Generation of simplified parametrised models for a selection of GEOENVI geothermal installations categories

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Executive Summary

The simplified models presented in this report were developed as one of the outcomes of the European project GEOENVI [Grant agreement n°818242 -- 2018-2021]. These simplified models estimate the environmental impacts of four different categories of geothermal installations, namely: (1) enhanced geothermal systems (EGS) for heat generation with very low direct emissions, (2) geothermal flash power plant producing electricity and a limited amount of heat from a geothermal source with moderate to high content of NCGs, composed mostly of CO_2, (3) combined Heat and Power (CHP) geothermal plant with low direct emissions, and (4) a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions.

The simplified models are based on equations with a small number of variable parameters and provide first environmental assessments of geothermal installations belonging to any of the four categories described, whenever the resources are lacking to conduct full life cycle assessments (LCAs).

The generation of the simplified models for each of the four categories of geothermal installations relied on a five-step protocol including (i) the definition of the scope of the study, (ii) the modelling and validation of the reference LCA model, (iii) the statistical process to identify the key input variable parameters for each impact category, (iv) the generation and validation of the simplified models, and (v) the description of the models' applicability domain. The reference LCA model was developed based on one representative geothermal installation per category and followed whenever possible the LCA guidelines developed within GEOENVI (Blanc et al., 2020). Adaptations were necessary to ensure that the developed reference LCA model was not too specific for the representative installation and thus general enough to represent all possible installations within that category.

Seven simplified models per category of geothermal installation were developed, describing impacts on climate change, minerals and metals resource depletion, fossil resource depletion, human carcinogenic effects, human non-carcinogenic effects, freshwater ecotoxicity, and freshwater and terrestrial acidification. Each model relied on two to six variable parameters specific to the geothermal installation and explaining around 75% or more of the variance observed per impact category. In addition, the simplified models for the EGS for heat generation includes electricity shares as inputs to consider different types of electricity mix used to power the pumps during the plant's operation phase. It appears that the influencing variable parameters vary depending on the impact category and the geothermal installation category, as shown in Table 1. Only the most influencing variable parameters were kept per simplified model, as explained in more details in the description of the protocol.

Table 1 – Variable parameters for the seven simplified models derived per category of geothermal installation: (EGS) enhanced geothermal systems (EGS) for heat generation with very low direct emissions, (Flash) geothermal flash power plant producing electricity and a limited amount of heat from a geothermal source with moderate to high content of NCGs, composed mostly of CO_2, (CHP) combined Heat and Power (CHP) geothermal plant with low direct emissions, and (HeatORC) a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. EQ stands for ecosystem quality, R for resources, and HH for human health.

	EGS	Flash	CHP	HeatORC
Climate change total	- Thermal output - Power of the production pump -Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Flow rate - Fraction of NCGs	- Fraction CO2 in geothermal fluid - Power output	- Operating hours - Power of the injection pump - Power of the production pump - Thermal output
EQ - freshwater and terrestrial acidification	- Thermal output - Power of the production pump -Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Flow rate - Fraction of NCGs - Fraction of NH3	- Lifetime - Well depth - Capacity factor - Diesel drilling	- Operating hours - Power of the production pump - Thermal output
R - fossils	- Thermal output - Power of the production pump -Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Make up well ratio - Average well length	- Lifetime - Well depth - Capacity factor	- Power of the injection pump - Number injection wells - Thermal output
R - minerals and metals	- Thermal output - Power of the production pump -Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Make up well ratio - Average well length	- Lifetime - Well depth - Capacity factor	- Operating hours - Power of the production pump - Thermal output

HH - non-carcinogenic effects	- Thermal output - Power of the production pump - Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Flow rate - Fraction of NCGs - Fraction of Hg	- Lifetime - Well depth - Capacity factor	- Operating hours - Power of the production pump - Thermal output
HH - carcinogenic effects	- Thermal output - Power of the production pump -Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Flow rate - Fraction of NCGs - Fraction of Hg	- Lifetime - Well depth - Capacity factor Number of production wells	- Operating hours - Power of the production pump - Thermal output
EQ - freshwater ecotoxicity	- Thermal output - Power of the production pump -Power of the injection pump - Number of production and injection wells - Average well length as well as shares of electricity	- Electrical capacity - Make up well ratio - Average well length	- Lifetime - Well depth - Capacity factor	- Operating hours - Power of the production pump - Thermal output

The simplified models presented in this report are specific to the four categories of geothermal installations analysed in this work. In addition, due to the modelling choices, they are applicable only within a certain range of the variable parameters and after consideration of the fixed parameters. It is therefore essential to carefully check the applicability domain of each simplified model prior to using them for other geothermal installations. Finally, it is important to underline that the presented simplified models do not replace thorough LCAs of geothermal installations but can give first estimates of their environmental performances, whenever time or resources are lacking to conduct full LCAs.

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General Introduction

Geothermal energy is a promising renewable energy source for electricity production and heating and cooling applications (IRENA, 2018). Like many of its renewable counterparts, the production of electricity and heat from the extraction of the geothermal energy implies less environmental impacts than the production from fossil fuels (Bayer et al., 2013; Marchand et al., 2015). The environmental impacts of the production of geothermal energy occur throughout the entire lifecycle of the installation, and not mainly during the use phase as for fossil fuels. In addition, the environmental impacts go beyond greenhouse gas emissions (GHG) so that a holistic and multicriteria approach is essential to robustly assess the environmental impacts of the production of geothermal energy (Frick et al., 2010; Lacirignola and Blanc, 2013).

Life Cycle Assessment (LCA) is a standardized tool used to quantify various environmental impacts of a technology or product throughout its entire life cycle (ISO 14040, 2006). LCA can provide very valuable information to ease decision making processes whenever, for example, different energy producing alternatives are compared. Despite the advantages of being standardised, holistic, multicriteria, and widely accepted, LCA suffers from a lack of guidance when applied to specific sectors and, in particular, energy pathways. When conducting an LCA, the user is faced with a lot of choices that can affect the final results. In fact, in the case of geothermal power plants, Eberle et al., (2017) showed that published life cycle GHG emissions for electricity production can vary from 20 g CO_2-eq/kWh to up to 75 g CO_2-eq/kWh for enhanced geothermal systems (EGS), between 20 and nearly 250 g CO_2-eq/kWh for hydrothermal flash plants, and between 5.7 and nearly 100 g CO_2-eq/kWh for hydrothermal binary plants. Ideally, the expert conducting an LCA should be aware of the consequences of methodological choices on the variability of environmental impact results. The latter depends also on the life cycle data inventory built for the analysis, which generally implies an extensive and time-consuming data gathering exercise.

Regulations increasingly recommend the use of integrated environmental impact assessment tools to support the decision-making process when comparing different energy pathways (European Commission, 2016; European Parlament, 2014; Ministère de l'Environnement, de l'Energie, et de la Mer, 2016). To support these recommendations, methodological guidelines specific to geothermal installations (D3.2) have been proposed within the GEOENVI project to provide LCA experts with methodological indications and assistance on how to perform LCAs of geothermal installations (Blanc et al., 2020).

However, given the difficulty conducting an LCA might represent for non-LCA experts, the development of novel processes to satisfy the need for reliable and integrated decision-making tools while keeping the necessary effort limited is increasingly required.

Simplified models are an example of such tools and within GEOENVI such simplified models have been developed for a selection of geothermal installation categories. A simplified model is meant to estimate the environmental impact of an installation from a limited number of independent input variable parameters. A simplified model is specific for an environmental impact. It is generated following a protocol to convert a reference LCA model into a range of models relying only on a limited number of key variable parameters, which influence the environmental impact the most. Within GEOENVI, this protocol uses Global Sensitivity Analysis (GSA) to identify these key variable parameters, as already explored for wind turbines (Padey et al., 2013) and EGS plants generating electricity (Lacirignola et al., 2015). The resulting simplified models are more quickly and easily applied to estimate the environmental impacts for a specific category of technological installation compared to conducting a comprehensive LCA study. However, these simplified models are specific to the category of installation they are obtained for, and their applicability domains need to be carefully reported and understood for a correct use.

Motivation and Objectives

The objectives of this deliverable are to present simplified models for non-LCA experts/practitioners to assess the environmental impacts of four categories of geothermal installations: (1) EGS heat generation with very low direct emissions, (2) geothermal flash power plant producing electricity and a limited amount of heat, (3) combined Heat and Power (CHP) geothermal plant with low direct emissions, and (4) heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. These models are developed following a protocol initially developed for wind turbines (Padey et al., 2013) and an EGS plant generating electricity (Lacirignola et al., 2015), and generalised for a wider range of geothermal installations. Only a brief description of this generalised protocol is presented here, a more exhaustive procedure is available in D3.5. The environmental impacts considered correspond to the seven impact categories of ILCD 2018 classified with high priority in the LCA guidelines for geothermal installations (D3.2.), namely: climate change total, freshwater ecotoxicity, freshwater and terrestrial acidification, mineral and metal resource depletion, fossil resource depletion, human non-carcinogenic effects, and human carcinogenic effects (Blanc et al., 2020). The use of ILCD 2018 does not comply with the guidelines but was inevitable given the current lack of implementation of the EF v3.0 impact categories in the software used when issuing this report.

This deliverable first gives a description of the protocol followed to generate simplified models for a specific category of geothermal installations and a set of impact categories. In a second

step, the four categories of geothermal installations analysed within the GEOENVI project are described in more details. This is then followed by four chapters, each one describing the application of the protocol to one category of geothermal installations to generate the simplified models. The Appendix then gives background information for each category of geothermal installation, such as a list of the fixed parameters used for the definition of the reference LCA model, the first order Sobol indexes of the variable parameters, and the equations of the simplified models.

Protocol to generate simplified models for a category of geothermal installation

Methodology

The generation of the simplified models relies on the five following steps.

Step 1: Definition of the scope of the study

First, the category of geothermal installation analysed should be precisely described, hence, describing the range of application of the models. The category of geothermal installation is defined with the support of a representative geothermal system (RGS). Within the GEOENVI project, four RGS specific to four categories of geothermal installations were used. The type of energy output (heat or electricity), the type of conversion technology (dry steam, flash, binary, direct heat…), the level of direct emissions (low or high) and whether there is or not a Non-Condensable Gas abatement system have been identified as key distinguishing features and should be specified. In addition, the chosen functional unit and the system boundaries should be clearly stated.

Step 2a: Modelling of the reference LCA model

A computational structure based on a parametrisation of the life cycle model for the geothermal installation category is designed to estimate the life cycle impacts according to a set of *N* independent input variable parameters. Such detailed description is referred to as “the reference LCA model” and represents the category of geothermal installation defined in step 1. Its modelling can hereby rely on the identified RGS. The validity range for each input variable parameter as well as its probability distribution result from the best technological knowledge of the selected geothermal installation category. Once the reference LCA model is defined, scenarios from the probability distribution functions defined for the input variable parameters are generated stochastically, referred to as Monte Carlo simulations.

Step 2b: Validation of the reference LCA model with literature

The results of Monte Carlo simulations derived from the reference LCA model are compared with published LCA studies as a validation step for the reference LCA model.

Step 3: Statistical process to identify the key input variable parameters for each impact category

Key variable parameters are defined for each impact indicator. These variable parameters explain most of the variance over the range of application of the reference LCA model. This step is undertaken by performing a Global Statistical Analysis (GSA) calculating the Sobol' indices (Saltelli, 2008) from the Monte Carlo simulations. Practically, the open access libraries Brightway2 (Mutel, 2017) and lca_algebraic v11.0 (Jolivet, 2020) are of great help to fulfil this task in the Python language. The key input variable parameters are chosen from a trade-off between selecting only a limited number (<10) of easily determined variable parameters for users and covering a sufficient share of the variance of the considered impact indicator (at least 75-80). Currently, the impact categories of the EF v3.0 recommended by the guidelines are not available on the open access tools. Hence, the models presented here were developed for the ILCD 2018 impact categories.

Step 4a: Generation of the simplified model per impact category

Each simplified model is generated using the selection of key variable parameters as input parameters and is obtained by setting the other non-key variable parameters to the value corresponding to the median of their respective variability intervals issued from the stochastic simulations. The level of fitting of each simplified model against the reference model is assessed with the R-squared (R^2), a statistical measure that quantifies to what extent the variance of one output explains the variance of the second output (Equation (1)).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (1)$$

Where n represents the number of realizations, y_i the value obtained with the reference LCA model, $\hat{y}_i$ the value obtained with the simplified model, and $\bar{y}$ the mean of all obtained values with the reference LCA model.

Step 4b: Validation of the simplified models with literature

Finally, the results of the simplified models are compared with the published literature, which might be the one already identified in Step 2. For each relevant literature case study, the values for the key variable parameters required to run the simplified models are identified.

1. The simplified model is then run with this specific set of values for the key variable parameters.
2. A final comparison is done between the literature case study and the simplified model outcome for the exact same configurations as defined by the key variable parameters.

Step 5: Applicability domain of the simplified models and optional iterative adjustment of the scope of the study

An additional step might be necessary for the protocol if the results from the previous step (Step 4) are not fully satisfactory. An adjustment of the definition of the applicability domain might be required and would imply to redefine the scope of the reference LCA model with either the parametrisation scheme, the set of variable parameters, or the range of validity for some variable parameters. After completing this possible adjustment, the final applicability domain of the simplified models should be summarised.

Description of the categories of geothermal installations

The categories of geothermal installations were chosen to represent the state-of-the art of some of the current geothermal installations. They cover heat and electricity production, and power plant data were gathered directly from the plant operators. Rocco et al., (2020) published a report, titled 'Geothermal plants' and applications' emissions: overview and analysis', with the aim to provide a consistent and harmonized life cycle-based assessment of the release of air pollutants in the deep geothermal sector in Europe for different clusters, representative groups of different geothermal installations. This implied the gathering of plant-specific data from numerous geothermal installations to derive equations for the quantification of some inventory flows, also applied in the reference LCA model presented in this report. The categorisation of the geothermal installation analysed here is consistent with the published clusters to align with these harmonization efforts (Table 2). More details for each category are provided in the following chapters.

Table 2 – Description of the categories of geothermal installations analysed to generate the reference LCA models from which simplified models are derived. RGS stands for representative geothermal system.

	EGS	Flash	CHP	Heat ORC
RGS	Rittershoffen (FR)	Bagnore (IT)	Hellisheidi (IS)	Balmatt (BE)
Installed capacity of the RGS	27 MWth	61 MWe 21.1 MWth	303.3 MWe 133 MWth	6.6 MWth 0.25 MWe
Geothermal source type	Liquid	Vapour	Liquid/Vapour	Liquid
Production technology	Downhole pumps	Self-Flowing	Self-Flowing	Downhole pumps
Power/Heat generation unit	Heat exchanger	Flash steam plant	Double flash, Combined heat and power plant	Binary / Heat exchanger
Cooling system	None	Wet cooling tower	Wet cooling tower	Air cooling tower
Gas control system	None	NCG abatement system	None	None
Stimulation	Hydraulic-Thermal-Chemical	None	None	Chemical
Final energy use	Industrial heat	Electricity + Industrial heat	Electricity + Heat	Heat (+ Electricity for self-consumption)
Cluster in (Rocco et al., 2020)	2DHC	3P CHP	1P CHP	7P CHP

Simplified models for the EGS category

This chapter presents the simplified models developed to assess the life cycle environmental impacts of the EGS category of geothermal installation, namely enhanced geothermal systems for heat generation with very low direct emissions. The results are presented following the steps of the protocol presented in the "Protocol to generate simplified models for a category of geothermal installation".

1. Scope of the study

The representative category of geothermal installation analysed here is an EGS for heat generation with very low direct emissions. The functional unit is the production of 1kWh of heat delivered to a user. The system boundaries include the upstream, meaning the secondary data, and the core module. The activities of the upstream module are derived from the ecoinvent database v3.6. The core module, for its part, includes the construction of the infrastructure, the operation and maintenance of the installation, and its end of life (Figure 1).

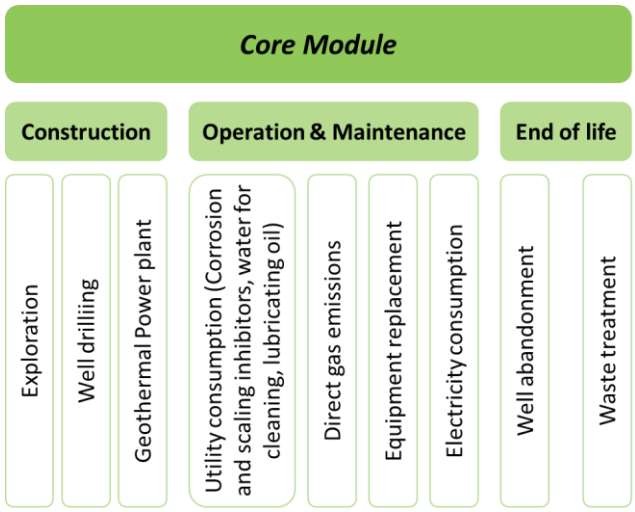

Figure 1 – Phases of the core module included in the modelling of the reference LCA model for EGS.

The geothermal heat plant of Rittershoffen is a typical example of the geothermal installation category analysed here, so that it will serve as a basis for the development of the reference LCA model.

The geothermal heat plant of Rittershoffen has been developed to supply heat to the industrial processes of a starch plant. This industrial user, located in Beinheim, France, totals 100 MW_{th} of thermal needs. The geothermal heat plant, with an installed capacity of 27.5 MW_{th}, has been successfully providing an average of 22.5 MW_{th} and 180 GWh/year of heat to this starch plant since June 2016.

The targeted reservoir is a Triassic sandstone and the top of a fractured carboniferous granite basement located at 2500 m depth. The first well, GRT-1, was drilled in 2012 and the first testing results after drilling showed a low productivity index. A stimulation program, including

thermal, chemical, and hydraulic stimulation, was therefore designed and successfully performed in 2013 (Baujard et al., 2017). Induced seismicity was very low and virtually unnoticeable for the surrounding population. The second well, GRT-2, was drilled in 2014. On the contrary to GRT-1, GRT-2 had a very good productivity index during the testing phase after drilling. Thus, the Rittershoffen geothermal power plant is classified as an EGS because of the stimulation program performed on GRT-1.

