} Their base case refers to the EGS plant in Soultz-sous-Forêts, France. In nine extra scenarios the role of the reservoir depth, number of boreholes, production temperature and flow rate are varied around typical central European geothermal and geological conditions (Table 2). Ecoinvent 2.2 serves as a basis for the assessment of background processes.^{33,59} Data for the construction and operation of the Soultz-sous-Forêts power plant are collected from the literature, reports and personal communications. While the LCI of Frick *et al.* and Lacirignola and Blanc are comparable, and similar uncertainty ranges of 10–40% for inventory data are assumed, there is one fundamental difference: both studies assume a similar diesel-based technology for drilling, but the amount of diesel consumed in Lacirignola and Blanc is around half of that in Frick *et al.*^{32,33}

A speciality of Lacirignola and Blanc is that the risk of seismicity is included as an extra environmental indicator.³³ They propose an empirical estimation (very low to very high risk) based on the ratio of the geothermal flow rate to the number of reinjection wells. This concept thus represents an indirect consideration of fluid pressure at reinjection based on observations by Cuenot *et al.*⁶⁶ However, though discussed, the risk of seismicity during reservoir stimulation is not integrated in the life cycle impact assessment (LCIA).

In a report by the Argonne National Laboratory, Sullivan *et al.* assess and compare CO₂-emissions and the primary energy use of geothermal energy in comparison to other non-renewable and renewable energy technologies (Table 2).³⁴ In addition to binary and flash hydrothermal scenarios for conventional geothermal power plants, results for a variant of EGS are presented. Calculations are performed with the LCA

Table 2 Overview of previous LCA studies on EGS plants. The ranges given for the values describe the variation in the parameters in the different scenarios analysed by the respective studies. Values in brackets refer to scenario A1³², the Soultz-sous-Forêts base case scenario³³ and the base case with medium capacity³⁵, which are evaluated in detail in the following chapters. Sullivan *et al.* analysed only two scenarios with a capacity of 20 and 50 MW, respectively, for which the corresponding parameter values are given³⁴

	Frick <i>et al.</i> ³²	Lacirignola and Blanc ³³	Sullivan <i>et al.</i> ³⁴	Treyer <i>et al.</i> ³⁵
Geographical reference	Germany	Upper Rhine Valley	Southwest US	Switzerland
Time reference	2006	n.a.	2010	n.a.
Functional unit	1 kW h _{el} (per net electricity)	1 kW h _{el} (per net electricity)	1 kW h _{el} (per net electricity)	1 kW h _{el} (per net electricity)
LCI database	Ecoinvent 2.0	Ecoinvent 2.2	US LCI database	Ecoinvent 2.2 (3.0)
LCI data available	Yes	Yes	No	Partly
System boundary	Connection to grid	Connection to grid	Connection to grid	Connection to grid
Life-cycle stage considered	Construction Operation Decommissioning	Construction Operation Decommissioning	Construction Operation	Construction Operation Decommissioning
Impact assessment method	CED, CO ₂ [−] , SO ₂ [−] , PO ₄ ^{3−} eq. in Ecoinvent 2.0	IMPACT 2002+	Energy ratio ϵ_{pec} , CO ₂ eq.	ReCiPe (H) Midpoints Europe
Number of scenarios	4	10	2	3
Reservoir (well) depth [km]	2.9–7.0 (3.8)	2.5–4.0 (4.0)	4.0–6.0	5.0–6.0 (5.0)
Reservoir temperature [°C]	98–200 (125)	145–165 (165)	150–225	165–255 (175) ^b
Reservoir stimulation	Hydraulic	Hydraulic and chemical	Hydraulic	Hydraulic
Flow rate [m ³ s ^{−1}]	0.03–0.14 (0.07)	0.02–0.14 (0.04)	0.03–0.09 <i>ca.</i> 20–67 ^a	0.15
Number of wells	2 (2)	2–3 (3)	<i>ca.</i> 20–67 ^a	3–6 (6)
Exploration wells	No	No	Yes	No
Well replacement	No	No	Yes	One triplet
Distance between wells [m]	1500	1500	600–1000	n.a.
Reinjection pump	No	Yes	Yes	n.a.
Binary working cycle	ORC	ORC	n.a.	ORC
Conversion efficiency ORC [%]	8.6–13.6 (9.7)	10.4–12.0 (12.0)	n.a.	13–17 (14)
Power capacity [MW]	0.46–11.1 (1.75)	1.14–5.46 (2.28)	20–50	2.9–14.6 (5.5)
Full load hours [h per year]	6000–8000	8000	8624	8363
Co-generation of heat	Optional (no)	No	No	Optional (no)
Auxiliary power need (ORC) [kW]	460	20% of net power	n.a.	Allocated with energy production
Auxiliary power need downhole pump [kW (m ³ h ^{−1}) ^{−1}]	1.3	1.5	n.a.	Allocated with energy production
Auxiliary power need reinjection pump [kW (m ³ h ^{−1}) ^{−1}]	No	1.0	No	No
Geothermal fluid return temperature [°C]	60	70	n.a.	n.a.
Cooling technology	Cooling tower	Air cooling	Air cooling	Air cooling
Technical lifetime [years]	20–40 (30)	25	30	20–30 (30)
Replacement/maintenance of equipment	Yes	n.a.	n.a.	n.a.
Make-up water	3 (m ³ h ^{−1}) per MW	n.a.	n.a.	n.a.
Working fluid losses	n.a.	n.a.	n.a.	8% per year
Disposal of hazardous materials from filters [kg per year]	1–1.4 kg (m ³ h ^{−1}) ^{−1}	1.1 kg (m ³ h ^{−1}) ^{−1}	n.a.	No

^a Calculated based on values of plant design and drilling data given in Sullivan *et al.*³⁴ ^b Calculated based on the geothermal gradients (30–40 °C km^{−1}, 35 °C km^{−1}) and the reservoir depths given in Treyer *et al.*³⁵

software GREET with a background inventory that is partly from the U.S. LCI database.⁶⁷ The LCI for the power plant is based on the ICARUS Process Evaluator for plant material composition. The design of the geothermal well field (*e.g.* number of wells) is derived by computation with GETEM (Geothermal Electricity Technology Evaluation Model),⁶⁸ and parameter settings for geothermal well construction are oriented at Tester *et al.*³

As noted by Sullivan *et al.*, the major differences in their LCI in comparison to Frick *et al.* are the lower amounts of concrete and cement, and the approximately eight times higher amount of diesel used for drilling in Frick *et al.*^{32,34} While well numbers in Frick *et al.* and Lacirignola and Blanc are defined in different

scenarios, Sullivan *et al.* also account for exploration wells and well replacement during operation due to thermal drawdown of the reservoir.^{32–34} In their conventional approach, exploration wells require the same materials as production wells. In contrast to the other studies, Sullivan *et al.* propose a “cradle-to-gate” LCA and thus neglect decommissioning and recycling.³⁴ Further reports of this working group elaborate in more detail on the specific aspects of their LCA for geothermal power plants. The study by Sullivan *et al.* is dedicated to the environmental evaluation of geo-pressured gas and electric (GPGE), *i.e.* the co-generation of geothermal energy and natural gas.⁶⁹ Clark *et al.* focus on water use in different energy production technologies, including EGS.⁷⁰

The most recent detailed LCA in this field is presented by Treyer *et al.*, which scrutinizes energy production and environmental impacts associated with hydrothermal and EGS under various conditions in Switzerland (Table 2).³⁵ LCI datasets for geothermal power generation are provided by Treyer and Bauer.⁷¹ Background processes are described using Ecoinvent 2.2.⁵⁹ The underlying data for material and energy consumption are related to the (stopped) geothermal projects in Basel or St. Gallen, *e.g.* the use of cement and steel for specific casing schemes, the volume of drilling fluids used, *etc.* The amount of energy consumed during drilling is calculated based on Legarth and Saadat accounting for different rock types, well depth and diameter.⁷² Here, the drilling technology is different to the other LCA studies. Based on experience from previous projects in Switzerland, electricity from the grid is considered as an energy source for drilling rigs. The LCI is integrated in a LCA model that is coupled with a physical model that calculates plant power capacity based on geological and plant specific information, such as the geothermal gradient and the well depth. As a result, three scenarios are presented to distinguish low, average and high capacity for power plants associated with different geothermal reservoirs, well designs, and additional co-generation.

A few other EGS studies exist, which have less detail for the description of data and assessment, or which build upon those fundamental studies listed in Table 2. For example, in their streamlined approach, Pehnt compares GHG emissions for renewable energy technologies in Germany for the year 2010 and in a future perspective for 2030.³⁷ Here, among others, the findings for geothermal energy (hot dry rock, HDR) are listed. The LCI is set up by means of the IFEU database, complemented with literature data, and modelled with the software Umberto.³⁷ Different results for the future case are caused by projected technological developments (*e.g.* improved efficiency in the production of raw materials), by predicting increased efficiency of most energy generation technologies, and by assuming an electricity mix in 2030 with significantly reduced GHG emissions.

Lacirignola *et al.* suggest a simplified LCA model for EGSs based on the LCI with Soultz-sous-Forêts data from previous studies.^{33,38} This variant was conceived as an easy-to-use tool for stakeholders and decision-makers to roughly estimate project-related greenhouse gas emissions (*i.e.*, the carbon footprint). The number of model input parameters can be reduced to three key parameters, namely the drilling depth, number of wells and installed capacity. The model is verified with data and results from related comprehensive LCAs.^{32,33,73} Uncertainty is accounted for by performing Monte-Carlo simulations with given input parameter ranges.

Gerber and Maréchal and Gerber *et al.* integrate LCA into a framework for the multi-objective optimal design and configuration of geothermal systems.^{36,74} Again, focus is set on GHG emissions, which are computed for a chosen plant design that is simulated by a thermo-economic model. They adopted most of the LCI from Frick *et al.*³² No uncertainties or ranges in LCI data are accounted for and EGSs are assumed to be a mature technology with borehole depths reaching 10 km. The optimization is applied to minimize investment

costs, to maximize annual revenue and exergy efficiency, and to optimize the environmental performance.

Environmental impacts of EGS power plants

The LCA results of the studies listed in Table 2 and of the streamlined approach by Pehnt are displayed in Fig. 1.^{32–35,37} We present four common impact categories: global warming potential, non-renewable energy demand, acidification and eutrophication potential. The latter two are not addressed by Sullivan *et al.*, and Treyer *et al.* offer no assessment of the non-renewable energy demand.^{34,35} In order to make the result of the impact assessment by the different studies comparable, we used the LCI given in Lacirignola and Blanc to calculate the environmental impact with the aggregation method given in Frick *et al.*^{32,33} The difference between the original values for climate change (global warming potential) and resources depletion calculated using the IMPACT 2002+ method and the values in this study are in all cases less than 10%. Sullivan *et al.* do not describe their method of calculating CO₂-equivalent emissions and finite energy demand in detail. However, they state that the discrepancy in the results from different methods, due to different weighting factors, is usually within a few percentage points, which is supported by our observations of the different LCIA of Lacirignola and Blanc.^{33,34} Thus, it seems unlikely that the slightly different weighting factors assigned in the impact assessment by Treyer *et al.* and Pehnt have an effect on the ranking of the results in Fig. 1.^{35,37}

All studies propose different scenarios and so the base cases from Frick *et al.*, Lacirignola and Blanc and Treyer *et al.* (Table 2) were chosen.^{32,33,35} From Sullivan *et al.* we compute the mean values of the presented two scenarios, and from Pehnt the average value of the scenarios is also calculated.^{34,37} The error bars depicted in Fig. 1 reflect the complete range of results from the different scenarios in the respective studies. Depending on the underlying scenario parameters, plant concepts and inventories, differing final impact values are found. For comparability, no co-generation of heat is assumed, because this is only included by Frick *et al.*³² As a general finding, the mean figures provided by Frick *et al.* are always the highest ones, and Sullivan *et al.* estimate the lowest impact.^{32,34} The reasons for these discrepancies will be further scrutinized in the following section.

