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# Environmental performance of a geothermal power plant using a hydrothermal resource in the Southern German Molasse Basin

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ABSTRACT

Every technology and anthropogenic activity affects the environment. This even applies to renewable, green energy forms, such as geothermal energy, which are often labelled as being climate neutral. Yet, a second glance reveals that this is not the case, as the construction, operation and decommissioning of geothermal power plants implies a consumption of materials and energy. Life Cycle Assessments (LCA) help to identify and quantify these impacts in order to ensure realistic comparability at different levels. Despite a growing number of surveys, however, either not all influencing parameters are explicitly considered, or the studies are only theoretical and based on generic data. Therefore, this study explores the binary plant of Kirchstockach located in Southern Germany in a comprehensive LCA. Corresponding scenarios identify leakages of used refrigerants and allocations of energy consumption during construction and operation as relevant impact factors. Results show that using refrigerants with low global warming potential ensures minimal effects even in case of larger losses. In addition, resource-saving drilling with electricity instead of diesel can effectively offset energy needs by later electricity production. In contrast, auxiliary energy usage from an electricity grid dominated by fossil sources has highly negative effects on the environmental performance.



## 1. Introduction

Geothermal energy is counted among the renewables and by some even considered as a carbon-free option for power generation [1–3]. A closer look at any mature renewable energy technology reveals that there are in fact low-carbon options, with often minor adverse effects on the environment [4–6]. These become apparent when considering the full life cycle of a technology. The common standardized methodology for full environmental performance evaluation of products, goods and services is life cycle assessment (LCA) [7,8]. In an LCA framework, all environmental footprints associated with items and processes during plant development, operation and decommissioning are taken into account. As a result, especially for any technology with almost carbon-free operation, the role of construction work, installations, facilities and plant buildings as well as decommissioning shows to be dominant within the bulk environmental impact. Prominent examples for such technologies are photovoltaic or nuclear power plants [9]. Moreover, LCA does not only account for climate change impact due to greenhouse gas (GHG) emissions, but further environmental impacts such as those related to the use of resources, land use, the release of photo oxidants or eutrophication are also examined. All such different impacts are simultaneously assessed in specific impact categories [10,11].

The global review of available work on the environmental assessment of geothermal electricity generation by Bayer et al. [12] focuses on geothermal power plants located in young geologic

*Abbreviations:* EGS, Enhanced Geothermal System; LCI, Life Cycle Inventory; GHG, Greenhouse Gas; LCIA, Life Cycle Inventory Analysis; GWP, Global Warming Potential; LT, Low Temperature; HT, High Temperature; ORC, Organic Rankine Cycle; LCA, Life Cycle Assessment.

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settings, often associated with active tectonics and volcanoes, where geothermal gradients are substantial and high-temperature reservoirs can be exploited at shallower depth than in most other places. These plants contribute by more than 95% to the geothermal electricity generated worldwide [13–15]. A major issue for many dry and flash-steam plants is the continuous release of $CO_2$ and methane from the extracted geofluids, which varies broadly and in rare extreme cases may yield GHG emissions as high as those from burning fossil fuels [5,12,16–18]. In order to overcome substantial on-site release of GHG, enhanced re-injection of non-condensable gases (NCG) such as by the novel CarbFix gas injection at the Hellisheidi power plant in Iceland is suggested [19–21]. Alternatively, high $CO_2$ concentrations in extracted geofluids are industrially used, for example at geothermal plants in Turkey [22,23].

In general, lower emissions are expected from closed systems with circulating fluids such as binary power plants [24,25]. Based on a review on worldwide geothermal electricity generation in 2014, nearly every second geothermal power plant unit is a binary type (279 of 613 total units), while contributing to only around 15% to the worldwide geothermal electricity production [26]. According to a more recent market analysis, this has not fundamentally changed with an increase of total installed worldwide capacity of all geothermal power plants from around 12 $GW_e$ in 2015 to 16 $GW_e$ in 2020 [13]. Also, geothermal power generation in areas without high-temperature conditions in shallow depth has gained attention. As this is the case for most part of the earth, the potential of such “low-enthalpy” resources with temperatures usually far below 180 °C is considered enormous [27–29]. Beside Kalina cycle systems, which are more complex to design, ORC technology is a common way for geothermal electricity generation in areas with such low-enthalpy reservoirs [30].

The major variants are hydrothermal power plants that utilize productive aquifers found in sedimentary basins [31,32], and enhanced geothermal systems (EGS) [27,33,34] that rely on artificial generation of fractures in deep rock formations for facilitating the circulation of water as heat carrier fluid. For both variants, a crucial hurdle are the efforts required for deep drilling and risks associated with reservoir development. The productivity of hydrothermal reservoirs in sedimentary basins is often uncertain and stimulation during EGS development may cause induced seismicity. This is why they still exist only in some well explored regions and substantial research activities are dedicated to more reliable and safe development of these geothermal power plants [12,35,36].

Previous studies on life-cycle based environmental assessment of geothermal power generation can be generally categorized. One family represents generic scenario analyses and reviews based on regional [37–39], national [25,40–44] or broader international conditions [12,45–47]. The other family represents a few case studies, which investigate the specific environmental aspects of selected geothermal facilities by means of LCA [48–52]. Among these, for example Karlsdottir et al. [20] and Wang et al. [53] state that both the case-specific geochemical and geothermal boundary conditions are crucial for the environmental performance of a plant.

Due to the diversity of geothermal resources, site conditions and facilities, detailed LCA case studies are essential for addressing the variability of environmental issues related to geothermal power generation. Such studies are also needed for validating global surveys and generic conclusions, which often serve as a baseline for predicting the performance of facilities planned in the future. Considering the increasing relevance of low-enthalpy based geothermal power generation in countries without high-temperature conditions in shallow ground [28,54], special interest is directed towards deep hydrothermal and engineered geothermal systems (EGS). For example, Pratiwi et al. [50] investigated an operating and a projected plant by comparing the production of heat, electricity or cogeneration within five scenarios. Even the evaluation only with a focus on GHG emissions showed that these operational strategies and plant conceptions have significant effects on the environment, due to different material consumptions, and are also influenced by the local electricity mix.

Another feasibility study by McCay et al. [55] showed the effects of low enthalpy geothermal heat production on $CO_2$ and other GHG emissions under different drilling scenarios. As in many related studies (e.g. Ref. [20,56,57]) it was shown that most environmental impacts of the construction phase can be avoided by low-carbon drilling and optimized material consumption.