The geothermal brine is a Na-Ca-K-Cl dominated brine with a Total Dissolved Solids content of approximately 100 g/L and a Non-Condensable Gas (NCG) content, mainly CO_2, of 0.24% in weight mass (Mouchot et al., 2018). As a result, the heat plant was designed with a pressurized geothermal loop: A downhole Line Shaft Pump (LSP) pressurizes the geothermal brine in the surface equipment over the Gas break-out pressure to prevent any NCG emission during operation. The wellhead production temperature at GRT-2 reaches 170°C and the flowrate is regulated at 75-85 kg/s, following the starch plant's heat demand. The geothermal heat is transferred to a secondary loop using several tubular heat exchangers and the brine is fully reinjected without additional pumps at 85°C into the injection well GRT-1. The secondary loop of the heat plant, containing freshwater, is then connected to a 15 km long transport loop to transfer the heat to the starch plant (Ravier et al., 2017).

Figure 2 – View of the Rittershoffen geothermal heat plant (ES-Géothermie)

2. a. Modelling of the reference LCA model

The reference LCA model aims at representing an EGS for heat production with very low direct emissions. It is a computational structure based on the parametrisation of the Rittershoffen geothermal heat plant designed to estimate the life cycle impacts based on a set of independent input parameters. These parameters can either be variable or fixed parameters. The reference LCA model was developed mostly following the recommendations of the guidelines for the life cycle assessment of geothermal energy systems, except for the use of equations reported in literature instead of primary data for some of the inventory flows to ease

the parametrisation (Blanc et al., 2020). If not specified otherwise, the transport of the materials used in the different processes is modelled with a 500 km distance covered by a 16-32 metric ton lorry of category EURO4. For the plant's operation phase, a tailor-made electricity mix was modelled, as described in the paragraph below. Further details of the different life cycle stages are given in the following chapters.

Tailor-made electricity mix

The electricity needed during the EGS geothermal heat plant's operation phase has been shown to contribute by approximately 20% to the total climate change impact category results (Pratiwi et al., 2018), for an electricity mix, representative for France, with a majority of nuclear electricity. The carbon-intensity of the European electricity mixes varies, however, between 97 g CO_2-eq/kWh (France) and 1,075 g CO_2-eq/kWh (Latvia) (Moro and Lonza, 2018), as do other environmental impacts (Wyss and Frischknecht, 2013). Rocco et al., (2020) showed that using an EU electricity mix for the energy consumption of the operational phase largely influenced the impacts for almost all indicators studied (up to 90% for example for the climate change impact category). Using a country-specific electricity mix thus leads to reference LCA models specific for a given country. To increase the geographical coverage of this model, the electricity needed during the plant operation has been modelled as a tailor-made mix with shares from solid fuels (coal and lignite), oil, natural gas, nuclear energy, biomass, wind, solar and hydropower. These inputs rely on representative ecoinvent processes as explained in more detail in Appendix 1 (A1).

The share of each electricity source has been considered as an input variable parameter described with a Beta distribution determined from the observed and forecasted European electricity mixes based on the PRIMES Model published in (Capros et al., 2016). More details are provided in A1.

The PRIMES model provides a good approximation of the rate of decarbonisation and increased penetration of renewable energy sources in the electricity sector, notably under the driving force of European Union policy objectives. The EU Reference Scenario 2016, based largely on the PRIMES model and projecting electrical shares in a five-year step until 2050, represents the consequences on the energy system, until 2050, of the implementation of existing policies and measures for climate and energy as of 2016, relying on cost assumptions from 2016 for renewable energy technologies, in a "business as usual" perspective. These assumptions do not consider potential technological developments since 2016. The PRIMES model used to derive the electrical shares does further not consider the potential of geothermal energy. This shortfall has been identified and discussed in (EGEC, 2018) and the potential of geothermal electricity quantified in (GEOElec, 2013). Nevertheless, the potential proposed in (GEOElec, 2013) is not put into perspective of other electricity sources and it was therefore

not included in the modelling of prospective electricity mixes. This modelling choice does however likely not greatly affect the simplified model's outcome: it is namely still possible to determine the potential environmental impacts of an EGS heat plant with very low direct emissions with high renewable electricity shares in the electrical mix. Overall, the electricity mix modelled is a simplification of the current electrical mixes within the EU but still represents a major advantage to assess the influence of different shares of electricity (including a high renewable electricity share) on the potential impact of geothermal energy.

When applying the reference LCA model and/or any of the simplified models, the user can therefore either input its own electricity shares, or use the national shares provided in Table 3. Since geothermal energy is not included in the tailor-made electricity mix, because of the use of the PRIMES Model, it is suggested to assign a potential share of geothermal electricity to electricity produced by wind power. The shares for the other EU28 countries are given in A1.

Table 3 – Shares of electricity sources for Belgium, France, Italy, Hungary, and EU 28 observed for 2010 and prospected for 2050 (Capros et al., 2016). The data for Iceland is provided only for 2010 (Orkustofnun, 2010).

	Belgium		France		Italy		Hungary		Iceland	EU 28	
	2010	2050	2010	2050	2010	2050	2010	2050	2010	2010	2050
Nuclear energy	51%	0%	76%	38%	0%	0%	42%	58%	0%	28%	18%
Coal	4%	0%	4%	0%	13%	0%	17%	0%	0%	25%	6%
Oil	0%	0%	1%	0%	7%	0%	1%	0%	0.01%	3%	0%
Natural Gas	35%	59%	5%	6%	53%	34%	31%	23%	0%	24%	21%
Biomass	6%	7%	1%	4%	4%	15%	7%	7%	0%	4%	10%
Hydropower	0%	1%	11%	12%	17%	13%	1%	2%	73.81%	11%	10%
Wind	1%	28%	2%	26%	3%	15%	1%	7%	0%	4%	24%
Solar	1%	5%	0%	12%	1%	21%	0%	1%	0%	1%	11%
Geothermal	0%	0%	0%	0%	0%	0%	0%	0%	26.18%	0%	0%

Construction

Exploration

Prior to the drilling phase, geophysical exploration of the underground on which the installation is foreseen is necessary. In the Upper Rhine Graben context, geophysical technic mostly used is seismic exploration (2D or 3D). The exploration phase is modelled with a variable parameter, $E_{exploration}$, describing the diesel consumption for seismic vibrators during the acquisition and a variable parameter describing the km travelled by the staff during this phase, assumed to be 880 km. A list of all variable parameters and their boundaries is given in Table 4 below.

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Well drilling

Drilling platform

Prior to drilling, a drilling platform, including retention basins, is built. The size of the platform, $A_{platform}$, and an assumed depth of 30 cm are used to estimate the amount of concrete and excavation necessary.

Next to the platform in itself, retention basins were also modelled following the indications of the GREET model. More details are provided in A1.

Drilling

The well drilling process requires energy, provided for this model by diesel, drilling mud, as well as steel and cement for the casing. The cuttings produced during well drilling are another important inventory flow. All these inventory flows were estimated from the equations provided in (Rocco et al., 2020) (A1) using the average meters drilled as input. The average meters drilled, MD, are estimated from the well length L_w, (Equation (2)).

$$MD = L_w * Ratio_{MD,well} \quad (2)$$

Where MD are the average meters length of drilling [m], L_w the length of the well [m], and $Ratio_{MD,well}$ a value larger than 1 describing the ratio between the average meters drilled and the well length. This ratio expresses the over length of drilling due to well cementing consolidation or side tracks.

The drilling mud was further modelled as consisting of 36% water, 11% bentonite, 10% calcium carbonate, 8% carboxmethylcellulose, 27% inorganic chemicals, 1% citric acid, 1% soda ash, 3% sodium chloride, 1% sodium hydroxide (Kanna et al., 2007; Pratiwi et al., 2018).

The drilling phase was therefore described using the following variable parameters:

- the well length, L_w,
- the ratio between the meters drilled and the well length, $Ratio_{MD,well}$,
- the number of production and injection wells, N_{in} and N_{prod}, and
- the distance over which the cuttings are transported to be disposed of, $km_{cuttings}$.

It is important to stress that only one well length is considered as a variable parameter in the reference model. The material and energy needs calculated for this well are then multiplied by the number of injection and production wells to represent all inventory flows for the heat plant.

Stimulation

The energy requirement, $E_{stimulation}$, for the one hydraulic and one chemical stimulation conducted was estimated using Equation (3) (Rocco et al., 2020).

$$E_{stimulation} = \frac{\Delta P * V_{stimulated}}{3.6 * 10^4 * \eta_P} \quad (3)$$

Where ΔP is set to 40 bar, η_P to 0.75, and $V_{stimulated}$ is a variable parameter describing the volume used during stimulation: $V_{Chemsti}$ for the chemical and $V_{hydrsti}$ for the hydraulic stimulation[m^3].

The chemical stimulation was modelled as a mix of 50% water, 25% potassium chloride, and 25% organic chemicals assuming a density of 1.45 kg/l for the latter (Pratiwi et al., 2018).

The variable parameters used to model the stimulation of the wells are

- the volume used for the chemical stimulation, $V_{chemsti}$, and
- the volume used for the hydraulic stimulation, $V_{hydrsti}$.

Well testing

The well testing was modelled with a variable parameter describing the amount of CO_2 emitted directly during the testing of the wells, $CO_{2\ testing}$.

Geothermal power plant

Building construction

The building housing all the electrical and pressure equipment for the heat generation was modelled by adapting the ecoinvent process 'building construction, hall, steel construction'. The material requirements then scale with the variable parameter describing the building's area, $A_{powerplant}$.

Pipes

Geothermal brine, in the geothermal loop, and freshwater, in the secondary loop, are transported to the heat exchanger using pipes made out of steel, insulated with rockwool and aluminium in this order. The amounts of each material are estimated assuming a cylindrical shape of the pipe. The lengths of the pipes are defined as variable parameters $L_{gw\ pipe}$ and $L_{fw\ pipe}$. The radius of the pipe is estimated from Equation (4). The thickness of steel, t_{steel}, is estimated from Equation (5) and assumed to be 2 mm for aluminium and 80 mm for rockwool. The density for rockwool is assumed to be 100 kg/m^3, 2,710 kg/m^3 for aluminium, and 8,000 kg/m^3 for steel.

$$r_{pipe} = \left(\frac{Q}{\pi * 3600 * 1.5}\right)^{0.5} \quad (4)$$

Where Q is a variable parameter describing the flow rate in t/h and assuming a water density of 1,000 kg/m^3 so that r_{pipe} is in m.

$$t_{\text{steel}} = 2 \text{ x} \frac{\text{r}_{\text{pipe}}}{25.4} \quad (5)$$

The transport of the materials is modelled with an average distance of 500 km.

Production pump

The production pump is modelled as a line shaft pump whose material requirements are estimated according to its power output: 100 kg steel/kW, 25 kg chromium steel/kW, and 9 kg

motor/kW. The motor was hereby assumed to consist of 50% steel and 50% copper following expert's recommendations. The number of line shaft pumps (LSP) depends on the number of production wells. The variable parameter necessary to model this equipment is the power of the line shaft pump, P_{LSP}. The transport of the LSP was modelled with 44,200km travelled by transoceanic ship and 7600 km by 16-32 metric ton lorry of category EURO4.

Injection pump

The inventory flows for the injection pump are calculated using the following mass weight percentages following expert's recommendations: 25% steel, 12% chromium steel, 8% aluminium, 8% copper, 38% cast iron, and 9% super duplex steel. The mass of the injection pump is then derived as in Equation (6) from the ratio of the pipe radius.

$$M_{Pump,new} = \frac{r_{known}}{r_{new}} * M_{Pump,known} \quad (6)$$

Where r_{known} is the radius of the pipes at the Rittershoffen plant (calculated from Equation (4) using 306t/h flow rate), r_{new} the radius of the pipes at another powerplant and $M_{Pump,known}$ the mass of the pump in Rittershoffen, namely 7.41E+03 kg.

The power requirement for the injection pump, P_{pump}, is also included as an input variable parameter.

Heat exchanger

The inventory flows for the heat exchanger are calculated using the following weight percentages: 23% super duplex steel, 74% unalloyed steel, 2% aluminium, 1% rockwool. The mass of the heat exchanger is proportional to the mass of the Rittershoffen heat exchanger and estimated from Equation (7).

$$M_{HE,new} = \frac{Q}{Flow_{known}} * M_{HE,Rit} \quad (7)$$

Where $M_{HE,Rit}$ is defined as a variable parameter describing the mass of the Rittershoffen heat exchanger [kg], $Flow_{known}$ equals to 306 t/h and Q the variable parameter describing the flow rate of the powerplant under study [t/h].

The transport of the materials is modelled with an average distance of 500 km.

Filter

The filters are modelled as consisting up to 100% of unalloyed steel and their mass is assumed to be proportional to the mass of the filters at Rittershoffen according to the pipe radius ratio (see Equation (6) and A1).

Valve

The valves consist up to 82% of unalloyed steel and 18% of chromium steel. The mass of these valves is estimated similarly to the one of the filters and pump (see Equation (6) and A1).

Air cooler

An air cooler is also modelled which consists of 99% unalloyed steel and 1% rockwool. Its mass is assumed to scale proportionally to the heat output of the power plant (Equation (8)).

$$M_{Air\ cooler,new} = \frac{P_{th_{new}}}{P_{th_{known}}} * M_{Air\ cooler,known} \quad (8)$$

Where $P_{th_{new}}$ is the heat output of the new plant modelled, $P_{th_{known}}$ the heat output of Rittershoffen, namely 22.5MW, and $M_{Air\ cooler,known}$ the mass of the air cooler at Rittershoffen, namely 15,691kg.

Electrical appliances

The cables and transformers necessary for the electrical installation of the powerplant are also modelled with ecoinvent processes, namely 'transformer production, low voltage use' and 'cable production, unspecified'. The mass of the cables is a fixed parameter set to 19,017 kg, while the mass of the transformer is estimated with Equation (9) derived from (France Transfo, 2020).

$$M_{transfo} = N_{prod} * 2 * P_{LSP} * \frac{1.1}{0.85} * 1.5055 + 946.16 + 2 * P_{pump} * \frac{1.1}{0.85} * 1.5055 + 946.16 \quad (9)$$

Where N_{prod} is the number of production wells, P_{LSP} the power of the line shaft pump, and P_{pump} the power of the injection pump

Operation and maintenance

Corrosion inhibitor, scaling inhibitor, salt, water for cleaning operations, and lubricating oil are used during the operation and maintenance of the plant. These material inventory flows are derived from the two variable parameters flow rate, Q, and operating hours, OH, or set to a default value, as explained in A1.

The mass of scalings, modelled with the variable parameter $M_{scaling}$, is disposed-off as low-level radioactive waste in a surface or trench deposit. It is assumed that 881 km are travelled every three years for their disposal.

In addition, direct gas releases might also take place during this phase. The reference model developed here is however typical for installations with small amounts of direct releases during operation and maintenance. These emissions are modelled with the fraction of gas released, f_{direct}, and the mass content of CO_2 and CH_4 in it, f_{CO_2} and f_{CH_4}. The equations used can be retrieved in A1.

Further, the maintenance of the equipment implies that certain parts are replaced throughout the geothermal plant's lifetime. The replacement rates are taken directly from the LCA guidelines.

The transport of the staff to and from the installation's site is also considered with the variable parameter km_{OM} describing the kilometers travelled by the staff to and from the installation site per day and assuming 250 working days a year.

Finally, the electricity requirement necessary to operate the geothermal power plant can be derived from the powers of the production and injection pumps as shown in Equation (10).

$$E_{OM} = \left(P_{LSP} * N_{prod} + P_{pump} * N_{in}\right) * OH * 1.1 \quad (10)$$

Where E_{OM} is in kWh per year, and the 1.1 factor accounts for 10% additional power requirement for the other equipment.

End of life

The well abandonment is described by two variable parameters: E_{abd} setting the amount of diesel required [MJ], and $M_{Cement,Abd}$ the mass of cement used during the well abandonment [kg].

According to the guidelines, the end of life excludes the decommissioning of power plant buildings and dismantling, sorting and recycling of machinery's components (Blanc et al., 2020). Only the wastes generated during well drilling (cuttings) and maintenance (scaling residues) are accounted for, as described in A1.

Thermal output

Equation (11) describes the thermal output in kWh throughout the plant's lifetime. This amount is necessary to express the potential environmental impacts of the installation in the defined functional unit of 1 kWh.

$$MW_{th} = P_{th} * (1 - Loss_{pyear} * LT) \quad (11)$$

With P_{th} a variable parameter describing the thermal output to the grid [MW], $Loss_{pyear}$ the loss of power per year set to 2.5/30) and LT a variable parameter describing the plant's lifetime [years].

Summary of variable parameters

Table 4 lists the 35 input variable parameters used in the reference LCA model together with their boundaries. These boundaries (min and max) have been selected to comply with a representative range of operating values valid for EGS heat plant with very low direct emissions. The default column refers to the Rittershoffen geothermal heat plant.

All variable parameters, except for the electricity sources shares (see section 2.a. and A1), were assumed to follow a uniform distribution, since no data was available to test the appropriateness of another distribution. Assuming a uniform distribution namely represents the most conservative approach, as it reflects the largest uncertainties related to a given variable parameter. The list of the fixed parameters used for the reference LCA model can be found in A1.

Table 4 – Variable parameters used for the reference LCA model for EGS. The "Default" values represent the values of the Rittershoffen power plant, the Min and Max values are the upper and lower boundaries of the single variable parameters.