The scenarios presented by Frick *et al.* are very diverse, with capacities ranging between 0.5 and 11.1 MW_{el} and well depths between 2.9–7.0 km (Table 2).³² This explains the long error bars for all impact categories in Fig. 1. The minimum values correspond to the best case scenario and the maximum values to the worst case scenario. The GHG emissions of the worst case scenario reach 754 g CO₂-eq. per kW h_{el} and are comparable to emissions from conventional energy generation based on fossil fuels, such as coal or oil combustion (for detailed comparison see chapter on environmental performance of energy technologies). The reasons for such extraordinarily high emission values are obviously due to the parameters chosen for this plant design outlet in addition to the assumed unfavourable EGS geothermal site conditions, such as 110 °C at 5 km depth and a flow rate of only 0.027 m³ s^{−1}. Since these conditions render this scenario

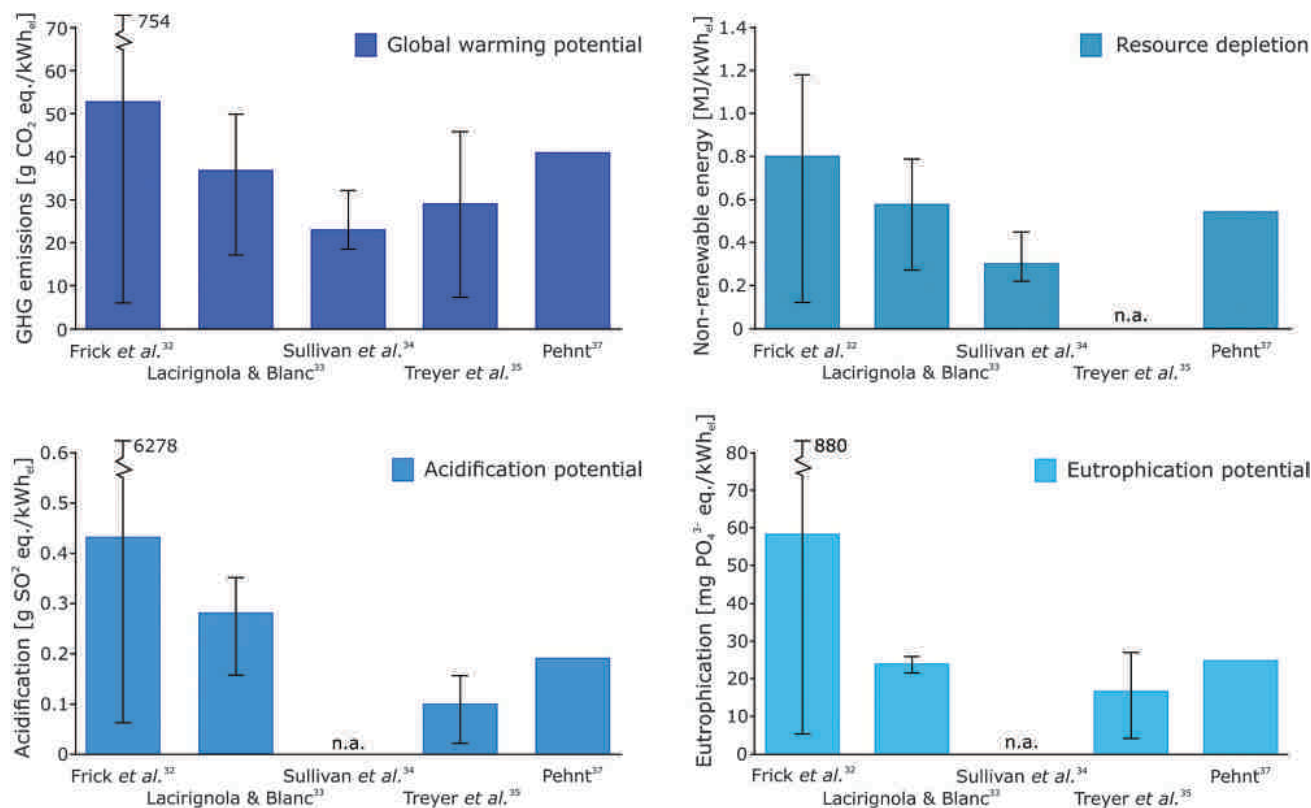


Fig. 1 Results for the environmental effects of EGS plants analysed by previous studies.^{32–35,37} Environmental effects not assessed by individual studies are marked with 'n.a.'. The height of the bars indicates the mean value from the different scenarios considered in each study. The whiskers refer to the minimum and maximum values obtained by scenario analysis in the individual studies.

economically unfavourable, however, such plants will hardly be realized in practice. Also, the assumed technical life time of the power plants differs in the individual scenarios, which will inherently increase the life time GHG emissions for plants with a shorter life time, as the absolute environmental burden of the construction phase remains equal.

A sensitivity analysis for environmental assessment in the form of a parameter study identifies the reservoir temperature (and its long-term decrease) as the most sensitive parameter, since it is crucial for the amount of energy produced due to the dependency of the conversion efficiency on the fluid temperature.³² Furthermore, the importance of the geothermal fluid flow rate and auxiliary power needs, *e.g.* for downhole pumps, is also emphasized. The largest share (>85%) in all evaluated impact categories is associated with the subsurface components during the construction phase of the plant, *i.e.* the deep geothermal wells and in particular the energy used for drilling the boreholes. In view of its relevance, we examine further details on the type and amount of energy used during drilling activities in the next chapter. In comparison, only a minor role is played by the decommission phase (<1% of overall emissions). This apparently is also the reason why this last life cycle stage was neglected by most of the other studies.

The LCA by Lacirignola and Blanc is comparable to that by Frick *et al.*, with similar geographical focus, reservoir characteristics, power plant design (Table 2), and also inventories.^{32,33}

In Fig. 1, the derived ranges by Lacirignola and Blanc of the four impact category indicators are smaller because their scenarios are less diverse and somewhat less extreme configurations are analysed.³³ The main difference from Frick *et al.* (as also identified by Lacirignola and Blanc and Sullivan *et al.*) is a lower amount of diesel assigned for drilling operations.^{32–34} Given the importance of well construction for the full life cycle, this has a significant effect on the total calculated impacts. For example, GHG emissions are only around 35 g CO₂-eq. per kW h for their base case, while emissions are over 50 g CO₂-eq. per kW h for Frick *et al.*^{32,33} In all impact categories, smaller values are obtained.

The study reported by Lacirignola and Blanc gives a detailed account of the individual background processes and substances affecting the different impact indicators evaluated in the LCIA, *e.g.* the influence of diesel combustion on human health through the emission of particulate matter (PM < 2.5 μm) and on climate change by the emission of CO₂.³³ Furthermore, the authors also highlight the large effect on finite resources by the production of crude oil used in background processes.

The results of the scenario analysis show that plants with two wells perform environmentally better than those with more wells, as long as the flow rate is sufficient to ensure favourable energy production conditions. Given the same power plant capacity, three wells lead to larger environmental effects in all impact categories, which is clearly due to the influence of geothermal well construction on the environmental assessment.

However, when we assume that a lower number of wells require a higher flow rate for generating the same power, the higher reinjection rates and pressures are expected to have a higher risk of seismicity.³³

In the two impact categories elaborated by Sullivan *et al.*, global warming and energy resource depletion, the obtained effects are less than half of those by Frick *et al.*^{32,34} Also, less variable scenarios (with respect to geothermal reservoir characteristics and plant design) are examined and thus small indicator ranges are calculated. There are several reasons for this more favourable environmental assessment. There are differences in the scenario set-up, and crucial assumptions, such as a smaller diesel demand for drilling. A main point is the discrepancy in the database inventory used for background processes. For example, emissions of the supply chain for steel based on the U.S. LCI database are 0.46–0.63 kg CO₂ per kg.⁶⁷ In contrast, in Ecoinvent 2.2 different types of steel exist with emissions of about 0.41–2.00 kg CO₂ per kg, which is attributed to differences in steel production or import in US and Europe.^{59,67}

A novelty of Clark *et al.* is the analysis of water use in EGSs based on the same scenarios as in Sullivan *et al.*^{34,70} It is revealed that it is in the same range as the amount of water used for other energy production technologies. However, the amount of water required strongly depends on the type of cooling technology used in the binary power plant (wet or air cooling). Also important is the amount of make-up water used for losses of geothermal fluid and the water used during the construction phase, *e.g.* for stimulation or cementation. Water use may be of minor relevance in Central Europe such as at Soultz-sous-Forêts or in Switzerland. Due to water scarcity in the South-western U.S. however restriction on water use in geothermal power plants is suggested.⁷⁵

The recent assessment by Treyer *et al.* is based on the conditions in Switzerland where no EGS is in operation but several exploratory boreholes have been drilled.³⁵ In Treyer's scenarios with higher energy generation capacities, more and deeper boreholes and higher conversion factors are expected. These may be major reasons for the better environmental performance in comparison to the two other European studies.^{32,33} Treyer *et al.* compared three scenarios, and demonstrated that the lowest capacity shows the highest impacts due to a lower output of electricity over the life time, while the crucial impacts of the construction phase are the same.³⁵ Their sensitivity analysis reveals that based on their model, the depth of the wells has the largest influence on the net plant capacity. The gain of energy produced mostly exceeds any additional impact from the energy and materials needed for the construction of deeper wells. This, however, strongly depends on the drilling technology and accessibility of deeper reservoirs. There are no plants assessed with co-generation in detail, but the authors state that the co-production of heat leads to a decrease in environmental impacts as well as a cost improvement.³⁵

Furthermore, less comprehensive LCA studies also provide impact assessments. The impacts of the "hot dry rock" power plant by Pehnt are within the ranges of Frick *et al.* and Lacirignola and Blanc.^{32,33,37} This is not surprising given the

similarity in the geographical settings (Germany) and the sources used for the LCI. As pointed out above, the work reported by Frick *et al.*⁶⁵ is based on a comparable LCA model and similar LCI data to Frick *et al.*,³² and so it is plausible that the calculated environmental impacts are comparable to those associated with the base case scenarios in Frick *et al.*³² Here, they report 54.9 and 57.5 g CO₂-eq. per kW h for the case studies, and emphasize again that the largest portion (>80%) of the emissions comes from well construction with respect to the overall life cycle emissions.⁶⁵ Additionally, a qualitative account of local environmental impacts, such as noise emissions during construction (70–125 dB)⁷⁶ and land-use, is presented. Surface land-use for an EGS power plant is small. It provides a large amount of energy per square meter of occupied land surface, compared to other energy production technologies. However, EGSs affect large volumes of rock in the subsurface, an impact that cannot be quantified with existing impact categories (*e.g.* land occupation and transformation category in ReCiPe Midpoint)⁶¹ and it is rarely identified as a critical environmental issue.³¹ Finally, Gerber and Maréchal do not provide specific figures for environmental impacts.³⁶ They refer to conditions in Switzerland and conclude that all optimized configurations in their synthetic analysis have a beneficial CO₂ balance, and that for EGSs with depths of around 5.5 km a combined production of heat and electricity is economically, thermodynamically and environmentally favourable.

With the overview of the potential impacts of EGS shown in Fig. 1, we can compare this to the environmental performance of other geothermal technologies. Frick and Kaltschmitt developed a LCA for hydrothermal geothermal power generation with a similar methodology and data to that used by Frick *et al.*^{32,77} Plant design is adopted from three reference power plants for different geographical and geological settings in Germany (Molasse Basin, Upper Rhine Valley, and North Germany). The computed GHG emissions range between 25 and 85 g CO₂-eq. per kW h and are similar to the base case EGS scenarios reported by the studies in Fig. 1.^{32–35,37}

The study reported by Karlsdottir *et al.* is on conventional geothermal power use from a sizable double-flash plant in Iceland producing 213 MW.⁷⁸ For the calculated 35–45 g CO₂ per kW h_{el}, drilling activities represent only the second largest contributor to life cycle emissions, because fugitive emissions of non-condensable gases from the extracted geothermal fluid pose greater environmental problems. Hondo obtains 15.0 g CO₂-eq. per kW h_{el} for a Japanese double flash,⁷⁹ and Rule *et al.* get 5.6 g CO₂-eq. per kW h_{el} for a binary cycle in New Zealand.⁸⁰ The range of 4.0–740 g CO₂-eq. per kW h_{el} given by Bertani and Thain is influenced by the fugitive emissions of non-condensable gases during the operation of flash power plants.⁸¹ This shows the huge range of potential environmental impacts from geothermal energy. For EGSs, these ranges are mainly influenced by the drilling, while in conventional high-enthalpy applications, the most critical factor is the release of non-condensable gases. Martín-Gamboa *et al.* set up a hypothetical European scenario with geothermal fluid temperatures of over 150 °C in shallow depths of 450–725 m.⁸² The derived environmental impact of

geothermal electricity and heat co-generation with binary power plants is very low. For example, for the global warming potential, emissions of 8.04 g CO₂-eq. for a combined production of 1 kW h electricity and 1 kW h heat are presented. The most relevant life cycle step here is the site preparation, *i.e.* the construction of boreholes. Elements of this work are comparable to the approach by Frick *et al.*, in particular with respect to diesel use and steel production, since both studies rely on mostly the same inventory data.³² A specific finding of Martín-Gamboa *et al.* is a rather large impact from working fluid losses (in this study HCFC-124, Hydrochlorofluorocarbon 124), which are not explicitly regarded by other studies,^{32,33} especially for the global warming potential (up to 28% of global warming potential are caused by losses of working fluids).⁸²

Environmental impact of geothermal drilling

Most of the LCA studies investigated above agree that no direct emissions and only minor indirect emissions occur during the operational phase of an EGS power plant due to the exchange of pumps, the make-up of working fluids, *etc.* Consequently, it has been found that the largest portion of the lifetime environmental impact from EGS plants occurs during the construction phase, in particular from the energy use for the drilling operations. For further examination of the reasons for the variations in the environmental impacts in different studies we focus on greenhouse gas emissions, non-renewable energy demand, acidification potential and eutrophication potential. The differences in the share of these four environmental impacts caused by energy use for drilling on the lifetime impact are visualized in Fig. 2 for the four most detailed LCA studies on EGSs, whose published LCIs enable a detailed inspection of the impact contributions to individual processes.^{32–35} Fig. 2 shows the overall lifetime impact per produced kW h_{el} (total bar height) and the impact caused by the consumption of energy during the drilling of geothermal wells (upper part of the bars).