Heberle et al. [58] investigated potential geothermal Organic Rankine Cycle (ORC) concepts and working fluids for typical geothermal conditions in Germany by means of LCA. In particular, the two-stage ORC shows the lowest environmental impacts for geothermal power generation by using low-GWP (Global Warming Potential) fluids or natural hydrocarbons. Compared to a conventional single-stage concept with common fluorinated hydrocarbon as an ORC working fluid the $CO_2$-equivalent can be reduced by up to 80%.

In this work, we focus on the Southern German Molasse Basin, which represents the most developed region for geothermal power production in Germany. Here, hydrothermal resources hosted by the Upper Jurassic formation are utilized for the supply of district heating and electricity. We have chosen the binary plant Kirchstockach. This is one of the few plants that provides only electricity, thus all environmental impacts can be referred to by the kilowatt hours of electricity produced. Here, we present the first case LCA study of a plant in the Molasse Basin, and facilitate a comparison to available generic studies. Thus, the goal of this work is to examine the consistency and differences between LCA studies on generic power plants and the findings for a specific site. In addition, we analyse the environmental impact of different ORC working fluids, such as R134a (1,1,1,2-tetrafluoroethane, $C_2H_2F_4$) and R245fa (1,1,1,3,3-pentafluoropropane, $C_3H_2F_4$), with different leakage rates and the effect of employing different supply schemes for auxiliary energy needs, such as power needs of the hydraulic pumps, within the LCA framework.

In the following, first, the study case is introduced. Then the procedures for life cycle based environmental analysis are presented. The subsequent results exhibit the environmental impacts for the Kirchstockach plant which are discussed and contrasted with predictions from related LCA studies.

## 2. Kirchstockach geothermal power plant

### 2.1. Geothermal power generation in the Southern German Molasse Basin

The plant operated at Kirchstockach is located in the South German Molasse Basin, which is part of the Alpine foreland between the river Danube and the Alpine margin. The basin has formed since the Tertiary as a depression trough, resulting from the flexure of the European plate under the weight of the developing Alps. For about 38 million years, the simultaneous subsidence in this region and erosion from the mountains caused the agglomeration of Molasse sediments onto inclined, mainly Jurassic sediments showing a gentle dip to the south [59,60]. The Upper Jurassic formation (Malm) represents the target strata of geothermal drillings with fractured and karstified limestones reaching a thickness of about 500–600 m. The Malm groundwater originates from both overlaying Tertiary layers and former recharge on the Swabian Alb. The confined conditions in the central part of the Molasse Basin ensure a favorable hydraulic head, supporting high production rates of the geothermal wells. In the Malm formation, the temperatures of thermal water increase with depth, reaching more than 140 °C in the south of Munich [61,62].

First exploration activities for deep geothermal resources in the Molasse Basin area were carried out in the early 1990s, whereby the first project, Simbach-Braunau, was realized at the German-Austrian border almost a decade later. As depicted in Fig. 1, to date, 22 deep geothermal plants with drilling depths of more than 1000 m are installed in the South German part of the Molasse Basin and two more are being constructed [63,64]. Only two sites, among them Kirchstockach, mainly generate electricity, while 16 plants primarily deliver district heating with total generation capacities ranging from 2.1 to 40.0 $MW_{th}$.

### *2.2. Technical properties of the Kirchstockach plant*

At Kirchstockach a two-stage ORC power plant has been in operation since 2013. The geothermal system is designed for a nominal electric capacity of 5.5 $MW_{el}$ according to an ambient temperature of 8 °C, a mass flow rate of 120 kg/s of the geothermal fluid and a production temperature of 138 °C. The power plant consists of two separate modules: a high-temperature (HT) and a low-temperature (LT) ORC unit. A scheme of the two-stage system is shown in Fig. 2 and an airborne view of the power plant in Fig. 3.

In both ORC-modules, the working fluid 1,1,1,3,3-Pentafluoropropane (R245fa) is used. In general, the turbine of the HT-ORC operates at higher inlet pressure compared to the LT-ORC. A detailed description of the system, operational parameters of the real power plant and a thermodynamic analysis of the examined power plant is available in Heberle et al. [65]. In addition, Eller et al. [66] developed a transient simulation model of the two-stage ORC power plant at Kirchstockach. This model is validated by real power plant data and is used in the study to predict the yearly gross and net electricity generation of the geothermal power plant (Table 1).

## 3. Life cycle assessment

The application of our LCA is described in the following chapters and customarily follows the normed methodology in line with the ISO 14040 and 14044 standards [69,70]: First, the system boundaries, goal and scope are defined. This also includes the clarification of the functional unit, for which all resource use and emissions are identified, calculated and expressed. Then, a Life Cycle Inventory (LCI) is developed that includes all relevant data on material and energy flows, organized as data base for the different processes inspected. In the subsequent Life Cycle Impact Assessment (LCIA), the related environmental impacts are evaluated using the IMPACT 2002+ methodology [71] and compared for pre-defined impact categories such as the impact on global warming, the impact on acidification or primary energy consumption. The LCIA step is commonly linked to the interpretation of the results.

### *3.1. Definition of goal and scope*

The functional unit chosen for environmental assessment here is 1 kW of electricity produced by the geothermal power plant. We follow a cradle-to-grave approach, focusing on electricity generation only, where the distribution of electricity is not considered. This is a common boundary chosen for comparison of different power generation options [37,45,51]. The life-cycle stages considered are the construction phase involving the devices installed underground and above the ground, the operation phase and a final stage of decommissioning (Fig. 4). The lifetime is assumed to be 30 years, which is consistent with other studies ([40], Table 1). The related material and energy flows, occurring as system in- and outputs during the sequential life cycle stages, are visualized in Fig. 4.