Phase	Variable parameter	Symbol	Default	Min	Max	Unit
Electricity mix	Share of coal	f_{coal}	See A1			-
Electricity mix	Share of natural gas	f_{NG}				-
Electricity mix	Share of nuclear	$f_{nuclear}$				-
Electricity mix	Share of oil	f_{oil}				-
Electricity mix	Share of hydropower	f_{hydro}				-
Electricity mix	Share of wind power	f_{wind}				-
Electricity mix	Share of biomass	$f_{biomass}$				-
Electricity mix	Share of solar power	f_{solar}				-
General	Thermal power output	P_{th}	22.5	10	40	MW
General	Lifetime	LT	30	20	40	y
General	Flow rate	Q	306	140	350	t/h
General	Operating hours	OH	8,000	5,000	8,500	h
Exploration	Energy for exploration	$E_{exploration}$	282,000	282,000	965,000	MJ
Drilling	Ratio meters drilled and well length	$Ratio_{MD,well}$	1.13	1	1.5	-
Drilling	Number injection wells	N_{in}	1	1	2	-
Drilling	Number production wells	N_{prod}	1	1	2	-
Drilling	Length well	L_W	2,888	1,300	5,500	m
Drilling	Area drilling platform	$A_{platform}$	20,000	6,500	20,000	m^2
Stimulation	Volume stimulated fluid (chemical)	$V_{Chemsti}$	40	40	250	m^3
Stimulation	Volume hydraulic stimulation	$V_{hydrsti}$	4,200	1,000	5,000	m^3
Well testing	CO_2 released	$M_{CO2,testing}$	312,000	0	312,000	kg
Power plant	Power injection pump	P_{Pump}	0	0	500	kW
Power plant	Length freshwater pipe	$L_{fw,pipe}$	160	100	300	m
Power plant	Length geothermal fluid pipe	$L_{gw,pipe}$	200	100	300	m
Power plant	Power line shaft pump	P_{LSP}	500	200	1,200	kW
Power plant	Area of the power plant	$A_{powerplant}$	692	400	1,200	m^2
Power plant	Mass Rittershoffen heat exchanger	$M_{HE,Rit}$	92,280	23,070	92,280	kg

OM	CH_4 content gas release	f_{CH4}	2.00E-05	0	0.0001	-
OM	CO_2 content gas release	f_{CO2}	0.00224	0	0.01	-
OM	Fraction of direct emissions	f_{direct}	0.006	0.001	0.02	-
OM	Mass scaling	$M_{scaling}$	300	200	500	kg
Transport	Transport operation and maintenance	km_{OM}	30	10	50	km
Transport	Distance for the cuttings	$km_{cuttings}$	50	50	500	km
End of life	Mass cement for well abandonment	$M_{cement,Abd}$	47,000	25,000	50,000	kg
End of life	Energy for well abandonment	E_{Abd}	1.45E+06	772,000	1.50E+06	MJ

2. b. Validation of the reference LCA model with literature

The results of the Monte Carlo simulations for the reference LCA model using the distributions of the variable parameters specified in Table 4 are shown in Figure 3.

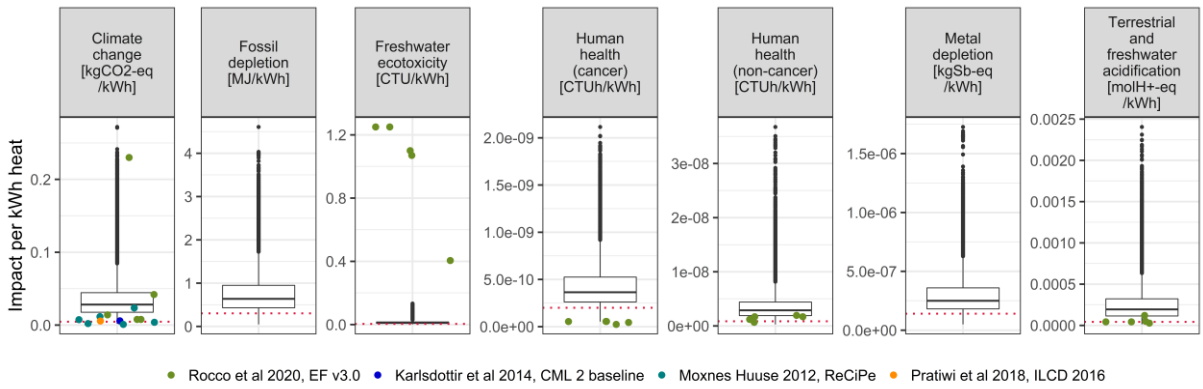


*Figure 3 – Results of the Monte Carlo simulations for the reference LCA model of EGS for the seven ILCD 2018 impact categories of interest. In the boxplots, the lower and upper hinges correspond to the 25th and 75th percentiles, while the whiskers extend from the hinge to the value no further than 1.5 * inter-quartile range from the hinge. The red dashed line represents the outcome of the reference LCA model using default values corresponding to the Rittershoffen geothermal heat plant. Also shown is a comparison with published LCA studies, the impact assessment methods used is indicated in the legend.*

Also shown in Figure 3 is a comparison of the results of the reference LCA model for four published studies. (Karlsdottir et al., 2014) present environmental impacts calculated for the CML baseline method for a geothermal district heating system in Iceland including the well drilling, heat exchanger, and distribution system. The results of (Pratiwi et al., 2018) relate to the Rittershoffen EGS power plant, without the heat distribution pipes. Finally, (Rocco et al., 2020) estimates the environmental impacts for geothermal heat power plants with different

characteristics using the EF v3.0. impact category for average EU characteristics. The estimates from all three studies are comparable to the Monte Carlo results of the reference LCA model, close to the value derived from the reference model with the default values for Rittershoffen. The only exception is for the freshwater ecotoxicity impact, where the values estimated in (Rocco et al., 2020) are ten times larger than the ones estimated with the reference LCA model. The reason most likely lies in the used impact assessment methodology: EF v3.0 uses a more conservative approach for ecotoxicity, namely the concentration potentially hazardous for 20% of the ecosystem instead of 50% for the ILCD 2018 method (Fazio et al., 2018).

A more thorough assessment of the validity of the reference LCA model was possible by using the modelling framework shared by Pratiwi et al. (2018) for the Rittershoffen geothermal heat plant including the heat network with the industrial user: This model is referred to as the “Pratiwi Model”. The reference LCA model developed here and describing EGS for heat generation used with parameter values specific to the Rittershoffen geothermal power plant is referred to as the “GEOENVI Model”. Several adjustments were made to both models to reduce their modelling differences and facilitate the comparison of the impact category results: (1) the specific equipment for the heat user (transport pipes, treatment of heat at the users’ site) was removed from the “Pratiwi Model”; (2) the lifetime of the powerplant was set to 25 years in the “GEOENVI Model”; (3) the “GEOENVI Model” was modified to rely on the French electricity mix available in ecoinvent and not the tailor-made electricity mix; (4) the ILCD 2016 impact assessment methodology was used for both models; and (5) the diesel requirements during well drilling and the electricity need during operation and maintenance in the “GEOENVI Model” were set equal to the values reported in the “Pratiwi Model”.

Table 5 compares the “Pratiwi Model” to the “GEOENVI Model” after adjusting for these aspects, and shows impact assessment results within 1.0 to 7% difference, except for the freshwater ecotoxicity impact and the carcinogenic human health category.

Table 5 – Comparison of the ILCD 2016 impacts for the "Pratiwi Model" and "GEOENVI Model" of the Rittershoffen geothermal heat plant. The electricity need during maintenance and the diesel requirement for the well drilling were adapted in the "GEOENVI Model" to match the ones modelled in the "Pratiwi Model":

Impact category	Reference unit	Pratiwi Model	GEOENVI Model	(GEOENVI -Pratiwi)/ GEOENVI
climate change - GWP 100a	kg CO_2-Eq	2.46E+07	2.36E+07	-4.4%
ecosystem quality - freshwater and terrestrial acidification	mol H+-Eq	2.07E+05	2.14E+05	3.0%
ecosystem quality - freshwater ecotoxicity	CTUh.m^3.yr	2.86E+08	6.59E+08	56.7%
ecosystem quality - freshwater eutrophication	kg P-Eq	7.22E+03	7.23E+03	0.2%
ecosystem quality - ionising radiation	mol N-Eq	1.21E+02	1.19E+02	-1.6%
ecosystem quality - marine eutrophication	kg N-Eq	4.68E+04	4.58E+04	-2.2%
ecosystem quality - terrestrial eutrophication	mol N-Eq	4.59E+05	4.56E+05	-0.5%
human health - carcinogenic effects	CTUh	2.44E+00	3.08E+00	20.6%
human health - ionising radiation	kg U235-Eq	6.71E+07	6.63E+07	-1.2%
human health - non-carcinogenic effects	CTUh	1.02E+01	1.08E+01	5.3%
human health - ozone layer depletion	kg CFC-11-Eq	1.25E+01	1.22E+01	-2.8%
human health - photochemical ozone creation	kg ethylene-Eq	1.33E+05	1.29E+05	-3.1%
human health - respiratory effects, inorganics	kg PM2.5-Eq	1.90E+04	1.78E+04	-7.0%
resources - land use	kg Soil Organic Carbon	4.61E+07	4.50E+07	-2.4%
resources - mineral, fossils and renewables	kg Sb-Eq	1.46E+03	1.44E+03	-1.6%

The remaining differences between the impact categories are linked primarily to an overestimation of the amount of steel needed for the building housing the electrical equipment in the "Pratiwi Model" compared to the "GEOENVI Model". For the freshwater ecotoxicity impact category, the different impact is most likely related to how the copper manufacturing is modelled in the ecoinvent database used for the "Pratiwi Model" and the "GEOENVI Model". In fact, the main three contributing flows for the "GEOENVI Model" are the cable production (39.1%), the heat exchanger (15.1%), and the electricity required during operation (12.1%). On the contrary, the cable production in the "Pratiwi Model" only influences the freshwater ecotoxicity by 9%, which is not the result of differences in the mass modelled (A1). For the carcinogenic human health impact, on the other hand, the difference comes from the fact that the treatment of wastes in landfill was included in the "GEOENVI Model", while it was not in the "Pratiwi Model".

In summary, the differences in the impact assessment results between the “Pratiwi Model” and the “GEOENVI Model” of the Rittershoffen geothermal heat plant can clearly be explained by the use of different ecoinvent versions, the approximation of inventory flows with equations instead of direct inputs in the “GEOENVI Model”, the simplification of the modelling of equipment pieces, and different boundary settings (lifetime, waste treatment). Overall, this comparison supports the statement that the “GEOENVI Model” is representative of an EGS for heat generation with very low direct emissions as well as the assumptions taken to parametrise the representative geothermal installation. In addition, the good overlap between the environmental impacts simulated by the “GEOENVI Model” and the results published in (Rocco et al., 2020) for geothermal heat plants without stimulations, is a first hint, that the reference LCA model presented here could be applied to other conventional hydrothermal systems for heat generation with very low direct emissions. This is further supported by the very low contribution of the hydraulic and chemical stimulation to the outcomes of the different impact categories (A1).

3. Statistical process to identify the key input variable parameters for each impact category

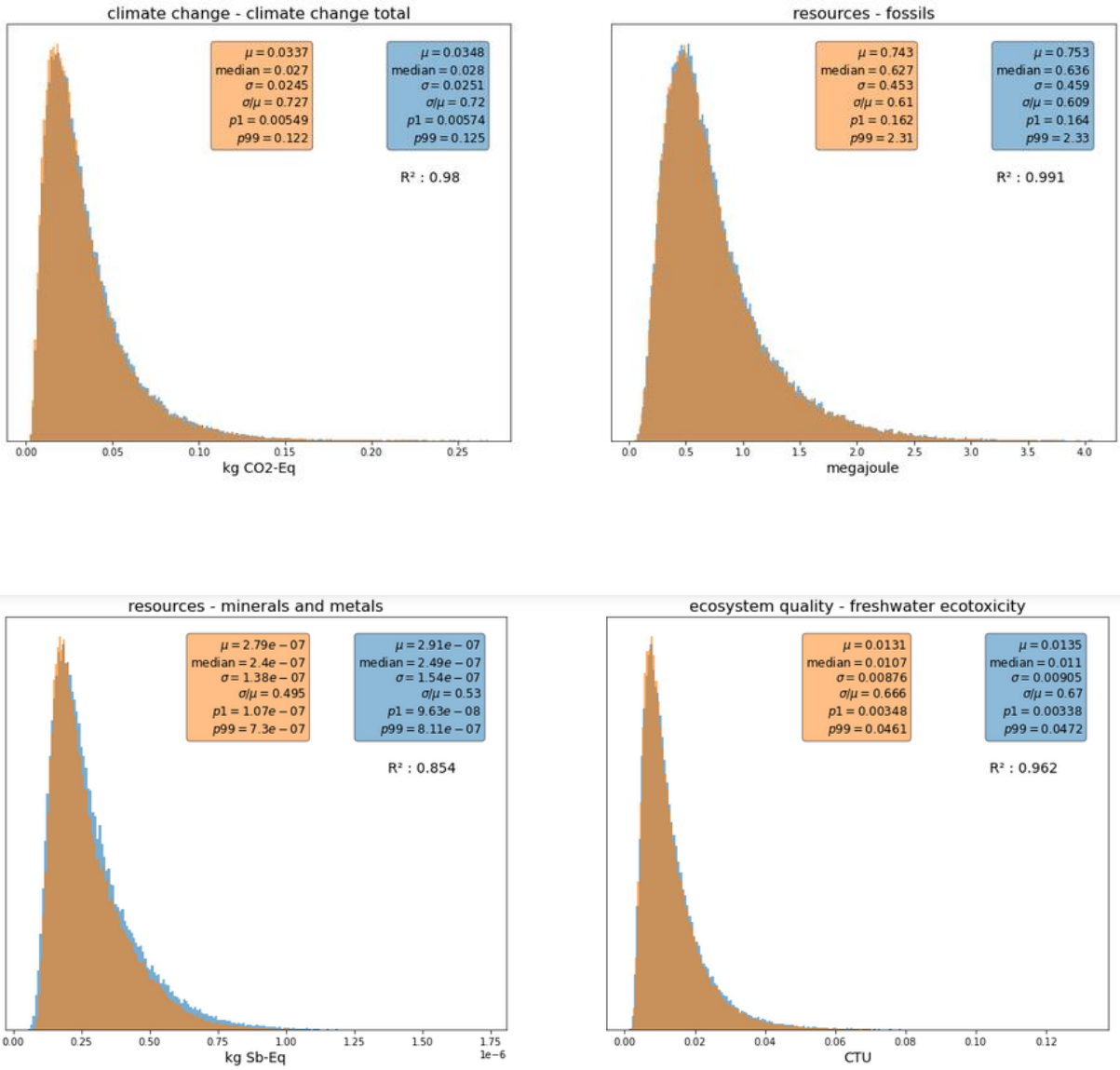
The shares of each electricity type were included as input variable parameters in the simplified models. For some impact categories, they were in fact explaining a large share of the variance, e.g. the oil share explained 25% of the variance of the freshwater ecotoxicity impact category. In addition to these eight variable parameters the following six were also included:

- **thermal output,**
- **power of the production pump (LSP),**
- **power of the injection pump,**
- **number of production wells**
- **number of injection wells,**
- **well lengths**

These six variable parameters explain between 53.1% and 83.7% of the total variance of all seven impact categories of interest. This set of six variable parameters combined with the electricity sources’ shares explained between 77.0% and 85.1% of the total variance and was kept to generate the simplified models. The first order Sobol indexes are reported in A1. The choice of the key variable parameters was hereby a trade-off between the ease with which they could be obtained, the level of explained variance, and the ease of application of the model.

4. a. Generation of the simplified model per impact category

The performance of the seven simplified models are shown in Figure 4 by displaying the overlap between the impact category distributions for the simplified (orange) and reference (blue) LCA models and calculating the level of fitting by means of the R^2. Overall, the R^2 are above 95% for all impact categories except minerals and resources depletion, where it is 84%. The equations each model is relying on is provided in A1.



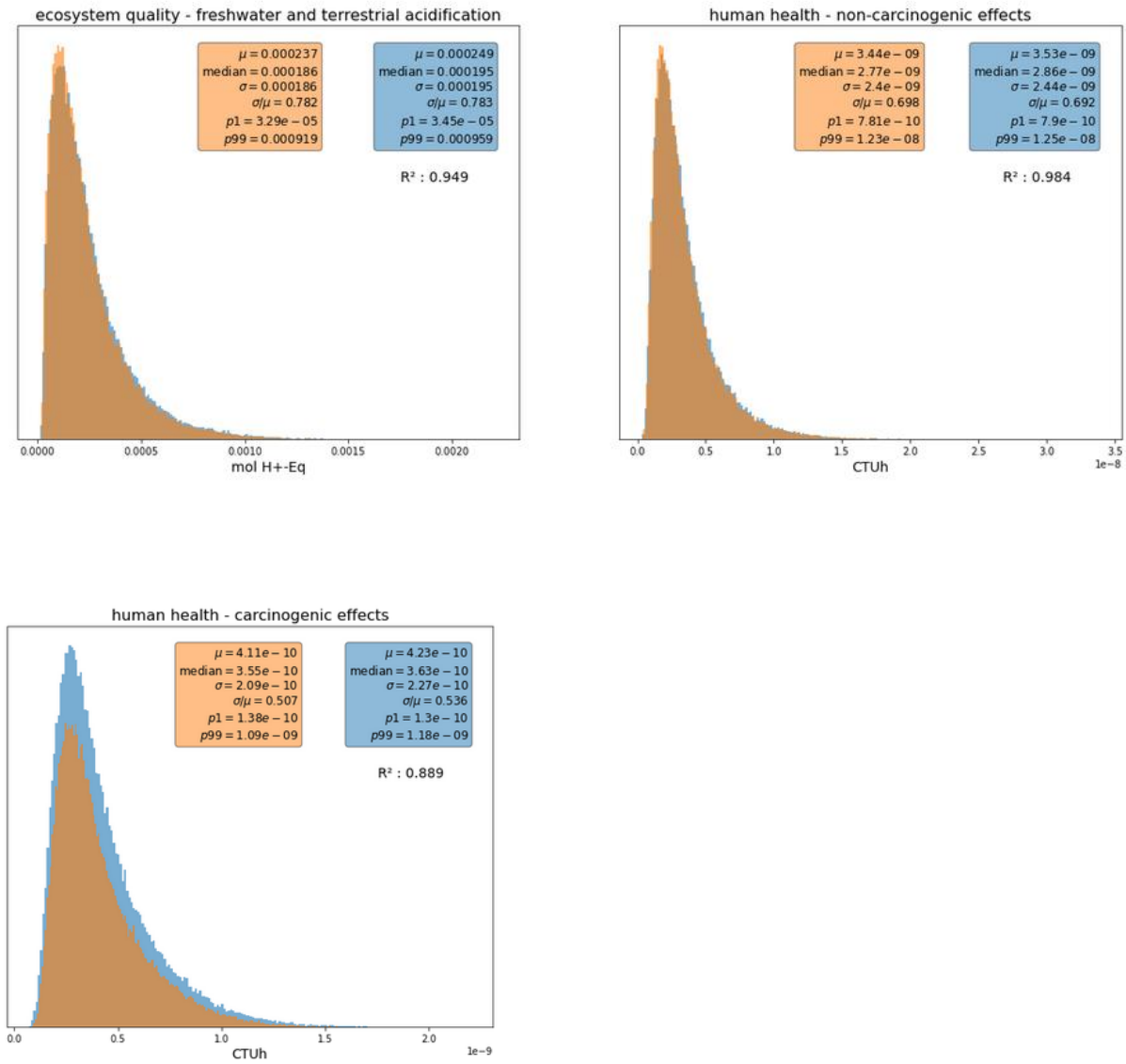


Figure 4 – Performance of the reference LCA model for EGS compared to the simplified models derived the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models.