From the comparison of the variations in the heights of the upper and lower parts of the bars, it becomes obvious that the variations in all four environmental impacts due to energy consumption for drilling are the main reasons for the divergent results of the investigated studies. The differences in the environmental impacts caused by the remaining components (lower part of the bars), on the other hand, are comparatively small. One reason for this similarity in environmental impacts for the components other than drilling is the similarity of the LCIs in the different studies regarding the amount of steel needed for the casing of the boreholes and the amount of cement needed for the construction of the power plant. The differences in the environmental impact of other components are mainly caused by the differing assumptions regarding reservoir parameters and plant characteristics, which influence the overall environmental performance, for example, the ratio of caused emissions to produced electrical power. In particular the power plant size in the study reported by Sullivan *et al.* with 20 MW and 50 MW respectively³⁴ is rather large compared to other LCA studies (Table 2), which results in a better overall environmental performance due to scale effects. Treyer *et al.*

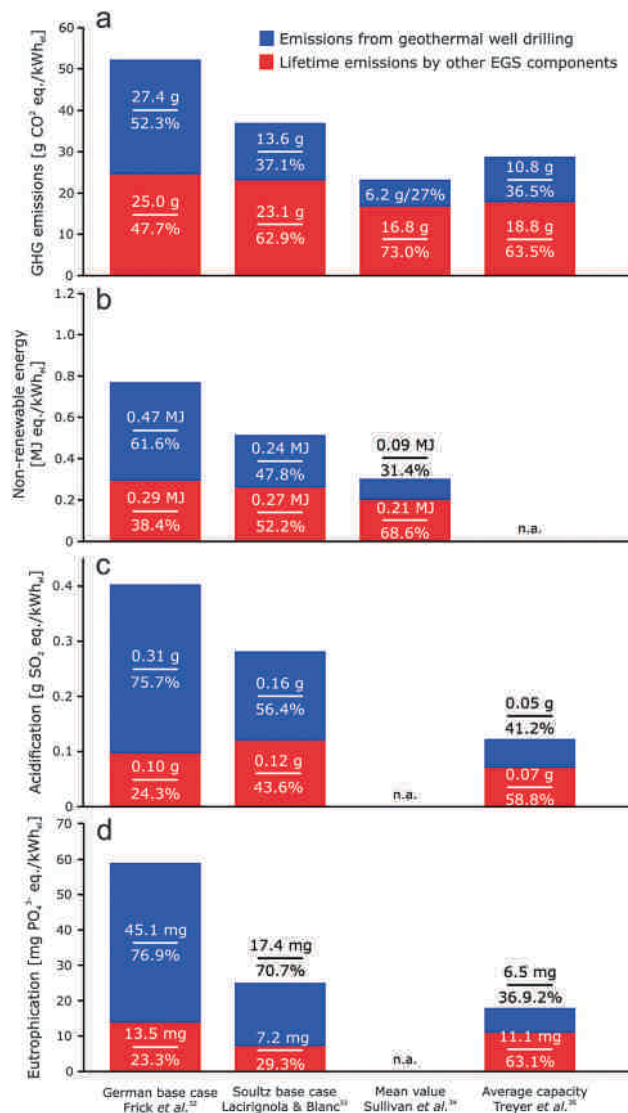


Fig. 2 Life time (a) GHG emissions, (b) non-renewable energy demand, (c) acidification and (d) eutrophication potential of EGS plants from previous studies and the respective share of the impact caused by energy use for drilling shown as absolute values per kW h and percentages. For the values from Frick *et al.* and Lacirignola and Blanc only the base case scenarios are evaluated without assigned parameter variations and uncertainties.^{32,33} For the results of Sullivan *et al.* the mean value of the two evaluated scenarios (20 mW and 50 mW plants) is shown here.³⁴

also observed this dependency of environmental performance on power capacity in their scenario analysis.³⁵

In contrast to the general components, the GHG emissions caused by drilling operations show a considerable range from 6.2 to 27.4 g CO₂-eq. per kW h_{el}. These differences in the released GHG emissions are due to the divergent assumptions regarding the type and amount of energy consumed by the drilling rig. Table 3 gives an overview of the main parameters for the energy type and use for operating the drilling rigs and other processes during the well construction in the investigated studies.^{32–35}

The first three studies all assume the use of diesel-driven rigs for drilling the wells. However, the energy consumption for

Table 3 Energy consumption for geothermal drilling activities in existing LCA studies of EGS plants

Parameter	Frick <i>et al.</i> ³²	Lacirignola & Blanc ³³	Sullivan <i>et al.</i> ³⁴	Treyer <i>et al.</i> ³⁵
Energy source for operation of drilling rig	Diesel	Diesel	Diesel	Electricity from grid
Energy consumption for drilling	7.5 GJ m ⁻¹ (6.0–8.0 GJ m ⁻¹)	4.0 GJ m ⁻¹	~1.5 GJ m ⁻¹ ^a	8.5–14.1 GJ m ⁻¹ ^b
Energy consumption of pumps for reservoir stimulation per stimulation job	3000 GJ	1600 GJ	~4251 ^a GJ	4000 MW h
Energy consumption of drilling mud pumps	0.18 GJ m ⁻¹	n.a.	n.a.	n.a.
Data source/reference	Survey of geothermal drilling data	Literature survey	Tester <i>et al.</i> ³	Literature survey

^a Calculated based on values of plant design and drilling data given in Sullivan *et al.*³⁴ ^b Varying with diameter and depth.

drilling one meter of borehole varies significantly. The highest assumed energy consumption of 7.5 GJ m⁻¹ in Frick *et al.* was derived from an internal report from 2007 on well drilling in deep geothermal projects located mostly in the Bavarian Molasse Basin.^{32,83} Lacirignola and Blanc assign an average value of 4 GJ m⁻¹ in their LCI, which was identified by calculations performed on several boreholes in comparison with literature values, though no specific details on the calculation methods or the literature used are given.³³ The lowest value of 1.5 GJ m⁻¹ is also derived by calculations, which are described in detail by Sullivan *et al.*³⁴ The energy demand is determined by the fuel consumption per day by a typical drilling rig for geothermal wells, and the number of drilling days is taken from an example project in Tester *et al.*³ The critical assumption in this calculation method is the assumed number of drilling days. For example, in Sullivan *et al.*, 43 days were required for drilling a 5 km deep well.³⁴ Though there are significant variations in the number of drilling days per well depending on the on-site geological conditions, delays due to faults, *etc.*, the assumed number of 43 days seems fairly optimistic given the fact that drilling operations for the 5 km deep well in the EGS Project in Basel took 160 days in 2006.^{34,84}

The LCA study reported by Treyer *et al.* is the only one taking electricity from the grid as an energy source for the drilling rigs.³⁵ The bases of their LCI are the geothermal projects in Basel (2005–2006) and St. Gallen (2012), Switzerland, in which electricity-driven drilling rigs were used for drilling and diesel generators were available in the case of a blackout. The use of electricity leads to a better environmental performance of the well drilling in the Swiss EGS plants compared to the diesel-driven rigs from Germany and France (Fig. 2).^{32,33} However, the environmental impact of the electric drilling rigs is still higher than the impact from the US case study, which takes diesel-driven rigs into account.³⁴ One reason for this deviation is the high energy demand in the Swiss study,³⁵ which is actually higher than in the work reported by Frick *et al.*³² In addition, the environmental burdens from the generation and distribution of the consumed electricity are not negligible.

These observations indicate that with the use of electricity from the grid instead of diesel the environmental impact of the drilling operations depends on the environmental burdens introduced by electricity generation and thus on the specific technologies used for power generation in the corresponding country. For instance, the high percentage of non-renewable electricity production from the combustion of coal and lignite coal in Germany has average GHG emissions of 641 g CO₂-equivalent per generated kW h electricity,⁵⁹ whereas average

GHG emissions of electricity from the Swiss account for only 127 g CO₂-eq. per kW h_{el} due to the large percentage of electricity being generated by hydropower (~60%) and nuclear power (~30%). Both technologies (hydropower and nuclear) have relatively low lifetime GHG emissions. However, electricity from national grids can also contain additional environmental burdens from the import of electricity from other countries.⁸⁵

A detailed analysis of the supply chains in the LCA model of Treyer *et al.* reveals that a considerable percentage (84%) of the GHG emissions due to electricity use for drilling in Switzerland can be attributed to emissions related to imported electricity from Germany.³⁵

Fig. 3 illustrates the influence of the use of electricity for drilling from different national grids on the environmental impact of EGS plants. Based on the data for energy consumption shown in Table 3, the lifetime environmental impacts of the EGS plants with electric drilling are calculated for the base case scenarios of three studies and shown as individual bars.^{32–34}

The bars in Fig. 3 show that the substitution of diesel by grid power does not necessarily result in a reduction of environmental impacts. The change from diesel to electricity from the German grid actually causes an increase in GHG emissions in all examined scenarios due to the carbon intensive electricity generation predominantly based on the combustion of fossil fuels (Fig. 3a). This increase is more pronounced the higher the value for energy consumption by the drilling rigs, leading to a considerable increase for the scenario from Frick *et al.* and only minor changes in the emissions calculated for the scenario by Sullivan *et al.*^{32,34} Switching the energy supply to power from the Swiss grid, on the other hand, leads to a reduction in GHG emissions as expected from the low carbon electricity generation in Switzerland. Changing to electric drilling also increases the environmental impact from non-renewable energy demand when using electricity from the German and the Swiss grid (Fig. 3b). Both the German and the Swiss national electricity mixes are quite primary energy intensive due to coal and uranium mining for coal and nuclear power, respectively, as well as material and energy consumption for the construction of dams for hydropower in Switzerland. However, the change in environmental performance due to electricity use shows a different trend when the acidification and eutrophication potential are examined (Fig. 3c and d). For these two impacts the change to grid electricity from diesel leads to a significant improvement in the lifetime environmental impact of EGS plants, in particular with regard to the eutrophication potential.

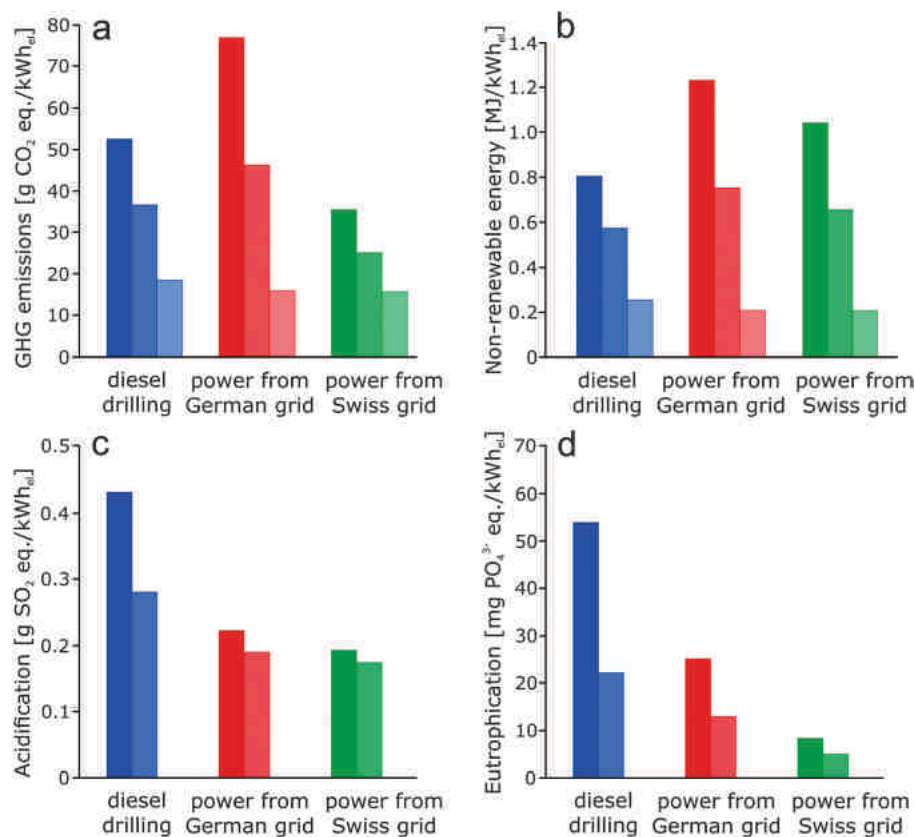


Fig. 3 Life time (a) GHG emissions, (b) non-renewable energy demand, (c) acidification and (d) eutrophication potential of EGS power plants with different energy sources used for geothermal drilling derived by changing the energy source in the LCI of previous LCA studies. Dark coloured bars represent the modified scenario A1 from Frick *et al.*, intermediate bars the Soutz-sous-Forêts base case from Lacirignola and Blanc and the light coloured bar the 50 mW scenario from Sullivan *et al.*, respectively.^{32–34} Values for acidification and eutrophication potential are not available for the study of Sullivan *et al.*³⁴

Alternative energy supply systems other than electricity from the grid have also been explored by the oil and gas industry for drilling operations. Yu explored a large number of environmentally more friendly alternative energy sources than diesel for driving the drilling rigs, including other fossil fuels, such as natural gas, and also renewable energy technologies, such as wind turbines and photovoltaic systems.⁸⁶ The most feasible alternative seems to be natural gas in the form of either liquefied natural gas (LNG), compressed natural gas (CNG) or a dual fuel machine in combination with an energy storage system to cover peak loads.^{87–90} For drilling wells in oil and gas fields the use of drilling rigs driven by natural gas may be convenient in particular when natural gas is already produced from existing wells. For geothermal drilling however, the rather costly transportation and storage of natural gas compared to diesel make natural gas probably a less suitable alternative.

