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Life-cycle climate-change impact assessment of enhanced geothermal system plants in the Upper Rhine Valley

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ABSTRACT

In this study the greenhouse gas (GHG) emissions of the Rittershoffen geothermal plant in France – an operating EGS (Enhanced Geothermal System) project developed in the Upper Rhine Valley are analysed and quantified. In this study a similar analysis for the forthcoming EGS in Illkirch Graffenstaden (Strasbourg) is also presented. Life cycle inventory is constructed based on a real project. Five different scenarios comprising a heat plant, power plants and cogeneration plants are developed respecting LCA (Life Cycle Assessment). Contribution of each phase and material type towards GHG emissions is studied using hot spot analysis. In this study some site-specific approaches to potentially reduce of GHG emissions are also assessed. This study is a useful reference towards LCA studies of EGS as it analyses the first EGS utilization for industrial heat.

1. Introduction

1.1. EGS development

Despite having comparatively higher efficiency and stability, the growth of power supplied by geothermal sources has been surpassed by that of wind and solar power. Solar PV is the leader in renewable energy growth with a growth rate above 200% since 2010, while the growth of geothermal utilization remains below 20%, seeming to be the least competitive form of renewable energy (Fig. 1).

The main reasons for the slow growth of geothermal power generation vary in different regions and different countries, from high initial investment, long payback and construction time or difficulty in the assessment of resources. Therefore, innovations in geothermal technology are needed to speed up geothermal growth (Li et al., 2015).

The innovations in deep geothermal technology in Europe, where geothermal reservoirs are mostly of low or medium enthalpy, has enabled a more efficient utilization of geothermal resources to fulfil the renewable energy demand in this region. One of these innovations is called EGS. The currently used term 'enhanced or engineered geothermal system' (EGS) has its roots in the early 1970s when a team from Los Alamos National Laboratories began the Hot Dry Rock (HDR) project at Fenton Hill, USA (Breede et al., 2013).

This concept inspired the initiation of an EGS research project in the Upper Rhine Valley region (France) starting in 1987, namely, Soultz-sous-Forêts, where a total of five wells has been drilled and three of them reach a depth of 5 km, penetrating the granitic basement (Genter et al., 2010). To date, Soultz-sous-Forêts wells are supplying thermal energy to commercially produce 1.7 MW_{el}. They use an ORC (Organic Rankine Cycle) system thanks to its success in improving the productivity of the wells through several enhancements. While the project did not establish a perfect underground closed loop system as initially intended in the HDR concept (as the maximum rate of injection recovery observed was 26% (Sanjuan et al., 2016)), Soultz-sous-Forêts is acknowledged as a successful EGS project. Furthermore, it was also discovered that a network of pre-existing fractures channelling natural brine exists in this basement (Gérard et al., 2006) and thus the project has achieved an improvement in its natural permeability. Following this and some other developments, the EGEC (European Geothermal Energy Council) defines EGS as an underground reservoir that has been created or improved artificially (Dumas and Angelino, 2015). EGS is an umbrella term for various other denotations, such as Hot Dry Rock, Hot Wet Rock, and Hot Fractured Rock (Rybach, 2014).

Since that development, several EGS projects have been initiated in the same area. The first example is Landau, which had a 2.9 MW_{el} capacity in 2008 (Hettkamp et al., 2013). However, due to a major surface deformation, the production stopped in March 2014 for safety reasons and geological investigations (Heimlich et al., 2015). The next one is Bruchsal which started in 2009 with a 550 kW_{el} capacity (Breede et al., 2013), followed by Insheim which started in 2012 with a 4.8 MW_{el} capacity (Teza et al., 2016). At the same time, EGS is also being developed in other parts of the world. This includes Habanero in South Australia which has a capacity of 1 MW_{el} since 2012 (Larking and Bendall, 2013). This plant is currently closed (Fedorowytsch, 2016)

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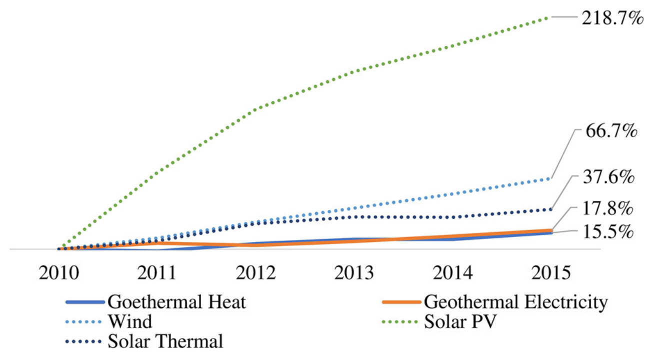


Fig. 1. a) Growth of geothermal energy in Europe. b) Growth of different renewable energy sources in Europe (Observ'ER, 2012, 2014, 2016).

because it faces challenging economic viability (Humphreys et al., 2014). The other projects are the Eden and United Down projects in the UK which envisage a total of 4 MW_{el} capacity (Batchelor et al., 2015) and a pilot EGS project in Pohang, South Korea which, despite several different problems, still progresses towards achieving a plant of 1 MW_{el} (Song et al., 2013).

1.2. Geothermal development in the Upper Rhine Valley

In the Upper Rhine Valley, after the accomplishment of the Soultz-sous-Forêts project, the utilisation of EGS energy in this region has once again been demonstrated to be highly feasible thanks to the Rittershoffen plant that has been successfully providing heat for the starch manufacturing process in the Roquette Frères factory since June 2016. This project was accomplished within the ECOGI (*Exploitation de la Chaleur d'Origine Géothermale pour l'Industrie*) project. It's the first industrial deep geothermal project in France aiming to supply high temperature water. Rittershoffen geothermal heat contributes to up to 25% of the required energy in the Roquette Frères factory, the leader in starch production in Europe and ranked number four worldwide (Baujard et al., 2017).

Not far from Strasbourg, in Illkirch-Graffenstaden, a seismic acquisition was also obtained in 2015 for evaluating the structure of the fault that will be used for a potential EGS cogeneration plant (Richard et al., 2016). The objective of this plant is to provide electricity and to supply heat to the district heating network for the surrounding community by 2020. The geothermal heat will be obtained from two wells of approximately 3-km depth and it is predicted to have a production temperature of 150 °C at the rate of 300 m^3/h.

Still in the Strasbourg area, in the city of Vendenheim, another geothermal plant is being developed and provisioned to come on line in 2019. This plant is projected to provide 6 MW_{el} and 40 MW_{th}. The drilling of one of the wells, over 4 km in depth, has started as of mid-2017 (Simon, 2017). A similar development is also taking place in Eckbolsheim, France. There, a cogeneration plant producing electricity and both high- and low-temperature heat for space heating and agriculture purposes will utilize a geothermal potential of 46 MW (Fonroche Géothermie, 2017).

1.3. Geothermal environmental impact in Europe

Still on the subject of energy generation, the European Commission has determined the 20-20-20 goal, which means achieving a 20% share of renewable energies, 20% energy savings and 20% CO_2 emission reduction by 2020 (Danish Energy Agency, 2015). Furthermore, its low-carbon economy roadmap suggests that by 2050, the EU should cut greenhouse gas (GHG) emissions to 80% below the 1990 levels, with the power sector being one of the main sectors where action is needed (European Commission, 2011). Therefore, it is necessary to assess the environmental impact of geothermal energy production to justify that this state-of-the-art energy production is in accordance with the whole scenario of climate-change mitigation.

Indeed, to date, there are numerous existing studies which estimate the GHG emissions of geothermal power plants. However, unlike wind and PV technologies where the CO_2 emission rate does not significantly vary around the world, the environmental impact of geothermal plants varies for the same technology. For instance, while it is known that geothermal binary technology emits low CO_2, this is not reflected by cases in Turkey. The binary plants in Turkey with a capacity of approximately 7 MW_{el} emit approximately 400–1100 gCO_{2eq}/kWh; potentially exceeding the CO_2 emission rate of a bituminous coal power plant (Layman, 2017). This high CO_2 emission rate is due to carbonate-dominated metamorphic rocks in the reservoir (Haizlip et al., 2016). This indicates that the environmental impact of a geothermal plant is geographically and geologically dependent and therefore it is valuable to perform a study based on actual cases. This current study begins with the high quality dataset of the unique case of the Rittershoffen geothermal plant and will expand its scope to study the geothermal plant in Illkirch-Graffenstaden.

2. Method

To quantify GHG emissions, this study follows the LCA method (Life Cycle Assessment) laid out by ISO 14040 as the framework and ISO 14044 as the guideline, both issued in 2006. LCA addresses the environmental aspects and potential environmental impacts throughout the product life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal.

2.1. Goal and scope

2.1.1. Goal definition

The goal of the study is to precisely estimate the climate change impact of electricity and heat production from an existing geothermal plant, Rittershoffen, and from the future geothermal plant in Illkirch. The study is aimed to meet two main objectives:

- Quantify the GHG (Greenhouse Gas) emissions in gCO_{2eq}/kWh_{th} and gCO_{2eq}/kWh_{el} for the different geothermal plant scenarios described in Table 1. The functional units are kWh_{el} and kWh_{th}.
- Analyse and identify the configurations that emit less GHG emissions and identify opportunities for GHG emission reduction.

S1 represents the actual Rittershoffen plant which provides heat to Roquette Frères (which will be referred to as the *heat user*) by transporting hot softened water at 160 °C. S2 is based on a hypothetical case of building an ORC (Organic Rankine Cycle) plant to produce electricity instead of supplying industrial heat, employing the geothermal heat from the same wells. S3–S5 are based on the Illkirch project whose geothermal potential has been studied and for which well drilling will commence in 2018. S3 considers producing purely electricity using ORC, S4 and S5 consider producing electricity using ORC and district heating with different distributions. More details for the parameters are stated in Table 1.