4. b. Validation of the simplified models with literature

A final validation step consisted in applying the simplified models' equations to specific configurations reported by other case studies. From the four references gathered in Section 4.b., only (Pratiwi et al., 2018) reported enough information to determine the variable parameters and apply the simplified models (Table 6). The results of the comparison are shown in Figure 5.

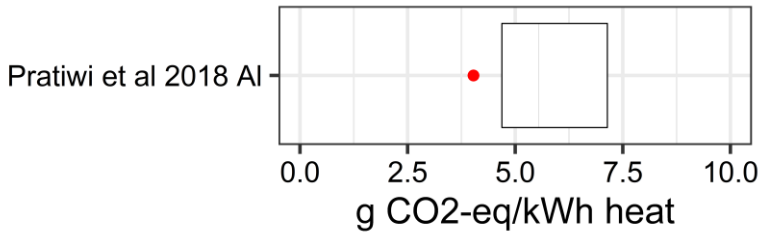


Figure 5 – Literature comparison when applying the simplified models for climate change to the geothermal power plant presented in (Pratiwi et al., 2018). The red dot represents the estimation when applying the simplified model and the boxplot the minimum, mean, and maximum values reported in (Pratiwi et al., 2018).

The comparison shows a relatively good overlap with the values reported by (Pratiwi et al., 2018), namely 4.2 g CO_2-eq/kWh when applying the simplified model vs. 5.55 g CO_2-eq/kWh reported.

Table 6 – Variable parameter values used to apply the climate change simplified model to the geothermal system described in (Pratiwi et al., 2018)

Variable parameter	Value
P_{th}	25 MW
P_{pump}	0 kW
P_{LSP}	400 kW
N_{in}	1
N_{prod}	1
L_W	2888 m
$f_{biomass}$	0
f_{coal}	0.036
f_{hydro}	0.45
f_{NG}	0
$f_{nuclear}$	0.503
f_{oil}	0
f_{solar}	0.006
f_{wind}	0

5. Applicability domain of the simplified models and optional iterative adjustment of the scope of the study

The tentative validation of the reference LCA and simplified models with literature was a difficult task because of the limited number of studies referring to heat generating powerplants, differences in the choice of impact assessment methods, as well as different study boundaries and methodological choices. The comparison of the climate change impact published by (Pratiwi et al., 2018) is the best comparison possible and shows a relatively good overlap which gives some confidence in the results presented here. Further comparisons with other geothermal heat plants would however be necessary to fully validate the developed models. In addition, it is essential to clearly acknowledge the range of use within which the reference LCA model and simplified models can be applied. The reference LCA model, and as a result the simplified models developed, are designed for:

- enhanced geothermal systems (EGS) for heat generation;
- diesel-powered drilling rig;
- very low direct emissions (0.001 – 0.02 mass fraction of the flow rate);
- located in continental Europe;
- connected to the power grid and using any electricity mix;
- fixed parameters as specified in A1;
- the range of values for the variable parameters as specified in Table 4.

Simplified models for the Flash category

This chapter presents the simplified models developed to assess the life cycle environmental impacts of the geothermal installations of category Flash, illustrated with the RGS Bagnore. The results are presented following the steps of the protocol presented in the ""Protocol to generate simplified models for a category of geothermal installation".

1. Scope of the study

The geothermal system of Bagnore is composed of flash type geothermal power plants whose primary scope are the production of electricity. Such plants produce also heat which is delivered through a heat transfer network for industrial uses. The analysed system is located in southern Tuscany, Italy, in the Monte Amiata area (Figure 6).

Figure 6 – Aerial picture of the Bagnore geothermal system

The Bagnore geothermal system is composed of two distinct power plants, namely Bagnore 3 and Bagnore 4, which share the production and reinjection wells. The total installed power is 61 MWe, 21 MWe for Bagnore 3 (20 MWe flash + 1 MWe Organic Rankine Cycle) and 40MWe for Bagnore 4 (2 X 20MWe flash). The annual production is about 533 GWh/y. The power plant is also designed with a thermal power of 21.1 MWth, which can produce 32 GWh/y for industrial purposes.

The geothermal source is a high enthalpy source presenting a content of non-condensable gases (NCGs) of about 7% in mass. The main NCGs component in mass fraction is CO_2 (6.7 % over the total geothermal flow rate). The temperature of the geothermal source at the wellhead is about 210 °C with a specific enthalpy of 2,800 J/kg.

The power plant was built by ENEL Green Power in the late 90's and has been operating ever since by employing the latest advancements in the field of environment protection and performance optimization. Thus, the system is a good candidate to well represent the category of flash power plants for electricity production.

The reference LCA model developed for the Bagnore geothermal system represents the category of a geothermal flash power plant producing electricity and a limited amount of heat, exploiting a geothermal source presenting moderate to a high content of NCGs with CO_2 as main component.

The functional unit of the reference model is the production of 1 kWh of electricity delivered to the high voltage distribution network. The model is divided into Upstream (background data) and Core module (foreground data). The activities of the upstream module are taken from the ecoinvent database v3.6. The core module includes the construction of the infrastructures, the operation and maintenance of the installation, and end of life activities. Figure 7 gives an overview of the different life cycle stages included in the reference LCA model for the described case study.

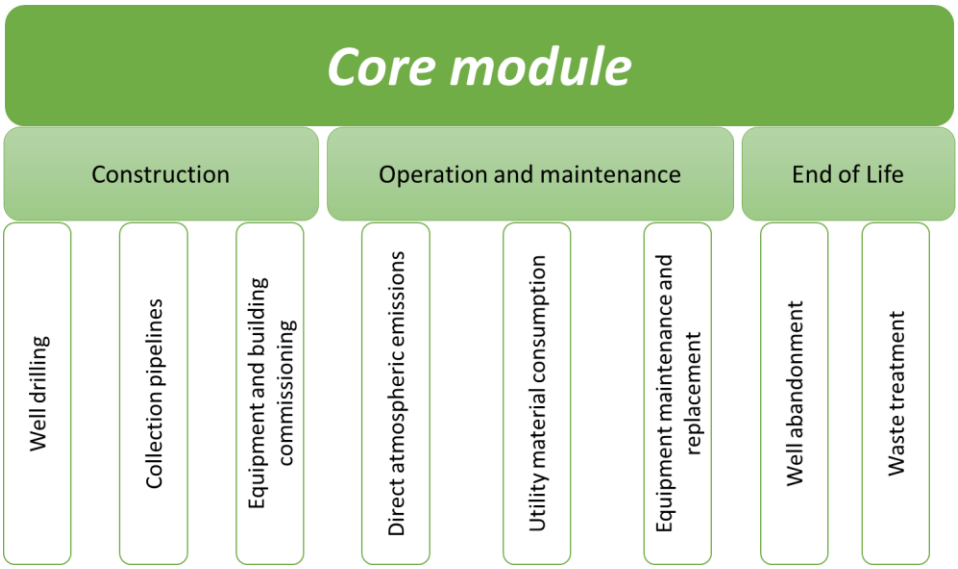


Figure 7 – Phases of the core module included in the modelling of the reference LCA model for Flash.

A more detailed description of the different life cycle stages is given in the following chapters. Following the indications reported in the guidelines (Blanc et al., 2020), the background processes are selected giving priority to the proper geographic location (IT>EU>World). Market processes are preferred to include also standardised transportation distances.

2. a. Modelling of the reference LCA model

Construction phase

Well Drilling

The well drilling process is performed by diesel-fuelled drilling rigs, making the amount of diesel used by the drilling process an important flow. The drilling mud and cuttings produced during the well drilling represent an important inventory flows as well, due to the disposal activity related to the latter. Steel and cement are used for the casing and well's platform construction. All these inventory flows were estimated from the equations provided in (Rocco et al., 2020) using the meters drilled (l) as an input variable parameter. These equations are listed in A1. The described drilling process is the same during maintenance activities in case make-up wells, meaning wells added to recover the productivity lost over the years, are needed.

Collection Pipelines

Geothermal flash power plants usually employ a considerable number of wells to drive the turbines compared to other geothermal technologies. As a result, the collection pipelines used to flow the geothermal fluid to the power plant consist of several thousand meters of insulated steel pipe. Therefore, this process should be considered important for LCA modelling because of the significant amount of material and energy required for earthwork.

The length of the pipelines needed is assumed to be proportional to the number of wells of the system. Equation (12) has been used to derived the pipelines' length.

$$PipelineLength\ (m) = 512 * WellsNumber + 3232 \quad (12)$$

More pipelines can be added to the system depending on the number of make-up wells drilled.

Equipment and building commissioning

The building housing, electrical and hydraulic systems relative to internal uses (e.g. first flush diverter, electronic management system, etc) employed in the construction of a geothermal flash power plant are modelled based on primary data provided by the operator and scaled to installed power following expert's advice. The building is a hangar holding the equipment's (turbine, condenser, compressor, electric generator) and the employer's settings. The amount of energy and material is scaled on the installed capacity as shown in Equation (13).

$$Building = 1.9 \cdot 10^{-5} * ElecCapacity + 0.24 \quad (13)$$

The equipment of the power plant is modelled as a single flash power plant with abatement system for Hydrogen Sulphide and Mercury (AMIS) with the main components being:

- Direct contact steam turbine
- Direct contact condenser

- Gas compressor for NCSs extraction
- Gas intercooler
- AMIS system (H_2S to SO_2 catalytic reactor, Hg adsorbent, SO_2 scrubber)
- Atmospheric cooling tower
- Electric generator

The inventory is constituted for the major part by steel for machinery, while the electric generator is also constituted by copper and the cooling tower by plastic. The AMIS, in addition to steel, makes use of titanium dioxide as a catalyser for the H_2S reactor and selenium used to adsorb mercury

Operation and maintenance

Direct atmospheric emissions

Flash geothermal power plants are characterised by direct atmospheric emissions connected to the operational phase due to the direct use of geothermal brine. The fluid exploited contains a typical amount of dissolved gases which are extracted from the geothermal fluid to ensure the operativity of the power plant and then emitted into the atmosphere.

Direct atmospheric emissions are strictly related to the gas fraction and composition of the geothermal source exploited. In the case of Bagnore, gas fraction in mass is 7% average and it is constituted by 92% of CO_2

The functions used to derive the mass of gases emitted are taken from (Rocco et al., 2020) and use the amount of NCGs ($fNCGs$) present in the geothermal fluid, the relative fraction of a specific gas (f_{NCG}) and the typical flowrate ($FlowRate$) (Equation (14)).

$$M_{NCG} = fNCGs * FlowRate * f_{NCG} \quad (14)$$

Some operators also implement systems able to reduce these direct emissions. In this case study, the system employed is called AMIS and it is designed to abate the gaseous emissions of selected compounds, H_2S and Hg. The hydrogen sulphide is oxidized through a catalytic oxidation reaction into a fixed bed reactor supporting titanium dioxide. This process produces SO_2. The gaseous mercury is adsorbed into a selenium filter. The obtained mercury selenide (HgSe) is a very stable compound which is disposed of as hazardous waste by specialized companies. At the end of the process a washing column avoids the direct emissions of SO_2, by letting the basic pH circulating geothermal water to react with SO_2 and to dissolve it into water. The abatement of the AMIS system is implemented in the model deducing the relative amount of gases from the atmospheric emissions through the relative abatement ratio ($H_2SAbatemenRatio$ and $HgAbatementRatio$).

Utility consumption

The operational stage is also characterised by the consumption of energy from the auxiliary's equipment, such as the reinjection pumps or the evaporative towers' fans. The reference model built for this case study accounts for the energy consumption only in terms of internal loss, meaning that no needs for electricity from the national network is considered. The internal loss is integrated into the calculation of the electricity production.

Equipment maintenance and replacement

The maintenance activities taken into account are all the most important planned periodic services, these include turbine refurbishment. In detail, a 10% of rotor weight loss every 4 years is assumed. The steel lost is integrated by new steel. The same assumption is made for the rotor compressor. The evaporative tower maintenance is also planned every 4 years, the substitution of steel and plastic parts is accomplished.

The modelled system is equipped with 2 systems devoted to reduce direct atmospheric emissions, employing the AMIS (reduction of H_2S and Hg emissions) and though acidification of the circulating fluids (reduction of NH_3 emissions). These processes have a specific material consumption: the AMIS employs selenium sorbent to reduce the amount of Hg released to the atmosphere and it is replaced every 4 years to maintain a good performance; the acidification of circulating fluid is accomplished by dosing H_2SO_4 to the fluid which circulate into the power plant so to keep the geofluid between a specific pH range thus avoiding stripping of NH_3.

End of life

Waste treatment

Waste treatment processes are used, according to (Blanc et al., 2020), for the waste treatment from drilling activities and disposal of selenium sorbent from the AMIS maintenance.

The disposal of drilling cuttings is modelled accordingly to the appropriate ecoinvent v3.6 process, while the spent selenium sorbent is treated as hazardous waste and modelled by using the relative landfilling ecoinvent activity.

Well abandonment

At the end of the service life of the system, a well abandonment program is foreseen. This program consists in the closure of all the wells drilled during the lifetime. The process is characterised by the use of diesel in engines and cement use.

Functional unit definition

Electricity production

The electricity production is the main purpose of the system and represents more than 75% of the total power output, therefore the electricity production is the functional unit of this system. The amount of energy produced is derived from Equation (15):

$$KWh_e = AVGLoad * ElecCapacity * OperatingHours * (1 - AuxNeed) \quad (15)$$

Heat production

The power plant can deliver heat, through a small heat delivery network, to closely production activities. Following the guidelines, the quantity of energy delivered to the final user is accounted for by employing system expansion and considering the avoided product approach (Blanc et al., 2020). In the model, the heat is used for industrial purpose, therefore the right process is selected in the ecoinvent database.

$$KW_{th} = HeatCapacity * HeatLoad * OperatingHours \quad (16)$$

Summary of variable parameters

Table 7 – Summary of all the variable parameters of the reference LCA model for Flash, together with boundaries of the uniform distribution which are used to describe a wider set of geothermal power plant. Default values represent the values for the Bagnore power plant. lists all the variable parameters used in the reference LCA model. All the variable parameters were modelled following a uniform distribution between the minimum and maximum value which describe a wider set of geothermal power plants, therefore are not linked to the case study investigated.

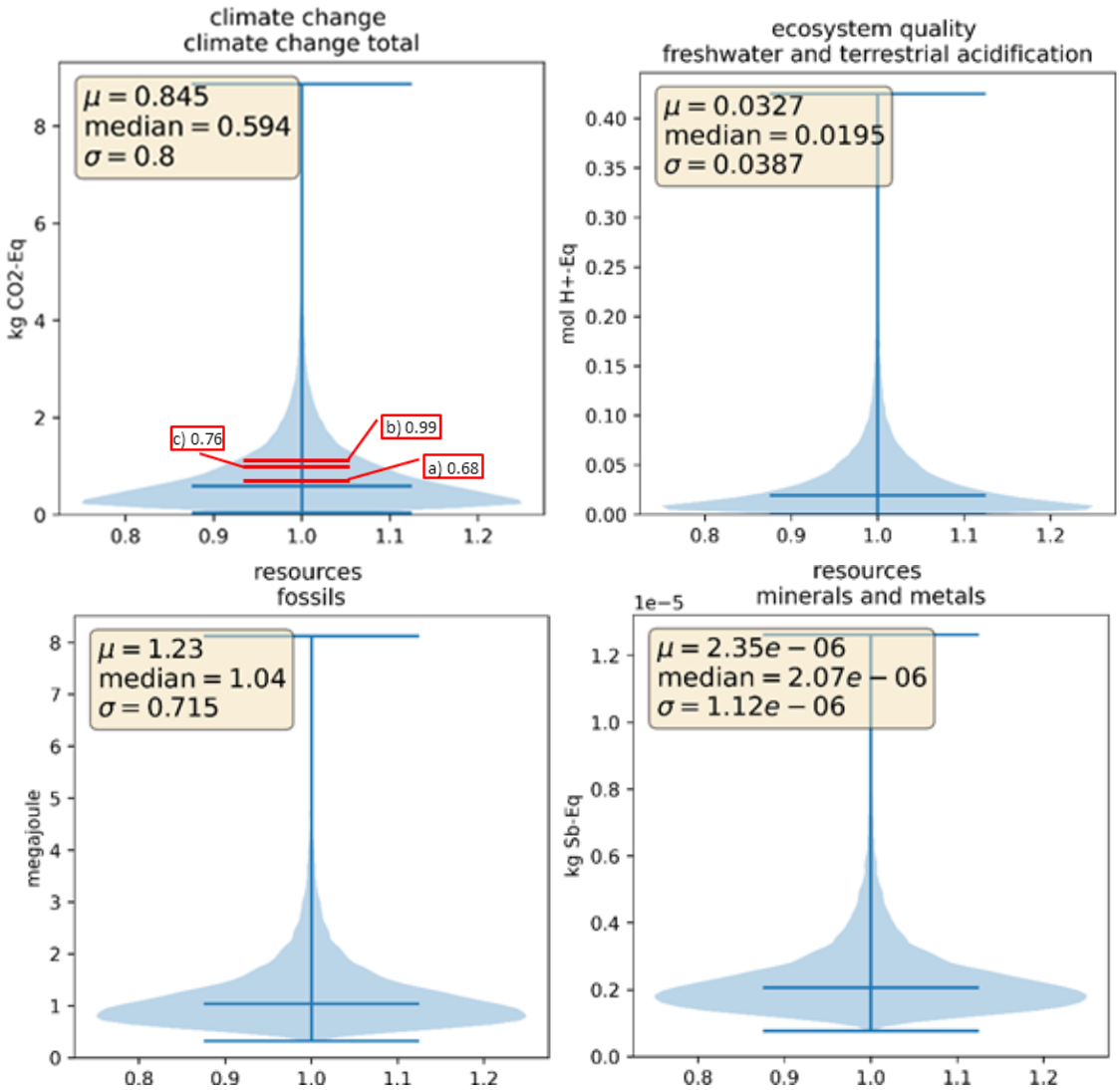
Table 7 – Summary of all the variable parameters of the reference LCA model for Flash, together with boundaries of the uniform distribution which are used to describe a wider set of geothermal power plant. Default values represent the values for the Bagnore power plant.