Improved LCA results as a function of drilling activity

The change from diesel driven drilling rigs to electricity from the grid as an energy source, as stated in the latest LCA study, reflects a rather general development of environmentally friendly drilling technologies that is not limited to the oil and gas industry.³⁵ Not only in Switzerland, but also in Germany, deep geothermal wells (*i.e.* depths > 3000 m or an expected

drilling time of more than 45–50 days) were drilled mainly by electricity-driven drilling rigs in the past few years.⁹¹ This applies also to some hydrothermal projects in the Bavarian Molasse Basin, such as Sauerlach in 2006, Kirchstockach in 2009 and Pullach in 2011. The reasons for using electricity in these projects were not only of financial nature. In some areas noise emission restrictions can be an issue when using diesel driven machines, as well as environmental regulations such as water protection areas. The costs for the drilling process itself are about 30–40% lower for electric drilling than with diesel use. However, the additional costs for setting up the electricity supply vary considerably for each site, depending on the distance to the nearest source of medium voltage electricity, the number of power transformers needed, *etc.*

The examination of the LCA studies above has shown that it can be challenging to make an estimate of the materials and processes of drilling operations within a narrow range due to the scarce data available. On the other hand, there is plenty of data available for deep well drilling from the oil and gas industry. Geothermal and gas or oil wells exhibit a similar range of depth, costs and materials, so the needs for geothermal wells are often estimated based on oil and gas wells.^{3,34} However, there are some significant differences between the two well types that have to be taken into account. Tester *et al.*

emphasize that geothermal wells for EGS plants are usually drilled in hard crystalline rocks with higher temperatures, which lead to higher equipment costs than for typical oil or gas wells.³ These circumstances, in combination with larger well diameters for geothermal wells, result in longer drilling times for equivalent depths. von Rohr *et al.* also discuss the differences between the typical settings for geothermal and oil and gas wells.⁹² While oil and gas wells are often drilled within developed production fields, deep geothermal wells of new EGS projects are often drilled in areas with no or only scarce data from previous well drilling. Furthermore, the longer life time planned for geothermal wells requires more extensive casing and cementation measures to ensure functionality and stability for a longer time than standard oil and gas wells.⁹²

The limitation of actual data and experience about drilling deep geothermal wells is probably the main reason for the wide range in the amount of materials and energy needed for the construction of the wells in the LCA studies examined in this work. At the same time, the type and amount of energy used for drilling has been shown to have a dominant impact on the environmental performance of the EGS power plant. However, not only does the amount of energy needed for drilling one meter of borehole vary in each study (Table 3), the depth and the number of boreholes needed to supply the EGS plant show a large range across the different studies and their scenarios. From the scenario parameters in the LCA studies (Table 2), it can be seen that increasing the power capacity of an EGS plant is often realized by assuming deeper boreholes for increased temperatures under the assumption of a specific geothermal gradient *e.g.* in Treyer *et al.*,³⁵ or by a larger number of boreholes in order to increase the total flow rate of geothermal fluid and thus the amount of thermal energy available for energy conversion.³³

The number of boreholes required for different types of wells, such as exploration wells, make-up and also unsuccessful wells during the life cycle of an EGS plant is rather difficult to estimate and depends on the on-site conditions.^{3,34} However, the prediction of on-site conditions in geothermal reservoirs with a depth of several kilometres is only possible within parameter ranges and is associated with rather large uncertainties; conditions may also change during the operation time.³⁴ In order to incorporate these parameter ranges and uncertainties within the LCA methodology, several scenario analyses are conducted in LCA studies, which can still cover only a limited number of possible combinations of parameter values associated with geothermal wells, such as the number of wells and the well depth. In addition, these input parameter ranges potentially lead to results characterized by average values with very large error bars (see Fig. 2), which allow only limited interpretation and comparison with the results of other studies. To overcome this problem of parameter ranges for borehole characteristics, this study employs the environmental performance of a projected EGS power plant as a function of the overall borehole length. The sum of the individual depths of all boreholes drilled during the life time is used to compare the environmental performance of different EGS plants against other power generation technologies.

For this evaluation, two European scenarios from previous LCA studies were selected; the German base case scenario and the Soultz-sous-Forêts base case scenario.^{32,33} The environmental impacts per produced kW h of electricity were calculated using the LCI data provided in the publications, except for the type of energy used for drilling. The amount of energy needed for drilling the boreholes assigned in our calculation is the same as in the corresponding LCIs in the corresponding studies.^{32,33} Yet, the energy is not provided by diesel generators, but instead, electricity is used to drive the drilling rigs. Due to the recent trend in drilling technologies discussed above, it seems reasonable to assume that deep boreholes of future EGS projects will be predominantly drilled by electricity driven rigs. Additionally, two projected EGS power plants in Switzerland are considered in the analysis, the EGS projects in Basel and in St. Gallen. The LCIs for these EGS projects were adopted from Treyer *et al.* and plant characteristics were calculated using a physical model assigning the expected site-specific reservoir characteristics in Basel and St. Gallen (see Table SI1 in the ESI†).^{35,63} Data for the type and amount of energy used to supply the drilling rigs were obtained from the corresponding project reports.^{93–95}

In order to evaluate the different EGS scenarios independently from the varying environmental impacts resulting from the different national electricity mixes in Switzerland, Germany and France, the energy amount used for drilling in the LCA model is accounted for by subtracting it from the amount of energy produced during the life time. From the LCA perspective it can be argued that the energy injected from the EGS plant into the national grid replaces the same amount of energy with the average environmental burden of the national electricity generation mix. Thus, the input of electric energy for drilling can be directly deducted from the energy output since the environmental impact is evaluated relative to the net energy produced during the life time of the power plants. However, this assumption is only valid as long as the national mix does not change significantly over the life time of the EGS power plant. Potential reductions in the average environmental impact by national electricity generation due to further developments in renewable and low carbon technologies are not accounted for in this analysis. On the other hand, the assumption of using part of the generated electricity to drill additional boreholes can be interpreted in a way that drilling activities in the proximity of an EGS power station would most likely be supplied with electricity from the power plant itself and it elegantly avoids the problem of selecting the replaced power in a grid by an attributional approach (or the marginal technology in a consequential approach).

Fig. 4 shows the environmental impact in the form of GHG emissions, non-renewable energy demand, acidification and eutrophication potential per produced kW h_{el} for the four analysed EGS scenarios depending on the total borehole length drilled during the life time of the power plants, including uncertainty ranges. With the minimum number of required boreholes (2–3), and boreholes depending on plant design, all four EGS scenarios show quite similar environmental impacts for all four categories. With increasing number of boreholes,

however, there are considerable differences in the trend of environmental performance between the different case studies. The different magnitudes in increasing environmental impacts with increasing borehole depths are caused by the substantial differences in the LCIs of the respective studies, as mentioned above. Each additionally drilled borehole adds a certain amount of GHG emissions, non-renewable energy demand, *etc.* to the overall lifetime impact due to the case-specific amount of concrete and steel used for casing, energy used for stimulation, *etc.*

In addition to this fixed increase in the environmental impact, the use of electricity for drilling additional boreholes reduces the amount of produced electricity supplied to the national grids during the life time of the plants, which leads to the exponential increase in the ratio of the environmental impact per kW h of electricity. This is particularly obvious for the German base case scenario,³² which exhibits the highest energy consumption for drilling (Table 3) and accordingly the steepest increase in environmental impacts with increasing total borehole length. The nearly vertical part of the curves implies that with a large number of boreholes already drilled (and a consequently large amount of electric energy used), any further drilling activities would result in a net electricity output close to zero. As a result, the EGS plant would consume more energy for drilling than it can produce from the wells, which results in an extremely high environmental impacts to produced

energy ratio. Thus, the general ranking of the evaluated EGS scenarios in Fig. 4 is directly linked to the amount of energy used for drilling due to the dominant share of the environmental impact by drilling compared to the impact by the remaining components.

Based on the very high energy demand for drilling and the assumed mediocre site conditions for the geothermal reservoir parameters, the German base case³² overall appears to be a rather pessimistic scenario, unlikely to be realized as a commercial project under current economic circumstances. In comparison, the EGS plant project at Soultz-sous-Forêts³³ was designed and carried out as a pilot-stage project with a focus on testing and gaining experience. Aside from this, the first deep geothermal wells in Soultz were drilled two decades ago.^{26,96} Thus, the drilling energy demand and related environmental impacts are hardly representative for present and future EGS power plant projects, which are supposed to use improved technology and do not include testing purposes.

The more recently drilled wells for the projected EGS projects in Basel and in St. Gallen consumed significantly less energy during drilling operations (see Table 1 in the ESI†) and consequently show a more linear increase in life-time environmental impacts with additional boreholes. This decrease in energy consumption for drilling from the German base case, which is based on drilling data prior to 2007,³² to the EGS

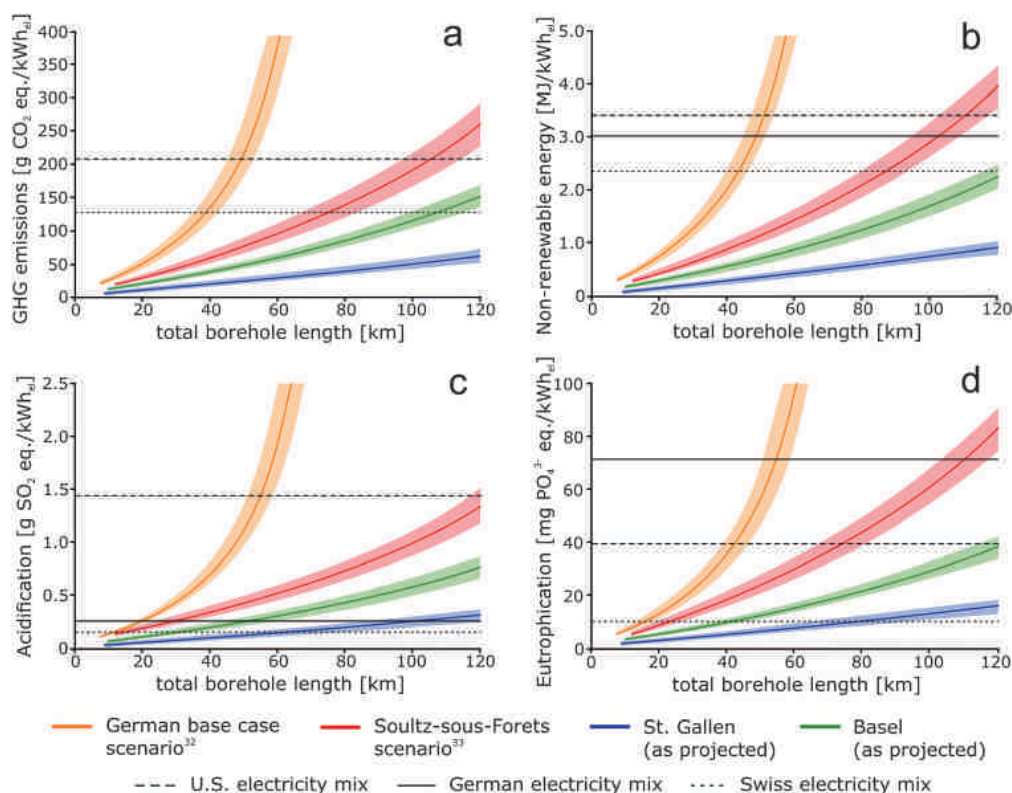


Fig. 4 (a) Life time GHG emissions, (b) non-renewable energy demand, (c) acidification and (d) eutrophication potential per produced kW h electricity for four EGS plants as a function of overall borehole depth (number of wells multiplied by the well depth). The German base case is identical to scenario A1 in Frick *et al.* and Soultz-sous-Forêts is identical to scenario case 6 in Lacirignola and Blanc.^{32,33} Data for the emissions caused electricity mixes are taken from Ecoinvent 2.2.⁵⁹ The band accounts for the standard deviation of LCI uncertainty.

project in Soultz-sous-Forêts, where multiple deep boreholes were drilled into the same reservoir,^{26,96} to the recently drilled deep well in St. Gallen in 2012 can be interpreted as an emerging trend of deep geothermal drilling becoming more energy efficient.

The analysis of the environmental impact presented here also allows for the evaluation of the environmental performance of EGS projects in relation to specific thresholds, such as comparison with competing energy technologies or average national electricity mixes. The horizontal lines in Fig. 4 represent the corresponding average environmental impacts per kW h caused by the national electricity mix in Switzerland and, for comparison, in the U.S.⁵⁹ The average GHG emissions of the German electricity mix are 641 g CO₂-eq. per kW h and are thus beyond the axis limits in Fig. 4a.⁵⁹

The environmental impacts of the national electricity mixes in Fig. 4 can be used as thresholds to explore the question of how many boreholes could be drilled for a specific EGS plant until the environmental performance becomes equal to or worse than the average performance of the corresponding national energy generation.

Taking the GHG emissions from the projected EGS power plant in Basel as an example, close to 100 km of boreholes could be drilled before the GHG emissions of the EGS power plant equal the average emissions from national energy production. Assuming a well depth of 5 km (like the production well drilled in 2006), 19 additional boreholes with the same depth or a correspondingly higher number with less depth could be drilled before the life time GHG emissions of the EGS power plant would be approx. 130 g CO₂-eq. per kW h and thus comparable to the Swiss electricity mix. Even for the German base case scenario with high emissions, boreholes with a total length of 54 km could be installed in addition to the first two wells with a depth of 3.8 km each before the life time GHG emissions would exceed those from the German national electricity mix,⁵⁹ and as a result, there would no longer be a beneficial effect of geothermal electricity production on the CO₂-emissions related to energy generation. For the demand of non-renewable energy, Fig. 4b shows a similar relation between the performance curve of EGS plants and the average of national electricity generation as for GHG emissions. This indicates that despite the use of materials such as steel and cement for borehole construction, many boreholes could be built before the non-renewable energy demand of EGS plants exceeds those of the national electricity mixes.

For the acidification and eutrophication potential the trends in the individual EGS scenarios are also similar to the impacts for GHG emissions and non-renewable energy demand, while the comparisons with environmental impacts from national electricity mixes yield quite different results for different countries. In particular, in Switzerland a low acidification and eutrophication potential from the nuclear power based electricity mix would result in EGS plants with a small number of boreholes exceeding the environmental impact of average electricity generation. More impact factors from the IMPACT 2002+ assessment methodology are displayed in the ESI† (Fig. SI1) for the same set of EGS scenarios and national electricity mixes

as in Fig. 4. Overall, a large variation in the relation between the results for individual impact categories and different national electricity mixes can be observed, but with regard to most of the assessed impacts even EGS plants with a large number of deep boreholes are environmentally competitive.