2.1.1.1. Elaboration of S1: actual Rittershoffen plant. The Rittershoffen EGS geothermal plant utilizes one production well having a true vertical depth (TVD) of 2708 m (GRT-2) and one reinjection well of 2508 m (GRT-1) to provide a closed cycle of geothermal fluid, the first loop. As well enhancement approach, a series of thermal, chemical and hydraulic stimulations was carried out to increase the efficiency of the natural fractures. Stimulations were only carried out on one of the wells (GRT-1) which later was decided to be the reinjection well.

By means of heat exchangers, the geothermal heat is transferred from the first loop to the second loop; the transport pipes containing softened water. The heated softened water travels 15 km away to the

Table 1
Explanation of geothermal plant scenarios being analysed in this study.

Scenario	Unit	S1	S2	S3	S4	S5
Analysed scenarios		Rittershoffen Actual	Rittershoffen ORC	Illkirch ORC	Illkirch Combined Plant[a] – Half Heat Capacity[a1]	Illkirch Combined Plant[a] – Full Heat Capacity[a2]
Type of energy		Heat	Electricity	Electricity	Electricity & Heat	Electricity & Heat
Surface equipment		12 Heat Exchanger & Canalization	ORC	ORC	3 Heat Exchangers & ORC	3 Heat Exchangers & ORC
Wells		GRT-1 & GRT-2	GRT-1 & GRT-2	GIL-1 & GIL-2	GIL-1 & GIL-2	GIL-1 & GIL-2
Total borehole length	m	5704	5704	6919	6919	6919
Production temperature at well head	°C	170	170	150	150	150
Reinjection temperature at well head	°C	70	66	66	66	66
Production flowrate	kg/s	70	82.5	82.5	82.5	82.5
Average net ORC electricity output	MW_{el}		4.1	3.26_{l}[c]	2.7[c]	2.2[c]
Average net plant electricity output[b]	MW_{el}		3.7	2.86[c]	2.31[c]	1.82[c]
Thermal Output	MW_{th}	25			3.38_{h}[c]	6.77[c]
Life Time	Y	25	25	25	25	25
Annual Operating Hours	hrs	8000	8500	8500	8500	8500
Annual Electricity Production	GWh_{el}		31.6	24.4	19.7	15.4
Annual Heat Production	GWh_{th}	180			29.1	58.3

[a] The scenario will produce electricity for the first three years and subsequently provide designed heat capacity until end of life with remaining of the exergy allocated to produce electricity.
[a1] This scenario will provide annual heat demand of 29 GWh_{th} (half capacity).
[a2] This scenario will provide annual heat demand of 58 GWh_{th} (full capacity).
[b] The net electricity capacity after being subtracted by LSP Pump consumption.
[c] The number is the average of power output in a year.

heat user's facility inside an insulated transport pipe, suffering a total heat loss of only 4 °C, thanks to the features of its layer of rock wool and vacuum insulation (Ravier et al., 2017).

After feeding heat to the processes in factory, the heated water will return to the Rittershoffen plant inside a 15 km return pipe to be reheated by the first loop. This pair of transport pipes is buried below the ground. As a result, the factory benefits from a continuous supply of 25 MW_{th} heat and an annual supply of 180 GW_{th}, taking into account the demand fluctuation from the processes. This circulation system is equipped with valves and pumps and some portions of them are housed in a building, both in Rittershoffen and in the heat user's facility.

Furthermore, the artesian flow in the GRT wells is not sufficient for operations and thus a downhole pump is necessary. In Rittershoffen, an LSP (Line Shaft Pump) is installed in the well GRT-2 for that purpose. During operation, the LSP pump is powered by electricity from the grid.

2.1.1.2. Elaboration of S2: Rittershoffen ORC. As mentioned above, S2 represents the concept of hypothetically producing electricity via an ORC binary plant. ORC binary plants are closed cycles that convert heat from the geothermal fluid into electricity by transferring the heat to another low-boiling-point working fluid (organic working fluid) to generate electricity. The heat exchange from geothermal water takes place in the preheater and the evaporator. Additionally, an air condenser is needed to bring the organic fluid to its initial state before it enters the next same cycle. Enthalpy itself is a function of mass flowrate and the difference between the inlet and exit temperatures. Efficiency increases with an increase in enthalpy. The efficiency of binary thermal plants varies as a function of the enthalpy of the geothermal water (Zarrouk and Moon, 2014) and outside temperature (which will affect the power needed for cooling). Assuming a heat capacity c_p = 3.8 kJ/kg K, an efficiency of 12.9%, and an outside temperature of 11 °C, the plant will have a capacity of 3.7 MW_{el}. Furthermore, when a geothermal plant produces electricity, a portion of its output is consumed by the LSP pump (Table 2).

Table 2
Calculation of theoretical electricity output of S2: Rittershoffen ORC.

Parameters	Unit	Sum
Flow Rate	kg/s	82.5
Geothermal Power	MW_{th}	32
ORC Efficiency	%	12.9
Gross ORC Power	kW_{el}	4943
Aux Power	kW_{el}	592
Net ORC Power	kW_{el}	4120
LSP Power	kW_{el}	400
Net Plant Power	kW_{el}	3717

2.1.1.3. Elaboration of S3: Illkirch ORC. This scenario is based on a future project in Illkirch-Graffenstaden. The electricity capacity estimation for Illkirch is based on an assumed production temperature of 150 °C and flowrate of 82.5 kg/s. The drilling for this plant is planned to start in 2018. The geothermal energy is dependent on the return temperature (T_{reinj}) whose relation with ambient temperature (T_{amb}) is expressed by Eq. (1), obtained by performing a regression of an existing dataset for Illkirch ORC performance provided by the appointed supplier. Additionally, another study was done outside this project and it resulted in Eq. (2) to describe electrical power (P_{el}) as a function of the ambient temperature for the parameters given for Illkirch. Accordingly, it will produce from 2.69 MW_{el} to 3.74 MW_{el} net ORC power before the LSP consumption. Furthermore, the total operating hours, defined monthly to accommodate maintenance activities, add up to 8500 h annually.

$$T_{reinj} = -0.0004 \times T_{amb}^{2} + 0.531 \times T_{amb} + 60.37 \quad (1)$$

$$P_{el} = -0.9017 \times T_{amb}^{2} - 37.95 \times T_{amb} + 3830.7 \quad (2)$$

2.1.1.4. Elaboration of S4 and S5: Illkirch ORC and district heating. S4 and S5 are expansions of S3. Here, the Illkirch Plant is projected to only produce electricity from the ORC plant during the first 3 years after its initiation. Thereafter, it will also supply heat to district heating until the end of its lifetime. The heat demand specification for the two scenarios was established prior to this study. The first scenario is to supply heat of 29 GWh/year (S4) and the second 58 GWh/year (S5). During this

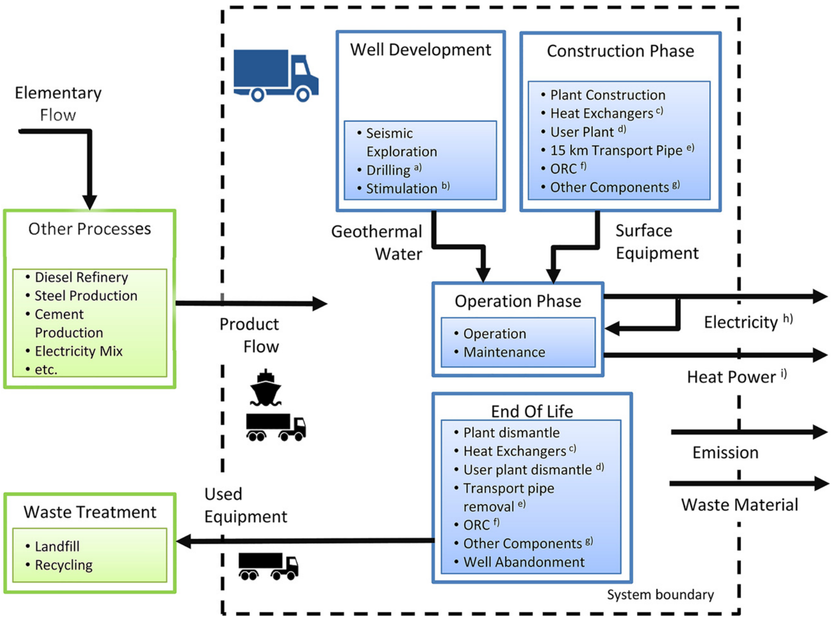


Fig. 2. LCA System Boundary for the study. The scenario includes all non-superscripted components and some of the rest as explained below: a) Drilling will refer to the well parameters of GRT-1 and GRT-2 for Rittershoffen and GIL-1 and GIL-2 for Illkirch. b) Stimulation for Illkirch is assumed to take place to consider worst-case scenario. c) 12 Heat exchangers for S1, 3 heat exchangers for S4 and S5. d) e)g) Only applicable for S1. f)h) Only applicable for S2–S5. g) Other component consists of LSP pump, pipes, pumps, filters and valves. Except for LSP pump, the composition of its contents for S2–S5 is half of those for S1. i) Only applicable for S1, S4, S5.

period, ORC electricity will be provided by the remaining geothermal energy after the heat demand is fulfilled. Consequently, S4 and S5 will annually generate 19.7 GWh_{el} and 15.4 GWh_{el} respectively, with the maximum net ORC output of 2.84 MW_{el} and 2.68 MW_{el} respectively. The installed ORC plant capacity remains at 4 MW_{el} to serve the demand during the first 3 years.

2.1.2. Definition of system boundaries of different scenarios

This study covers the development stages from exploration to end-of-life of the geothermal power plant (cradle-to-grave). Fig. 2 illustrates the scope of the study being performed for different scenarios. Impact assessment is limited to the climate-change impact of GHG, expressed in gCO_{2eq}/kWh_{el} and gCO_{2eq}/kWh_{th}. Exploration activities taking place during well development are neglected except for seismic acquisition. Transportations to bring the materials to the site are always considered, both during construction, operation, and disposal, as well as that for mobility of personnel. Additionally, at the end of the lifetime, the transportations of the used equipment to the intended waste treatment plant (landfill or recycling) are inside the boundary, but not the treatment itself.