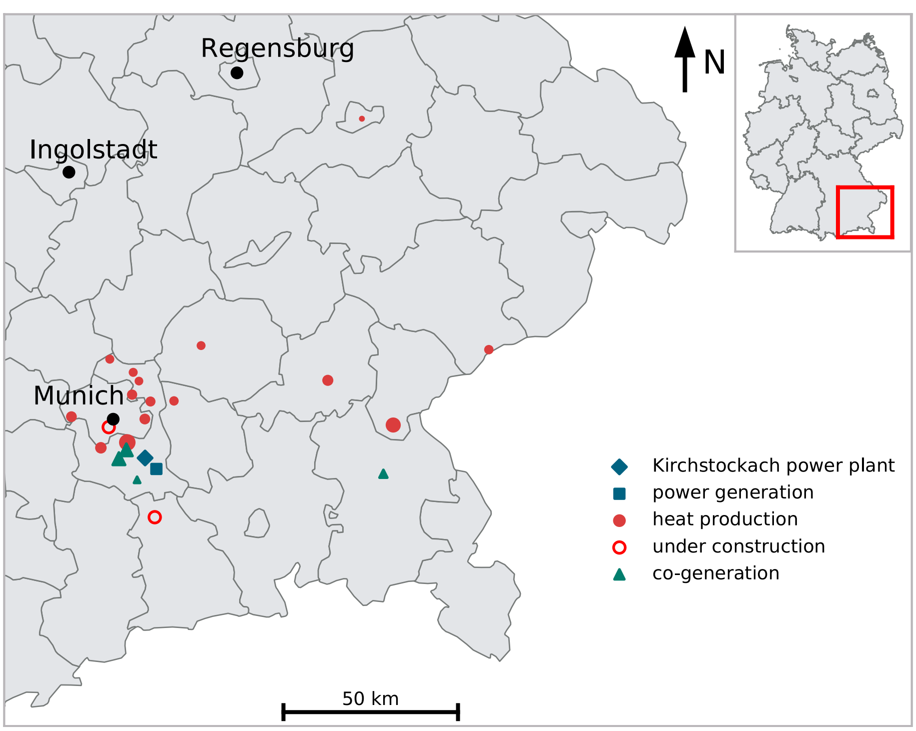


**Fig. 1.** Map of the Eastern part of the Southern German Molasse Basin with the locations of hydrothermal power, heat and co-generation plants currently operating and under construction according to Refs. [63]. The size of the markers indicates the amount of heat production between 2.1 and 40 $MW_{th}$.

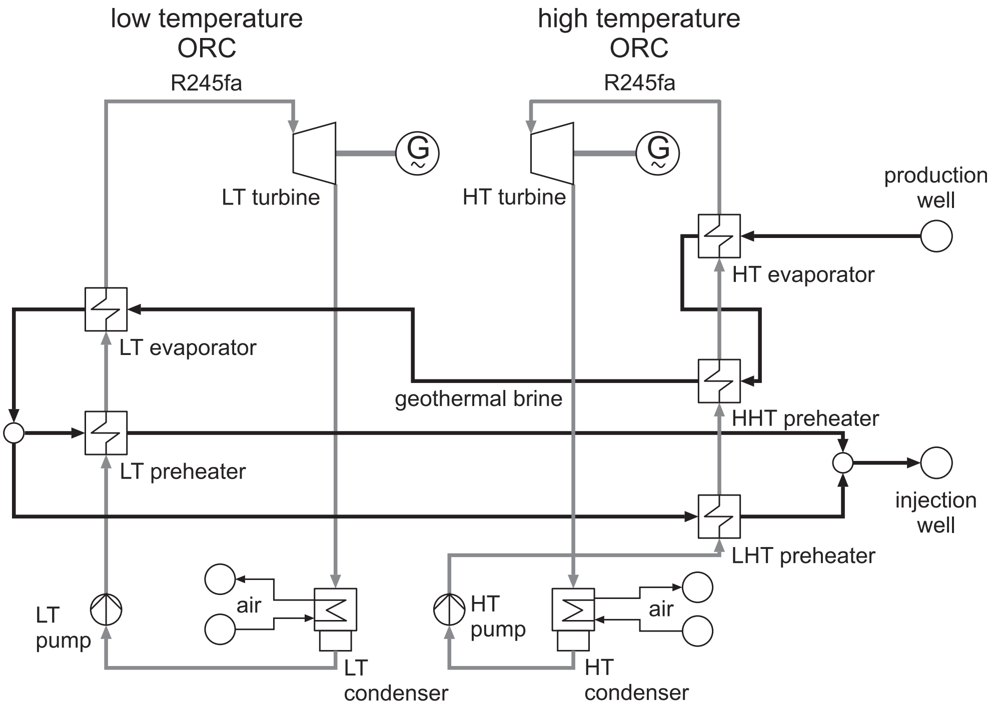


**Fig. 2.** Scheme of the two-stage ORC system in Kirchstockach.

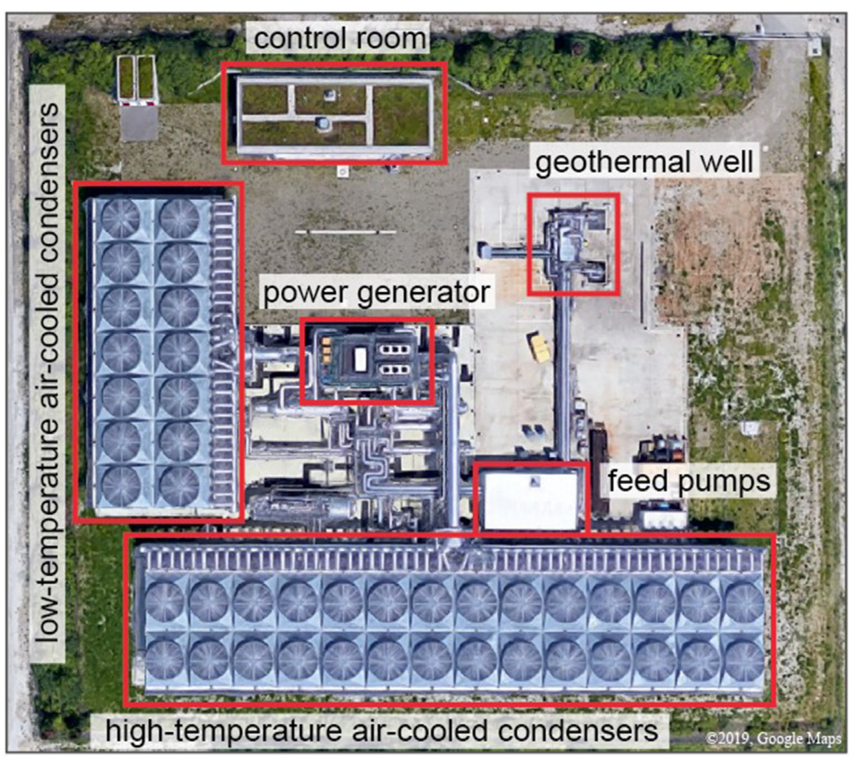


**Fig. 3.** Airborne view of the Kirchstockach geothermal power plant and its main technical installations.

### 3.2. *Life cycle inventory analysis*

The life cycle inventory specific to the Kirchstockach plant is listed in Table 2. The components installed in the subsurface include in particular the boreholes and the pump. The electricity needed for drilling is obtained from the information on drilling days spent at Kirchstockach (Table 1), the power consumption of the drilling rig (3.23 MW) and assuming an average part load ratio of 45%. The obtained drilling energy consumed per meter borehole is 2630 MJ and thus similar to the one estimated for the case of St. Gallen (2830 MJ/m, depth 4450 m) [45]. Information on cementation and drilling mud for the geothermal wells, reservoir

**Table 1**
Kirchstockach binary power plant characteristics used for the LCA (base case); SWM is the Stadtwerke München and the operator of the plant.