The Swiss EGS projects in Basel and St. Gallen were both designed not only for the generation of electricity, but also for the co-generation of heat to be supplied to a district heating network. Based on available data,^{35,94,95} the environmental performance of the planned EGS power plants in Basel and St. Gallen was also evaluated for energy production with co-generation of heat. For allocation, the same scheme based on the exergy content of 1 kW h electricity and 1 MJ thermal energy as in Frick *et al.* was used, which is described above.³²

The resulting environmental impacts as a function of total borehole length are shown in Fig. 5 for the projected EGS plants in Basel and St. Gallen. Both EGS plants show a considerable decrease in environmental impacts for the plant designs with co-generation of heat, as emissions are shared between the produced amount of electricity (St. Gallen: 45%, Basel: 40%) and heat (St. Gallen: 55%, Basel: 60%). This finding is in accordance with the observations by previous studies that EGS plants with co-generation perform environmentally better than plants with electricity generation only.^{32,35,36} Furthermore, Fig. 5 shows that with increasing total borehole length the difference in environmental performance between EGS plants with and without co-generation increases, because the drilling of additional boreholes only reduces the amount of net produced energy, but not the generation of heat.

Due to this environmental improvement the number of boreholes that refer to the threshold of the average environmental impact based on the national electricity mix also increases. The comparison of the impact due to acidification from the projected EGS plant in Basel with and without co-generation with the average national electricity, for instance, reveals that the threshold of borehole meters increases from approx. 60 km to 110 km of total borehole length with co-generation of heat. Fig. SI2 in the ESI† shows the improvement in environmental performance with co-generation of heat based on the additional impact categories from the IMPACT 2002+ characterization method. A significant increase in environmental performance for both EGS plants in Basel and St. Gallen is observed for all impact categories and highlights the overall environmental benefits from the co-generation of electrical power and heat.

Finally, it should be emphasized that the purpose of the analysis presented in Fig. 4 and 5 is to show the exceedingly good environmental performance of EGS power plants compared to typical national energy mixes, even for cases in which several unplanned, additional boreholes are needed. However, with drilling and completion costs for deep geothermal wells amounting to up to 10–30 Mio. US\$,⁹ EGS projects with a projected number of several wells are prone to be economically unprofitable and are unlikely to be realized. As an alternative for drilling additional wells to maintain the required production flow rates, Limberger *et al.* suggested in

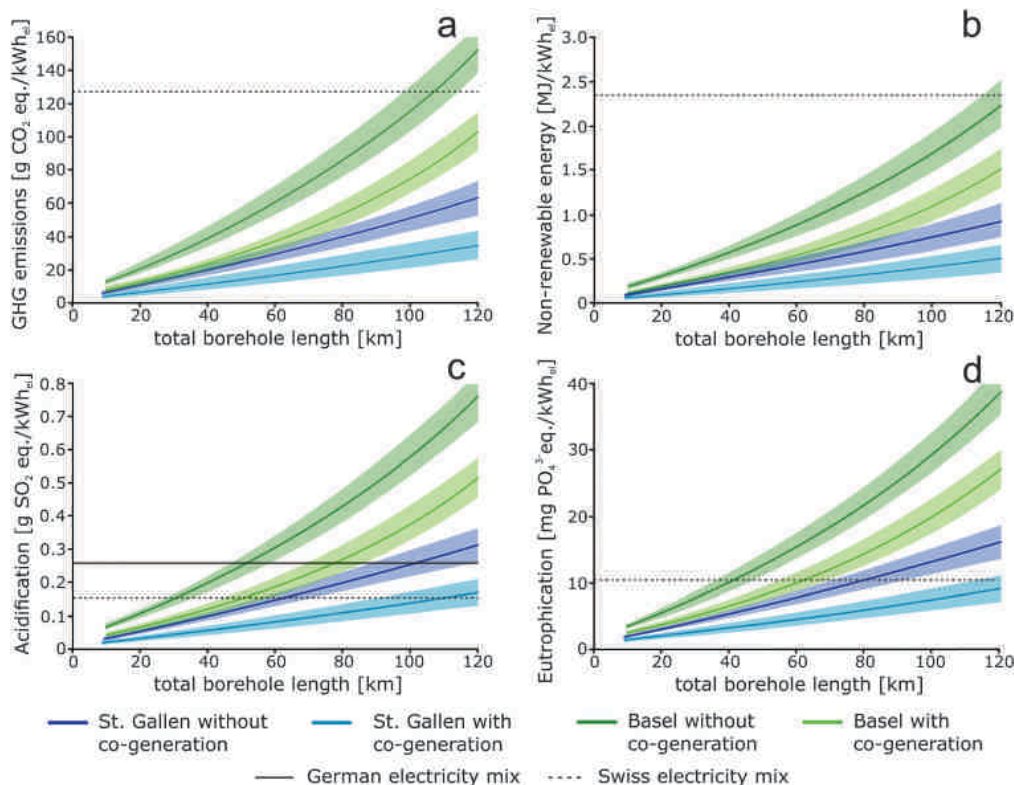


Fig. 5 Life time (a) GHG emissions, (b) non-renewable energy demand, (c) acidification and (d) eutrophication potential per produced kWh electricity for the projected EGS plant in St. Gallen and Basel with and without co-generation of heat. The band accounts for the standard deviation of LCI uncertainty. Data for the emissions caused electricity mixes are taken from Ecoinvent 2.2.⁵⁹

their assessment for future perspectives for EGS plants that flow rates could also be sustained by repeated stimulation of the reservoir.²¹

Future LCA perspectives for EGS power plants

The results shown in Fig. 4 only contain past and present day projects and take into account currently available contact drilling technology like electric rotary drilling. Hence, future LCA perspectives considering various existing and evolving non-contact drilling technologies, such as hydrothermal spallation, flame jet thermal spallation and electro pulse drilling are also investigated.^{97–101} An overview of these and other emerging thermal drilling technologies is provided by Ndeda *et al.*¹⁰²

In addition, learning effects are included based on the estimated learning curves provided by Lukawski *et al.*⁹ Although, these learning curves are originally derived for cost savings, here these curves are transferred to a reduction in energy demand for drilling based on decreased drilling time due to an increase in drilling efficiency. Lukawski *et al.* provide examples for average, least and best learning curves, which are adopted as an average value for drilling energy in the future rotary scenario, and upper and lower bounds, respectively.⁹ This learning effect is also applied for future scenarios with advanced non-contact drilling technologies. Geothermal reservoir and power plant parameters are adopted from the future scenario for 2030 in the study reported by Limberger *et al.* (Table SI2 in the ESI†).²¹

The main differences between the conventional rotary drilling and the non-contact drilling technologies are the required specific energy, *i.e.* the energy required to disintegrate a specific volume of rock, and the penetration rate.¹⁰² The latter is typically a factor of 2–3 higher for the thermal drilling technologies (Table SI2 in the ESI†). In contrast, the required specific energy for disintegration can be higher or lower depending on the drilling technology. For all studied drilling technologies the auxiliary energy that is consumed by the drilling rig is assumed to be equal to rotary drilling and taken from the electricity grid. Furthermore, hydrothermal and flame jet thermal spallation drilling technologies cause additional direct and indirect CO₂ emissions due to fuel oxidation (ethanol, petrol) during drilling operations and fuel production, which are also considered as background processes in the LCA.

In comparison with previous LCA studies assuming well depths ranging mostly between 3–5 km, deeper wells of 7 km are considered for the future scenarios based on the assumption that advanced drilling technologies also enable the drilling of deeper wells.²¹ Likewise, future EGS binary power plants are assumed to be a more advanced and mature technology with an increased number of load hours and shorter downtimes compared to the present EGS power plants.²¹ In addition, some influential reservoir and technological parameters identified by previous studies^{21,32,38} are varied within each drilling technological scenario to reflect different geothermal conditions and are presented as upper and lower bounds for the studied future scenarios (Table SI2, ESI†).

The variation in the production temperature (150–250 °C) reflects changes in the geothermal gradient and also a potential decline in the production temperature over the life time of the EGS plant. As a consequence of varying production temperature, the efficiency of the binary cycle and also the gross power output are modified. In addition, the geothermal flow rate, which strongly depends on the success of reservoir stimulation and development, is varied between 300 and 420 m³ h⁻¹.

The resulting life time GHG emissions per produced kW h electricity for the investigated EGS future scenarios considering various advanced drilling technologies and varying geothermal reservoir characteristics are presented in Fig. 6. The baselines for all advanced drilling technologies are very similar, but significantly lower than for the projected St. Gallen case, which is mainly caused by the cutback in drilling energy demand and an increase in power production. It may seem surprising that the baseline future scenarios show almost identical values despite the different amounts of drilling energy. However, these differences in drilling energy play only a minor role in relation to life time electricity production. The amount of energy generated in the future EGS scenarios is several orders of magnitude higher than the energy demand for drilling, so that the difference in energy demand of the different advanced technologies has only a minor effect on the ratio of emissions per produced amount of electricity (see energy values in Table SI2, ESI†).

In general, the learning effect and the lower energy demand for drilling additional wells result in rather linear relation of GHG emissions and total borehole length, in comparison with the previously considered present day scenarios (Fig. 4). At the initial stage of the EGS plant with 3 wells (*i.e.* a total borehole

length of 21 km), the future scenarios show only marginally lower GHG emissions, despite the low energy consumption for the drilling. At this stage other sources of indirect GHG emissions, such as steel used for casing, are predominant since EGS is already very efficient under these conditions. However, with the increasing number of wells, the difference between the present day and future scenarios intensifies, due to the lower energy demand for the advanced drilling technologies.

The dissimilarities of the energy demand for the advanced drilling technologies can only be recognised in the scenarios with less optimistic reservoir conditions (upper bounds). Here, electric rotary drilling indicates the highest GHG emissions. The impact of additional CO₂ emissions due to the fuel use for hydrothermal and thermal spallation drilling is insignificant (0.01 g CO₂-eq. per kW h_{el} for a EGS plant with 3 wells) compared to emissions caused by other materials and processes, such as steel and aluminium, construction work, *etc.*

The range between the upper and lower bounds of the future scenarios is mainly caused by the differing assumptions on the reservoir temperature and the production flow rate, which result in significant differences in life time energy production (see Table SI2, ESI†), and directly impact the ratio of GHG emissions per produced kW h electricity. Thus, with the assumption of energy efficient geothermal drilling in the future, the impact of potential variations in reservoir parameters on the environmental performance becomes more important than the rather small differences in energy demand between drilling technologies. Compared to the impact of variations in geothermal reservoir characteristics, the possible range in GHG emissions of a specific scenario, such as the EGS plant in St. Gallen, resulting from the uncertainty in the background processes in the LCA is

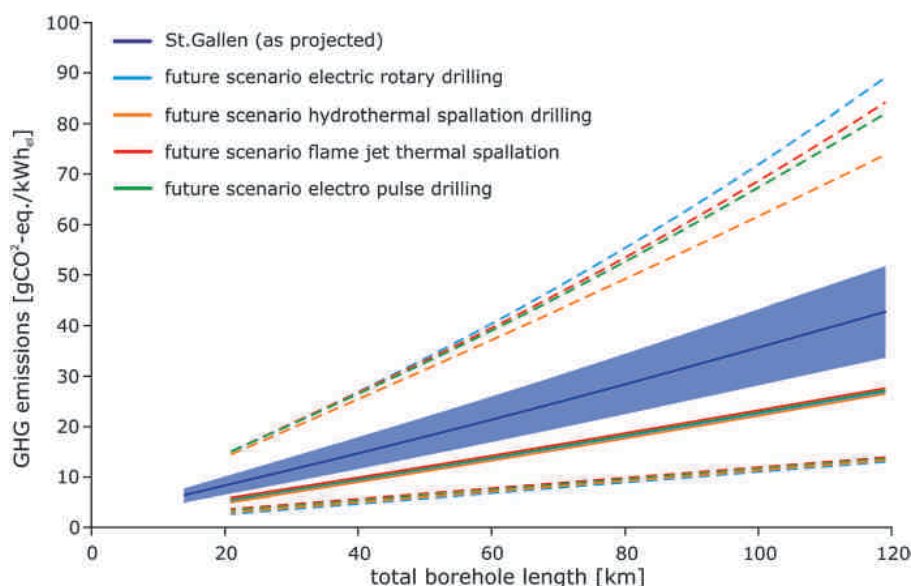


Fig. 6 Life time GHG emissions per produced kW h electricity for the investigated EGS future scenarios considering different existing and evolving drilling technologies. The bold lines refer to the baseline scenarios assuming an average learning effect regarding the energy consumption for drilling and average geothermal reservoir conditions. The dashed lines indicate the upper and lower bounds for each technology scenario assuming least and best learning effects, and best and worst case reservoir parameters, respectively. To enable comparison to a present-day scenario the baseline and uncertainty range (blue shadow) for the projected EGS power plant in St. Gallen is also displayed.

comparatively small (Fig. 6). Regarding the discussion of threshold values from above, which related the environmental performance of an EGS plant with a specific number of wells to other current energy technologies, it can be stated that for all four future baseline scenarios a total of approx. 91 borehole kilometres could be drilled before the life time GHG emissions would exceed those of an average nuclear power station.^{79,103}

Yet, it must be noted that the data used here to infer the future scenarios with advanced drilling technologies, such as thermal spallation and electro pulse drilling, were obtained from reports on laboratory and/or field tests and are based on several assumptions, as described above.¹⁰² Accordingly, the assumed values, such as the specific energy use, will most likely not be identical to the energy consumption of a mature technology potentially being developed in the future, which would be subject to further improvements and increases in efficiency.