2.1.3. Literature study

The existing literature on LCA in geothermal energy is a valuable foundation for this research. Tomasini-Montenegro et al. (2017) comprehensively reviewed existing life-cycle-analysis studies performed for all types of geothermal plants, including EGS plants. Based on their observations, most LCA studies have focused on the evaluation of global warming impact, and for this impact the diesel consumption during construction and operation is the biggest contributor. Additionally, they have identified the construction phase as the biggest contributor to CO_2 emissions for an EGS plant.

While all studies provide important highlights, the studies performed by Lacirignola and Blanc (2013) and Frick et al. (2010) are the ones of highest relevance to the current research being performed and will be regarded anytime validation or comparison is needed (Table 3). They were chosen because they provide a fair amount of detail that offers a clear understanding of the methods, scope, and assumptions being employed. This current study is based on a real case and it is performed less than a year after the commissioning of the plant. This is an advantage as the existing studies are not based on real data of real projects. One exception is the LCA study which considered the Soultz-sous-Forêts geothermal plant as a reference, and which was performed 3 years after the plant started operating (Lacirignola and Blanc, 2013).

2.2. Inventory analysis

The LCI (Life Cycle Inventory) analysis gathers the inputs and outputs of all processes within the scope of study. The data comes from different sources: information from reports, technical programmes, technical specifications, quotations, supplier emails, ÉS Géothermie engineers and the subcontractors. When records do not exist, some justified estimations are done. A summary of the LCI for Rittershoffen is displayed in Table 8.

Validation, a crucial step of LCI construction, is equally executed for critical data by communicating them to experts or by comparison to literature studies. The elementary material flows of all involved

Table 3
Geothermal plant LCA literature studies taken for validation.

Author	Lacirignola and Blanc (2013) (base case taken as reference)	Frick et al. (2010) Plant A1&A2 as reference
Geothermal Plant	Soultz-sous-Forêts EGS-Binary	Hypothetical EGS-Binary in Germany
LCA Software/Database	Simapro/Ecoinvent	Not Specified/Ecoinvent
Impact	(IPCC 2001 and IPCC 2007 for CH_4, N_2O and CO)	Not Specified
Well Depth/Net Plant Capacity/ Lifetime	2 of 4 km/1.6 MW_{el}/25 Y	2 of 3.8 km/1.75 MW_{el}/30 Y
CO_{2eq} (g/kWh)	36.7	A1: ~42–~62 (electricity) A2: ~4.50–~6.48 (heat) ~38–~56 (electricity)
Remarks	Comparison of 10 possible EGS scenarios with Soultz-sous- Forêts, France, as base case.	Study of 10 hypothetical cases in Germany, including district heating application.

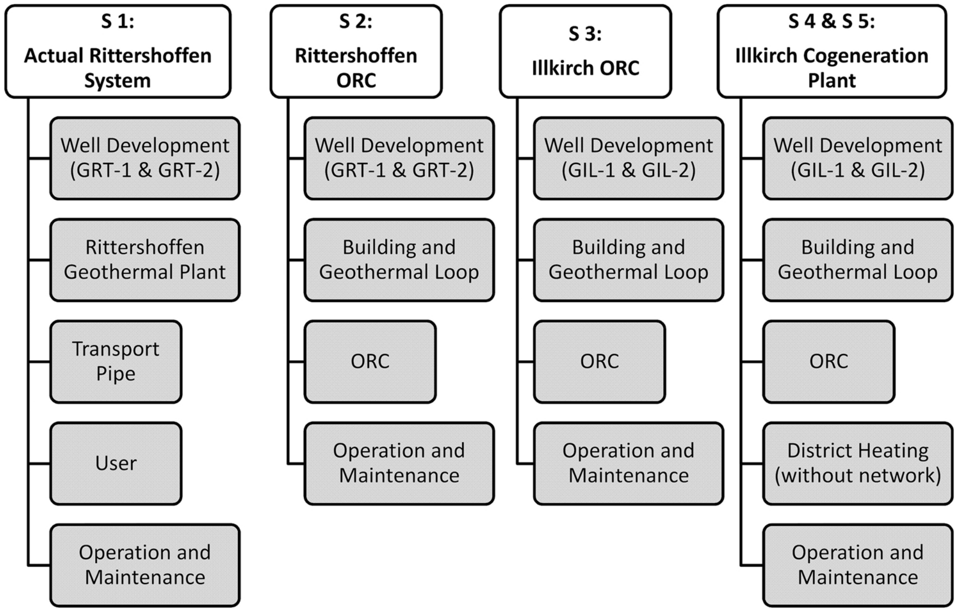


Fig. 3. LCA Technical processes of the scenarios.

processes refer to the Ecoinvent 3 database. When exact materials cannot be found in this database, the USLCI and Agri-BALYSE databases are used as alternatives. Finally, some similar materials are selected when they do not exist in either database.

To accommodate inaccuracy in estimation and material selection, uncertainty is introduced by using Ecoinvent Pedigree Matrix (Weidema et al., 2013). The calculation is done using OpenLCA 1.6.3 from GreenDelta. During the calculation, the systems are grouped as depicted in Fig. 3. Well development includes exploration, drilling, well testing and well stimulation.

2.2.1. *Exploration*

The Rittershoffen inventory covers the seismic exploration as it was the only exploration activity whose emissions of GHG can be quantified. The seismic exploration was performed after GRT-1 had been drilled. Based on the report, the fuel consumption rate of this activity was 1000 l/day where it lasted for 7 days for Rittershoffen and will last for 14 days for Illkirch.

2.2.2. *Drilling*

The drilling inventory covers all the drilling of GRT-1 and GRT-2, the material employed during drilling (such as casing, cement, and mud) and the transportation.

The drilling platforms covering 4150 m^2 were topped with macadam placed on concrete. Two steel conductor casings of 36-m depth were installed. Afterwards, GRT-1 was drilled. GRT-1 is a vertical well and it was drilled in the second semester of 2012, while GRT-2 is a deviated well with a vertical depth of 2708 m and it was drilled in the first semester of 2014. The future Illkirch project will drill two wells, namely, GIL-1 and GIL-2 that are planned to reach measured depths of 3409 m and 3513 m respectively.

2.2.2.1. Drilling energy consumption. The diesel consumption was obtained from daily reports and the value includes the energy needed for the circulation system. GRT-2 required a more powerful machine to accomplish the well design, and it consequently used more energy. The rig was powered by electricity produced by a diesel generator. However, GRT-2 drilling is also observed to have consumed a greater volume of mud and cement and a greater number of runs than GRT-1 (Table 4).

This is partially due to a well stability issue with GRT-2 that was triggered by a loss of circulation which took 30 days and 7 BHA (bottom hole assembly) runs to solve. For comparison, an adjustment to take this issue out of the calculation was carried out and it gives a realistic estimate of GRT-2 drilling assuming good conditions. This is represented as GRT-2b in Table 5. This table also gives a comparison of energy consumption with a study carried out by Lacirignola (2011) in nearby Soultz-sous-Forêts, presumably on a well having similar characteristics. GPK-3 is currently the reinjection well for Soultz-sous-Forêts. GPK-4 is another reinjection well for Soultz-sous-Forêts but was not used as a reference. GPK-3 fuel consumption is quite similar to that of GRT-1. GPK-4 fuel consumption was high because GPK-4 drilling faced several problems, including 15 runs of downhole tool failures and well stability issues. It is important to note that other literature studies from different regions introduce a fuel consumption ranging from 2.1 GJ/m to 9 GJ/m. This high variation is possibly due to very different rock conditions,

Table 4
Comparison of the main material consumption of GRT-1 and GRT-2.

	Unit	GRT-1	GRT-2
Function		Injection Well	Production Well
Total Depth	m	2580	3196
Duration	days	94	131
Number of runs		18	28
Type of Machine		MR 8000 (1080 HP)	HH 300 (1542 HP)
Diesel Consumption	m^3	297.4	619.5
Fuel Energy per meter	GJ/m	4.21	7.08
Stimulation		YES	NO
Mud Volume	m3	3048	4286
Cement tonnage	ton	236	303

Table 5
Comparison of energy consumption between Rittershoffen and Soultz-sous-Forêts (SsF).

	Unit	GRT-1	GRT-2	GRT-2b	SsF GPK-3	SsF GPK-4
Well Depth	m	2580	3192	3192	5100	5200
Energy Consumption	GJ/m	4.21	7.08	5.8	3.9[a)]	7.4[a)]

a) Initially obtained by (Lacirignola, 2011) using fuel density of 35.86 MJ/l. It is recalculated with fuel density of 40.3 MJ/l used in this study.

technology and equipment, and the actual progress of the drilling process (Treyer et al., 2015). For drilling of the Illkirch wells, 5.8 GJ/m is taken as reference. Additionally, electricity was equally needed to power auxiliary equipment when the drilling was taking place. Each metre of drilling at Rittershoffen required 23 kWh, and this is adopted for the Illkirch study.

2.2.2.2. Drilling mud. In the Rittershoffen wells bentonite was the main viscosity agent used for the drilling mud, while in Illkirch wells mainly glycol mud is expected to be used. Unfortunately, not every mud component can be precisely represented by the Ecoinvent database, and thus the generic "*inorganic chemical*" was chosen to characterize these components. Consequently, inorganic chemical occupies 23% and 48% of the total weight of mud for GRT-1 and GRT-2 respectively and 5% for the case of the Illkirch well. In addition, LCI for calcium carbonate is taken from Agri-BALYSE, a public LCA database of French agricultural raw products.

