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Life Cycle Assessment of a Geothermal Power Plant in the Southern German Molasse Basin (Germany)

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ABSTRACT

In this work, a life cycle assessment (LCA) is conducted for a geothermal power plant in the Southern German Molasse Basin. The considered power plant is a two-stage Organic Rankine Cycle (ORC) power system with a nominal electrical power output of 5.5 MW. By considering the environmental impacts resulting from the construction, operation and decommissioning of the geothermal power plant, CO_2-emissions, cumulated energy demand (CED), acidification and eutrophication have been determined as the four main impact indicators. For a comprehensive analysis, available data sets like borehole depth, casing material or material demand of the power plant are evaluated. In the first step, no leakage of the ORC working fluid and a self-supply regarding the auxiliary requirements of the power plant are assumed. Compared to common, rather theoretical LCA of geothermal applications, the conducted analysis for a specific binary power plant shows significantly lower values for the selected impact indicators. In particular, a CO_2-equivalent of 11.8 g/kWh$_{el}$ and a CED of 164.6 kJ/kWh$_{el}$ are quantified. In context of CO_2-emissions, the effect of the subsurface construction dominates with 82 % and is mainly due to the operation of the drilling rig and the consumption of steel for the casing of the wells. The constructions at the surface contribute by 15 % and the operation of the power plant yields 3 %. Based on the described LCA, further scenario calculations are performed. In scenario I, a leakage rate of 1 %/a of the filling quantity of the ORC working fluid R245fa is considered. In scenario II the leakage rate is increased to 2 %/a. For scenario I, a CO_2-equivalent of 29.3 g/kWh$_{el}$ is obtained and in case of scenario II a value of 46.8 g/kWh$_{el}$ results. Furthermore, a replacement of the ORC working fluid R245fa by R1233zd(E) with a low impact on climate is evaluated. This leads to a CO_2-equivalent of 13.6 g/kWh$_{el}$ at a conservative leakage rate (2 %/a). The present LCA of a specific binary power plant shows that in general, mainly theoretical analyses tend to overestimate the environmental impact of a geothermal power plant and thus create a negative image compared to other renewable power sources. In particular, using ORC working fluids with low GWP, the environmental impact of a geothermal power plant is shown to be in the same range as for wind turbines. Under consideration of moderate leakage rates of the fluorinated ORC working fluid R245fa the environmental impact is still lower than for photovoltaic systems.

1. INTRODUCTION

Life cycle assessment (LCA) is an important method for evaluating the sustainability of energy conversion systems. Applying a LCA, the environmental impacts arising from potential technical approaches can be evaluated. As well, impacts by using different renewable energy sources or conventional fuels for electricity or heat generation can be compared. Regarding the transition to renewables, geothermal sources show a great potential. From 2010 to 2015 the total worldwide installed electric capacity of geothermal power plants increased by about 16 % to 12.6 GW (Bertani, 2015). In the last years the installation of binary power plants has been increasing significantly due to the enhanced exploitation of low-temperature reservoirs and sometimes for environmental reasons. At the moment, about 50 % of newly installed geothermal power plants are based on Organic Rankine Cycle (ORC) or Kalina Cycle (KC) systems. In this context, a reliable LCA of an existing geothermal ORC power plant supports decision-makers in industry and politics to expand future activities and investments into geothermal power generation.

The geothermal power plant in Kirchstockach (Germany) exploits a low-temperature reservoir with a brine temperature of about 140 °C for electricity generation. In order to prove the ecological reasonability of such a power system, material and energy expenses for the exploitation of the reservoir as well as measures for the installation and operation of the power plant are determined based on the LCA methodology. For this purpose, a wide range of site-specific data is provided by the plant operator.

In comparison to existing analyses (Frick et al., 2010, Pratiwi et al., 2018, Heberle et al., 2016) this allows a first plant-specific LCA for a geothermal power system in Central Europe. In this paper, the LCA methodology according to ISO 14040 and ISO 14044 is carried out. As impact indicators, emissions of greenhouse gasses, Cumulated Energy Demand (CED), acidification and eutrophication of natural ecosystems are considered. The results are compared to the mentioned theoretical studies. In order to identify the most important input parameters, a sensitivity analysis is conducted by varying the ORC working fluid leakage rate, material usage for piping and foundation as well as energy demand for drilling. In addition, different potential scenarios are considered to quantify the potential for reducing the ecological impacts by technological measures like a replacement of the ORC working fluid.