Regarding the potential economic perspective for geothermal drilling in the future, several studies predict decreasing drilling and completion costs for deep geothermal wells due to learning effects, advanced drilling technologies and more mature plant designs.^{9,21} In addition, a decrease in the rate at which well costs increase with depth has been observed for the past few years and a potential shift from a power-law increase of drilling costs with well depth to a linear relationship was discussed by recent studies.^{9,21} This would make deeper reservoirs with higher temperatures economically more accessible and accordingly shift the environmental performance of potential future EGS scenarios closer to the lower bounds in Fig. 6.

Environmental performance of main power production technologies

This chapter presents a comparison of the environmental performance of EGS power plants and other energy generation technologies. We conducted a literature review of LCA studies that evaluate the impacts related to the life time electricity generation of non-renewable as well as renewable energy technologies. Due to the abundance of LCA studies in this field this brief overview does not claim to be a whole or complete assessment in any way. The scope of this chapter is solely to show the position of EGSs in the environmental ranking of electricity generation technologies.

One important issue for the comparability of different LCA studies is the manifold number of methods to quantify the environmental impacts within the LCIA. One focus is on the global warming potential, but there are still many different ways to quantify this. For the assessment of GHG emissions, some studies evaluate only pure CO₂ emissions, while most assign individual weighting factors to several GHG (CO₂, CH₄, etc.) and aggregate them to CO₂-equivalent emissions, as done by the IPCC reports.^{32,35,37,104} These GHG emissions can also be evaluated with respect to different time scales, though it is set as 100 years in most cases. Yet, Sullivan *et al.* reported that the differences in the resulting environmental impact between the different aggregation methods account for up to a few percentage points, so that they can be largely neglected for the purpose of this chapter.³⁴ For a broader view of environmental

impacts, in addition to the global warming potential, we compare the impacts with respect to non-renewable energy demand, acidification potential and eutrophication potential. These represent standard impact categories in many LCA studies. All studies reviewed for this analysis are listed in Table 4 according to the evaluated energy generation technologies. Many of these studies are review studies themselves, so the number of values used for analysis in this study is actually higher than the number of citations listed in Table 4. Detailed information about the reviewed studies and number of estimates provided by each study is given in Table SI3 in the ESI.†

For the evaluation of the environmental impact of EGSs with electric drilling, values were taken from different scenarios in Treyer *et al.*³⁵ and from the analysis of the EGS plants in Basel and St. Gallen in this study. As there are no case studies for EGS plants with co-generation and electric drilling, the calculated impacts from the plants in St. Gallen and Basel from this study are used as minimum and maximum impact values for EGS with co-generation, respectively.

The data used for the evaluation of coal-firing power plants includes data from conventional coal power plants and power plants using, *i.e.* power plants using two or more combustion materials (*e.g.* combined coal-gas, or coal-biofuel); pulverized coal plants and coal-fired power plants with carbon capture and storage (CCS) technology are also considered here. The same applies to the data for power generation from natural gas, oil and lignite coal. Other geothermal power plants include plants using single-flash and double-flash technologies, as well as electricity production from hydrothermal resources using binary conversion cycles.

Data for hydropower plants were collected from studies assessing hydro dams as well as run-of-river and reservoir power plants. Likewise, data from wind power from onshore and offshore plants were merged into one technology category, as significant differences in the environmental performance are mostly related to the capacity of the wind farms.¹⁴⁰

Table 4 List of reviewed studies according to the assessed power generation technology. Detailed information about the reviewed studies is given in Table SI3 in the ESI

Technology	Citations
EGS (electric drilling)	35 and result from this study
EGS co-generation (electric drilling)	Result from this study
Coal	34, 59, 67, 79, 80, 82 and 105–115
Natural gas	34, 59, 67, 79, 80, 82, 105–107 and 109–118
Oil combustion	59, 67, 79, 107, 109, 111 and 113–115
Nuclear power	34, 59, 67, 79, 107, 109, 111, 115 and 119–121
Lignite coal	59, 67, 109 and 110
Diesel combustion	59, 67 and 115
Conventional geothermal	30, 34, 37, 78–82, 107, 109, 115 and 122
Hydropower	34, 37, 59, 79, 80, 105–107, 109, 111, 114, 115 and 123
Wind power	34, 37, 59, 79, 80, 105–107, 109, 114, 115 and 124–127
Solar power	34, 37, 59, 79, 105–107, 109, 114 and 128–130
Tidal and wave power	80, 107, 109, 131 and 132
Biogas	34, 59, 107, 114 and 133
Biomass	37, 59, 67, 107, 109, 114 and 134–139
Waste incineration	59

For the evaluation of solar power, we reviewed different studies that assessed a wide range of photovoltaic systems, from single home roof panels to solar parks and also solar panels made of different materials. Tower and trough concentrated solar power (CSP) plants are also included. Data on tidal and wave power plants are scarce, as there are still very few power plants worldwide using this energy source.⁸⁰ More data are available for power generation from biogas and biomass, though there is a large variety of biological materials used for fermentation and combustion.

Fig. 7 shows the arithmetic mean values of the results for the four impact categories derived from the studies listed in Table 4 and Table SI3 (ESI[†]), and the overall range between the maximum and minimum values. The environmental impacts from typical renewable and non-renewable energy technologies are displayed together with the emissions from EGS plants with power production and co-generation of heat assuming electric energy used for drilling. The ranges in emissions from non-renewable energy technologies given by the evaluated studies are mostly due to differences in technological details, such as boiling-water and pressurized-water reactors for nuclear power plants, and differences in the efficiency of the individual technologies. Thus, more recent studies typically provide lower values for the same technology than older studies due to an increased efficiency, and likewise, lower emission values are usually reported from power plants with larger capacities.

The comparatively small range of impacts from EGS plants is also due to the small number of studies available for the analysis (Table 4) and the similarity amongst the investigated scenarios. EGS power plants employing flash technology are not considered in this comparison, because the majority of existing studies on EGSs focus on low temperature reservoirs with binary cycle electricity generation without direct GHG emissions. EGS flash power plants are anticipated to have direct GHG emission values similar to conventional geothermal power generation.¹⁴¹

With respect to the mean values, the environmental impacts associated with EGSs are at the lower end in all categories. For example, with an average value of 20.1 g CO₂-eq. per kW h_{el} for EGS power plants and 5.8 g CO₂-eq. per kW h_{el} for EGS with co-generation, they show a significantly better environmental performance than typical non-renewable energy technologies. EGS plants with co-generation potentially outperform nuclear power with regard to all four environmental impacts in Fig. 7. Detailed comparison of further impact categories, however, is beyond the scope of this paper.

Compared to other renewable energies, the average values of the environmental impacts from EGS plants with and without co-generation are in the same range as the impacts from wind power and tidal power generation (Fig. 7). Conventional geothermal power plants cause on average higher GHG emissions of 167 g CO₂-eq. per kW h_{el}, because they entail a comparable amount of GHG during drilling operation and often cause additional emissions during operation due to the emission of non-condensable gases. The large variation in emissions

caused by non-condensable gases during operation reported in the different studies is the main reason for the large range between 2 and over 1000 g CO₂-eq. per kW h_{el} of GHG emissions in Fig. 7.

Regarding the demand of non-renewable energy for other geothermal technologies, the impact value is only slightly higher than for EGS plants. The reason is because these indicators are mostly influenced by the energy and material demand for plant construction and operation, which yield similar values and smaller ranges for all geothermal technologies. The eutrophication potential of conventional geothermal power plants exceeds that of EGS plants due to high values from one study associated with sludge management during drilling operations and potential working fluid losses.⁸² More detailed assessments and discussion of the specific technological aspects that cause EGSs and other geothermal technologies to perform differently with respect to various environmental impacts are available in other studies.^{31,34,69,141}

Energy generation from the combustion of biomass, biogas and waste incineration also shows rather high mean values in most impact categories, as the combustion process also causes direct emissions besides the embodied indirect emissions.¹³⁹ The overall picture for the environmental performance of EGS is favourable. This is not only with respect to the global warming potential, but also in the other impact categories. The calculated mean impacts are among the lowest in comparison with other technologies, especially when co-generation is considered. As depicted in Fig. 7, the average global warming potential, the acidification potential and the eutrophication potential of EGS with co-generation are the smallest.

Martín-Gamboa *et al.* compared the environmental performance of a Spanish EGS scenario to typical coal and natural gas power plants for further impact categories.⁸² They also found that EGS is a promising alternative in all environmental aspects, excluding ozone layer depletion potential due to the potential loss of refrigerant fluids. Bauer *et al.* conducted a comprehensive analysis of the environmental impact of several energy technologies in Switzerland using Eco-indicator 99 as LCIA.^{142,143} The general ranking of the different technologies is similar to that in Fig. 7, with the impact from energy generation from coal being significantly larger than from natural gas, and the renewable energies having a comparatively small expected influence on climate change.

Hirschberg *et al.* also assessed the environmental impact of energy technologies that contribute electricity to the Swiss grid.¹²² Here, the worst performance with regard to impact on climate change falls to electricity generation from natural gas followed by biogas and photovoltaics. However, unlike the results in Fig. 7, nuclear, hydro and wind power perform slightly better than EGS power plants with regard to impact on climate change. This might be due to the wider range of power plants with different technological settings included in the analysis in this study.

Similar to the approach in Fig. 4 and 5 one can also assign the typical value for GHG emissions from other energy technologies as a threshold value for an EGS scenario with a varying

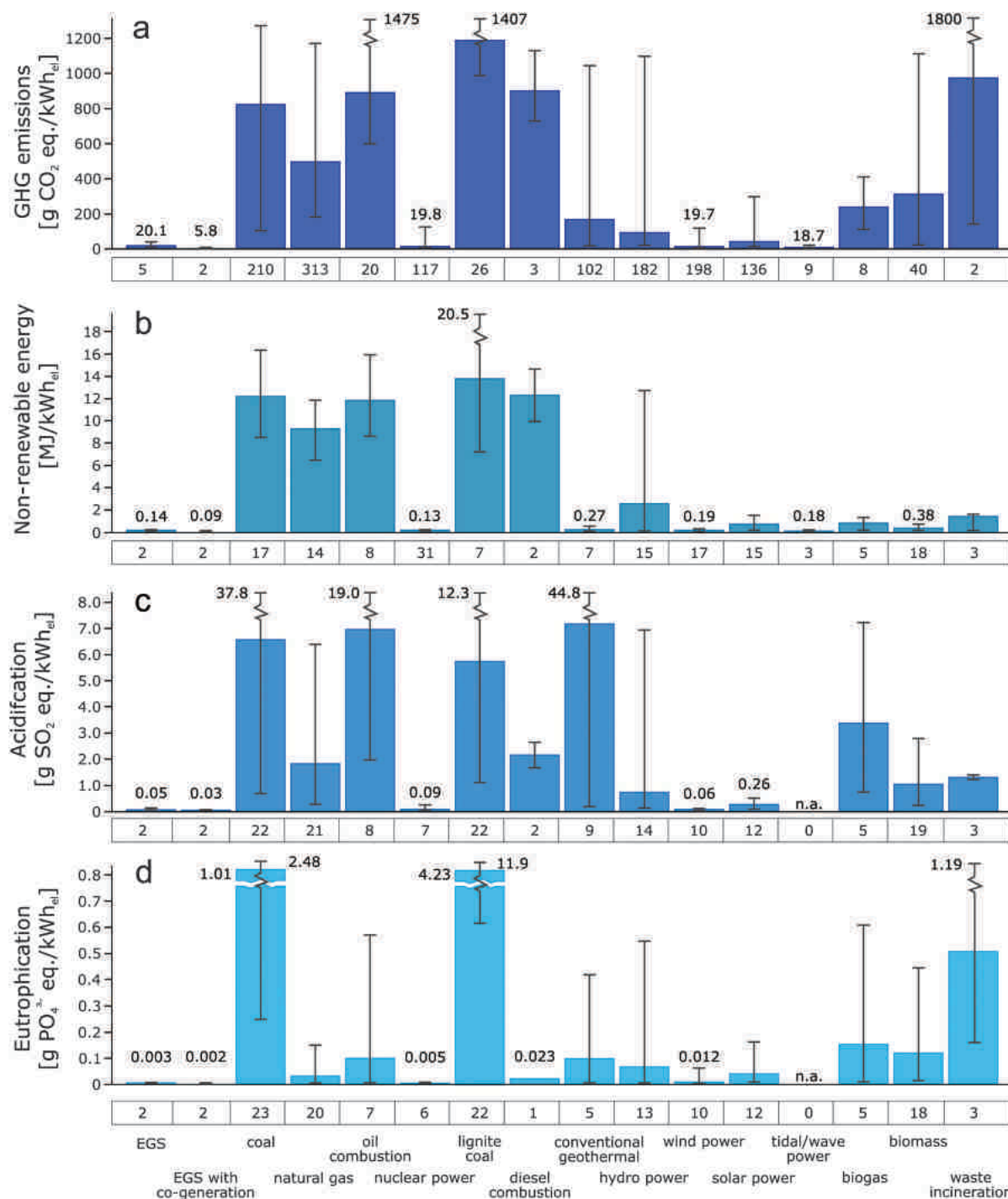


Fig. 7 Life time environmental impact due to (a) GHG emissions, (b) non-renewable energy demand, (c) acidification potential and (d) eutrophication potential from EGS power plants with electric drilling operations and EGS plants with co-generation compared to conventional and other renewable energy technologies. 'n.a.' indicates that no values for the respective environmental impact were available. The numbers given below each bar represent the number of estimates for each technology provided by the examined studies. The height of the bars and numbers above indicate the arithmetic mean value of emissions from these estimates, while the whiskers refer to the minimum and maximum values, respectively, obtained from the reviewed studies.

number of boreholes drilled during the life time. In the case of a favourable plant design and location, as in the scenarios of Basel or St. Gallen, the GHG emissions of the energy technologies based on the combustion of fossil fuels are much higher than

those from EGS plants, even when one additional borehole is needed for each year of the plant lifetime. The lifetime GHG emissions from a typical nuclear power plant with 20 g CO₂-eq. per kW_{h_{el}} are comparable to a 4 and 5 borehole EGS plant in

Basel or St. Gallen, respectively (with co-generation of heat from 8 and 16 boreholes, respectively).