2.2.2.3. Casing and cement. The casing installation is designed uniquely for every well programme due to the unique geological properties of each well, thus it will differ in diameter and depth. For the same reason, the volume to be filled with cement will also vary. The casing is normally made from steel and the inventory is calculated considering the API K-55 standard. Cement slurry is a mix of different chemicals, dominated by cement. GRT and GIL wells use a greater amount of silica compared to other wells.

Table 6 shows the comparison of steel and cement consumption per metre of well considered for LCA studies. The Rittershoffen and GPK-3 wells have a similar casing configuration. Illkirch has comparatively more weight per metre of casing steel mainly because its 9⅝" liner will sit at the depth of the 20" casing shoe, and not at the depth of the 13⅜" casing shoe. Meanwhile, the GPK-3 well has a 9⅝" casing which is installed from the surface and larger casings only envelop one third of the well depth; this is relatively short in comparison with GRT and GIL wells.

For the cementing operation, the calculation considers an excess volume of 50%. The GPK-3 well has a different cementing arrangement, leaving a significant length of 9⅝" casing uncemented (from 1400 m to 4100 m). This results in a smaller volume of cement per metre depth.

2.2.2.4. Well testing. During well testing a significant amount of GHG was released to the environment while geothermal water was being discharged to the basin. The calculation of the quantity of CO_2 assumes that the chemical composition of the geothermal water fluid is similar to that of the total fluid from Soultz-sous-Forêts. It has a 107% gas-to-liquid ratio, which means that for each 1 m^3 of geothermal water there is 1.07 m^3 of gas and the CO_2 content of the gas is 86.2% (Sanjuan, 2011). As a result, 312 tCO_2 were released to the atmosphere during well testing.

2.2.3. Stimulation

LCI of stimulation covers the activities of thermal, hydraulic, mechanical and chemical stimulation (Economides and Nolte, 1989). Chemical stimulation is performed by injecting KCl (potassium chloride), and acidic chemicals are later mixed with an inhibitor diluted with water. The chemical glutamic acid, does not exist in Ecoinvent, nor does the inhibitor chemical. These chemicals are represented by the generic "*organic chemical*" in Ecoinvent with an average volume density of 1.45 kg/l. Rodriguez and Ouyang (2013) reported a case of stimulation during which approximately 135,000 bbl of fluid using approximately 21,000 gallons of diesel fuel were pumped. This ratio is used for this fuel estimation.

Table 6
Comparison of steel and cement quantity per metre of well depth.

	Unit	GRT-1	GRT-2	GIL-1	GIL-2	SsF GPK-3
Casing Steel	kg/m	95.7	94.3	132.6	130.7	111.3
Cement Materials						
Cement G	kg/m	73.0	96.1	77.0	78.5	38.3
Silica	kg/m	48.7	43.5	31.0	31.3	1.5
Bentonite	kg/m	1.1	3.3	4.8	3.9	2.1

2.2.4. Well abandonment

At the end of the operation, the wells will be abandoned. Over time the casing structure of the abandoned well will deteriorate due to corrosion and will allow communication within aquifer layers and pose a risk of contamination of ground water. To avoid this, some critical sections of the well must be properly plugged by cement, such as the top of the well, the last casing shoe, and the open hole section (Ministère de l'Economie des Finances et de l'Industrie, 1997). For the case of geothermal wells, the open-hole section is a loss zone and thus cementing is performed at the top of the loss zone. Additionally, depths with a known permeable zone must also be cemented. Temperature changes have been observed at a depth of 1700 m from the surface in the Keuper formation of the Rittershoffen wells, (Baujard et al., 2017). These are recognized as permeable zones. The thickness of each cement plug is 50 m, and where there is a change in internal diameter, it is 100 m.

Fig. 4 illustrates the sections in which the cement plugs are to be installed. Well abandonment for Illkirch is foreseen to be similar, except for the top section which requires a 150-m depth of cement due the existence of a shallow water aquifer.

2.2.5. Rittershoffen geothermal heat plant

The Rittershoffen heat plant consists of an LSP Pump, heat exchangers, piping, pumps valves, electrical components and the building that houses the geothermal installation.

2.2.5.1. Plant construction. The building at Rittershoffen houses the heat exchange system, the offices, and the electrical room. This inventory includes the construction materials of foundation, steel structures, enclosures, insulation, and electrical installations (electrification and transformers). During the construction, electricity and diesel were consumed. Materials include mainly concrete, galvanized steel, rock wool, and cladding. Wall cladding is

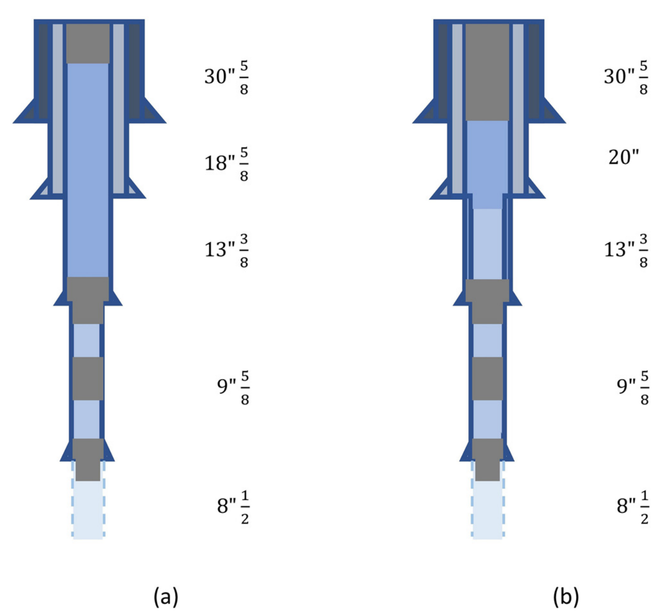


Fig. 4. Cement placements for abandoned wells of Rittershoffen (a) and Illkirch (b). Not at scale.

represented as MCM (Metal Composite Material) and roof cladding is represented as insulated metal panel, both taken from the USLCI database.

2.2.5.2. Heat exchangers. There are 12 active shell-and-tube heat exchangers that serve the heat exchange between the geothermal water and the softened water in the Rittershoffen plant. Each exchanger contains a set of super duplex tubes housed in a steel shell, insulated with rock wool and externally protected by aluminium. Super duplex was selected due to its high corrosion resistance (Ravier et al., 2016).

2.2.5.3. Other components. There is one 400 kW LSP that is currently in operation in the GRT-2 well. This LSP pump, having 39 stainless steel stages where impellers are installed, is submerged at 460 m downhole and is retained by a steel tube, while its motor is installed on the surface. A set of surface pumps and valves are employed to have the water circulate through the right path and at the intended flowrate. The bodies of the pumps and valves are made of either steel or stainless steel and the pump motors are of aluminium and copper. Additionally, carbon steel pipes are installed for carrying geothermal water and steel is used in the secondary pipes for the fresh water loop leaving the plant. To minimize the heat loss, these pipes are insulated with rock wool and enveloped with aluminium. Additionally, it is assumed that overhaul maintenance is performed every certain number of years during which many parts are replaced. For simplification, this maintenance is approached by a replacement of some portion of the equipment. The replacement scenario follows Table 7. Additionally, we assume a decrease of productivity index of 1% each year. To maintain a constant flowrate with the reducing productivity index, the LSP pump will be installed 30 m deeper whenever it is replaced, i.e. each 7 years. As a result the corresponding increase of metal consumption and electricity consumption is taken into account.

2.2.6. Transport pipes

The inventory of the 15-km transport pipe covers the installation of outgoing steel-cased pipe-in-pipe system carrying heated water from the plant and incoming pipe system carrying warm water from the heat user's facility. Fig. 5 shows the cross sections of these pipes. The outgoing channel is also equipped with a cathodic corrosion protection. Additionally, a fibre optic cable is installed along the pipe for communication purposes. The working activity includes welding and vacuum insulation operation, an excavation along the line, horizontal drilling under a county road, a highway and a railway that took 6 days to complete. These activities consumed fuel for machinery and required transportation for the pipe and sand.

2.2.7. User

This inventory includes the installation of the heat exchangers, the building, the electrification and the transformers. Eight heat exchangers and five thermal batteries are installed in the heat user's facility. These are equipped with rock wool insulation and enveloped in aluminium. Three tanks are also installed to maintain pressure during the cycle. In this study, 2.5 km of pipe is installed to carry the heated water. This circuit is equipped with pumps, valves, and pipes. No replacement is foreseen.

Table 7
Replacement requirement for system components.

Equipment	Portion Replaced	Replacement Period (Y)
Heat Exchangers	1/2	10
LSP Pump	1	7
LSP Pump Steel Tube	1/2	7
Pumps	1/2	10
Valves	1/2	10
Filter	1	20
Pipe	1/4	10
Beinheim Pumps	1/3	10
Beinheim Valves	1/3	10
ORC Heat Exchangers	1	10
ORC Turbine & Generator	1	20
ORC Pump	1	20
Air Condenser	1/50	20

2.2.8. ORC

The theoretical ORC component is considered as an installation with a capacity of 4 MW_{el}. This inventory includes a turbine, a generator, heat exchangers, an air condenser system, piping, a transformer and a frequency controller. This installation is made from carbon and alloy steel. An additional 9% copper content is considered for the generator.

2.2.9. Operation and maintenance

During the operation, electricity is needed to run the LSP and other equipment, both in Rittershoffen and at the heat user's facility. Additionally, maintenance of the heat exchangers by water blasting also needs to be performed. Water blasting is to be carried out annually to remove the scaling inside the tubes. Scaling and corrosion inhibitors are to be continuously supplied, as well as salt and oil for lubrication. Furthermore, an estimated 0.5% annual leakage of isobutane is also taken into consideration for ORC plants (S2–S5).