Label	Param	Default	min	max	unit
Average length for one well	l	2,273	586	4,727	meters
Average yearly operating hours	OperatingHours	8,670	7,600	8,760	hours
Yearly out of service hours of the AMIS abatement system	AMISOutOfServiceHours	226	17	457	hours
Abatement efficiency for Hg	HgAbatementRatio	0.98	0.7	0.99	ratio
Abatement efficiency for H2S	H2SAbatementRatio	0.99	0.7	0.99	ratio
Abatement efficiency for CO2	CO2AbatementRatio	0	0	0.25	ratio
Abatement efficiency for NH3	NH3AbatementRatio	0.9	0.75	0.95	ratio
Previsioned lifetime of the system	LifeTime	30	20	40	years
Maintenance interval time for periodic maintenance operations	MaintenancePeriod	4	2	6	years

Average load of the power plant	AVGLoad	0.99	0.8	1.1	ratio
Percentage of energy absorption from auxiliaries	AuxNeed	0.02	0.01	0.1	ratio
Ratio of make-up wells drilled yearly	MakeUpWellsRatio	0	0	0.76	items
Flow rate of the geofluid at the power plant inlet	FlowRate	400,000	110,000	1.00E+06	kg/h
Electric power installed	ElecCapacity	60,000	20,000	120,000	kWe
Heat power installed	HeatCapacity	21,100	0	21,100	kWth
Average load for heat production	HeatLoad	0.17	0	0.25	ratio
Numbers of wells drilled in the commissioning phase	WellsNumber	14	4	26	items
Mass fraction of NCGs in the geofluid	fNCG	0.07	0.006	0.12	ratio
Relative fraction of CO2 in the geofluid	fCO2	0.92	0.58	0.92	ratio
Relative fraction of CO in the geofluid	fCO	0.000368	0.0003	0.0004	ratio
Relative fraction of CH4 in the geofluid	fCH4	0.025	0.002	0.025	ratio
Relative fraction of H2S in the geofluid	fH2S	0.017868	0.0013	0.054	ratio
Relative fraction of NH3 in the geofluid	fNH3	0.028348	0.0012	0.032	ratio
Relative fraction of Hg in the geofluid	fHg	1.80E-05	9.00E-06	3.00E-05	ratio

2. b. Validation of the reference LCA model with literature

To evaluate the representativeness of the reference model, results published in literature were selected and compared to the reference model's results. The applied procedure adapts the reference LCA model to the literature cases by varying the right parameters, therefore it is possible to use data coming from several power plants on the same model. The results reported in (Bravi and Basosi, 2014; Parisi et al., 2019; Tosti et al., 2020) were used for comparison. The characterised results reported in the selected papers are integrated into the violin graph obtained from the Monte Carlo analysis of the reference model and displayed in Figure 8. Overall, the results for climate change published in the three studies and the results obtained from the reference LCA model show a good overlap.


climate change
climate change total
μ = 0.845
median = 0.594
σ = 0.8
kg CO2-Eq
c) 0.76
b) 0.99
a) 0.68
ecosystem quality
freshwater and terrestrial acidification
μ = 0.0327
median = 0.0195
σ = 0.0387
mol H+-Eq
resources
fossils
μ = 1.23
median = 1.04
σ = 0.715
megajoule
resources
minerals and metals
1e−5
μ = 2.35e − 06
median = 2.07e − 06
σ = 1.12e − 06
kg Sb-Eq

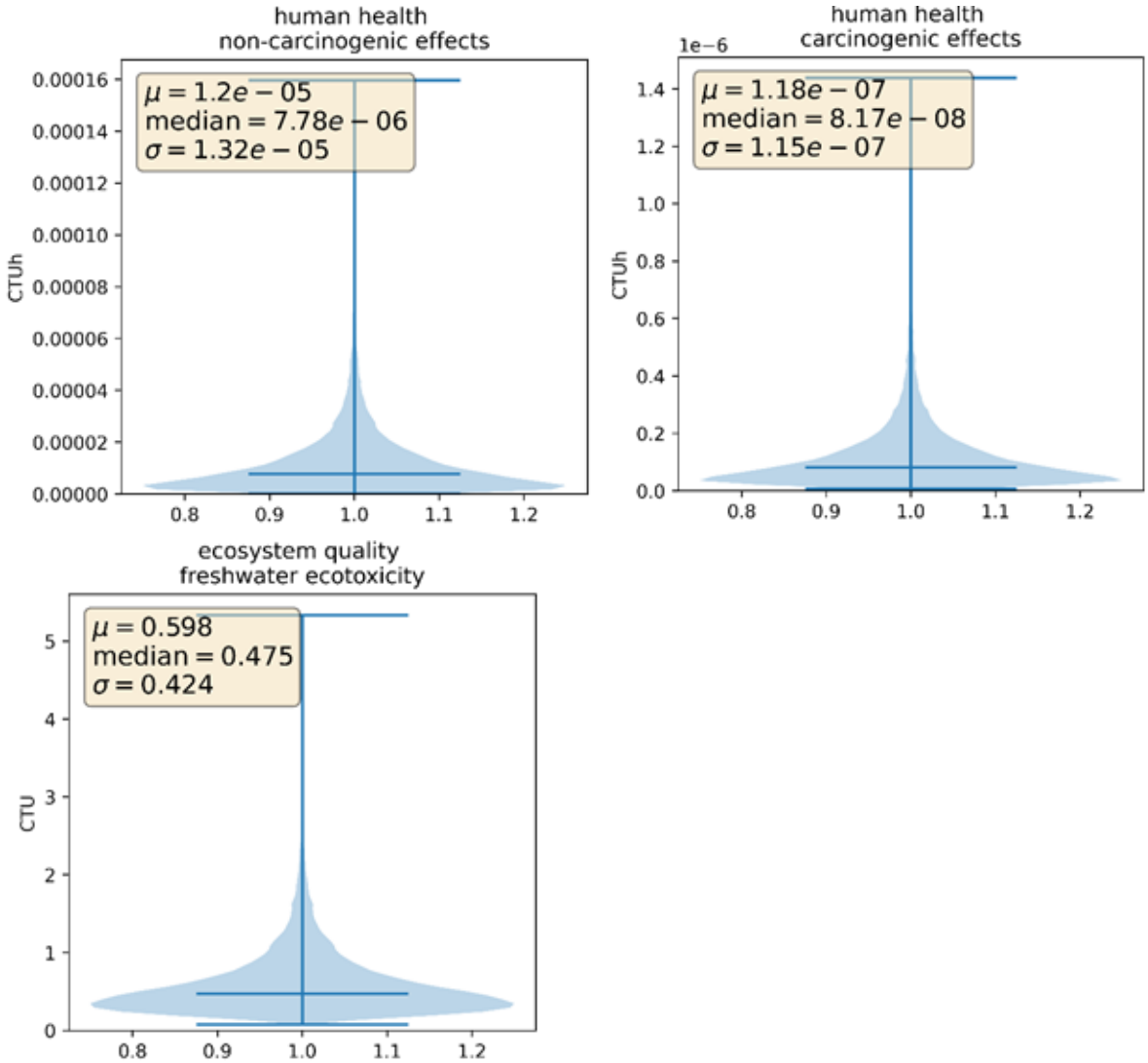


Figure 8 – Violin plot reporting the statistical distribution obtained after the Monte Carlo analysis of the reference LCA model for Flash taking into account the definition of the parameter of the reference model. Lines correspond to 95th, median and 5th percentile, while the light blue shape shows the probability density. a) stands for the results published in (Bravi and Basosi, 2014), b) (Parisi et al., 2019), and c) (Tosti et al., 2020).

3. Statistical process to identify the key input variable parameters for each impact category

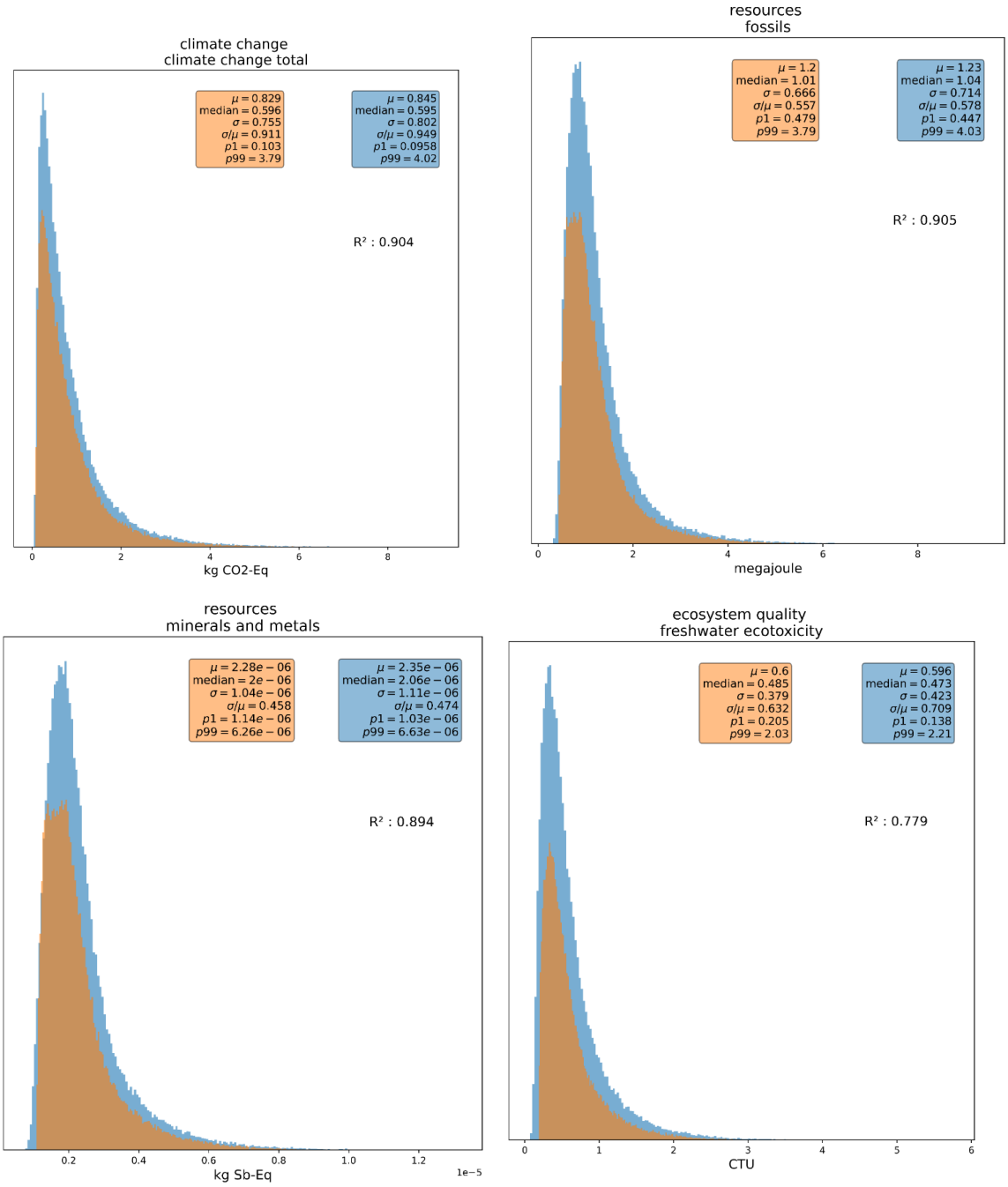
Using the first order Sobol indices, different variable parameters were selected as key input variable parameters for the different simplified models due to their ability to explain a large portion of the reference model variance. These key variable parameters are:

- **Elec capacity**
- **fNCG**
- **FlowRate**
- **fNH3**
- **make-up wells ratio**
- **l (average lengths of the well)**

These six variable parameters explain above 80% of the total variance of all seven impact categories of interest. The first order Sobol indexes are reported in A2. The choice of the key variable parameters was hereby a trade-off between the ease with which they could be obtained, the covered variability, and the ease of application of the model. Some variable parameters refer to the geochemical properties of the geothermal field *(fNCG*, *fNH3*) while the others are more technology-related (*Elec capacity*, *Flow Rate*, *make-up wells ratio* and *l*). Per simplified model, only three to four of the six variable parameters listed above are used.

4. a. Generation of the simplified model per impact category

The performances of the seven simplified models are shown in Figure 9 – Performance of the reference LCA model for Flash compared to the simplified models derived for the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models. by displaying the overlap between the impact category distributions for the simplified and reference LCA models and calculating the level of fitting by means of the R^2. The equations each model is relying on are provided in A2.


climate change
climate change total
μ = 0.829
median = 0.596
σ = 0.755
σ/μ = 0.911
p1 = 0.103
p99 = 3.79
μ = 0.845
median = 0.595
σ = 0.802
σ/μ = 0.949
p1 = 0.0958
p99 = 4.02
R² : 0.904
kg CO2-Eq
resources
fossils
μ = 1.2
median = 1.01
σ = 0.666
σ/μ = 0.557
p1 = 0.479
p99 = 3.79
μ = 1.23
median = 1.04
σ = 0.714
σ/μ = 0.578
p1 = 0.447
p99 = 4.03
R² : 0.905
megajoule
resources
minerals and metals
μ = 2.28e − 06
median = 2e − 06
σ = 1.04e − 06
σ/μ = 0.458
p1 = 1.14e − 06
p99 = 6.26e − 06
μ = 2.35e − 06
median = 2.06e − 06
σ = 1.11e − 06
σ/μ = 0.474
p1 = 1.03e − 06
p99 = 6.63e − 06
R² : 0.894
kg Sb-Eq
1e−5
ecosystem quality
freshwater ecotoxicity
μ = 0.6
median = 0.485
σ = 0.379
σ/μ = 0.632
p1 = 0.205
p99 = 2.03
μ = 0.596
median = 0.473
σ = 0.423
σ/μ = 0.709
p1 = 0.138
p99 = 2.21
R² : 0.779
CTU

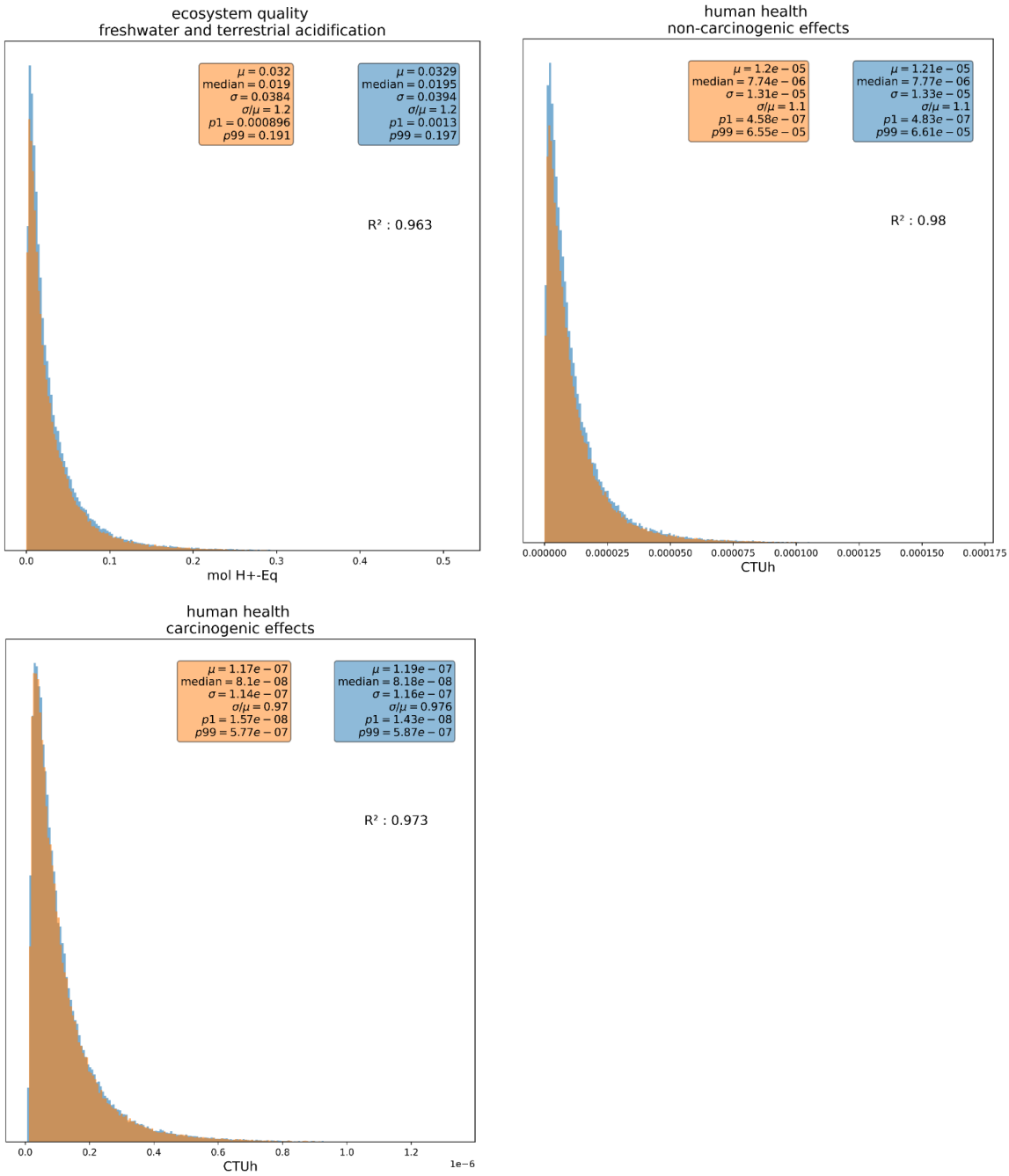


Figure 9 – Performance of the reference LCA model for Flash compared to the simplified models derived for the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models.