2. GEOTHERMAL POWER PLANT IN KIRCHSTOCKACH (GERMANY)

In this work, the geothermal power plant in Kirchstockach (Germany) is considered. Kirchstockach is located in the Southern German Molasse Basin, about 20 km in the south-east of Munich city center. This ORC power system consists of two separate modules, a high-temperature (HT) and a low-temperature (LT) ORC (Figure 1). The subsurface construction of the power plant was completed in 2009. For the exploitation of the geothermal reservoir, a doublet was drilled (production and injection well) with the help of an electricity-driven drilling rig (Herrenknecht Vertical Terra Invader 350, B-004). The first well with a depth of 4214 m was completed after 101 days, while the second well with a depth of 4452 m was completed after 81 days. The power plant has been in operation since 2013. The power unit has a nominal electric capacity of 5.5 MW referred to an ambient temperature of 8 °C, a mass flow rate of 120 kg/s and a temperature of 138 °C of the geothermal fluid (Heberle et al., 2015). In both ORC modules, R245fa is used as a working fluid. Figure 1 shows a scheme of the double-stage power plant. For both ORC modules, a preheater and an evaporator are used to transfer the thermal energy of the geothermal fluid to the ORC system. At the outlet of the evaporators, saturated vapor is obtained and expanded in the turbine. Each cycle is closed by an air-cooled condenser and a feed pump.

For the base case of the conducted LCA the following conditions are defined:

- During the stage of the subsurface construction an electricity-driven drilling rig is used. As the drilling operations took place in 2008 and 2009, a corresponding mean German electricity mix is considered. This is composed of 24 % lignite, 23 % nuclear power, 19 % coal, 13 % natural gas, 15 % renewable energy sources (hydro, wind, solar, tidal/wave), 2 % crude oil and 4 % other (biogas, biomass, waste incineration). The corresponding CO_2-equivalent emissions are 614.8 g/kWh_{el}. The injection pumps used for reservoir enhancement measures are electricity-driven and power is supplied by the above mentioned mean German electricity mix.
- The auxiliary power demand including ORC pump, ORC air coolers and borehole pump is supplied by the geothermal power plant itself.
- It is assumed that no working fluid is lost during the operation of the power plant (i.e. 0 %/a leakage rate). A variation of the leakage rate is conducted in form of a parameter study.

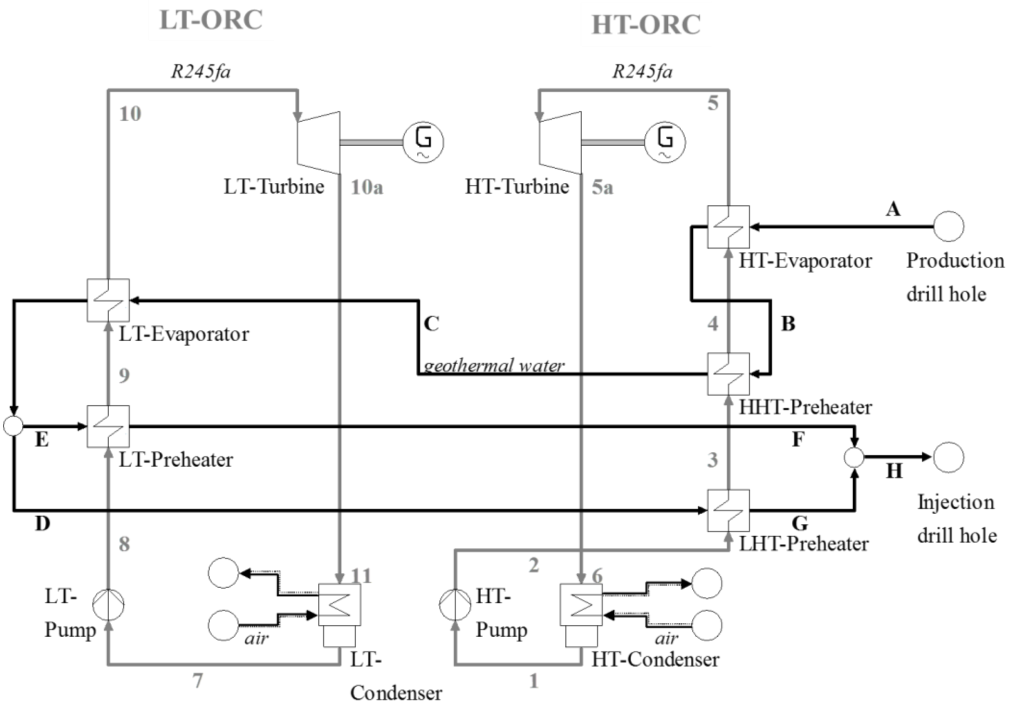

Figure 1: Scheme of the geothermal power plant in Kirchstockach, Germany

In addition, Table 1 shows the relevant site-specific data and selected technical parameters for the geothermal power plant in Kirchstockach (Germany). In case no site-specific data were available, literature data are used.