| | Parameter | Value | Unit | Source |
|---|---|---|---|---|
| subsurface | overall borehole depth | 8664 | m | operator data (SWM) |
| | overall length of casing | 13,200 | m | operator data (SWM) |
| | drilling days | 182 | d | operator data (SWM) |
| | power need downhole pumps[a] | 608 | kW | Frick et al. [40] |
| surface | installed capacity | 5.5 | $MW_{el}$ | Heberle et al. [65] |
| | power need ORC | 615 | kW | Eller et al. [66] |
| | ORC refrigerant R245fa[b] | 70,000 | kg | operator data (SWM) |
| | annual refrigerant leakage rate[c] | 1 | % | |
| operation | load hours[d] | 7582 | h/y | |
| | lifetime | 30 | y | Frick et al. [40] |
| | gross power production[e] | 39,734 | $MWh_{el}$/y | Eller et al. [66] |
| | net power production[e] | 27,645 | $MWh_{el}$/y | Eller et al. [66] |

[a] Calculated according to Frick et al. [40] with 1.3 $kW_{el}/(m^3/h)$ per $m^3$/l and 468 $m^3$/h.
[b] This value refers to the first-time filling of the ORC before operation.
[c] Assumption based on values reported in previous studies [67].
[d] Assuming an average of 10 days for maintenance, and a probability of downtime of 10% for the remaining time, and based on data from Bonafin et al. [68].
[e] Modelled as described above using actual temperature values.

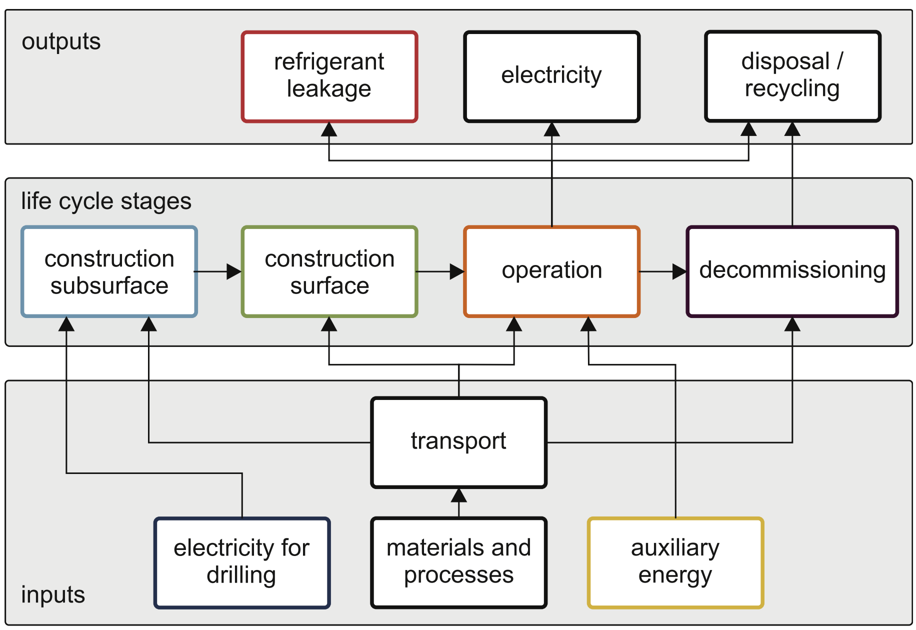


**Fig. 4.** Overview of the life cycle model for the Kirchstockach power plant illustrating the analysed life cycle stages with related inputs and outputs. The colour scheme refers to colours in the following figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 2**
Life cycle inventory (LCI) showing the data specific to the Kirchstockach power plant. Subsurface materials refer to 1 m length of geothermal well, surface materials correspond to the total amount needed. LCI data on further components is adopted from Frick et al. [40] and listed in detail in Appendix A. The information in brackets refers to the chosen geographical reference in Ecoinvent 3 [72].

| | Component | Material | amount | uncertainty |
|---|---|---|---|---|
| subsurface | casing | steel, low-alloyed (GLO) | 124.4 kg/m | ±5% |
| | drilling energy | electricity, medium voltage (DE) | 2630 MJ/m | ±10% |
| surface | heat exchanger | steel, chromium steel 18/8 (GLO) | 87.6 t | ±5% |
| | air coolers LT & HT | steel, chromium steel 18/8 (GLO) | 289.3 t | ±5% |
| | ORC turbine | steel, chromium steel 18/8 (GLO) | 13.7 t | ±5% |
| | ORC pipes | steel, chromium steel 18/8 (GLO) | 96.8 t | ±5% |
| | ORC feed pump | steel, chromium steel 18/8 (GLO) | 1.1 t | ±5% |
| | Refrigerant | refrigerant R134a (GLO)[a] | 70,000 kg | ±5% |
| | plant building | concrete, sole plate and foundation (CH) | 1290 $m^3$ | ±5% |
| | | diesel, burned in building machine (GLO) | 1000 MJ | ±5% |
| operation | Refrigerant | direct emissions from leaked fluid[b] (GWP only) | 0–5% | scenarios |
| | | refrigerant R134a (GLO)[a] (leakage make up) | 0–5% | scenarios |

[a] Background emissions from R245fa are not available in Ecoinvent 3 [72], so R134a is here chosen as proxy.
[b] Base case = 1%, for scenarios with leakage of working fluid. Direct emissions in form of GWP as well as emissions from the make-up fluid are considered here. R134a GWP = 1300, R245fa = 1050, R1233zd = 6 [73].

enhancement, transport, drill site and installation of geothermal fluid cycle are taken from Frick et al. [40]. The amount of steel for casing of the boreholes is calculated according to available borehole data (depth, diameter, etc.), and for 1 m casing it is higher by 21 kg/m than the value listed in Frick et al. [40].

The surface components include the binary plant facility, heat exchanger and cooling devices (Table 2), which are described based on site-specific information. Further information on materials and transportation (distance by train, truck, etc.) are oriented at Frick et al. [40] and listed in Appendix A. This standard reference is also chosen to define operational parameters regarding the exchange of the downhole pump, disposal of filter material and related transport activities. However, some characteristic of the LCI are significantly different for the hydrothermal plant at Kirchstockach: First, the amount of steel associated with the heat exchanger here is around 75% less than given in Frick et al. [40]. Second, the amount of organic chemicals (i.e. refrigerants) (Frick et al. [40]: 0.3 kg/kWh × 1750 kW = 525 kg) is here around two orders of magnitude higher. Furthermore, R245fa is used as ORC working fluid at Kirchstockach, which is not available in Ecoinvent 3 [72]. Thus, we use the available refrigerant R134a as a proxy in our LCI for construction and make-up during the operation phase (Table 2), due to the similarity of the chemical production process of the two refrigerants (see Appendix B for detailed information). At Kirchstockach, the energy for drilling is supplied by electricity from the grid, whereas Frick et al. [40] assume diesel-driven engines. Overall, one has to bear in mind that the LCI reported by Frick et al. [40] aims at providing an overview on a range of different power plants setups and geological settings in Germany, which will naturally differ from a site-specific case. In addition, the data in the LCI from Frick et al. [40] stems from reports and studies dating back as far as 1999, leading to significant differences for more recent geothermal projects.