4. b. Validation of the simplified models with literature

The validation of the simplified models is performed using the equation obtained for the Climate Change impact category (A2), and the works of (Tosti et al., 2020) and Buonocore et al., (2015) were selected to tests the simplified model for climate change impact category. Tosti et al., (2020) report results based on the same power plant of the reference model, while Buonocore et al., (2015) rely on a different system of dry steam type installed in Italy but currently not

operating. The input variable parameters used in the simplified model for climate change and the results of the comparison are reported in Table 8.

Table 8 – Comparison of results on Climate Change (CC) impact category considering two different case studies, (Tosti et al., 2020) and (Buonocore et al., 2015)

Variable Parameter	(Tosti et al., 2020)	(Buonocore et al., 2015)
ElecCapacity (kWe)	61,000	20,000
FlowRate (kg/h)	400,000	80,000
fNCG	0.08	0.06
CC simplified model (gCO2eq/kWe)	**0.71**	**0.51**
CC literature (gCO2eq/kWe)	**0.63**	**0.24**

The results published in (Tosti et al., 2020) are in good agreement with the results obtained from the simplified model. The minor difference observed could be explained by the fact that a different impact assessment method is used. In detail, the ILCD 2018 reports higher characterisation factors than the ILCD 2011 Midpoint+ method v1.0.9 used by Tosti et al., (2020) for the Climate Change impact category. The same is observed when comparing to the results of (Buonocore et al., (2015). The larger difference is here related to the fact that Buonocore et al., (2015) used an older method than ILCD, namely the CML method.

5. Applicability domain of the simplified models and optional iterative adjustment of the scope of the study

The reference LCA model, and as a result the simplified models developed for the seven impact categories, are designed for:

- Flash or dry steam power plant exploiting high enthalpy field
- Power plant producing only electricity, or electricity and heat for industrial purposes. Heat must be less than 50% of the electricity produced
- The models are suitable for geothermal sources showing low to a high content of NGCs, the boundary of the gas composition is specified in Table 7
- Diesel power rig
- No electricity demand for auxiliaries taken from the electric network

Simplified models for the CHP category

This chapter presents the simplified models developed to assess the life cycle environmental impacts for the CHP category of geothermal installations, namely a combined Heat and Power geothermal plant with low direct emissions. The results are presented following the steps of the protocol presented in the "Protocol to generate simplified models for a category of geothermal installation".

1. Scope of the study

The representative category of geothermal installation analysed here is a CHP geothermal plant with low direct emissions. The functional unit is the production of 1 kWh of electricity. Figure 10 illustrates the system boundaries and core life cycle processes included.

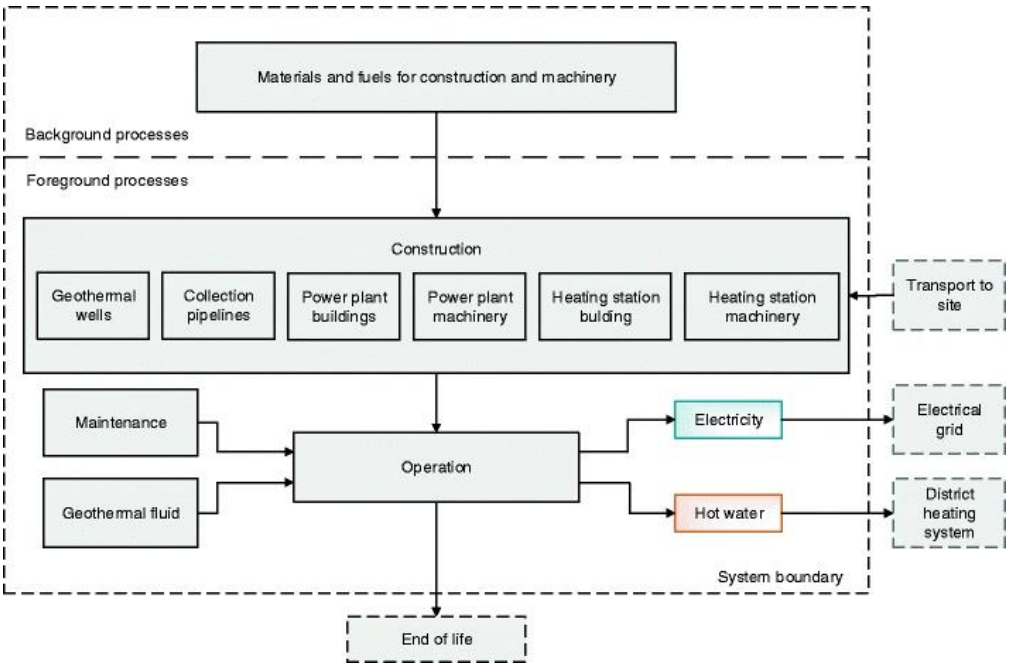


Figure 10 – Phases and sub-processes of the core module included in the modelling of the reference LCA model. The end of life only includes the well closure and treatment of anti-scaling only.

The Hellisheiði power plant is an RGS of the category analysed here and will serve as a basis for the development of the reference LCA model.

The plant is owned and operated by Orka Náttúrunnar and was initiated in 2006 mainly due to the increased demand for hot water in the society (Orka náttúrunnar, 2020a). It is situated within the Hengill area in SW-Iceland, one of the country's largest geothermal reservoir, that hosts several sub-areas of geothermal activity (OS). The area covers approximately 112 km^2 based on the distribution of heat, surface alteration, and resistivity measurements of 5 ohm line (Orkuveita Reykjavíkur, 2015). The Hellisheiði plant produces 303 MW_e and 133 MW_{th} in a double flash cycle, with planned capacity of 267 MW_{th} within the next 30 years (Karlsdottir

et al., 2020) and uses both geothermal fluid from Hellisheiði and Hverahlíð sub-areas, in the western part of the Hengill area and south of Hengill, respectively (Orkustofnun, 2020). The aim of drilling for Hellisheiði power plant is to penetrate feed zones located by known fractures and fissures within the geothermal reservoir, with high permeability, for maximum productivity of each well. In total 47 geothermal wells have been drilled, the most recent well drilled for power production is HE-66, in 2020 (OS). Wells for Hellisheiði power plant are mostly drilled through hyaloclastite (basaltic breccia, pillow basalt, and basaltic tuff), basaltic lava, and intrusions at deeper levels, of various composition (Níelsson, 2011). The heat source of the geothermal system are intrusions in the crust. Alteration temperature, based on the observed composition of alteration minerals in the drill cuttings, often indicates >300°C within the geothermal reservoir, and the relationship between suggested alteration temperature and measured rock temperature has proven to be variable (Níelsson, 2011). The well depth is mainly in the range of 1800-2800 m, some reaching depth >3000 m (borholuskrá). 17 injection wells are used to inject the geothermal fluid back into the ground.

An air purification plant is located at the power plant that utilizes the Carbfix and Sulfix process to purify about 75% of the hydrogen sulphide and about 30% of the carbon dioxide dissolved in geothermal water for re-injection (Sigfússon et al., 2018). The gas content in the geothermal fluid has proven to be quite variable over time, with the most abundant dry gas species CO_2 and H_2S (Karlsdottir et al., 2020).

Figure 11 – Hellisheiði power plant in SW-Iceland (Orka náttúrunnar, 2020b).

2. a. Modelling of the reference LCA model

The reference LCA model for this geothermal installation category is intended to represent a CHP geothermal plant with low direct emissions using diesel drilling and operating no abatement system. The goal is to develop parametrised models from the reference LCA model which rely on the lowest possible number of variable parameters while still accurately estimating the life cycle impacts of the analysed system. The following sections will describe each of the phases and key sub-processes of the geothermal installation. Overall,

transportation was analysed based on the total weight of material required to make the power plant operational, i.e. all material in the boreholes, pipelines, building and machinery (including replacement rate). It is estimated that the products are shipped by container ship from Netherlands and there is on average 1,000 km distance travelled in lorries inland.

Construction

Well Drilling

In the Hellisheiði case study's construction phase, 47 geothermal wells were drilled, with 17 reinjection wells. Of the 47 production wells drilled, 36 were drilled wide and the remaining 11 wells were drilled narrow. The distinction between the well diameters (wide or narrow) were defined by their own LCI, in which wide wells had a greater fuel demand and greater material inputs per meter well drilled. The narrow wells had an average well depth of 2,147 meters, with a min and max of 1,473 and 3,118 meters respectively. The wide wells had an average well depth of 2,242 meters, with a min and max of 1,394 and 3,323 meters respectively. It was assumed that all reinjection wells were drilled wide. The extraction (drill rig) site impact was modelled using data extracted from ecoinvent v3.6, process name: well for exploration and production. The cement and steel used for the drilling of the different wells was estimated following the equations presented in (Rocco et al., 2020) (Equations listed in A1B). The diesel requirement was modelled as a variable parameter because it was considered a significant input to the power plant.

Collection Pipelines

Within the Hellisheiði site, it was estimated that 36,000 meters of pipelines were required in the construction phase. Steel was the highest input required within this LCI, where it was estimated that 197 kg of steel was needed per meter of the collection pipeline, where 86 % of steel used in pipes, 14 % used in supports. The steel was assumed to be Black steel with a density of 7,850 kg/m^3 (Karlsdóttir et al., 2015)

Buildings and Machinery

To model the material requirement of the plant, the LCIs were broken into two sets of categories creating a set of LCIs, buildings and machinery for both the powerplant and for the heating station. This disaggregation allows for allocation when analysing a CHP plant, which is often a critical component for a multi-product LCA such as a CHP plant. Steel, stainless steel, and asphalt were the highest material requirements cumulatively for all buildings and machinery (Karlsdóttir et al., 2015). When including the construction required for the abatement system, this further adds to the steel requirement for the construction phase.

Operation and maintenance

Non-condensable gases emissions

The NCGs associated with the geothermal energy production were taken from (Karlsdottir et

al., 2020), in which it was estimated that 1.4 grams of CO_2 and 0.0021 grams CH_4 were emitted for every kilogram of thermal fluid extracted. The variability of the NCG's emissions were taken from (Karlsdottir et al., 2020), as well as from primary data from Reykjavik Energy.

Thermal and electrical output

Within the operation phase, the extraction rate of geothermal fluid and the production of electricity associated with the conversion of the thermal energy imbued within the geothermal fluid are taken from (Karlsdóttir et al., 2015) LCI. The nameplate capacities of the Hellisheiði power plant are 303 MWe and 133 MWth. The estimated electrical capacity factor for the Hellisheiði case study is 87% with a min and max estimated capacities of 79% and 94% respectively (ON). The estimated thermal capacity factor for the Hellisheiði case study is 55% with a min and max estimated capacities of 42% and 67% respectively (ON). Within the Hellisheiði case study, it was estimated to have a 4-6% parasitic load, meaning that 4-6% of the electricity produced by the plant was consumed for operational purposes.

Abatement

At the Hellisheiði case study, the novel CarbFix system developed a method to permanently sequester CO_2 and H_2S into the young basaltic formations located in the Hengill area in which the Hellisheiði case study is located (Snæbjörnsdóttir et al., 2020). Primary data from Reykjavik Energy estimated that at full capacity, the CarbFix/SulFix could sequester 33.8% and 71.4%. The CarbFix system as a pilot system sees a variability in operating time for continuous improvement and testing, and has an estimated capacity factor between 75-100%, with an average capacity factor of 88.5%. To operate this system, three different pump types are required, with a total power demand requirement of 585 kW. The energy use required by these pumps can then be calculated using the capacity factor of the abatement system. The abatement system was however not included in the reference model.

Maintenance

In terms of part and machinery replacement, for full-scale component replacement, all key components were estimated to have a lifetime of 30 years, which was a determining factor for the lifetime of the plant. It was assumed however that replacement maintenance requirements would be 5% of the material requirements needed for construction, in line with the published guidelines (Blanc et al., 2020).

It was determined that 23 makeup wells would be required during the lifetime of the Hellisheiði case study with a variability of ±7 wells. This estimate was an increase from the Karlsdottir's et al.'s (2013) LCI estimate of 16 wells being required, updated according to updated projections provided by Reykjavik Energy. To transport the additional geothermal fluid produced by these make-up wells, it was estimated that an additional 9,000 meters of collection pipelines would be needed (ON).

End of life

End of life is accounted for by assuming diesel use and cement requirements to close each well, as well as by including the treatment of anti-scaling material.

Summary of variable parameters

Table 9 summarises the variable parameters used in the reference LCA model together with their boundaries used to assign the uniform distribution.

Table 9 – Variable parameters used for the reference model for CHP. The "Default" values represent the values of the Hellisheiði power plant, the Min and Max values are the upper and lower boundaries of the single variable parameters.

Variable parameter	Description of factors	Unit	default	min	max
Number_of_production_wells	Number of production wells required (wide and narrow)	number of	47	28.2	65.8
Number_of_injection_wells	Number of injection wells required	number of	17	10.2	23.8
Number_of_makeup_wells	Number of make-up wells required	number of	23	16	30
Well_depth	Depth of each well	meter	2,242	1,394	3,323
Steel_in_casing	Steel amount in casing	kg/m well depth	90.4	81	118
Diesel_use_during_drilling	Diesel use during drilling	MJ/m well depth	2,270.1	1,022	3,632
Length_of_pipelines	Length of collection pipelines from boreholes to power plant	meter	36,000	21,600	50,400
Steel_in_pipelines	Steel use in pipelines	kg/meter	197	118.2	275.8
Steel_in_building	Steel use in buildings	kg/MW	35,115	21,069	49,161
Steel_in_machinery	Steel use in machinery	kg/MW	9,850	5,910	13,790
CO2_in_geofluid	CO2 in geofluid	g/kg geofluid	0.0014	0.0012	0.0023
Capacity_factor	Power generation capacity factor	-	0.87	0.6	1
Power_output	Electrical output	MW	303	200	500
Lifetime	Lifetime of the power plant	Years	30	20	40

2. b. Validation of the reference LCA model with literature

The results of the Monte Carlo simulations for the reference LCA model using the distributions of the variable parameters specified in Table 9 are shown in Figure 12.

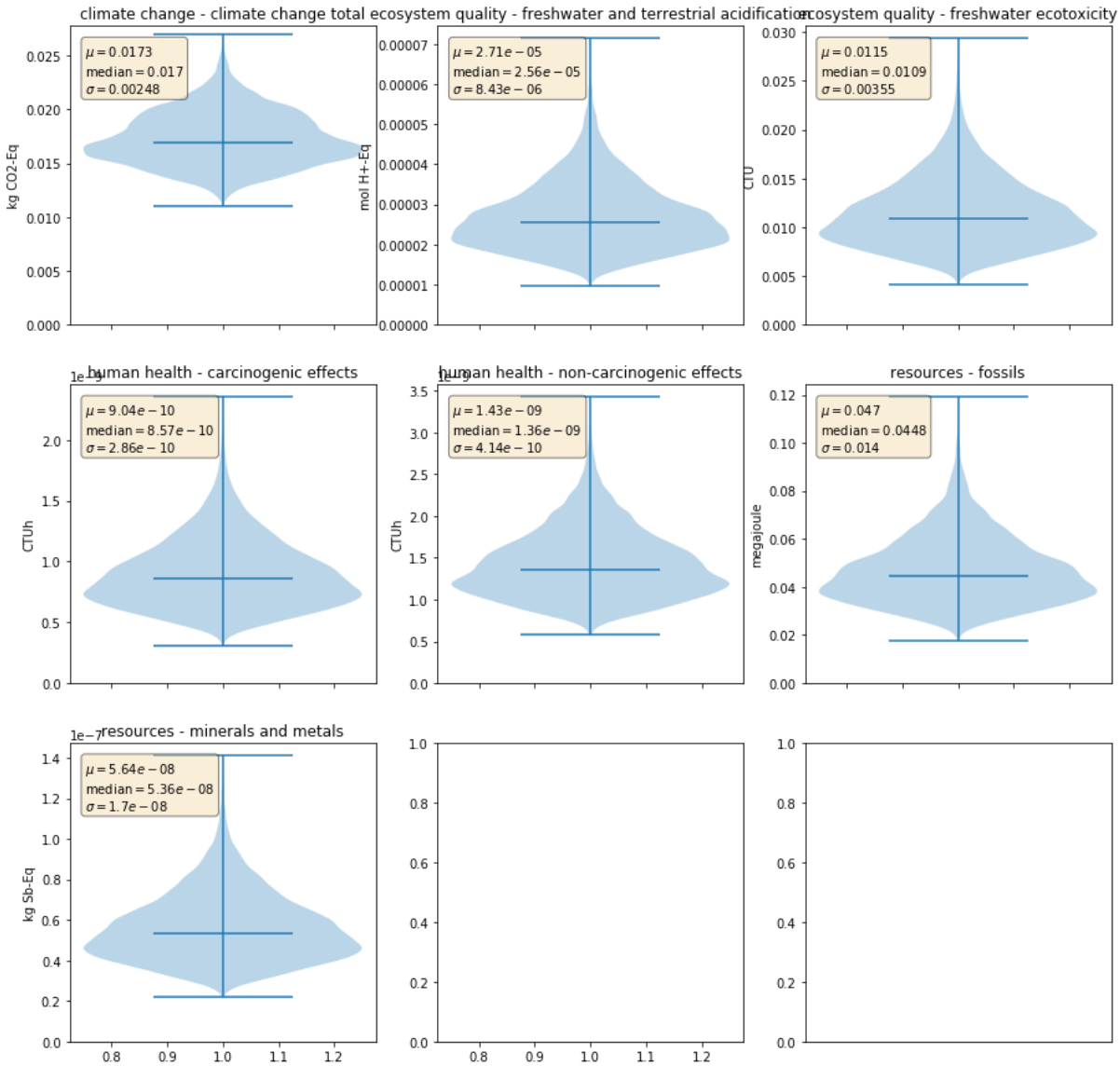


Figure 12 – Results of the Monte Carlo simulations for the reference LCA model for CHP for the seven ILCD 2018 impact categories.