3. METHODOLOGY

The main objective of the conducted LCA is to consider the environmental impacts of the product. Here, electricity generation is focused throughout the whole life span. This includes the three life stages of the power plant, namely construction (surface and subsurface), operation and decommissioning. Furthermore, the supply chain activities are also included in the LCA, for example steel production and supply for the casing of the wells, or disposal of waste material. The LCA is carried out according to ISO 14040 and ISO 14044 in a four stage procedure.

(1) Defining goal and scope: In this LCA an ecological evaluation of the geothermal power plant in Kirchstockach (Germany) is performed. The scope of the LCA is given by the area and depth required for the power plant and the doublet. The functional unit is defined as 1 kWh_{el} generated net electricity. In this context, it should be pointed out that for the net power output the auxiliary power demand of the ORC as well as the consumption of the borehole pump are considered. For the technical life-time of the power plant in Kirchstockach (Germany) a period of 30 years is defined.

(2) Life cycle inventory analysis: In this stage all relevant mass and energy flows of products and processes during the life cycle of the power plant are quantified. For example, the amount of steel and cement needed for casing the wells. Here, airborne emissions do not occur during the construction on site, but during the manufacturing processes. The life cycle data of these emissions are provided by the ecoinvent database (Ecoinvent Centre, 2010). Furthermore, the data for common products (diesel, steel, concrete, etc.) and basic processes (transportation, disposal of waste, etc.) are also included in this database.

(3) Impact analysis: Based on the total mass and energy flows resulting from the life cycle inventory analysis, four impact indicators are quantified. The impact indicators considered in this work are CO_2-equivalents (emissions of greenhouse gasses), Cumulated Energy Demand (CED) (demand of finite energy sources), SO_2- and PO_4^{3-}- equivalents (acidification and eutrophication of natural ecosystems).

(4) Interpretation: The environmental effects are discussed with respect to the previously defined goal of the LCA. Next to the described base case, a parameter study and different scenarios are considered. The results are compared to literature data of rather theoretical studies. In addition, the parameter studies identify the most significant input factors. The considered scenarios enable a quantification of selected potential technological measures to reduce the environmental impacts of geothermal power generation in case of low-temperature sources.

Table 1: Selected site-specific data and selected technical parameters for the geothermal power plant in Kirchstockach (Germany)

Parameter	Unit	Quantity	Reference
Nominal electric capacity	MW	5.5	Heberle et al. (2015)
Net power output	MWh/a	29936	
Gross power output	MWh/a	38500	
Full load hours	h/a	7000	Frick et al. (2010)
Technical life-time	a	30	Frick et al. (2010)
Subsurface			
Number of wells	-	2	Information provided by operator
Depth well 1	m	4214	Information provided by operator
Days to completion	d	101	Information provided by operator
Depth well 2	m	4452	Information provided by operator
Days to completion	d	81	Information provided by operator
Power supply for drilling rig	MW	3.23	Bauer (2014)
Steel for casing of the doublet	t	1077.9	
Cement for casing of the doublet	t	406.6	Frick et al. (2010)
Surface			
Auxiliary power demand of ORC	kW	615	Eller et al. (2019)
Auxiliary power demand of downhole pump	kW	608	Frick et al. (2010)
Amount of working-fluid (R245fa)	kg	50000	
Leakage rate (base case scenario)	%/a	0	
Steel used for ORC components	t	488.6	

4. RESULTS

4.1 Base case analysis

The determined environmental effects of the analyzed base case scenario are summarized in Figure 2 according to the base case scenario of the geothermal case study. In addition, the distribution of the impact indicators considering the three main life stages of the geothermal power plant, namely subsurface construction, surface construction and operation, are shown. The environmental effects resulting from decommissioning of the geothermal power plant are negligible compared to the aforementioned life stages.