This LCI equally considers the commuting of employees and the transportation needed for the maintenance of the geothermal plant. During maintenance, geothermal water does not circulate and is channelled to a separator and will consequently emit CO_2. This event lasts for a day and occurs 3 times a year with a flowrate of geothermal

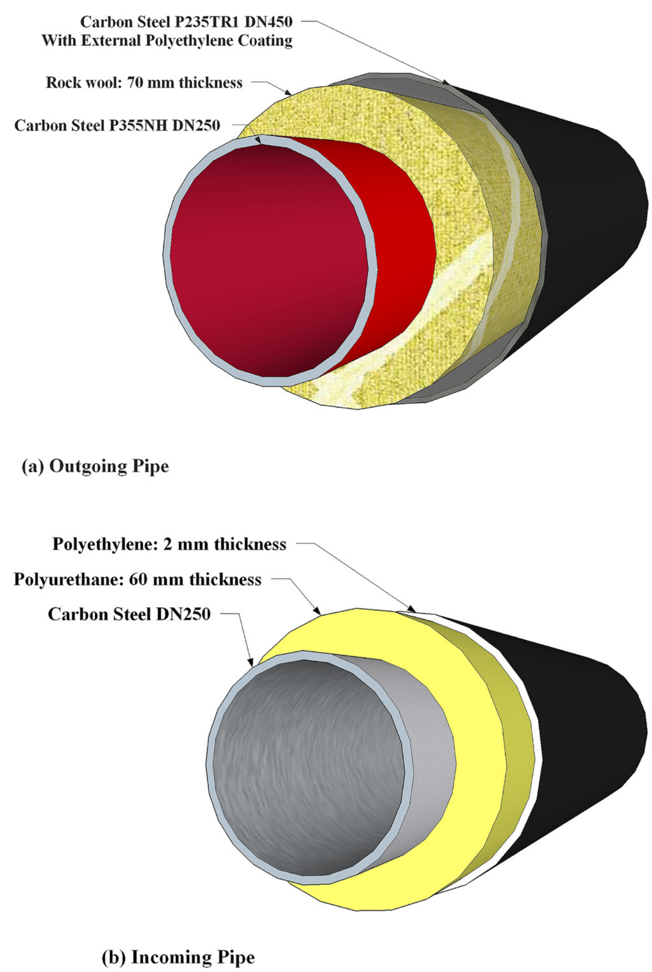


Fig. 5. Cross section of transport pipes.

Table 8
Life Cycle Inventory of the Rittershoffen Plant. This table does not cover all inventories taken for calculation. Important elements are selected to be displayed. *PM: Product Manufacturing processes needed to transform raw material into ready-made product.

Activities	Product	Unit	Qty	Activities	Product	Unit	Qty
Exploration	Diesel for Seismic Campaign	GJ	282	Transport Pipe	Carbon Steel	ton	1999
	Land Transport	tkm	88,612		Carbon steel PM*	ton	1999
	Passenger Transport	km	880		Diesel in Building Machine	GJ	13,285
Drilling	Asphalt	ton	747		Disposal Transportation	tkm	139,551
	Bentonite	ton	98		Land Transport	tkm	3,071,950
	Calcium carbonate	ton	89		Polyethylene pipe	km	26
	Carbon Steel	ton	528		Polyurethane, rigid foam	ton	69
	Carbon steel PM*	ton	507		Rock Wool	ton	66
	Diesel for Drilling	GJ	37,796		Sand	ton	14,434
	Diesel in Building Machine	GJ	1161		Arc Welding	km	6
	Direct CO_2 Emission	ton	312	Heat User	Aluminium	ton	25
	Drilling Mud	ton	548		Aluminium PM*	ton	25
	Electricity	MWh	230		Cable	ton	5
	Inorganic Chemical	ton	229		Carbon Steel	ton	291
	Land Transportation	tkm	4,964,069		Carbon steel PM*	ton	291
	Passenger Transport	km	5100		Electricity	MWh	37,500
	Portland Cement	ton	448		Galvanized Steel	ton	33
	Sea Transport	tkm	1,528,880		Land Transport	tkm	387,061
	Silica Sand	ton	186		Rock Wool	ton	40
Stimulation	Organic Chemical	ton	58		Stainless Steel	ton	59
	Electricity from Diesel Generator	GJ	1765		Chromium steel PM*	ton	45
	Land Transport	tkm	141,404		Sea Transport	tkm	252,853
	K_2O	ton	48		Portland Cement	ton	119
Rittershoffen Geothermal Plant	Aluminium	Ton	11		Transformer	ton	3
	Aluminium PM*	Ton	11	Operation and Maintenance	Scaling Inhibitor	ton	132
	Asphalt	ton	541		Direct CO_2 Emission	ton	898
	Brick	ton	36		Electricity	MWh	123,000
	Cable	ton	7		Corrosion Inhibitor	ton	42
	Carbon Steel	ton	391		Land Transport	tkm	629,238
	Carbon steel PM*	ton	409		Lubricating Oil	ton	149
	Stainless Steel	ton	69		Passenger Transport	km	390,000
	Super Duplex	ton	36		Sea Transport	tkm	39,760
	Chromium steel PM*	ton	105		Sodium Chloride	ton	167
	Diesel in Building Machine	GJ	803		Treated Water	ton	45,000
	Electrical Cable	ton	11	Well Abandonment	Bentonite	ton	3
	Galvanized Steel	ton	77		Diesel for Drilling Rig	GJ	1451
	Gravel	ton	368		Land Transport	tkm	592,550
	Land Transport	tkm	1,071,616		Portland Cement	ton	32
	Portland Cement	ton	128		Silica Sand	ton	13
	Rock Wool	ton	31				
	Wall & Roof Cladding	m^2	2562				
	Sea Transport	tkm	3,514,440				
	Transformer	ton	20				

water of approximately 150 m^3/h. Considering the chemical composition as explained in Section 2.2.2, this discharge will amount to 36 tCO_{2eq} annually.

2.2.10. Disposal and waste treatment

At the end of the life time of each piece of equipment, steel and concrete will be dismantled and the materials are to be disposed of. For buildings and the transport pipe for S1, the dismantling activity is considered, and for the rest of the processes, only the material and transportation to the designated treatment plants are considered. Additionally, for the case of the Illkirch well, mud and cuttings must be disposed of to a specific treatment site close to Paris.

2.2.11. General assumptions

Stainless steel material is modelled with *steel, chromium steel 18/8* and super duplex is modelled with *iron-nickel-chromium alloy* and each steel product is additionally represented by a metal-working activity. Electricity is supplied by the electricity mix of Alsace which, in 2013, consisted in 50.3% nuclear, 45% hydro, 3.6% coal and 0.6% PV (Bortoli, 2013).

All freight inventories are stated in tkm units (ton kilometre) and are assumed to comply with the EURO4 emission regulation which was issued in 2005–2008. For disposal, however, EURO5 is considered applicable. Additionally, it is considered that steel will be disposed of to a site 60 km away from the site, and concrete and inert material 50 km away. Rock wool is to be recycled and it is assumed that in 25 years recycling facilities will exist within the radius of 200 km from the plant.

2.2.12. Uncertainty

In this study, both background LCA and foreground uncertainty are taken into account. Background uncertainty is incorporated in Ecoinvent 3 database. Foreground uncertainty is developed with the help of a Ecoinvent data quality pedigree matrix; a feature embedded in OpenLCA.

Data sources are assessed according to the five independent characteristics *reliability*, *completeness*, *temporal correlation*, *geographic correlation*, and *further technological correlation* (Weidema et al., 2013). Each characteristic is divided into five quality levels with a score between 1 and 5, with 1 having the best data quality. Based on these inputs a lognormal distribution will be created. As a real case, the uncertainty for S1 is mainly due to the discrepancy of integrating the Ecoinvent 3 database, which leads to having low *geographic* and *technological correlation*. In contrast, for other scenarios, the question of *reliability* adds to the uncertainty due to further assumptions.

2.2.13. Allocation

For the case of Illkirch where the plant is designed to produce electricity and heat, the intended configuration is a parallel combination. In a parallel configuration, geothermal energy is distributed between the ORC and the district heating network right after the production well. A physical allocation based on a *shared emission savings* method (Abusoglu and Kanoglu, 2009) is exercised based on a 25-year lifetime, also considering the sole electricity production for the first 3 years. As a result, 11% and 22% of the emission is allocated to heat production for S4 and S5, respectively, and the rest is allocated to electricity production. This allocation is applied for shared systems only. The emissions from the ORC components, for example, are entirely tied to electricity production.

2.3. Impact assessment method

This study employs the climate change impact category of impact assessment method ILCD 2011, midpoint available in OpenLCA as recommended by the European Commission. It uses the 2007 GWP 100 (Global Warming Potential) of the IPCC for characterization.

3. Results and discussion

3.1. Comparison between lifetime

The advantage of having a longer life time in terms of GHG emissions is shown in Fig. 6. Regardless of type of the plant, doubling the lifetime of the plant could reduce the GHG emissions by at least 30%. The constraints of prolonging lifetime are the heat capacity that a duplet can produce and equipment deterioration due to a high corrosion rate caused by the salinity of the brine.

In some other parts of the world, such as in New Zealand, the practice of periodically drilling another well is pursued to maintain the plant production. The Rittershoffen plant lifetime is predicted to be 25 years which is the objective after corrosion inhibitor injection. Furthermore, the Rittershoffen geothermal plant was awarded a concession of 25 years up to 2040. For these reasons, the following analyses are carried out for a 25-year lifetime.

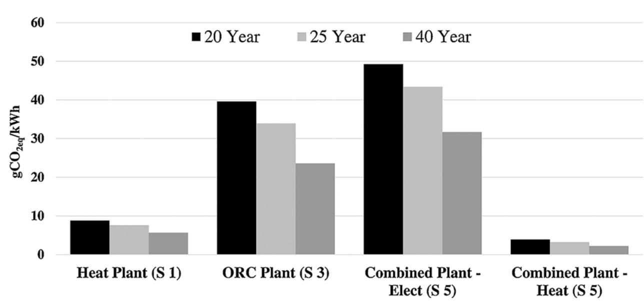


Fig. 6. Impact of Life Time to GHG emissions per functional unit (kWh_{th}, kWh_{el}).