The median results for climate change impact is 17 gCO_2-eq/kWh. Below is Figure 13 giving the climate change impact results of various flash geothermal power plants and the Hellisheiði power plant with various allocation procedures. Following the guidelines, the allocation used to generate the results presented here for the reference LCA model and the simplified models is exergy. It can be seen that the results are quite similar.

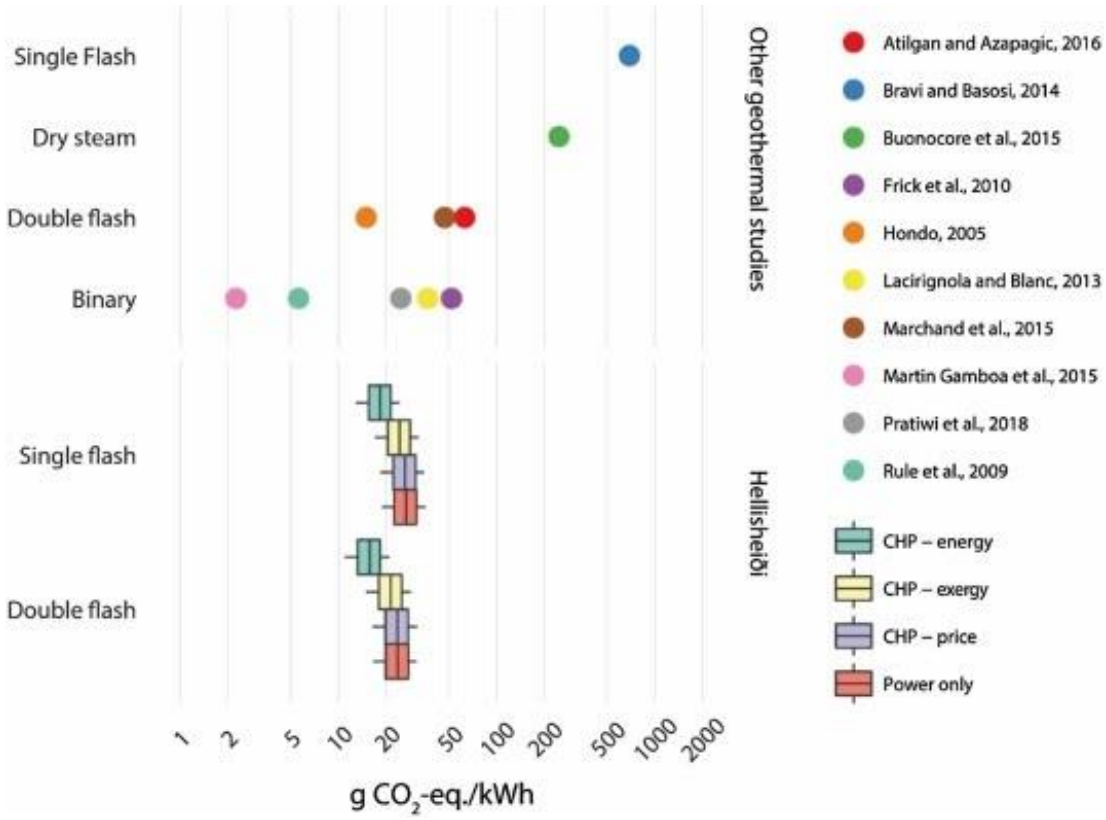


Figure 13 – Literature comparison when applying the simplified models for climate change to the geothermal power plant presented in (Paulillo et al., 2019).

3. Statistical process to identify the key input variable parameters for each impact category

Using the first order Sobol indices, several variable parameters were selected to be used as key input variable parameters in the simplified models for the seven impact categories chosen. The variability in climate change impacts was explained up to 83% by the:

- **CO2 content in the geothermal fluid**
- **power output**

The simplified models for the other six impact categories rely on at least three variable parameters, which explain more than 80% of the total variance.

- **lifetime**
- **well depth**
- **capacity factor**

The simplified model for the acidification impacts relies additionally on the **diesel required for the drilling**. Further, the simplified model for the carcinogenic effects on human health includes the **number of production wells** as an additional variable parameter.

4. a. Generation of the simplified model per impact category

The performance of the seven simplified models, listed in A3, are shown in Figure 14 by displaying the overlap between the impact category distributions for the simplified and reference LCA models and calculating the level of fitting by means of the R^2. The equations each model is relying on is provided in A3.

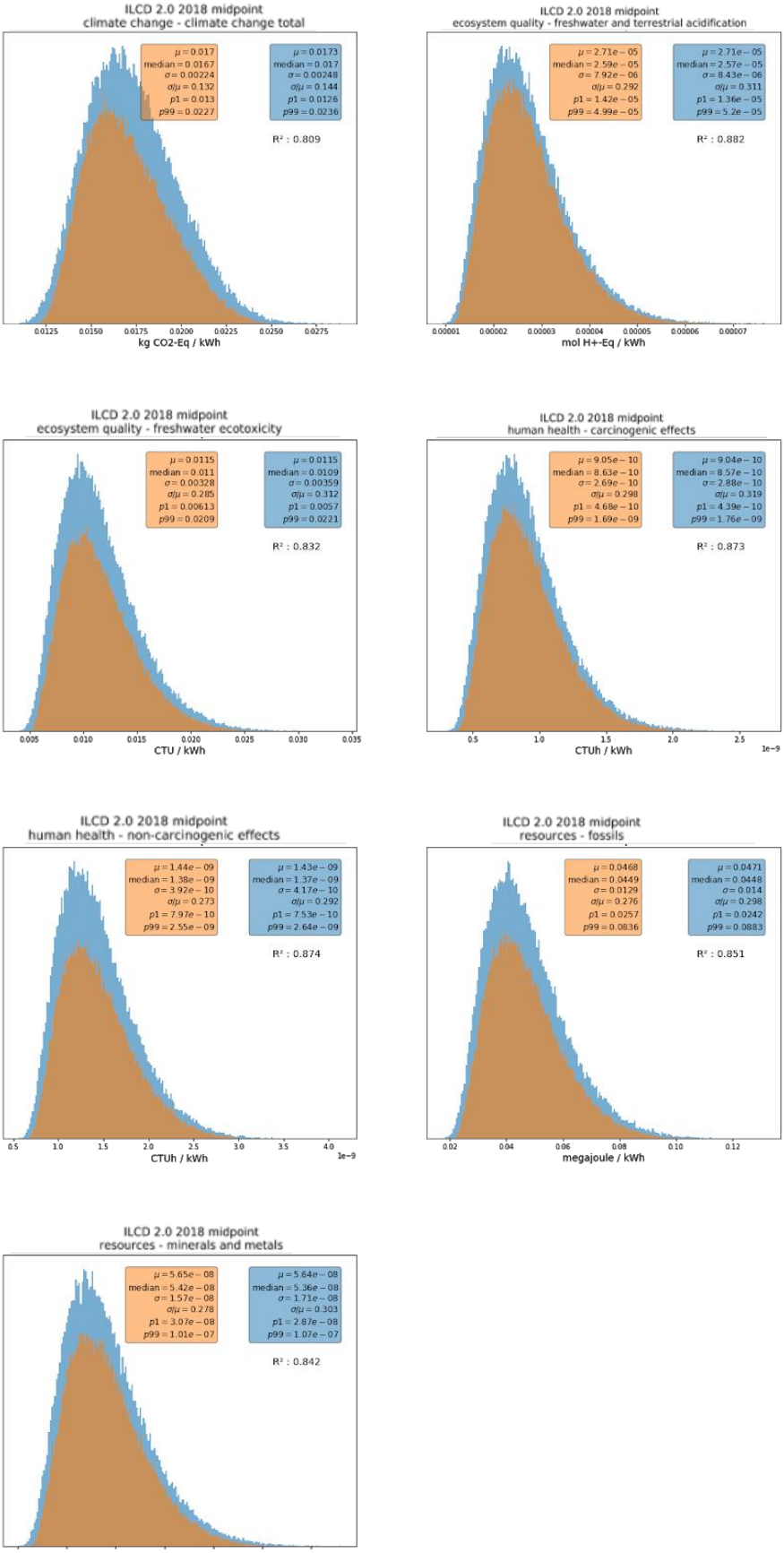


Figure 14 – Performance of the reference LCA model for CHP compared to the simplified models derived for the seven ILCD 2018 impact categories of interest.

4. b. Validation of the simplified models with literature

A final validation step consisted in applying the simplified models' equations to specific configurations reported by other case studies (Figure 13). Paulillo et al., (2019) use 303 MW as Power output and 1.4 g/kg geofluid. This results in 21.6 g CO_2/kWh for the climate change impact category which is well in line with the results from the paper, reporting between 18 and 24 g CO_2-eq./kWh for single flash configuration and between 15 and 23 g CO_2-eq./kWh for double flash configuration.

5. Applicability domain of the simplified models and optional iterative adjustment of the scope of the study

The reference LCA model, and as a result the simplified models developed, are designed for a system with a hydrothermal liquid/vapor geothermal source, natural flow & single or double flash system producing both heat and electricity. The results are relative to the electricity production. There is no abatement technology connected and the electrical output is in the range of 200 to 400 MWe (high capacity factor) and thermal output is 133 MWth about 50% capacity factor. The reference LCA model is further valid for the variable parameter ranges as reported in Table 9.

Simplified models for the Heat ORC category

This chapter presents the simplified models developed to assess the life cycle environmental impacts of the Heat ORC category of geothermal installations, namely a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. The results are presented following the steps of the protocol presented in the "Protocol to generate simplified models for a category of geothermal installation".

1. Scope of the study

The category of geothermal installation analysed here is a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. The functional unit is the production of 1 kWh of heat delivered to a user. The system boundaries include both the upstream module – based on secondary data – and the core module – based on primary data and representing the construction of infrastructure, operation and maintenance phases of a geothermal energy conversion plant (system). The 2D seismic exploration campaign that took place prior to the first drilling is excluded from the study as no accurate data is available on the fuel consumption.

The geothermal heat plant of Balmatt serves as a basis for the development of the reference LCA model (Figure 15). Balmatt is a deep geothermal demonstration project in Mol, Belgium, started in 2009 by VITO. In 2015 – 2016, VITO drilled two deep geothermal wells (3,610 and 4,341 m MD) on its premises in Mol-Donk. The geothermal capacity installed mainly consists of thermal capacity (6.6 MW_{th}) and a smaller ORC demonstration electrical capacity (0.25 MW_e). Among others, the geothermal plant will include facilities for materials research (e.g. corrosion testing and development of coatings) and a bypass for testing heat exchanger or prototypes of innovative binary systems under real conditions. Moreover, both wells are accessible to test new stimulation and production techniques and equipment.

Figure 15 – Geothermal power plant of Balmatt (VITO)

The depth of the top of the fractured carboniferous limestone geothermal reservoir was encountered between 3,170 and 3,300 meters at the project location. An overview of the 2 operational wells (MOL-GT-01 and MOL-GT-02) and of the originally additional foreseen production well (MOL-GT-03) is given in Table 10.

Table 10 – Operational and foreseen production wells for the Balmatt power plant.

Type well	Reference	Depth	Date	Well treatment after drilling
1 production well	MOL-GT-01	3,610 m MD, 3,608 m TVD	January 2016	Chemical stimulation
1 injection well	MOL-GT-02	4,341m MD, 3,830m TVD	September 2016 Autumn 2018	Chemical stimulation
1 extra (production) well	MOL-GT-03	4,905m MD, 4,236 m TVD	July 2018	

Since the partial completion of the plant on 14th May 2019, it has operated for 16 days accumulatively, with a last joint period of 10 days. On Sunday 23rd June 2019, 2 days after terminating the longest operational period, an induced earthquake occurred close to the injection well MOL-GT-02 with a magnitude M=2.1. The Balmatt project team and partners are further investigating the data from the seismometer network to better characterise this event. During the testing phase, the production temperature observed ranged from 121 to 126 °C and

the average production flowrate achieved was between 70 and 150 m^3/h provided by an Electrical Submersible Pump (ESP).

The geothermal brine is highly saline with TDS of about 165 g/L, mainly dominated by Na-(Ca)-Cl elements, with a Gas Liquid Ratio of 2.3 Nm^3/m^3. The gas consists mainly of CO_2 (~75 vol.%) and CH_4. Due to the high amount of dissolved gasses, surface installations are operated under a pressure of 40 bars to avoid degassing (NCG emissions), linked flashing and corrosion issues. Two heat exchangers with a total capacity of 6.6 MW transfer the geothermal heat to a secondary loop with fresh water. The brine is fully reinjected by the reinjection pump in the injection well MOL-GT-02.

Once in full operation, the plant will be used to supply 50 GWh/year:

- 50% for heat delivery (25,000 MWh_{th}): supply heat to an existing district heating network providing energy to VITO's research facilities, as well as facilities of SCK-CEN and Belgoprocess. There is a temperature regime of 95-70 °C.
- 50% for electricity production (10% efficiency: 2,500 MWh_e)

The amount of electricity consumed by the pumps is 3,300 MWh, so all produced electricity will be self-consumed.

2. a. Modelling of the reference LCA model

A reference LCA model was developed for the Balmatt geothermal plant. It aims at being representative for a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. The Balmatt geothermal heat plant is in many ways similar to the Rittershoffen case study but specific characteristics of geothermal plants in Belgium have been accounted for. The model follows mostly the recommendations of the guidelines for the life cycle assessment of geothermal energy systems (Blanc et al., 2020).

The chapters below describe the various life cycle stages in more detail. The reference model is based on the reference model of the Rittershoffen case study, as the plant characteristics are very similar. Therefore, the full model explanation is not repeated and only the differences with the Rittershoffen reference model are highlighted. For the default values of the variable parameters, specific data of the Balmatt plant is used. In addition, unlike the Rittershoffen reference model, the Belgian electricity grid mix is used for the Balmatt model.

Construction

Exploration

The diesel required and staff transport during exploration phase and the CO_2 released during well testing are excluded from the Balmatt reference model, as no sufficient primary data is available.

Well drilling

The construction of the drilling platform and retention basin is excluded from the Balmatt reference model, as no primary data is available.

Three wells were drilled within the Balmatt project: two production wells and one reinjection well. The drilled length is based on primary data.

Other aspects are modelled in the same way as the Rittershoffen reference model.

Geothermal power plant

In addition to the elements modelled for Rittershoffen, an ORC unit is modelled using the ecoinvent process 'heat and power co-generation unit construction, organic Rankine cycle, 200kW electrical', corrected for the actually installed electrical power.

Piping for freshwater, filters and valves are excluded from the reference model, as no primary data is available for Balmatt. Other aspects are modelled in the same way as the Rittershoffen reference model.

Operation and maintenance

No direct emissions, scaling inhibitor, water, filters, valves and pipes for freshwater are taken into account. Unlike the Rittershoffen reference model, the Belgian electricity grid mix is used for the Balmatt model. Other aspects are modelled in the same way as the Rittershoffen reference model.

End of life

End of life is modelled in the same way as the Rittershoffen reference model, including well abandonment.

Thermal output

The total power capacity of the geothermal plant is 6.6 MW_{th} and 0.25 MW_e. The generated electrical power is used for self-consumption. The total thermal energy produced in kWh is calculated as in Equation (17).

$$E_{th} = P_{th} * (1 - 0{,}5) * OH \quad (17)$$

with E_{th} the thermal energy produced (in kWh), P_{th} the thermal power capacity of the geothermal plant (in kW_{th}), OH the yearly operating hours (in hours), and 0.5 is the capacity factor employed to balance the extracted heat transferred to the Organic Rankine Cycle for electricity production.

Summary of variable parameters

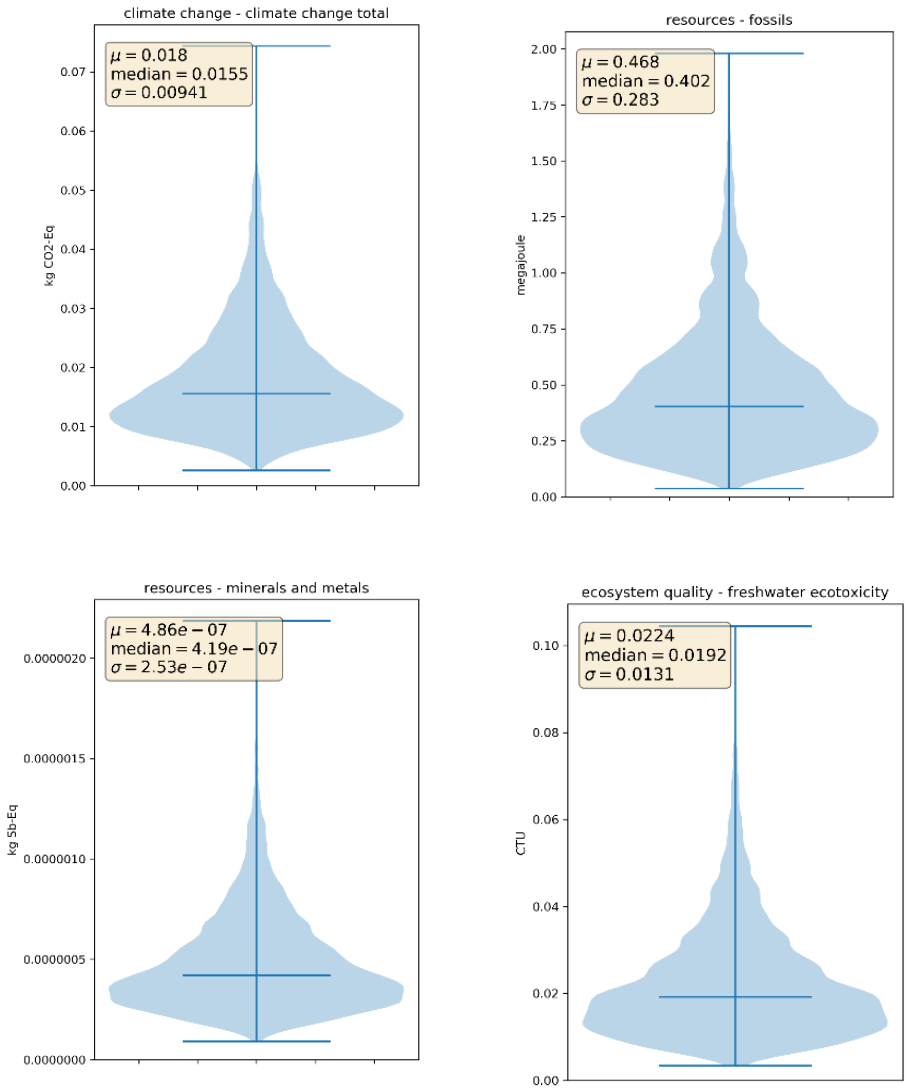
Table 11 lists all the variable parameters used in the reference LCA model for the HeatORC category, their default value for the Balmatt geothermal plant, as well as their boundaries. A uniform distribution is assumed for all variable parameters, as no information is available to justify applying alternative distributions.