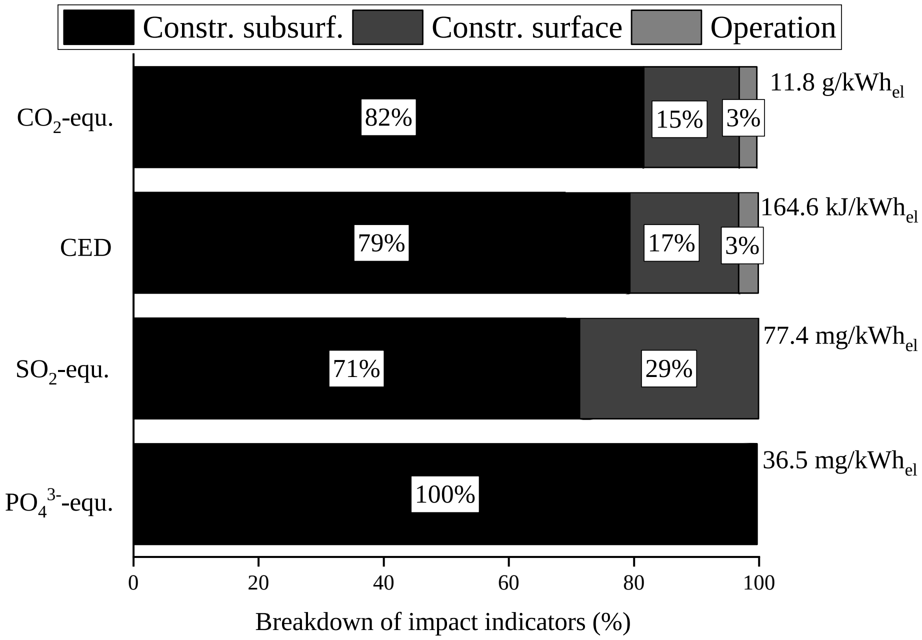

Figure 2: Breakdown of the selected environmental impact indicators based on emissions caused by construction (surface and subsurface) as well as operation for the base case scenario

The results clearly illustrate that the environmental effects resulting from the subsurface construction dominate. For the two impact indicators CO_2-equivalent and CED the subsurface construction accounts for about 80 % of the total value (11.8 g/kWh$_{el}$ and 164.6 kJ/kWh$_{el}$). The surface construction contributes around 15 %, while less than 5 % are due to the operation, respectively. Roughly 70 % of the calculated SO_2-equivalent emissions (77.4 mg/kWh$_{el}$) are the result of subsurface construction and about 30 % are due to surface construction. The contribution of the life stage operation is negligible. The calculated value for the PO_4^{3-}-equivalent emissions of 36.5 mg/kWh$_{el}$ results nearly entirely from the subsurface construction. This general tendency is confirmed by several previous studies (Frick et al., 2010; Menberg et al., 2016; Heberle et al., 2016; Pratiwi et al., 2018).

For a more detailed analysis of the environmental effects in the construction stage, the main material and energy demands responsible for CO_2-equivalent emissions are shown. Therefore, Figure 3 is divided in subsurface (left) and surface (right) part of the construction stage. In case of subsurface construction, the major part of CO_2-equivalent emissions is caused by the electricity needed to operate the drilling rig (49.4 %), followed by steel used for the casing of the production and injection well (29.5 %). Reservoir enhancement (16.5 %) takes into account that electricity is used for the operation of the well stimulation pump, and water is used as a working fluid during the enhancement process. The remaining share of CO_2-equivalent emissions is caused by cement used for the casing of the two wells (4.6 %). Considering surface construction, the main share of CO_2-equivalent emissions is caused by steel which is used as main material for the ORC components (52.7 %). Almost one quarter (20.3 %) of CO_2-equivalent emissions related to the surface construction are due to concrete used for building the foundation of the geothermal power plant. The production of the working fluid and steel needed for piping have an equal share in the total CO_2-equivalent emissions with 14 % and 13.1 %, respectively. CO_2-equivalent emissions of the production of the working fluid are estimated according to the production of R134a (McCulloch and Lindley, 2003) due to lacking data for R245fa. In Figure 3, a detailed visualization of the operation life stage is not implemented. However, as the CO_2-equivalent emissions for this life stage strongly depend on the presumed leakage rate of the working fluid, this aspect is addressed separately in a corresponding scenario calculation (see section 4.3).

Error! Reference source not found. lists the results of the considered base case scenario in comparison to similar scenarios in literature. In this context, the "Site A1"-scenario of Frick et al. (2010) as well as the the scenario "Rittershoffen ORC" of Pratiwi et al. (2018) are chosen.

Table 2: Environmental impact indicators for the analyzed base case scenario of the geothermal case study compared to the base case results from Frick et al. (2010) ("Site A1") and the results from Pratiwi et al. (2018) ("Rittershoffen ORC")

Study	**CO_2-equ. (g/kWh$_{el}$)**	**CED (kJ/kWh$_{el}$)**	**SO_2-equ. (mg/kWh$_{el}$)**	**PO_4^{3-}-equ. (mg/kWh$_{el}$)**
Present	11.8	164.6	77.4	36.5
Frick et al. (2010)	51	735	427	56
Pratiwi et al. (2018)	35	n.a.	n.a.	n.a.