3.2. Hot spot analysis

One of the features of LCA analysis is to identify hot spots, i.e., the most eminent GHG emitter. Fig. 7 shows an overview of hot spots for each scenario. For S2–S5, well development, including the drilling and stimulation, is the activity that causes the greatest GHG emissions, ranging from 46% to 55%. A slightly larger contribution observed for well development for S3–S5 compared to S2 is due to the deeper wells. This confirms one of the conclusions of existing studies carried out for geothermal ORC plants as mentioned by Tomasini-Montenegro et al. (2017) that drilling during the construction stage is the main contributor. On the other hand, it appears that the GHG emissions from the transport pipe installed for S1 overtake those of well development. Indeed, the emissions form metal consumption for the transport pipe are significant, considering the distance between the plant and the heat user. Each km of distance represents 2% of the total emission of S1. In addition, the portion of the operation and maintenance of the S1 heat plant is larger than of other scenarios. This is due to its electricity consumption from the grid, whereas other scenarios auto-consume their ORC electricity output.

In Fig. 8 the processes of each activity are grouped into several categories. For instance, all metal resources, such as steel, stainless steel, and aluminium, are grouped into "*metal products*", including the processes to convert them into final product. The chemical products for chemical stimulation and the mud mixture are grouped in "*chemical products*", etc. Due to their similarity, the S2 presented in the top part of the figure also represents S3–S5. From the top section, it is observed that during well development, diesel consumption, represented by "*fossil fuel*", contributes most to GHG emissions, followed by "*metal products*" for casing as the second highest contributor. Afterwards, except during operation, GHG emissions are mostly derived from "*metal products*".

Specific to S1, *"metal products"* dominates the activity of transport pipe construction. Equally observed, the electricity needed for the operation is a significant GHG contributor unlike in any of the other scenarios.

The bottom image in Fig. 8 shows that in all scenarios, "*metal products"* is persistently the biggest GHG contributor, followed by *"fossil fuel"*, and *"transportation"* (except for S1 where electricity takes the 3rd place).

3.3. Comparison of scenarios

Fig. 9 shows that in total, S1 emits most GHG throughout its lifetime compared to the others, at least 30% more than the next-highest source. Transport pipe construction and electricity during operation are responsible for this.

Fig. 10 shows the emission from each scenario in CO_{2eq}/kWh_{th} and CO_{2eq}/kWh_{el}. These numbers are obtained in OpenLCA by running Monte Carlo simulations of 150 samples for each scenario with a defined uncertainty as explained in Section 2.2.12. The lower and upper

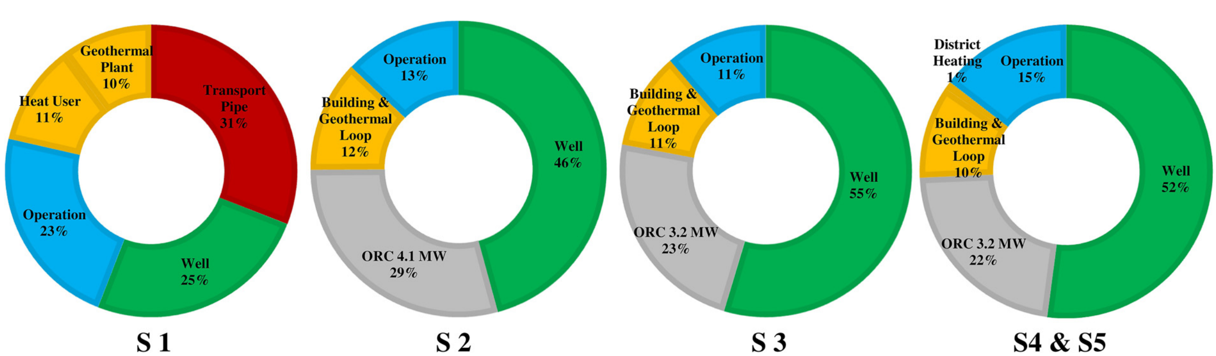


Fig. 7. Relative contributions of life cycle activities to GHG emissions for S1–S5 for the life time of 25 years.

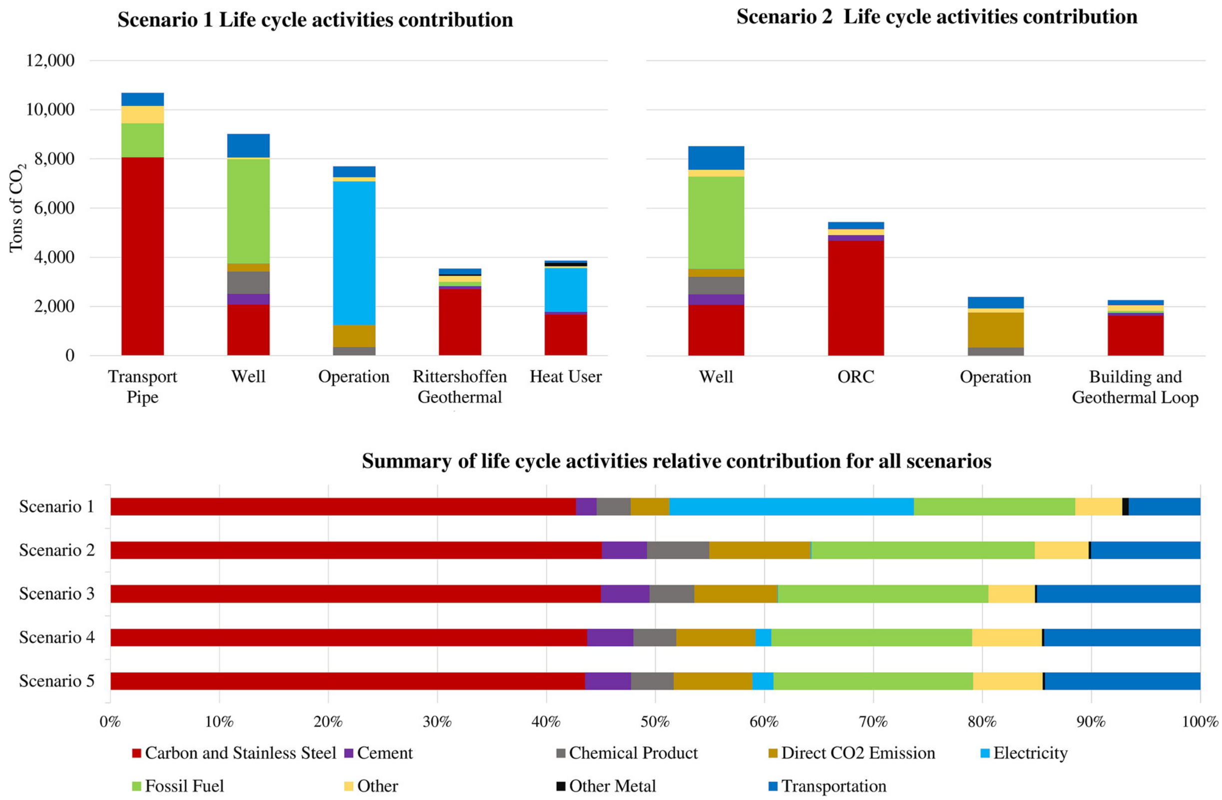


Fig. 8. Contribution of process category to GHG emissions.

boundaries of the boxes are the 5th percentile and the 95th percentile, representing the minimum and the maximum values respectively. S1 is observed to have a lower range of uncertainty – having maximum deviation of 14% from the mean value, whereas that of S3–S5 is 20% or beyond.

In terms of CO_{2eq}/kWh_{th}, S1 still emits significantly more GHG ($8.00\ gCO_{2eq}/kW_{th}$) than S4 and S5 despite greater flow as shown in Fig. 10. The comparatively lower operating hours for S1 also contribute to this value. When the transport pipe is removed from S1, it has a significantly lower emission of $5.55\ gCO_{2eq}/kW_{th}$. However, this value is still higher than that of S4 and S5 because the GHG emissions for the heat production of S4 and S5 are resulted from allocated processes where only small percentage falls under heat production.

Fig. 10 shows that between S2 and S3, S2 emits less gCO_{2eq}/kWh_{el}. This is because compared with S3, S2 produces from a shallower depth and higher electricity production due to its elevated temperature (refer to Table 1).

Fig. 10 also presents comparison of possible configurations of the Illkirch Plant applicable to S3–S5. This gives an indication that for a given infrastructure (well and construction) the more heat that is allocated to the system, the less electricity could be produced, and thus the greater the emissions that will be burdened to each kWh of electricity. In contrast, the variation in emissions is not as apparent for heat production for the same reason that it bears a smaller percentage of GHG allocation.