For the decommissioning phase we adopt the approach from Frick et al. [40] and assume that the wells will be filled with gravel and cement, while the surface installations will be disposed of or, if possible, recycled. The corresponding amounts of gravel, cement and disposed (or recycled) material are calculated based on the installations at Kirchstockach and listed in Table A1.

### 3.3. Scenarios for life-cycle impact assessment

Fig. 4 reveals that electricity as the main output quantity of the power plant is also required as an input to the life cycle model for drilling the wells in the construction phase and during operation as auxiliary energy for driving the ORC and borehole feed pumps and other system components, like the fans of the air-cooled condensers (Fig. 3). Accordingly, different supply schemes can be adopted to relate these energy inputs to the life time electricity production. As a base case, we consider electricity needs for construction to be supplied by the German grid, including inherent background environmental emissions from average electricity generation (e.g. 659 $gCO_2$-eq./kWh [74]). The energy demand during operation on the other side is set off against the generated electricity, thus reducing the gross power output of the plant [45]. This reflects the assumption that the on-site power needs of the hydrothermal plant would most likely be supplied by electricity from the power plant itself. As there is a 3% difference between electricity production and the final electricity supply from grid, due to transmission and transformation losses, this approach represents an approximation. However, with respect to the inherent uncertainties in the LCI (Table 2 and A1), this seems to be a reasonable simplification (as compared to a consequential life cycle assessment framework). The impact of these different supply schemes for the power needs on the environmental performance will be tested in this study.

Finally, focus here is set on the role of long-term loss of ORC refrigerants due to leaking connections and seals or loss of refrigerants due to mishaps during maintenance. In our base case scenario, we assume an average of 1% leakage per year, which is considered as plausible by the operator and based on literature data. For example, Gerber and Maréchal [67] provide in their theoretical LCA of an ORC-based geothermal plant a range of between 0 and 2% of annual leakage based on personal communication with another operating company (Ormat Systems Ltd.). The direct environmental impact of the leaked fluid is quantified in terms of global warming potential (GWP), using reference values for the individual refrigerant types. In the following, the role of this sensitive leakage rate is examined in more detail.

## 4. Impact assessment and interpretation

### 4.1. Base case LCA results

For the base case analysis of power generation in Kirchstockach we use the LCI listed in Table 2 assuming an average leakage rate of 1% p.a. and provide the auxiliary electricity needs during operation (downhole pumps, ORC, etc.) with a corresponding share of the produced power output. For these assumptions, Fig. 5 shows the relative and absolute contributions of the different life-cycle stages and the most important materials and processes to the four main environmental impact categories, following the same colour scheme as in Fig. 4.

The most prominent feature in Fig. 5 is the dominating share of the direct GHG emissions caused by the leakage of R245fa which contributes by more than 60% to the overall global warming potential impact category. Assuming a GWP for R245fa of 1050 and a leakage rate of 1%, this corresponds to an average annual release of 700 kg of R245 to the atmosphere, where each kg causes a damage equivalent to 1050 kg of pure $CO_2$. Compared to this direct effect, the secondary effects from the production and transportation of R245fa used during construction and for make-up in the operational stage are rather small. Only for aquatic acidification, a slightly more pronounced impact of around 15% can be seen which stems from the use of a sulphuric acid during refrigerant production. Similar observations were made by Martín-Gamboa et al. [75] who found that 28% of the GWP of geothermal power production originate from working fluid loss. However, the relative loss of working fluid per electricity produced is ca. 5 times higher in our case study here. Besides, Martín-Gamboa et al. [75] assumed the usage of HCFC-124 as working fluid, which has a significantly lower GWP (ca. 609 [76]) than R245fa.

Apart from the ORC refrigerant the most significant environmental impacts occur during the construction phase (Fig. 5: blue and green colours). These account for over 90% of the total emissions in all impact categories except of global warming due to the mentioned effect of refrigerant leakage. In particular, the construction of the geothermal wells requires large amounts of energy for drilling and steel for the well casing, which was also found by previous studies [20,39,40,45,53,55–57,77]. However, the relative share of the impact from geothermal drilling in our case study is smaller than in most previous studies, due to the use of electricity from the grid, instead of diesel-driven drilling rigs. Also, as discussed in detail by Menberg et al. [45], the actual energy needs for geothermal drilling are often significantly lower than values found in literature.

The high impacts from well drilling with respect to the non-renewable energy demand reflect the large shares of energy-intense electricity generation in Germany (i.e. lignite and hard coal, natural gas, nuclear power). Also, this influence of the electricity mix has a significant impact when considering different