Conclusions

Numerous studies are comprehensively reviewed in this work, but studies on environmental performance and LCA for EGS are still rare. This is mainly due to the limited number of commercial plants and the immaturity of the EGS technology, which is also reflected by the presence of pilot projects such as Soultz-sous-Forêts. EGS is still an evolving technology, thus long-term data from commercial operation are scarce. These long term data, however, are crucial for the assessment of the entire life cycle. Our study demonstrated that LCA of EGSs or other geothermal power plants are highly case-specific. This is shown by previously conducted studies that reveal large variations in the environmental impacts such as GHG emissions. The reasons for these deviations are plentiful, such as varying assumptions (*e.g.* data for diesel consumption for drilling) and data sources (*e.g.* actual drilling geothermal reports *vs.* US database for oil and gas wells). Furthermore, the environmental impact of EGS strongly depends on the drilling operation, such as the drilling technology and duration. They are therefore prone to site-specific conditions such as subsurface properties, which strongly influence the required drilling depth, drilling time and number of boreholes. In addition, a shift from diesel-driven drilling rigs to electric rigs can be observed. Thus, the environmental impact increasingly depends on the national electricity mix and the embedded environmental burdens from different energy technologies (unless this demand is deducted from the output as done above in this study).

Currently, no LCA procedure for EGS plants considers the risk of seismicity, except for the work of Lacirignola and Blanc³³ that takes into account seismicity based on the reinjection of geothermal fluid during production. However LCA procedures should also address induced seismicity during hydraulic stimulations, as this plays a major role in EGSs in densely populated regions such as central Europe. For example, the planned EGSs in Basel caused seismic events reaching Richter magnitude ML 3.4 six days after the main stimulation. This ultimately led to the suspension of the project.⁸⁴

During the operation of EGS plants, it is also crucial to know how many boreholes are actually needed to maintain the power production at decreasing flow rates and reservoir temperatures. For example, for the case in Basel, 19 additional wells could be drilled until the environmental performance regarding GHG emissions would equal the national electricity mix. This number is presumably sufficient to account for potentially unsuccessful wells and required make-up wells. For countries with more carbon-intensive electricity generation like in Germany, this number of wells would be even larger. Hence, in general, a large number of boreholes can be drilled for EGS projects until beneficial effects would cancel out the use of the existing national electricity supply. A comparison of potential EGS plants in Switzerland (Basel and St. Gallen) with regard to

various impact indicators showed that the co-generation of heat would significantly improve the environmental performance. Due to the allocation of produced power and heat to the life time emissions, additional boreholes would also have less of an impact on the environmental performance.

An analysis of potential future EGS scenarios shows that significant improvements in the present day environmental performance are possible when emerging advanced drilling technologies, such as thermal spallation drilling, and more efficient, mature EGS power plants are taken into account. Due to the forecasted lower energy demand for drilling with advanced technologies and the increase in the life time generation of electricity, a future EGS plant with a theoretical total borehole length of 90 km could be environmentally competitive with today's average nuclear power plants regarding GHG emissions.

Finally, the power generation from EGSs is compared with other non-renewable and renewable power generation technologies. The results demonstrate that EGSs are advantageous over fossil fuel based power generation technologies with regard to GHG emissions, non-renewable energy demand, acidification and eutrophication potential. Environmental impacts from EGS plants with co-generation show values that are in the same range as impacts from nuclear energy, without creating problematic waste. In comparison to renewable power generation technologies, EGSs with electric drilling can compete with other geothermal systems, hydro power, solar power, biomass and biogas. Compared to wind and tidal/wave power EGSs with electric drilling and no co-generation of heat have about the same GHG emissions per life time electricity generation, but lower other environmental impacts. In addition, EGSs have the advantage of stable energy production, which is important for phasing out fossil fuels.

A future change in energy use to more renewable technologies (*i.e.* lower environmental impacts) will consequently also lower the impact of EGS plants and therefore will improve the competitiveness of these technologies. Furthermore, in contrast to most renewable technologies, EGSs can cover the base load demand, which is mainly provided by nuclear power at present and therefore might be considered as an option when phasing out non-renewable power production.

Acknowledgements

The authors acknowledge financial support from the Competence Center Energy and Mobility and the Competence Center for Environment and Sustainability of the ETH-Domain for the GEOTHERM-2 Project. Furthermore, we would like to thank Stefanie Frick (GFZ German Research Centre for Geoscience Potsdam, Germany), Dirk Koch (ITAG Deep Drilling Celle, Germany), and Michael Sonderegger (Stadtwerke St. Gallen, Switzerland) for the valuable support with data and additional information.

References

- 1 L. Rybach, Proceedings World Geothermal Congress, Bali, Indonesia, 2010.

- 2 S. Held, A. Genter, T. Kohl, T. Kölbel, J. Sausse and M. Schoenball, *Geothermics*, 2014, **51**, 270–280.
- 3 J. W. Tester, B. J. Anderson, A. S. Batchelor, D. D. Blackwell, R. DiPippo and E. M. Drake, *The future of geothermal energy—impact of enhanced geothermal systems (EGS) on the United States in the 21st century*, Massachusetts Institute of Technology and US Department of Energy, 2006.
- 4 R. Bertani, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 2015.
- 5 G. Dauncey and P. Mazza, *Stormy Weather: 101 Solutions to Global Climate Change*, New Society Publishers, Gabriola Island, British Columbia, Canada, 2001.
- 6 R. Bertani, *JGA News*, 2003, **53**, 1–3.
- 7 F. Stauffer, P. Bayer, P. Blum, N. M. Giraldo and W. Kinzelbach, *Thermal use of shallow groundwater*, CRC Press, 2013.
- 8 K. Yost, A. Valentin and H. H. Einstein, *Geothermics*, 2015, **53**, 85–99.
- 9 M. Z. Lukawski, B. J. Anderson, C. Augustine, L. E. Capuano Jr, K. F. Beckers, B. Livesay and J. W. Tester, *J. Pet. Sci. Eng.*, 2014, **118**, 1–14.
- 10 S. Cloetingh, J. D. Van Wees, P. Ziegler, L. Lenkey, F. Beekman, M. Tesauero, A. Förster, B. Norden, M. Kaban and N. Hardebol, *Earth-Sci. Rev.*, 2010, **102**, 159–206.
- 11 Y. Feng, X. Chen and X. F. Xu, *Renewable Sustainable Energy Rev.*, 2014, **33**, 214–223.
- 12 G. R. Beardsmore, L. Rybach, D. Blackwell and C. Baron, *GRC Trans.*, 2010, **34**, 301–312.
- 13 M. Flores, D. Davies, G. Couples and B. Palsson, Proceedings World Geothermal Congress 2005, Antalya, Turkey, 2005.
- 14 M. Grant, *Geothermal reservoir engineering*, Elsevier, 2013.
- 15 L. Xie, K.-B. Min and Y. Song, *Renewable Energy*, 2015, **79**, 56–65.
- 16 D. C. Karvounis, V. S. Gischig and S. Wiemer, *Shale Energy Engineering*, 2014, 246.
- 17 E. L. Majer, R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith and H. Asanuma, *Geothermics*, 2007, **36**, 185–222.
- 18 K. Breede, K. Dzebisashvili, X. Liu and G. Falcone, *Geothermal Energy*, 2013, **1**, 4.
- 19 A. Franco and M. Vaccaro, *Renewable Sustainable Energy Rev.*, 2014, **30**, 987–1002.
- 20 C. R. Chamorro, J. L. García-Cuesta, M. E. Mondéjar and A. Pérez-Madrado, *Energy*, 2014, **65**, 250–263.
- 21 J. Limberger, P. Calcagno, A. Manzella, E. Trumpy, T. Boxem, M. Pluymaekers and J.-D. van Wees, *Geoth. Ener. Sci.*, 2014, **2**, 55–71.
- 22 H. Hofmann, S. Weides, T. Babadagli, G. Zimmermann, I. Moeck, J. Majorowicz and M. Unsworth, *Energy*, 2014, **69**, 578–591.
- 23 X. Huang, J. Zhu, C. Niu, J. Li, X. Hu and X. Jin, *Energy*, 2014, **75**, 360–370.
- 24 B. Goldstein, A. Hill, A. Long, A. Budd, F. Holgate and M. Malavazos, Proceedings of the 34th workshop on geothermal reservoir engineering, Stanford University, Stanford, California, 2009.
- 25 T. Agemar, J. Weber and R. Schulz, *Energies*, 2014, **7**, 4397–4416.
- 26 A. Gérard, A. Genter, T. Kohl, P. Lutz, P. Rose and F. Rummel, *Geothermics*, 2006, **35**, 473–483.
- 27 J. Majorowicz and S. E. Grasby, *Nat. Resour. Res.*, 2010, **19**, 177–188.
- 28 R. DiPippo, *Energy Policy*, 1991, **19**, 798–807.
- 29 J. Chen and F. Jiang, *Renewable Energy*, 2015, **74**, 37–48.
- 30 M. Bravi and R. Basosi, *J. Cleaner Prod.*, 2014, **66**, 301–308.
- 31 P. Bayer, L. Rybach, P. Blum and R. Brauchler, *Renewable Sustainable Energy Rev.*, 2013, **26**, 446–463.
- 32 S. Frick, M. Kaltschmitt and G. Schröder, *Energy*, 2010, **35**, 2281–2294.
- 33 M. Lacirignola and I. Blanc, *Renewable Energy*, 2013, **50**, 901–914.
- 34 J. L. Sullivan, C. E. Clark and M. W. J. Han, *Life-cycle analysis results of geothermal systems in comparison to other power systems*, Argonne National Laboratory, Energy Systems Division, US Department of Energy, 2010.
- 35 K. Treyer, H. Oshikawa, C. Bauer and M. Miotti, in *Energy from the Earth – Deep Geothermal as a Resource for the Future*, ed. S. Hirschberg, S. Wiemer and P. Burgherr, Centre for Technology Assessment zurich, Switzerland, 2015, vol. TA-SWISS 62/2015, p. 524.
- 36 L. Gerber and F. Maréchal, *Energy*, 2012, **45**, 908–923.
- 37 M. Pehnt, *Renewable Energy*, 2006, **31**, 55–71.
- 38 M. Lacirignola, B. Meany, P. Padey and I. Blanc, *Geothermal Energy*, 2014, **2**, 8.
- 39 M. Lacirignola, B. H. Meany and I. Blanc, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 2015.
- 40 R. Allis, *Geophys. Res. Lett.*, 1982, **9**, 629–632.
- 41 R. Batra, J. N. Albright and C. Bradley, *Downhole seismic monitoring of an acid treatment in the Beowawe geothermal field*, Los Alamos National Lab., NM (USA), 1984.
- 42 M. C. Fehler, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 1989, **26**, 211–219.
- 43 R. DiPippo, *Geothermal power plants: principles, applications, case studies and environmental impact*, Butterworth-Heinemann, 2012.
- 44 R. Jung, Proceedings of the ISRM International Conference for Effective and Sustainable Hydraulic Fracturing, Brisbane, Australia, 2013.
- 45 T. Hettkamp, J. Baumgärtner, D. Teza and C. Lerch, Proceedings of the Third European Geothermal Review, Mainz, Germany, 2013.
- 46 B. Bendall, C. Huddleston-holmes and B. Goldstein, Proceedings of thirty-eight workshop on geothermal reservoir engineering, Stanford, California, USA, 2013.
- 47 E. Chabora, E. Zemach, P. Spielman, P. Drakos, S. Hickman, S. Lutz, K. Boyle, A. Falconer, A. Robertson-Tait and N. C. Davatzes, Proceedings of the thirty-seventh workshop on geothermal reservoir engineering, Stanford University, Stanford, 2012.
- 48 B. R. Julian, G. R. Foulger and F. C. Monastero, Proceedings of the Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, 2009.
- 49 F. C. Monastero and J. R. Unruh, Proceedings of the 64th EAGE Conference & Exhibition, 2002.