3.4. Comparison with other literature studies

3.4.1. Heat plant – S1

S1, the real Rittershoffen plant that produces industrial heat at a

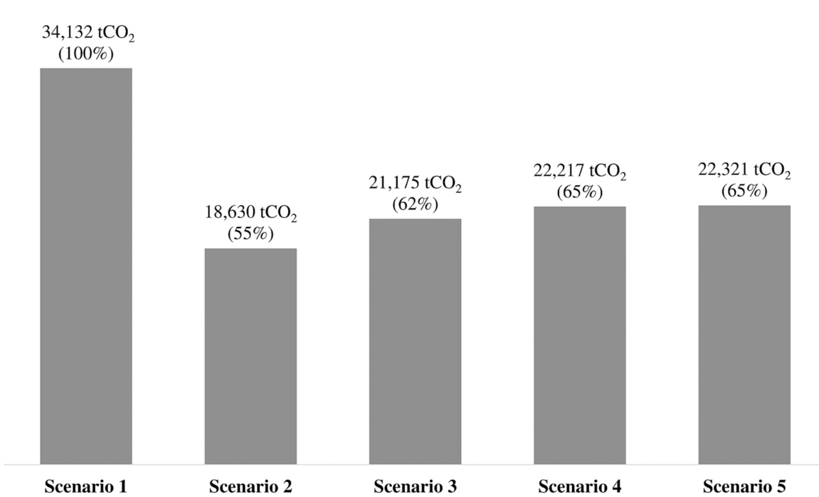
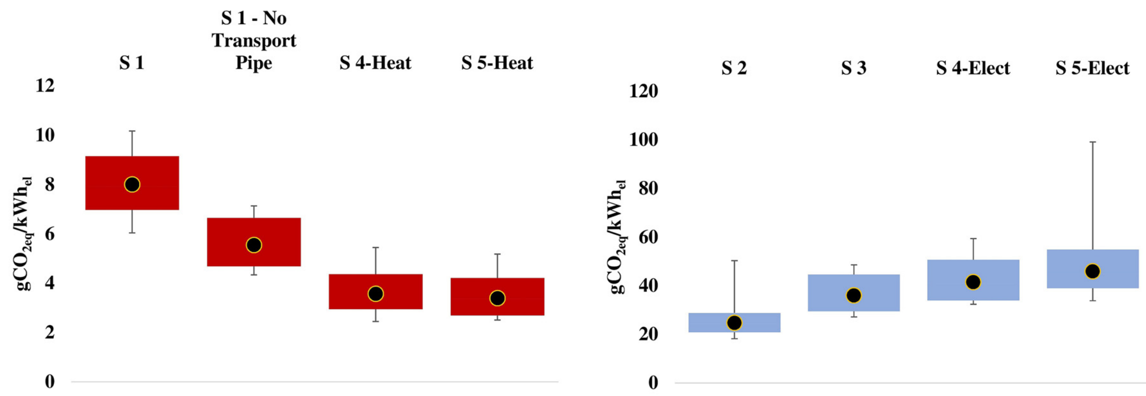


Fig. 9. Comparison of total GHG emissions between scenarios.



	S 1	S 1 - Without Transport Pipe	S 4 - Heat	S 5 - Heat	S 2	S 3	S 4- Elect	S 5 - Elect
95% Percentile	9.15	7.14	4.36	4.21	28.80	44.60	50.71	54.92
Mean	*8.00*	*5.55*	*3.57*	*3.39*	*24.73*	*35.99*	*41.50*	*45.94*
5% Percentile	6.97	4.69	2.94	2.69	20.85	29.53	33.96	38.98

Fig. 10. Comparison of GHG emissions among scenarios per kWh_{el} and kWh_{th}.

high temperature, is a unique configuration that does not commonly exist. Similar to this are the geothermal utilizations in the Paris basin dedicated for space heating only at a low temperature (80 °C). In all, 30 geothermal duplets that have been operating for over 30 years exist in this region. However, a comparison cannot be performed as no literature study exists for the Paris basin.

3.4.2. ORC plants – S2 and S3

When compared to the GPK-3 of Soultz-sous-Forêts which is taken by Lacirignola and Blanc (2013) as their base case, S2 emits a lower amount of GHG than GPK-3 (20.85–28.80 vs. 36.7 gCO_{2eq}/kWh_{th}). This is due to several factors. For triple wells of 4 km each, they considered a lower production temperature (165 °C), a higher re-injection temperature (70 °C) and, most importantly, a smaller production flowrate (40 l/s) than S2. It is important to note that if GRT-2 had not faced any problems, it would have much lower emissions than GPK-3. In contrast, it is observed that the GPK-3 emissions fall in the range of the potential emissions of S3. This is because each metre of S3 consumes more diesel (1.5 times that of GPK-3) and steel than GPK-3. This compensates for the S3 annual production that is double that of GPK-3. Therefore, the result is in agreement.

Fig. 11displays the GHG emissions of S2 and S3 in comparison with those reported in previous studies.

Frick et al. (2010) proposed several scenarios. One of them is Plant A, the scenario which consists of a duplet geothermal well with a depth of 3.8 km and a production temperature of 125 °C. They proposed

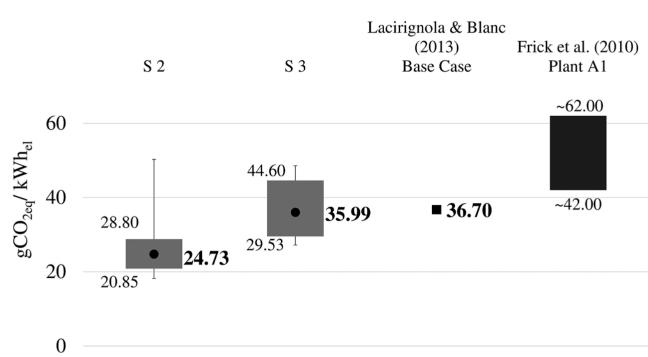


Fig. 11. Comparison of CO_2 emissions of S2 and S3 with literature studies.

options of both electricity (A1) and cogeneration (A2) plants. Both plants incorporate a 330 kW downhole pump to produce a 250 m^3/h flowrate. When compared to Plant A1, S2 and S3 emit relatively less CO_{2eq}/kW_{el}. The main reason for this difference is the amount of electricity produced. For the deeper wells, their study assumed a lower production temperature of 125 °C, lower ORC efficiency of 9.6%, and lower load hours.

3.4.3. Combined plants – S4 and S5

Plant A2 proposed by Frick et al. (2010) considered a cogeneration plant – the only European EGS cogeneration plant found in the literature. This comparison must be done carefully, because while this study considers a parallel configuration, their cogeneration plant is configured in series. In a series configuration, energy for district heating is extracted after the ORC electricity production. Serial configurations valorise geothermal energy at the lower temperatures at which electricity cannot be produced, and thus improve the overall gain of a plant. This is not the case for parallel configurations (Section 2.2.13).

Concerning heat production, it is observed in Fig. 12(a) that Plant A2 emits significantly more GHG than S4 or S5. This is due to the low heat energy and low annual load hours (1800 h/y) considered by Frick et al. (2010) for heat production. Plant A2 would produce approximately 10 GWh_{th} annually – a number much smaller than S4 and S5.

Concerning CO_{2eq}/kWh_{el} emissions, Fig. 12(b) shows that while the emissions increase for the cogeneration plants of this study, it decreases in the case of Plant A2. To compensate for heat production, this study estimates a reduction of approximately 4.7 GWh_{el} and 9 GWh_{el} annually for S4 and S5, respectively. Frick et al. (2010) considered a reduction in annually electrical production of only approximately 400 MWh_{el} but at the same time the plant valorises more geothermal energy in the form of heat. Therefore, the CO_{2eq}/kWh_{el} emission of Plant A2 is less than that of Plant A1 even with less electricity, because the emission is allocated to both the electricity and the additional heat production. In contrast, S4 and S5 emit more GHG than S3 because there is no improvement in geothermal energy valorisation.

This shows that a series configuration is preferred over parallel in terms of GHG emissions. However, S4 and S5 are constrained by the district heating temperature range required in the project. The district heating inlet temperature is set at 100 °C, which is unattainable with a series configuration. On the other hand, district heating inlet temperature is set at 70 °C for Plant A2 and therefore a series configuration is applicable.

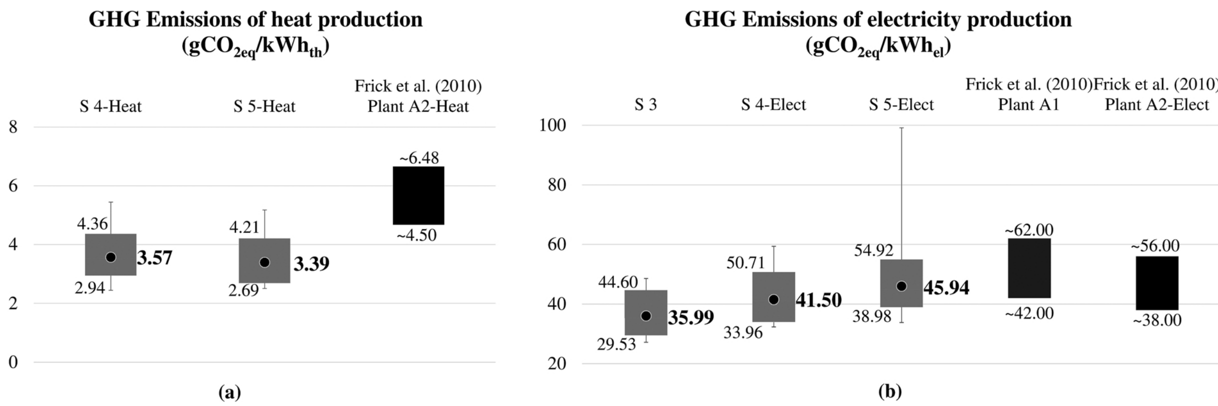


Fig. 12. Comparison of CO_2 emissions of S4 and S5 with literature studies.

3.5. *Possible improvement of GHG emissions for an EGS geothermal plant*

3.5.1. *Comparison of different electricity mixes*

As mentioned in the previous section, the operation of S1 consumes electricity during its lifetime and its emissions will depend on the electricity mix available in the market. As shown in Fig. 13, the source of electricity matters to the GHG emissions for a heat plant (S1). A greener electricity mix will consequently produce lower emissions. On the other hand, this mix creates only a small variation when the plant produces pure ORC electricity. Thus, when a combined plant produces both heat and electricity, its GHG emissions vary much less with the type of electricity mix, as seen in the case of S5.