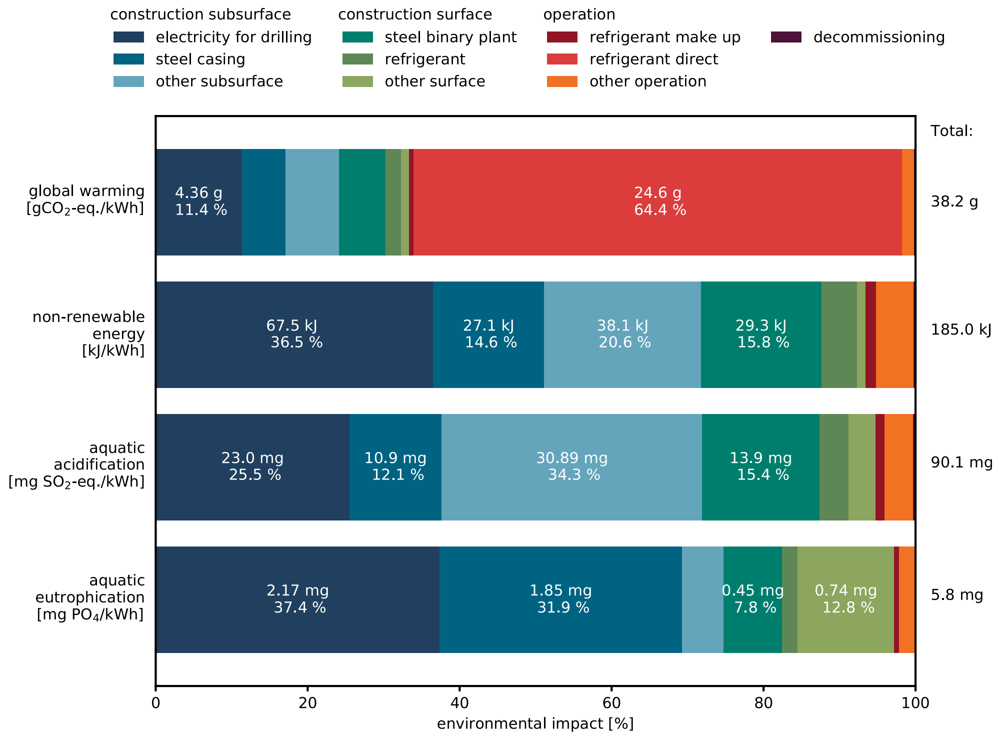


**Fig. 5.** Life cycle assessment results for the Kirchstockach geothermal power plant under base case assumptions (1% leakage of R245fa) for four impact categories. Please note that the impacts from the decommissioning phase are very minor and therefore not visible for all impact categories.

scales (regional, national, EU-wide), as Lopez et al. [56] concludes. The major impact of close to 50% in terms of aquatic eutrophication potential also stems from lignite coal mining and environmental issues during disposal of mining spoils. Another important aspect for eutrophication is the use of copper during construction of the binary power plant, which makes up for the largest portion (13.9%) of the other surface components of 14.1%. The aquatic acidification category on the other side is dominated by impacts from steel production and the use of diesel in construction machines (see also [56,57]). Materials and processes in the operational phase, excluding the refrigerant, such as maintenance and exchanging of equipment, generally contribute only little to the lifetime environmental impact (Fig. 5). The decommissioning phase plays a negligible role for all impact categories, which was also observed by previous studies [40,58]. A detailed comparison of the total emissions for the four impact categories with previous studies is provided in section 4.4.

### 4.2. Impact of refrigerant leakage

In order to investigate the environmental impact of employing alternative refrigerants in the ORC and varying leakage rates, we conduct a theoretical scenario analysis with R245fa, R134a and R1233zd. Due to similar material properties of R245fa and R1233zd, a drop-in replacement is currently discussed for the plant and seems to be technically feasible. Nevertheless, recent studies have shown a reduction in thermodynamic efficiency in case of a direct replacement, and thus a loss in the gross power output of 12.17% is considered for the examined scenario using R1233zd [64,78–80]. With R134a a drop-in solution would not be feasible due to significantly differing thermodynamic properties; rather the technical setup of the power plant would be designed differently and the operating parameter would vary widely. Assuming an optimized power output similar for all technical options, the main difference between power generation with different refrigerants, from an environmental point of view, would lie in the construction of the ORC, i.e. single-stage for R134a instead of two-stage for R245fa (Fig. 2). As the impact of construction materials for the ORC on the results is shown to be rather small (Fig. 5), we use the same LCI for the analysis with R134a.

As refrigerant leakage only has a considerable impact in terms of global warming potential, life-cycle results for this impact category are shown in Fig. 6a for annual leakage rates between 0 and 5%, while the error bars in Fig. 6a reflect the uncertainty in background emissions as specified in Ecoinvent 3 and in the LCI (Table 2). The above-mentioned reduced lifetime and electricity output with R1233zd leads to slightly higher emissions per kWh in the 0% leakage scenario as for R134a and R245fa. Likewise, the emissions embedded in the subsurface and surface construction stage are higher for R1233zd in the 1% leakage-scenario (Fig. 6b). Yet, compared to scenarios with occurring leakage this effect due to reduction in net power production is more than compensated by the much smaller GWP of 6 for R1233zd which highlights the environmental benefit of using a refrigerant with a low GWP. Heberle et al. [58], who compared the environmental impacts from different ORC types under generalised conditions, found a reduction in GHG emission of 78% by substituting R245fa with R1233zd. In case of the Kirchstockach power plant, this value is slightly lower with 66% (assuming 2% leakage as in Heberle et al. [58]).

The differences between GHG emissions from power plant scenarios with R134a and R245fa are solely due to the different GWP of the two refrigerants (1300 for R134a, 1050 for R245fa), which leads to a growing gap for higher leakage rates. The increase in the uncertainty ranges for higher emission rates is mainly caused by the larger amount of make-up refrigerant needed and the uncertainty about the embedded emissions therein. Yet, even with the environmentally worst performing refrigerant R134a and a leakage rate of 5%, the overall environmental impact of 136 $gCO_2$-eq./kWh

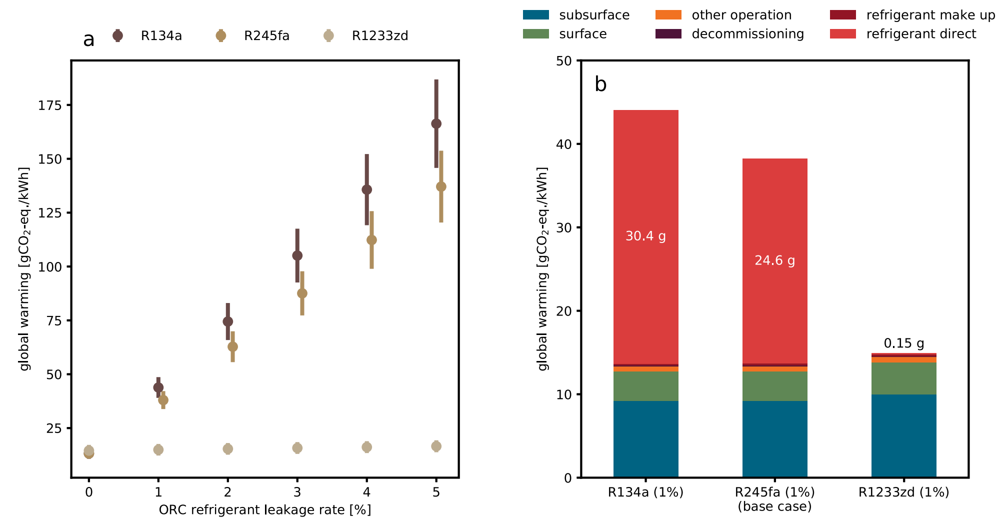


**Fig. 6.** Results from scenario analysis of refrigerant leakage. a) Global Warming Potentials for different refrigerants and ORC leakage rates. b) Emissions by life cycle stage for the 1% leakage scenario.

of the binary power plant in Kirchstockach would still be much lower than conventional, fuel-based power generation (e.g. coal, natural gas, etc.) and in a similar range as geothermal power plants with direct use, i.e. flash power plants [20,45,52,81,82].