- 50 B. Sanjuan, P. Jousset, G. Pajot, N. Debeglia, M. De Michele, M. Brach, F. Dupont, G. Braibant, E. Lasne and F. Duré, Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 2010.
- 51 J. Meixner, E. Schill, E. Gaucher and T. Kohl, *Geothermal Energy*, 2014, **2**, 1–17.
- 52 A. Minissale, *Earth-Sci. Rev.*, 1991, **31**, 133–151.
- 53 L. R. Reyes, *Geothermal Energy in El Salvador*, Tokyo, Japan, 2012.
- 54 R. Herrera, F. Montalvo and A. Herrera, Proceedings of the World Geothermal Congress, Bali, Indonesia, 2010.
- 55 International Organization for Standardization (ISO), ISO 14040: Environmental management – Life cycle assessment – Principles and framework, 2006.
- 56 International Organization for Standardization (ISO), ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines, 2006.
- 57 R. Dones, C. Bauer, R. Bolliger, B. Burger, M. Faist Emmenegger, R. Frischknecht, N. Jungbluth and M. Tuchschnid, *Life cycle inventories for energy systems: results for current systems in Switzerland and UCTE countries*, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, 2007.
- 58 Swiss Centre for Life Cycle Inventories, Ecoinvent database v2.0, 2007.
- 59 Swiss Centre for Life Cycle Inventories, Ecoinvent database v2.2, 2010.
- 60 NREL, US LCI database, 2010.
- 61 M. J. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs and R. Van Zelm, *ReCiPe 2008*, Ministry of Housing, Spatial Planning and Environment (VROM), Den Haag, The Netherlands, 2009.
- 62 M. Owsianiak, A. Laurent, A. Bjørn and M. Z. Hauschild, *Int. J. Life Cycle Assess.*, 2014, 1–15.
- 63 S. Frick, S. Kranz and A. Saadat, Proceedings of the World Geothermal Congress 2010 Bali, Indonesia, 2010.
- 64 S. Frick, personal communication.
- 65 S. Frick, J. D. Van Wees, M. Kaltschmitt and G. Schröder, in *Geothermal Energy Systems*, ed. E. Huenges, Wiley, Weinheim, 2010, pp. 373–421.
- 66 N. Cuenot, M. Frogneux, M. Calo and C. Dorbath, Proceedings Soultz Geothermal Conference, Soultz-sous-Forêts, France, 2011.
- 67 National Renewable Energy Laboratory, U.S. LCI Database, 2010.
- 68 U.S. Department of Energy, GETEM-Geothermal Electricity Technology Evaluation Model, 2014.
- 69 J. L. Sullivan, C. E. Clark, L. Yuan, J. Han and M. Wang, *Life-Cycle Analysis Results for Geothermal Systems in Comparison to Other Power Systems: Part II*, Argonne National Laboratory, Energy Systems Division, US Department of Energy, 2011.
- 70 C. E. Clark, C. B. Harto, J. L. Sullivan and M. Q. Wang, *Water Use in the Development and Operation of Geothermal Power Plants*, Environmental Science Division & Energy Systems Division, Argonne National Laboratory, US Department of Energy, 2011.
- 71 K. Treyer and C. Bauer, *Int. J. Life Cycle Assess.*, 2013, 1–19.
- 72 B. Legarth and A. Saadat, Proceedings World Geothermal Congress 2005, Antalya, Turkey, 2005.
- 73 *Geothermal Energy Systems: Exploration, development and utilization*, ed. E. Huenges, Wiley-VCH, Weinheim, 2010.
- 74 L. Gerber, M. Gassner and F. Maréchal, *Comput. Chem. Eng.*, 2011, **35**, 1265–1280.
- 75 C. Clark, C. Harto, J. Sullivan and M. Wang, *GRC Trans.*, 2011, **35**, 593–596.
- 76 H. Kristmannsdóttir and H. Ármannsson, *Geothermics*, 2003, **32**, 451–461.
- 77 S. Frick and M. Kaltschmitt, *Erdöl, Erdgas, Kohle*, 2009, vol. 125, pp. 37–42.
- 78 M. R. Karlsdóttir, O. P. Pálsson and H. Pálsson, Proceedings World Geothermal Congress 2010, Bali, Indonesia, 2010.
- 79 H. Hondo, *Energy*, 2005, **30**, 2042–2056.
- 80 B. M. Rule, Z. J. Worth and C. A. Boyle, *Environ. Sci. Technol.*, 2009, **43**, 6406–6413.
- 81 R. Bertani and I. Thain, *Geothermal Power Generating Plant CO₂ Emission Survey*, 2002.
- 82 M. Martín-Gamboa, D. Iribarren and J. Dufour, *Geothermics*, 2015, **53**, 27–37.
- 83 A. Sperber, *Internal report for the project FKZ 205 42 110 carried out for the German Federal Environment Agency (UBA) by IDEAS (Independent drilling Engineering Axel Sperber) based on well planning tool*, Institute for Energy and Environment, Leipzig, Germany, 2007.
- 84 M. O. Häring, U. Schanz, F. Ladner and B. C. Dyer, *Geothermics*, 2008, **37**, 469–495.
- 85 P. Bayer, D. Saner, S. Bolay, L. Rybach and P. Blum, *Renewable Sustainable Energy Rev.*, 2012, **16**, 1256–1267.
- 86 O. Y. Yu, PhD thesis, Texas A&M University, 2009.
- 87 J. D. Rogers, B. Knoll, R. Haut, B. McDole and G. Deskins, *Assessments of Technologies for Environmentally Friendly Drilling Project: Land-Based Operations*, 2006.
- 88 D. G. Hill, J. Johnson, J. Bell, N. Mayer, H. Giberson, R. Hessler and W. Matthews, Proceedings SPE/IADC Drilling Conference and Exhibition 2011, Amsterdam, The Netherlands, 2011.
- 89 R. Thompson, B. Murphy, K. Williams, H. Giberson, J. Garaghty and G. Pace, Proceedings SPE/IADC Drilling Conference and Exhibition 2013, 2013.
- 90 A. Verma and D. Burnett, Proceedings SPE/IADC Drilling Conference and Exhibition 2009, Cartagena, Colombia, 2009.
- 91 D. Koch, personal communication.
- 92 R. P. von Rohr, M. Kant, T. Rothenfluh, M. Schuler and P. Stathopoulos, in *Energy from the Earth - Deep Geothermal as a Resource for the Future?*, ed. S. Hirschberg, S. Wiemer and P. Burgherr, Centre for Technology Assessment Zurich, Switzerland, 2015, vol. TA-SWISS 62/2015.
- 93 M. Sonderegger, personal communication.
- 94 M. O. Häring, *Deep Heat Mining Basel: Voruntersuchung und Pflichtenheft für die Umweltverträglichkeits-Prüfung*, Basel, Switzerland, 2003.

- 95 M. Kaiser and M. Fäs, *Umweltverträglichkeitsbericht, Deep Heat Mining, Basel*, Geothermal Explorers Ltd., Basel Switzerland, 2004.
- 96 A. Genter, J. Baumgärtner, N. Cuenot, J. J. Graff, T. Kölbel and B. Sanjuan, *Proceedings of the Second European Geothermal Review*, Mainz, Germany, 2010.
- 97 R. M. Rauenzahn and J. Tester, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 1989, **26**, 381–399.
- 98 C. R. Augustine, PhD thesis, Massachusetts Institute of Technology, 2009.
- 99 P. R. Von Rohr, T. Rothenfluh and M. Schuler, *US Pat.*, 8967293, 2015.
- 100 T. W. Wideman, N. Sazdanoff, J. Unzelman-Langsdorf and J. Potter, *GRC Trans.*, 2011, **35**, 283–285.
- 101 H. O. Schiegg, A. Rødland, G. Zhu and D. A. Yuen, *J. Earth Sci.*, 2015, **26**, 37–46.
- 102 R. Ndeda, E. Sebusang, R. Marumo and E. Ogur, *Proceedings of Sustainable Research and Innovation Conference*, Juja-Thika, Kenya, 2015.
- 103 V. M. Fthenakis and H. C. Kim, *Energy Policy*, 2007, **35**, 2549–2557.
- 104 IPCC, *Fifth Assessment Report (AR5)*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2014.
- 105 E. G. Hertwich, J. Aloisi de Larderel, A. Arvesen, P. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, P. Purohit, A. Ramirez and S. Suh, *Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production*, UNEP, 2015.
- 106 E. G. Hertwich, T. Gibon, E. A. Bouman, A. Arvesen, S. Suh, G. A. Heath, J. D. Bergesen, A. Ramirez, M. I. Vega and L. Shi, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 6277–6282.
- 107 IPCC, *Renewable Energy Sources and Climate Change Mitigation - Special Report of the Intergovernmental Panel on Climate Change*, Cambridge, 2012.
- 108 M. Whitaker, G. A. Heath, P. O'Donoughue and M. Vorum, *J. Ind. Ecol.*, 2012, **16**, S53–S72.
- 109 N. Y. Amponsah, M. Trolldborg, B. Kington, I. Aalders and R. L. Hough, *Renewable Sustainable Energy Rev.*, 2014, **39**, 461–475.
- 110 B. Atilgan and A. Azapagic, *J. Cleaner Prod.*, 2014, **106**, 555–564.
- 111 Varun, I. K. Bhat and R. Prakash, *Renewable Sustainable Energy Rev.*, 2009, **13**, 1067–1073.
- 112 K. K. Agrawal, S. Jain, A. K. Jain and S. Dahiya, *Int. J. Environ. Sci. Technol.*, 2014, **11**, 1157–1164.
- 113 R. Turconi, C. O'Dwyer, D. Flynn and T. Astrup, *Appl. Energy*, 2014, **131**, 1–8.
- 114 R. Garcia, P. Marques and F. Freire, *Appl. Energy*, 2014, **134**, 563–572.
- 115 E. Santoyo-Castelazo, H. Gujba and A. Azapagic, *Energy*, 2011, **36**, 1488–1499.
- 116 G. A. Heath, P. O'Donoughue, D. J. Arent and M. Bazilian, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, **111**, E3167–E3176.
- 117 P. R. O'Donoughue, G. A. Heath, S. L. Dolan and M. Vorum, *J. Ind. Ecol.*, 2014, **18**, 125–144.
- 118 R. Kannan, K. C. Leong, R. Osman, H. K. Ho and C. P. Tso, *Energy Convers. Manage.*, 2005, **46**, 2145–2157.
- 119 E. S. Warner and G. A. Heath, *J. Ind. Ecol.*, 2012, **16**, S73–S92.
- 120 R. Dones, *Kernenergie. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, 2003.
- 121 M. Lenzen, *Energy Convers. Manage.*, 2008, **49**, 2178–2199.
- 122 S. Hirschberg, P. Burgherr, W. Schenler, M. Spada, K. Treyer and C. Bauer, in *Energy from the Earth - Deep Geothermal as a Resource for the Future?*, ed. S. Hirschberg, S. Wiemer and P. Burgherr, Centre for Technology Assessment Zurich, Switzerland, 2015, vol. TA-SWISS 62/2015.
- 123 Varun, R. Prakash and I. K. Bhat, *Energy*, 2012, **44**, 498–508.
- 124 S. L. Dolan and G. A. Heath, *J. Ind. Ecol.*, 2012, **16**, 136–154.
- 125 P. Padey, I. Blanc, D. Le Boulch and Z. Xiusheng, *J. Ind. Ecol.*, 2012, **16**, S28–S38.
- 126 A. N. Celik, T. Muneer and P. Clarke, *Proc. Inst. Mech. Eng., Part A*, 2007, **221**, 1107–1117.
- 127 B. Reimers, B. Özdirik and M. Kaltschmitt, *Renewable Energy*, 2014, **72**, 428–438.
- 128 J. J. Burkhardt, G. Heath and E. Cohen, *J. Ind. Ecol.*, 2012, **16**, S93–S109.
- 129 D. D. Hsu, P. O'Donoughue, V. Fthenakis, G. A. Heath, H. C. Kim, P. Sawyer, J. K. Choi and D. E. Turney, *J. Ind. Ecol.*, 2012, **16**, S122–S135.
- 130 H. C. Kim, V. Fthenakis, J. K. Choi and D. E. Turney, *J. Ind. Ecol.*, 2012, **16**, S110–S121.
- 131 R. P. M. Parker, G. P. Harrison and J. P. Chick, *Proc. Inst. Mech. Eng., Part A*, 2007, **221**, 1119–1130.
- 132 C. A. Douglas, G. P. Harrison and J. P. Chick, *Proc. Inst. Mech. Eng., Part M*, 2008, **222**, 1–12.
- 133 M. Fuchsz and N. Kohlheb, *J. Cleaner Prod.*, 2015, **86**, 60–66.
- 134 P. A. Gerin, F. Vliegen and J.-M. Jossart, *Bioresour. Technol.*, 2008, **99**, 2620–2627.
- 135 S. M. Shafie, H. H. Masjuki and T. M. I. Mahlia, *Energy*, 2014, **70**, 401–410.
- 136 T. Ramjeawon, *J. Cleaner Prod.*, 2008, **16**, 1727–1734.
- 137 M. Kami Delivand, M. Barz, S. H. Gheewala and B. Sajjakulnukit, *J. Cleaner Prod.*, 2012, **37**, 29–41.
- 138 H. Liu, K. R. Polenske, Y. Xi and J. e. Guo, *Energy Policy*, 2010, **38**, 6153–6160.
- 139 F. Sebastián, J. Royo and M. Gómez, *Energy*, 2011, **36**, 2029–2037.
- 140 M. Caduff, M. A. Huijbregts, H.-J. Althaus, A. Koehler and S. Hellweg, *Environ. Sci. Technol.*, 2012, **46**, 4725–4733.
- 141 J. Sullivan, T. Stephens and M. Wang, *Geothermal Power Production: Alternative Scenarios and Critical Issues*, Argonne National Laboratory (ANL), 2014.
- 142 C. Bauer, R. Dones, T. Heck and S. Hirschberg, *Comparative environmental assessment of current and future electricity supply technologies for Switzerland*, Laboratory for Energy System Analysis, Paul-Scherrer-Institut (PSI), Villigen, Switzerland, 2006.
- 143 C. Bauer, T. Heck, S. Hirschberg and R. Dones, *Environmental assessment of current and future Swiss electricity supply options*, Interlaken, Switzerland, 2008.