Frick et al. (2010) investigated different plant scenarios which represent typical geothermal binary plants in Europe. Pratiwi et al. (2018) focused on greenhouse gas emissions as an indicator for the environmental effects and considered conditions of the Upper Rhine Rift Valley for the geothermal power plant. The results of the present work suggest that a LCA conducted for a specific geothermal case study allows for a more positive picture on geothermal power generation than a LCA conducted for representative plant scenarios. The findings from Pratiwi et al. (2018) support this suggestion. Considering a representative plant scenario, the environmental impacts of geothermal power generation tend to be overestimated because generalization is inevitable. Without the use of average values in the life cycle inventory analysis of the LCA, it is hardly possible to obtain a representative plant scenario. Frick et al. (2010), for example, generally stated the amount of energy needed to drive a drilling rig during the subsurface construction phase per drilled meter (7492 MJ/m per well). For the geothermal power plant in Kirchstockach (Germany), this value results in a total energy demand of $6.5 \cdot 10^7$ MJ. In the present work, the calculated total energy consumption of the drilling rig drive is based on the depth of the two wells, the time needed for their drilling and the energy supply of the drilling rig that was used in the specific geothermal case study. This results in a more realistic total energy demand of only $2.3 \cdot 10^7$ MJ. Another example is the yearly produced electricity. For the base case scenario of Frick et al. (2010), a value of 6476 MWh/a was calculated. However, for the base case of the present work a yearly produced electricity of 29,936 MWh/a is derived. The impact indicators are quantified with regard to the yearly produced electricity of the power plant. Therefore, a higher value of the yearly produced electricity results in lower values for the impact indicators.

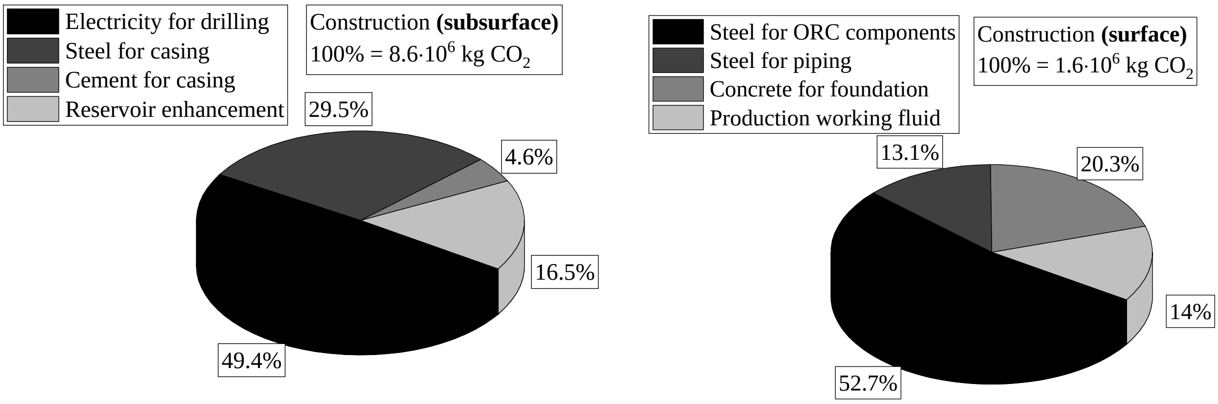

Figure 3: Distribution of CO_2-equivalent emissions resulting from subsurface (left) and surface (right) construction for the base case scenario

4.2 Parameter study

A parameter study is conducted in order to identify the most important products or processes of the life cycle inventory analysis (i.e. parameters). In this context, the influence of selected input values on the CO_2-equivalent emissions are determined. The results are shown in Figure 4 for the subsurface (left) and the surface construction stage (right), respectively. A variation of 0 % corresponds to the result of the base case scenario (see **Error! Reference source not found.**). The gradient of the curves in Figure 4 indicates the sensitivity of the results to the respective parameter. Generally, the subsurface construction has the stronger impact on the CO_2-equivalent emissions of the geothermal case study. Here, a variation of ±15 % results in a CO_2-equivalent ranging from 11.1 g/kWh$_{el}$ to 12.4 g/kWh$_{el}$, while the parameters of surface construction thereby only range from 11.7 g/kWh$_{el}$ to 11.9 g/kWh$_{el}$. Regarding the selected parameters, the electricity needed for driving the drilling rig plays the most sensitive role regarding the CO_2-equivalent emissions.