### 4.3. Impact of electricity supply

As already mentioned for the base case results, different supply schemes can be applied for the auxiliary energy needs during construction and operation of a power plant. While the base case assumes that the energy demand for drilling is supplied from the German electricity grid (Fig. 5), the auxiliary power needed for the operation of the downhole pumps and the ORC is set off against the amount of generated electricity. Here, we additionally analyse two other electricity supply schemes: the first one assumes that both the energy for drilling and the auxiliary power demand are supplied from the German grid; in the second scheme all electricity needs during construction and operation are fully set off against the generated power, i.e. the auxiliary power needs are self-supplied by the power plant.

Fig. 7 reveals similar patterns between the different scenarios for all investigated impact categories. In general, setting off the energy for drilling (as credit) against the power output leads to a slight reduction in life time environmental impacts. As the life time energy output in the full self-supply scenario is also slightly lower, the emissions caused by the remaining materials and processes (see Fig. 7: other components) increase, which is similar to the effects observed for switching to R1233zd in the leakage scenarios. Naturally, the magnitude of this change in life time emissions strongly depends on the energy demand for drilling, the borehole depth and number of boreholes needed, which are all highly site-specific factors. While the effect is only small for the two boreholes with an overall combined depth of 8664 m as in Kirchstockach, Menberg et al. [45] showed that the impact of setting off drilling energy against the generated energy can be significant for a large overall borehole depth.

The change from the base case scenario to fully supplying the auxiliary power demand by electricity from the grid is much more pronounced than for the drilling energy (Fig. 7). Even though the instant power demand of the downhole pumps and the ORC is quite small, the electricity consumption and thus the embedded emissions sum up over the lifetime. Due to the highest life time energy production in this scenario the share of emissions from the drilling and other components is again reduced. Yet, this reduction is at least one order of magnitude smaller for all four impact categories than the overall increase in emissions. In fact, the increase in life time $CO_2$-eq. emissions in this scenario is similar to considering an annual leakage rate of 5% for a refrigerant with a high GWP (Fig. 6).

Regarding the differences between the four impact categories, the effects observed and described above are most pronounced for the non-renewable energy demand and the aquatic eutrophication. This is again due to the large portion of energy-intense electricity in the German grid, and the environmental impacts of lignite coal mining in particular. In our LCI, we assigned the German electricity mix from 2014 (Ecoinvent 3 [72]). 24% of German electricity in 2014 was supplied from lignite coal, further 19% by hard coal and 22% by nuclear power [72]. Obviously, an increasing share of cleaner, renewable energies in the future will also lead to lower environmental burden from the grid.

### 4.4. Comparison with other studies

Fig. 8 shows a comparison of the LCA results for the Kirchstockach power plant (base case) and results from previous studies for the four main impact categories. Due to the small number of previously assessed hydrothermal power plants, we include enhanced geothermal power plants (EGS) in this comparison. Also, both types of binary power plants are rather similar in terms of their life cycle inventories, with major differences being the lack of well enhancement and generally shallower wells in the case of hydrothermal use.

Fig. 8 reveals that the Kirchstockach power plant performs environmentally better than the two generic studies on hydrothermal binary power plants analysed for similar geological settings by previous studies [58,83]. This is despite the disregard of refrigerant leakage in the study by Frick and Kaltschmitt [83], and due to a lower energy consumption for well drilling at Kirchstockach, as well as the transition to electric drilling. For a generalised two-stage ORC power plant with R245fa in the Southern German Molasse Basin, Heberle et al. [58] obtained higher values than in our case study in Kirchstockach, in particular for global warming potential, due to an assumed leakage rate of 2% and a larger environmental impact from drilling.

Considerably lower values for hydrothermal power plants for all investigated impact categories were obtained by Sullivan et al. [84],

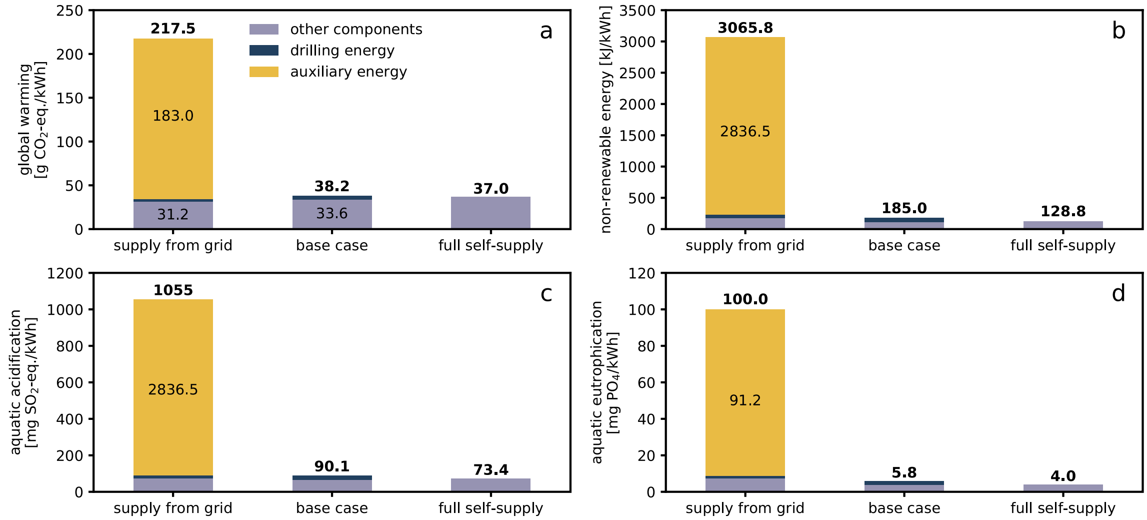


**Fig. 7.** LCA results for the electricity supply scenarios for four impact categories. a) global warming potential, b) non-renewable energy demand, c) aquatic acidification and d) aquatic eutrophication. All scenarios contain R245fa as ORC refrigerant and assume 1% refrigerant leakage per year (base case scenario as described in section 4.1).