3.5.2. *Best energy distribution between electricity and heat*

From the point of view of GHG emissions, it is possible to determine the best power and heat distribution by identifying the avoided impact from the existing GHG emissions from electricity and heat sources that are currently in operation as done by Gerber and Maréchal (2012). In this study, this avoided impact is estimated with the assumption that the electricity is supplied by the Alsace electricity mix while the heat is supplied by natural gas, emitting approximately 47 gCO_{2eq}/kWh_{el}[1] and 248 gCO_{2eq}/kWh_{th}[2] respectively. Furthermore, the maximum values of the emissions from each scenario are considered to allow a conservative estimate of CO_2 avoidance. The comparison is summarized in Table 9, showing that for S1, where it is possible to supply a large amount of heat for industrial purposes rather than district heating, GHG emissions from natural gas is significantly avoided. Meanwhile, among S3 to S5, S5 achieves the greatest GHG avoidance. It means that fulfilling a greater heat demand is a greener practice. This conclusion is similar to that of Gerber and Maréchal (2012). In the case of S1, the GHG avoided in a year exceeds the GHG emitted during its 25-year lifetime.

Table 9 also shows that S3 is the least favourable in terms of CO_2 avoidance. This is because the Alsace electricity mix has low CO_2 emissions. However, if such ORC replaced the German electricity mix, 16.5 kiloton of CO_2 emissions could be avoided annually. It shows that the benefit of the result of this configuration comparison depends on the energy mix in the region.

3.5.3. *Electric grid for drilling machine*

Fig. 14 presents the improvement of GHG emissions by consuming electricity from the grid during drilling instead of diesel. The use of diesel is the reference (set as 100%) while others are related to the

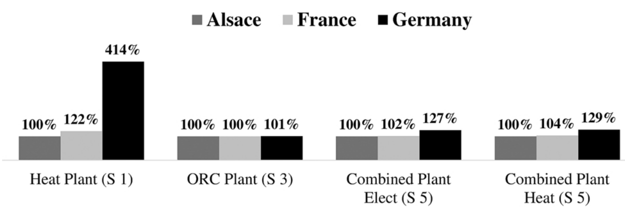


Fig. 13. Relative impact of different electricity mixes on GHG emissions for different types of plant. Impact from the German mix is set as 100%. Electricity mix reference for Germany and France are obtained from the Ecoinvent 3 database.

power supply from the Alsace electricity mix. For S2 and S3, this change creates at least 15% lower emissions, while for S1 the impact is less significant because the S1 transport pipe is responsible for most of the GHG instead of drilling. When the transport pipe is taken out of the calculation, the impact becomes comparable to others. As additional reference, Lacirignola and Blanc (2013) estimated that this approach could reduce the climate change impact by more than 25%. However, its implementation is constrained by the cost of electricity and grid connection.

3.5.4. *Efficiency in transportation*

As mentioned in Section 3.2, transportation is ranked as one of the highest GHG contributors. In the case of Rittershoffen, the delivery of the transport pipe is the greatest contributor, followed by the transportation of the drilling machine and then the casing delivery. Whereas for scenarios related to Illkirch plant, the transport required for mud treatment and cutting disposal at the end of drilling is of the first rank, followed by the drilling machine transportation and the casing delivery.

The transport pipes went through the manufacturing and insulation installation processes in different countries (Germany and Sweden) before being delivered. This could be improved by installing the insulation near the pipe manufacturer, or sourcing material from a closer location. With an assumption that insulation of the incoming pipe could be carried out in by the manufacturer in Germany, CO_2 emission of the transportation for the transport pipes could be reduced by 0.8% of the total emission.

The Rittershoffen wells required two types of drilling machine as explained in Section 2.2.2, and therefore, two sets of delivery took place. Drilling several wells with one drilling machine is one means to reduce frequency of this transport. The Illkirch project already anticipates this improvement by drilling two wells with one machine. In fact, it is also possible to drill two or more sets of duplet with one machine. For instance, taking S2 as the base case, having two such plants (i.e., 4 wells) with one machine (delivered once) could reduce the total gCO_{2eq}/kWh_{el} by approximately 4%. However, since the rental cost is a constraint, it requires careful planning to minimize the number of

[1] Calculated by OpenLCA for the Alsace electricity mix having 50.3% nuclear, 45% hydro, 3.6% coal and 0.6% PV. Ecoinvent LCI database and ILCD 2011 (midpoint) are used.

[2] Reference for France Natural Gas CO_2 emission: ADEME (2014). Sum of CO_2 emissions from upstream and combustion activities = 66.9 tCO_2/TJ PCI. Reference for boiler efficiency is assumed to be 97% (Garcia et al., 2012).

Table 9
Comparison of annual avoided GHG emissions for various configurations.

Scenarios	Scenario Description	gCO_2 per kWh		Annual Production (GWh)		Annual Avoided Ton CO_2		Annual Ton CO_2 avoided
		Heat	Electricity	Heat	Electricity	Heat	Electricity	
S1	Geothermal 100% Heat Capacity	9.15	–	180.00	–	45,404.42	–	45,404
S3	Geothermal 0% Heat Capacity	–	44.60	–	24.40	–	58.56	289
S4	Geothermal 50% Heat Capacity	4.36	50.71	29.10	19.70	7089.92	−73.09	7017
S5	Geothermal 100% Heat Capacity	4.21	54.92	58.30	15.40	14,212.96	−121.97	14,091

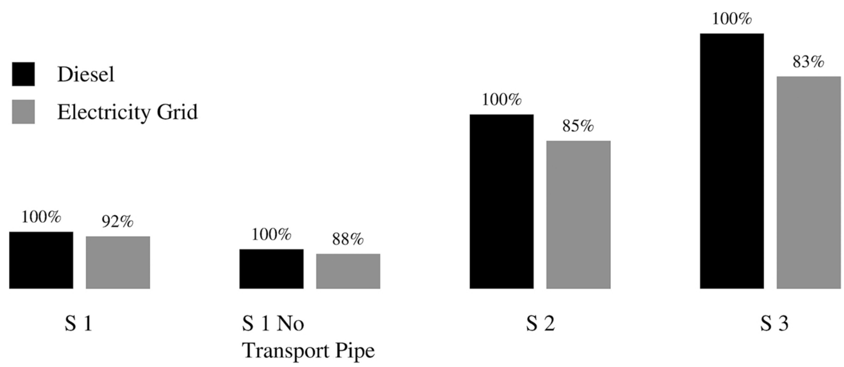


Fig. 14. Comparison of impact of electricity grid vs. diesel during drilling on GHG emissions, expressed in percentage and in gCO_{2eq}/kWh.

unproductive days. When the delay between wells is too long, it is no longer economical to keep the rig onsite.

Casings installed in GRT wells originated in both South Korea and the Czech Republic (approximately 25% and 75% respectively) and were partially inspected in Dubai. Procuring the casing from a closer location is an alternative that will reduce GHG emissions. For instance, GHG emissions would be reduced by 0.7% if all casings were delivered from the Czech Republic for S2.

In the Illkirch project, a huge amount of mud and cuttings is estimated to be delivered for treatment and disposal, even after removing 20% of the original weight by reutilizing the water onsite. This amount is to be delivered to a competent supplier close to Paris as no local competence exists yet. Considering that geothermal resource can be favourably developed in the Upper Rhine Valley and that the environmental regulations will only become more stringent, it is essential for enterprises to build such competence in the area to reduce the distance required for mud transport. Based on S3, this could reduce GHG emissions up to 2.9%.

4. Conclusions

The study quantifies and analyses life cycle GHG emissions from five different scenarios comprising a heat plant, power plants and cogeneration plants using a life cycle inventory of a real project and respecting LCA methodology. Additional to having values of GHG emissions in gCO_{2eq}, LCA methodology also allowed identifications of GHG emissions from each phase and material type. Based on this methodology some conclusions can be drawn:

- The operating Rittershoffen plant emits between 6.97 gCO_{2eq}/kWh_{th}–9.15 gCO_{2eq}/kWh_{th} throughout its 25-year lifetime. Whereas the upcoming plant, Illkirch-Graffenstaden, will potentially emit 2.69–4.39 gCO_{2eq}/kWh_{th} and 29.53–54.92 gCO_{2eq}/kWh_{el} depending on the portions of heat and electricity productions.
- The study shows that for all scenarios the longer the lifetime of the plant, the less gCO_{2eq} is emitted per kWh because construction phase is the stage most responsible for GHG emissions.
- Well development, including drilling and stimulation, in general contributes the most to GHG emissions. However, when transport piping is needed, the emissions of its construction could exceed that of well development if the length is significant. Additionally, in term of resources, metal product consumption and production contribute most to GHG emissions.
- GHG emissions of an ORC plant vary least with the type of electricity mix due to its electricity auto-consumption.
- More GHG emissions can be avoided when more heat is produced. The highest avoidance can be achieved when there is an opportunity to use geothermal heat for industrial use. Furthermore, for district heating purposes, a cogeneration plant will allow auto-consumption and thus produce fewer emissions compared to consuming electricity solely from the grid. However, this also depends highly on the heat and electricity mix in the region. Additionally, when possible, it is preferable for the cogeneration plant to be in a series rather than a parallel configuration. This is because a series configuration valorises geothermal energy more by utilizing the lower temperatures at which electricity cannot be produced, and thus improves the overall gain of a plant.

This study also assessed some site-specific approaches to potentially reduce of GHG emissions. Accordingly, some other conclusions are:

- Feeding on Alsace electricity mix during drilling will potentially result in highest GHG emissions reduction, which is at least 15% for ORC plants.
- The second most impacting approach is reduction the total transport distance or frequency. Reducing the transport frequency of drilling machine will potentially reduce 4% of total emissions. Treating post-drilling mud in nearby regions has a potential of 2.9% total emissions reduction.

This study is a useful reference towards LCA studies of EGS as it analyses the first EGS utilization for industrial heat. Going forward, there is a wide possibility of directions in which this study can be developed. An example is an extended analysis of the scenarios comprising all impact categories such as resource depletion, land use, etc. Furthermore, studies to analyse strategies within a circular economy framework will also be beneficial. These studies could include analysing the environmental impacts from consuming recycled products, prolonging plant lifetime with a help of anti-corrosion material, or installing low-temperature ORC system before the injection system to optimize geothermal energy valorisation.

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