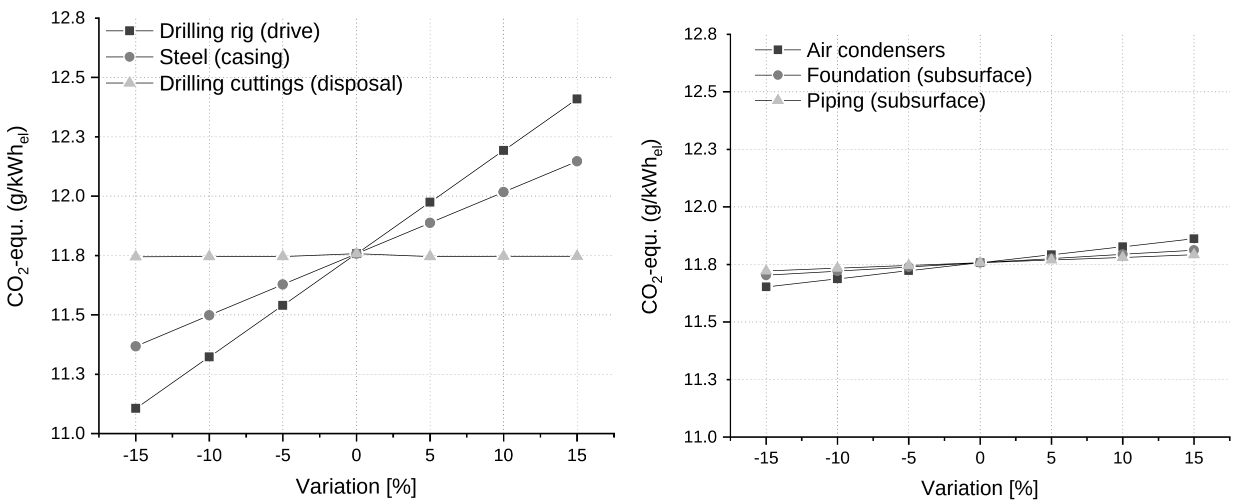

Figure 4: Parameter study showing the behavior of CO2-equivalent emissions (base case scenario) while varying selected parameters for subsurface (left) and surface (right) construction

In addition, the yearly produced electricity is varied. The corresponding CO_2-equivalent emissions are shown in Figure 5. This comparison illustrates that the annual amount of electricity is the most sensitive parameter within the conducted parameter study. The resulting CO_2-equivalent varies from 13.8 g/kWh$_{el}$ to 10.2 g/kWh$_{el}$ as the net power output is modified by ±15 % compared to the calculated value of this LCA's life cycle inventory analysis (29,936 MWh/a). A higher annual amount of electricity can be regarded as an enhanced compensation for the high material and energy inputs arising from the life stages of subsurface and surface construction. With respect to the underlying assumption, an increase of the yearly generated amount of electricity corresponds to an increase in operation hours of the geothermal power plant.

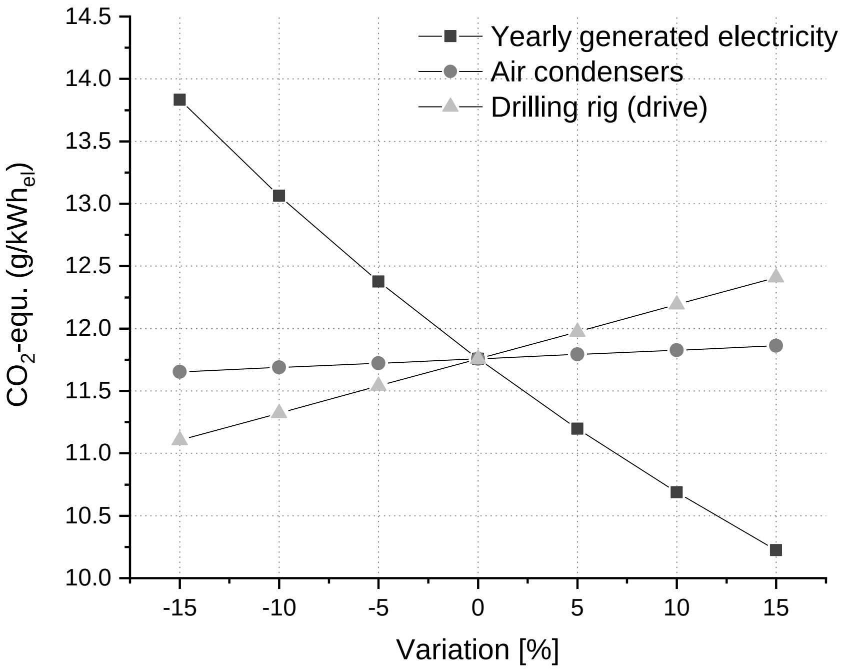

Figure 5: Parameter study showing the behavior of CO_2-equivalent emissions (base case scenario) while varying the yearly generated electricity as well as the most sensitive parameter of subsurface and surface construction, respectively