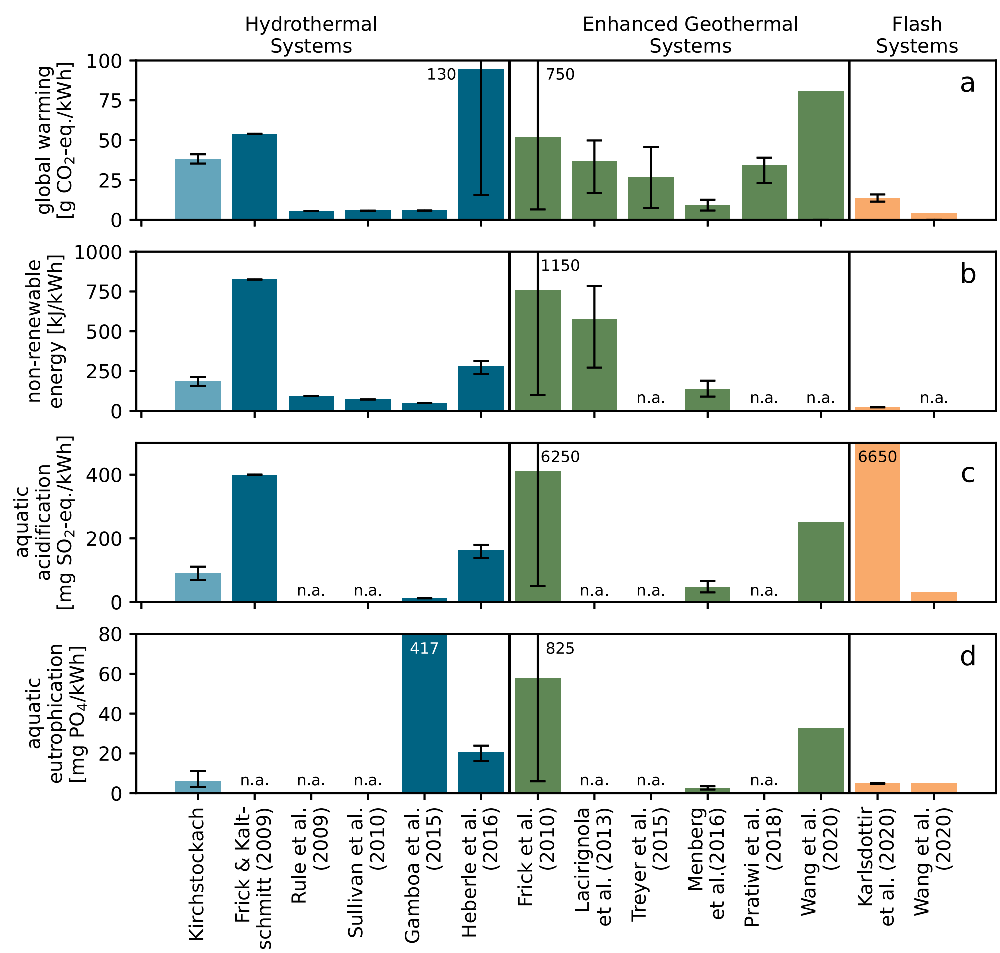


**Fig. 8.** Comparison of the Kirchstockach LCA results with other case and generic LCA studies for hydrothermal and enhanced geothermal systems. Note that results for non-renewable energy demand, acidification and eutrophication are not available for all studies.

Rule et al. [38] and Martín-Gamboa et al. [75]. This is mainly related to assumptions of larger power plant capacities with significantly higher production temperatures (e.g. 10 MW, 150–185 °C in Ref. [84]), shallower well depths (<2 km in Refs. [38,75,84]), and in the case of the Wairakei geothermal field, extremely long life times of 100 years in Ref. [38], compared to an average of 30 years in most other studies. Also previous studies [50,57] stress that extended life times have strong positive effects by compensating for the high environmental impact of the construction phase. The exceedingly high value for the eutrophication potential obtained by Martín-Gamboa et al. [75] is caused by emissions from sludge management during the construction phase.

The environmental impacts of enhanced geothermal systems (EGS) are in the same range as for hydrothermal systems, which is related to the technological similarities and also reflected in the life cycle inventories. Indeed many studies shown in Fig. 8 for enhanced geothermal as well as hydrothermal systems built their LCI upon the one presented in Frick et al. [40] to varying extents [39,45,50,58,75]. In contrast to the hydrothermal systems, one can observe a declining trend for the environmental impact from EGS for newer and more case-specific studies. An exception to this observation presents the latest LCA study by Pratiwi et al. [50], where in contrast to Treyer et al. [85] and Menberg et al. [45] geothermal wells are drilled using diesel-driven drilling rigs, which show an energy consumption per meter well similar to the study by Lacirignola and Blanc [39]. In addition, it should be noted that none of the LCA studies on EGS considers leakage of working fluid but only the background emissions from the one-time amount of organic chemicals needed for the ORC. Without refrigerant leakage and considering the ranges of uncertainty, the environmental performance of the power plant in Kirchstockach is very similar to the EGS case studies of St. Gallen and Basel by Menberg et al. [45].

## 5. Conclusions

The Kirchstockach binary geothermal power plant located in southern Germany consists of a two-stage ORC system for electricity generation and has been in operation since 2013. It therefore provides information from a prolonged operation phase, serving to evaluate ecological impacts of geothermal electricity generation. Based on the standardized procedure of ISO 14040 and 14044, the Life Cycle Inventory of the plant was used within a cradle-to-grave approach to investigate several scenarios on the impacts of several key factors.

The significant effect of refrigerant leaks was already evident within the base case scenario, where a loss of only 1% R245fa has the greatest impact of 24.6 g$CO_2$-eq./kWh on the total GWP. Drop-in replacement scenarios of R134a and R1233zd with leakage rates between 0 and 5% revealed great potential to reduce GHG emissions by using R1233zd. Despite a lower thermodynamic efficiency, its higher production emissions would be offset rapidly. However, even in the worst-case scenario (R134a and 5% loss), the overall impact is significantly lower than with conventional power generation and in the range of other geothermal facilities.

In addition, three scenarios with different energy supply schemes were analysed, significantly extending the LCA perspective in the area of geothermal energy. Compensating all energy needs of construction and operation by self-produced outputs offers greatest environmental benefits in all impact categories (up to 60% in case of non-renewable energy demand), although the overall produced energy would be reduced. Remarkably, this influence can be equalized with a 5% leakage scenario of a climate-damaging refrigerant. For complex construction phases (e.g. deeper drillings) and long lifetimes, the differences are even more intensified.

Comparing the Kirchstockach plant with similar studies beyond the field of hydrothermal systems demonstrates considerably less environmental impacts (in case of GWP between 26 and 94%), although leakages of refrigerants are included here. This is a result of other energy sources used for drilling. To ensure realistic comparability, it is therefore recommended to include these dominating and potentially decisive parameters for ORC systems in future LCA studies. Many site-specific features, such as differing LCIs, output capacities, and lifetime estimates remain crucial, emphasizing the importance of detailed case studies such as the present case, as generic LCAs tend to yield much more conservative estimates.

## CRediT authorship contribution statement

**Kathrin Menberg:** Formal analysis, Visualization, Writing - original draft. **Florian Heberle:** Investigation, Writing - review & editing. **Christoph Bott:** Writing - original draft. **Dieter Brüggemann:** Writing - review & editing. **Peter Bayer:** Conceptualization, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2020.11.028.

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