4.3 Scenario analysis

According to the mentioned theoretical LCA studies, the considered base case scenario assumes no working fluid leakage during the operation of the power plant. Nevertheless, an ORC module is not hermetically sealed. Using a fluorinated refrigerant like R245fa, a leakage detection system to comply with the European Union's regulation on fluorinated greenhouse gases (EU No 517/2014) (European Parliament and Council of the European Union (2014)) is mandatory. Corresponding to the German chemical climate protection regulation (ChemKlimaschutzV) geothermal power plants like the considered system represent an ORC-application that uses more than 100 kg of working fluid. In order to comply with this regulation, the operator of the power plant is obligated to guarantee that annual working fluid losses are restricted to 1 % of the total filling quantity (Bundesministerium der Justiz und für Verbraucherschutz, 2017a). In this context, two scenarios regarding the annual leakage rate are considered in this LCA study. In scenario I an annual leakage rate of 1 % is assumed, while in scenario II the annual leakage rate is increased to 2 %. For the conducted life cycle inventory analysis, an amount of 50 t of R245fa as working fluid is defined. R245fa has a Global Warming Potential (GWP) of 1030 CO_2-eq. (Forster et al., 2007). This ORC working fluid thus can be regarded as a high-GWP working fluid. Therefore, the impact on CO_2-equivalent emissions resulting from its leakage is significant. Figure 6 demonstrates this clearly by displaying the emissions for both leakage scenarios and the base case scenario. For scenario I, the calculated CO_2-equivalent emissions are 29.3 g/kWh$_{el}$, while scenario II results in 46.8 g/kWh$_{el}$ of the emitted CO_2-equivalent.

Next to the working fluid R245fa, Figure 6 indicates a theoretical scenario corresponding to the low-GWP working fluid R1233zd(E). In this scenario, a potential drop-in replacement of the working fluid R245fa is estimated. The GWP of R1233zd(E) is set to 7 CO_2-eq. and the net power output of a geothermal power plant is 12.2 % lower than the one operated with R245fa (Eyerer et al., 2016). Hence, the CO_2-equivalent emissions at the respective leakage rates only increase slightly from 13.4 g/kWh$_{el}$ (0 %/a) to 13.5 g/kWh$_{el}$ (1 %/a) and 13.6 g/kWh$_{el}$ (2 %/a). This slight increase is related to the reduced net power output of the geothermal power plant when R1233zd(E) is used as a working fluid instead of R245fa.

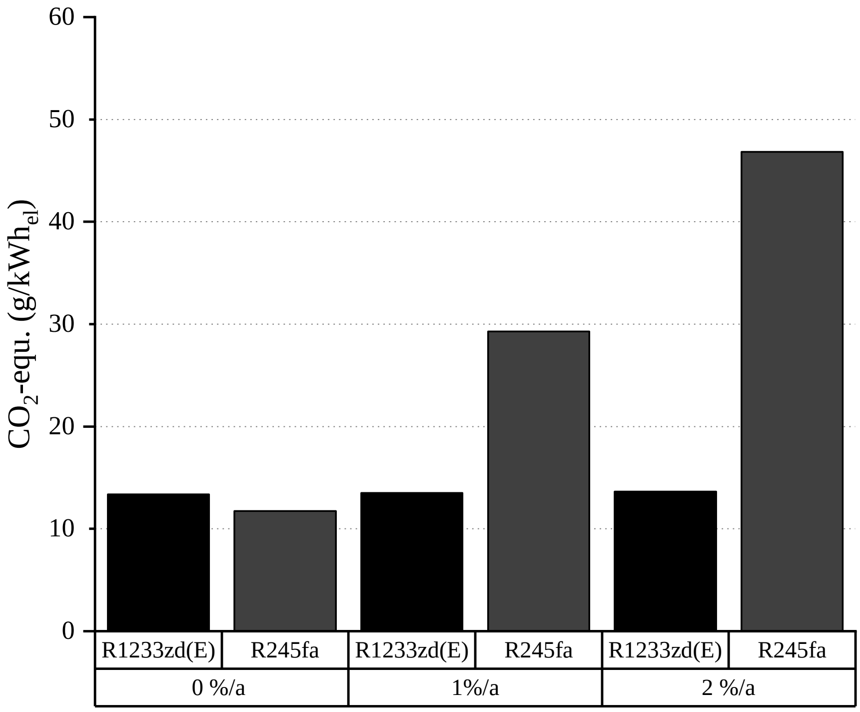

Figure 6: CO2-equivalent emissions of the working fluid R1233zd(E) compared to those of R245fa at different leakage rates

To conclude the conducted scenario analysis, Figure 7 compares the results of scenarios I and II with an average CO_2-equivalent emissions for wind and solar power, respectively (Menberg et al., 2016). It can be stated that, compared to alternative renewable energy sources like wind and solar power, power generation from the present geothermal case study has a lower impact on global warming if working fluid losses during the operation of the power plant are minimized.

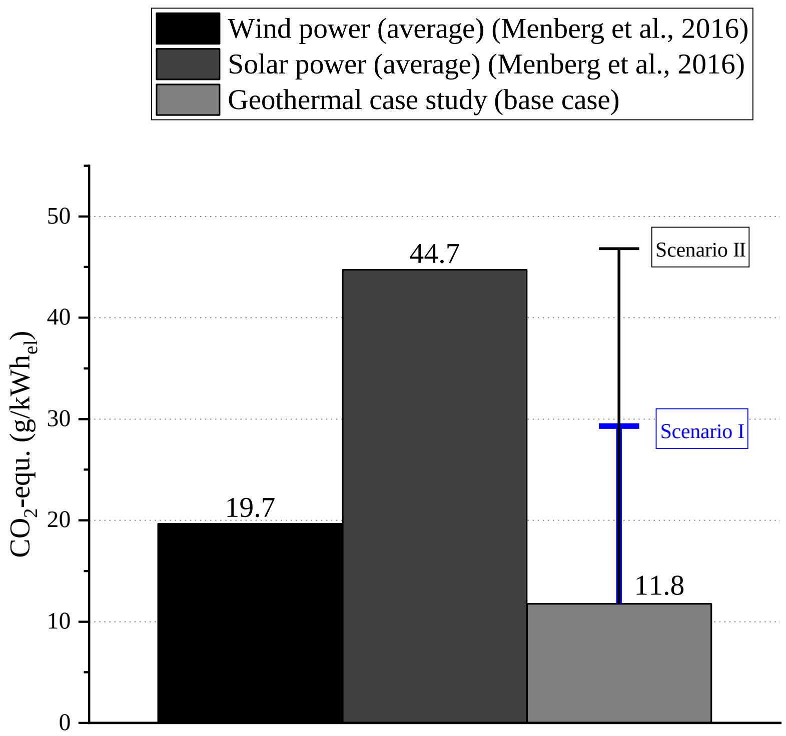

Figure 7: CO2-equivalent emissions of the scenario analysis in comparison to average emissions of wind and solar power

5. CONCLUSIONS

A LCA for a specific geothermal power plant is conducted. Compared to previous rather theoretical studies considering similar boundary conditions, significantly lower environmental impacts were determined for the ORC power plant in Kirchstockach (Southern German Molasse Basin; Germany). One main reason therefore is a considerable amount of steel associated with the heat exchanger in Kirchstockach compared to theoretical scenarios. In addition, the energy for drilling is supplied by electricity from the grid, whereas in literature generally diesel-driven engines are assumed. For the base case, CO_2-equivalent emissions of 11.8 g/kWh$_{el}$ are obtained. For all considered impact indicators the effects of the subsurface construction are crucial. The performed parameter study identifies the energy demand for drilling and the operational hours of the power plant as the most important input parameters of the LCA. Additionally, scenarios for different leakage rates for the ORC working fluid are considered. Generally, it can be stated that the leakage of the working fluid has a considerable impact on global warming in particular using state-of-the-art fluorinated refrigerants. Furthermore, a theoretical estimation shows that the usage of R1233zd(E) as a drop-in replacement for R245fa seems to be environmentally reasonable. In this context, next to present research activities (Eyerer et al., 2019, Welzl et al., 2018) further investigations have to be carried out regarding the economic and technical feasibility. Preliminary results considering an additional geothermal heat generation show a global warming potential in the range of 2 and 7 grams of CO_2-equivalent per Megajoule of thermal district heating. Such a low value suggests the competitiveness of geothermal CHP systems under environmental aspects compared to alternative renewable energy sources like biomass (Guest et al., 2011).

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