Table 11 – Variable parameters used for the reference LCA model for HeatORC. The "Default" values represent the values of the Balmatt power plant, the Min. and Max. values are the lower and upper boundaries of the single variable parameters. OM stands for operation and maintenance.

Phase	Label	Variable parameter	Default	Min.	Max.	Unit
General	Flow rate	Flow_rate_tph	108	72	144	t/h
General	Electric power	MWe	0.25	0	1	MW
General	Operating hours	Operating_hours	8,000	5,000	8,500	h
General	Lifetime	LT_years	30	20	40	y
General	Thermal power	MWth	6.6	6.6	25	MW
Power plant	Length geothermal fluid pipe	L_gw_pipe_m	200	100	300	m
Power plant	Power ESP pump	power_ESP_kW	600	200	1,200	kW
Power plant	Power reinjection pump	power_pump_kW	350	0	500	kW
Power plant	Mass Balmatt heat exchanger	M_heatexchanger_Balmatt_kg	57,679.2	23,070	92,280	kg
Power plant	Area of the power plant	A_powerplant_m2	800.05	400	1,200	m2
Stimulation	Volume stimulated fluid (chemical)	V_stimulated_m3	240	40	250	m3
Drilling	Length well	well_length	3,725	1,300	5,500	m
Drilling	Ratio meters drilled and well length	Ratio_MD_well_length	1.25	1	1.5	-
Drilling	Number injection wells	N_well_injection	1	1	2	-
Drilling	Number production wells	N_well_production	1	1	2	-
Transport	Distance for the cuttings	km_cuttings	275	50	500	km
Transport	Transport operation and maitenance	km_passenger_OM_pday	0	10	50	km
End of life	Energy for well abandonment	E_abd_diesel_MJ	570,000	38,600	750,000	MJ
End of life	Mass cement for well abandonment	M_cement_abd_kg	18,750	12,500	25,000	kg

2. b. Validation of the reference LCA model with literature

The results of the Monte Carlo simulations for the reference LCA model using the distributions of the variable parameters specified in Table 11 are shown in Figure 16.



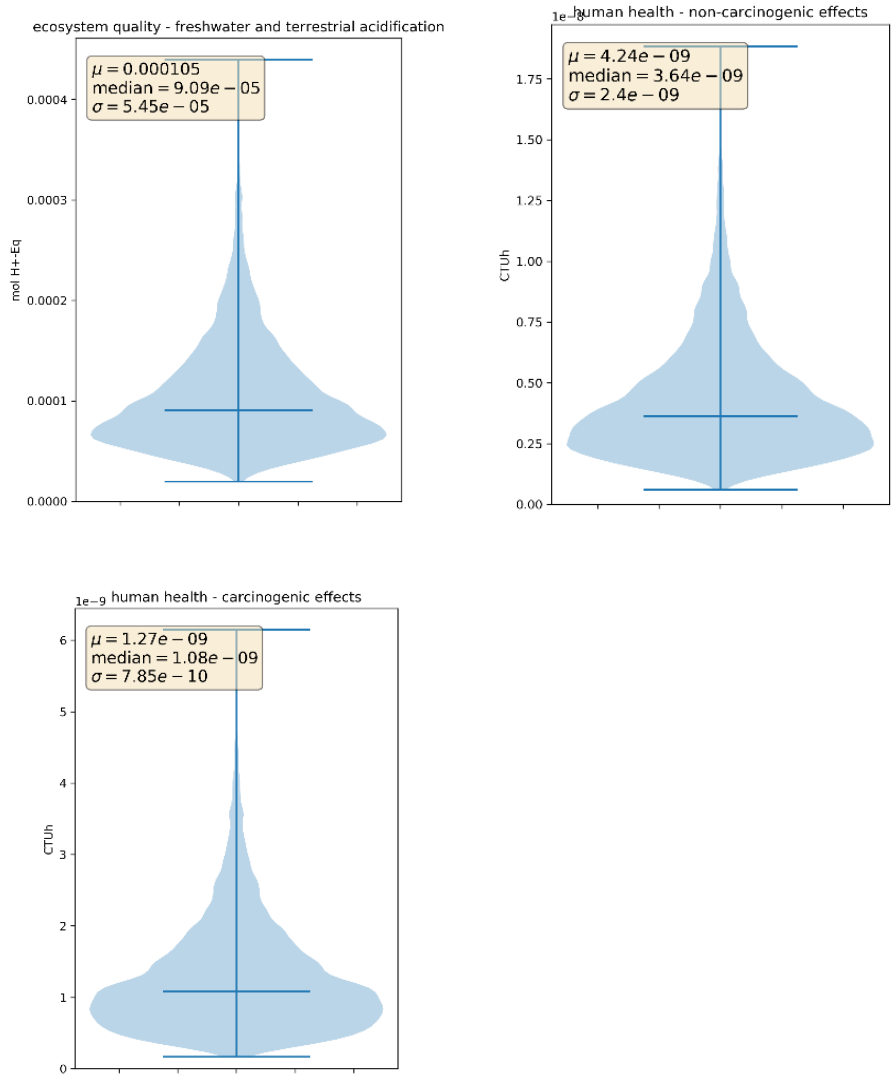


Figure 16 – Results of the Monte Carlo simulations for the reference LCA model for HeatORC for the seven ILCD 2018 impact categories of interest. In the violin plot, the horizontal lines correspond from top to bottom to the 95th percentile, the median and 5th percentile, while the light blue violin shape represents the probability density.

The impact values derived from the reference model with the default values for Balmatt are presented in Table 12.

Table 12 – Impact category results for the reference LCA model for HeatORC using the default values of Balmatt for the fixed and variable parameters

Impact category	Reference unit	Balmatt default values
climate change - total	kg CO_2-Eq	0.026854
ecosystem quality - freshwater and terrestrial acidification	mol H+-Eq	0.00014
resources - fossils	MJ	0.7864

resources – minerals and metals	kg Sb-Eq	5.8941E-07
Human health – non-carcinogenic effects	CTUh	4.9735E-09
Human health – carcinogenic effects	CTUh	1.3298E-09
Ecosystem quality – freshwater ecotoxicity	CTU	0.024626

The total climate change impact of geothermal binary power plants using EGS reported in (Frick et al., 2010) is around 0.047 kg CO_2-eq./kWh. This value falls within the 95% confidence interval shown in Figure 16, but is relatively high. This is easily explained by the many differences between the study and the Balmatt reference model: the LCA study in Frick et al. (2020) considers the production of both electrical power and thermal power (3.45 MWth and 1.75 MWe), while Balmatt primarily produces heat, with a demonstration of electrical power production using an ORC (6.6 MWth and 0.25 MWe). Due to the lower efficiency of conversion to electricity, this is associated with higher environmental impacts per functional unit. Moreover, only chemical stimulation is applied at Balmatt, consisting of 40-250 m^3 of fluid injected and 13 MJ diesel consumed by the injection pump, while the plant assessed in Frick et al. (2010) considers hydraulic stimulation, including a large volume of injected fluid (260,000 m^3) and 3,000 GJ diesel consumed by the injection pump. The larger need for diesel consumption for the hydraulic stimulation could explain the large value of the indicator climate change. There are also large methodological differences: the LCA study in Frick et al. (2010) uses an older method and characterisation factors and is based on ecoinvent 2 background data, while the Balmatt reference model uses ecoinvent 3. All these factors can have a significant effect on the results of the LCA.

Rocco et al. (2020) estimate the environmental impacts for geothermal heat power plants with different characteristics using the EF v3.0. impact category for average EU characteristics (Table 13). The estimates from this study lie within the boundaries of the Monte Carlo results of the reference LCA model for the impact categories climate change, freshwater and terrestrial acidification, human health non-carcinogenic effects. It does not for the impact indicators human health carcinogenic effects and freshwater ecotoxicity. It is important to note that both these indicators have a level of confidence indicating to use the indicators with caution due to the large uncertainty associated with the methods (Blanc et al., 2020).

Table 13 – Environmental impacts of geothermal heat power plants generated for the EF v3.0. impact category and reported in (Rocco et al., 2020)

Impact category	Reference unit	Min.	Max.
Climate change - total	kg CO_2-Eq	7.5E-03	1.0E-02
Ecosystem quality – freshwater and terrestrial acidification	mol H+-Eq	7.2E-05	1.1E-04
Human health – non-carcinogenic effects	CTUh	3.1E-09	3.7E-09
Human health – carcinogenic effects	CTUh	7.7E-11	9.1E-11
Ecosystem quality – freshwater ecotoxicity	CTUe	2.0	2.6

Overall, due to the specific nature of the Balmatt case, only few literature studies provide a meaningful comparison. Nevertheless, the values reported in (Frick et al., 2010; Rocco et al., 2020), are mostly within the interval reported by the reference model, except for two indicators that have a large uncertainty.

3. Statistical process to identify the key input variable parameters for each impact category

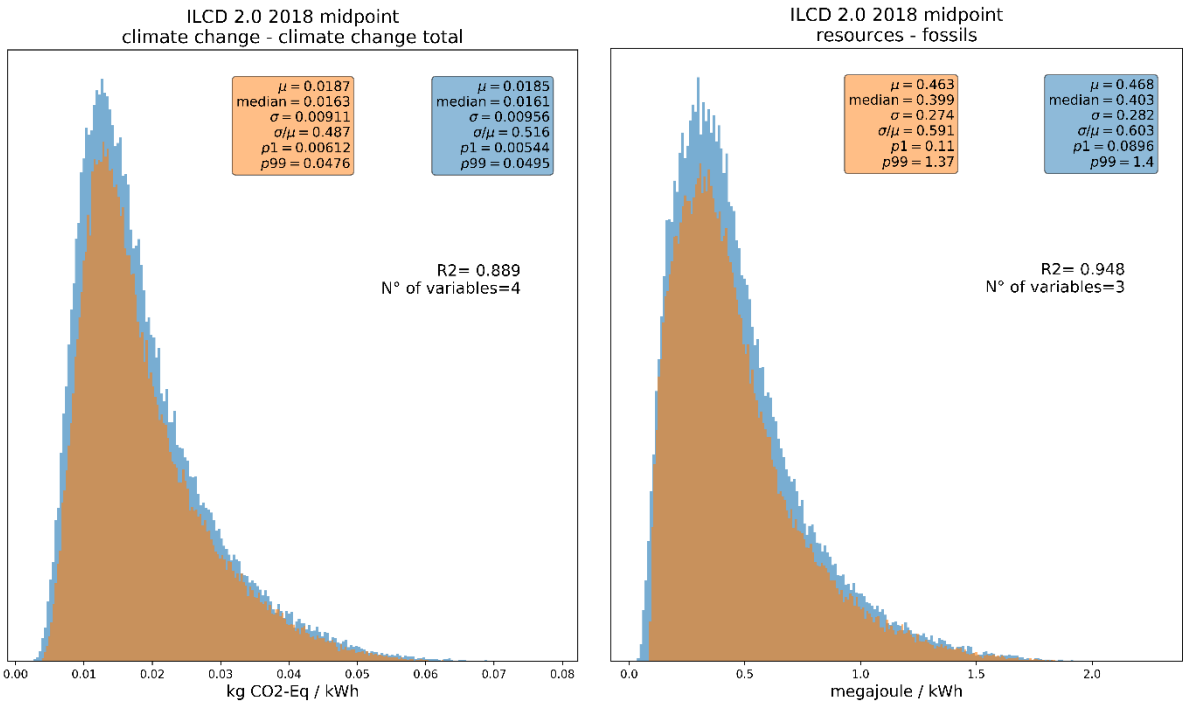
The A4 lists the first order Sobol indexes of all variable parameters. The following variable parameters explain large part of the variance:

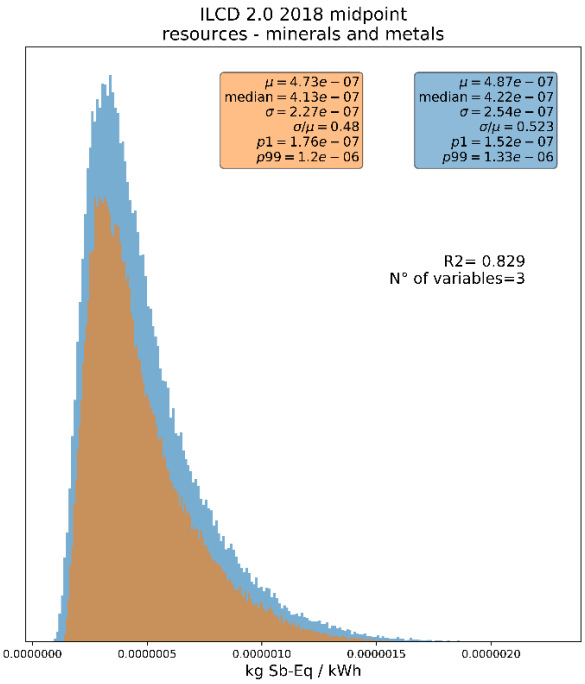
- **Installed thermal power**
- **Power of the reinjection pump**
- **Power of the production pump (ESP)**
- **Yearly operating hours of the plant**
- **Number of injection wells**

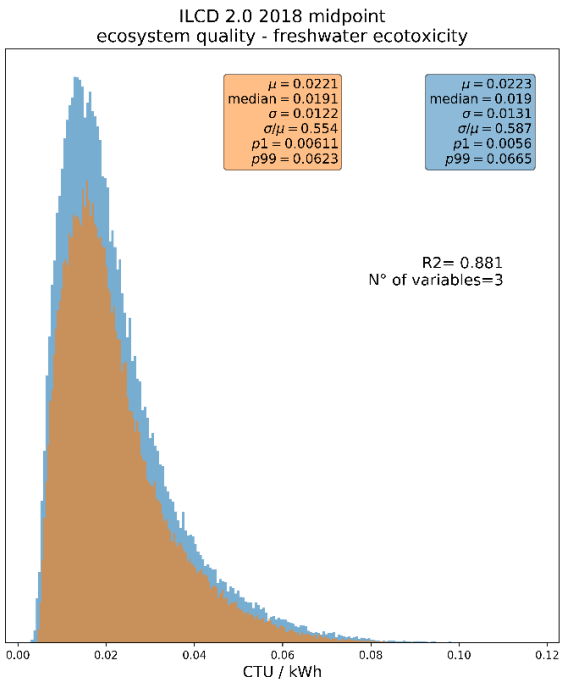
These five variable parameters are therefore selected to generate the simplified models. Per indicator, the simplified model for that indicator includes the three to four most important variable parameters of the five mentioned above.

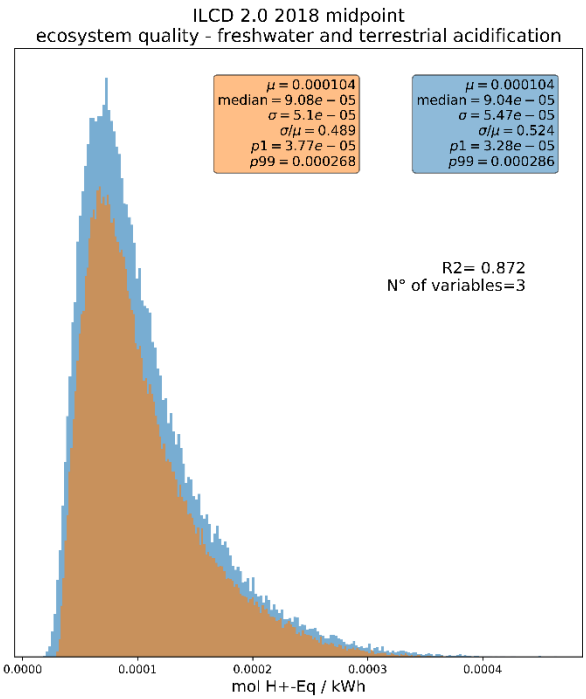
4. a. Generation of the simplified model per impact category

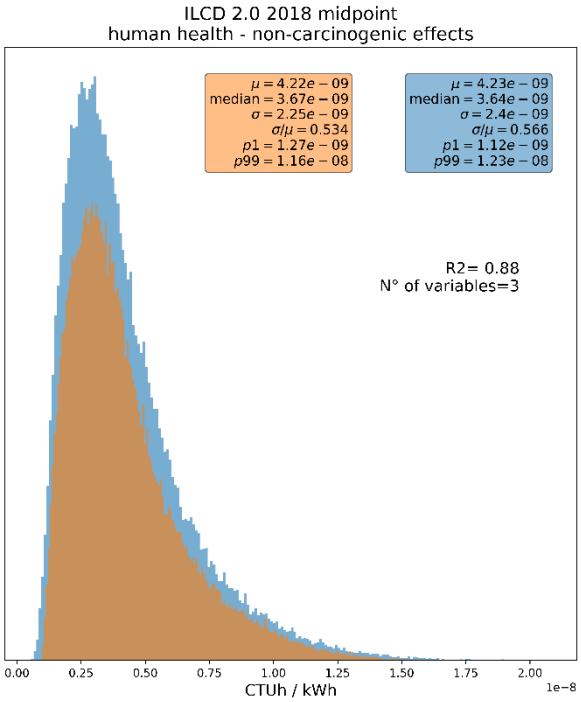
Per indicator, the simplified model for that indicator includes the three to four most important variable parameters, selected from the five most relevant ones listed above. The equations each model is relying on are provided in A4. The performance of the seven simplified models are shown in Figure 17 by displaying the overlap between the impact category distributions for the simplified and reference LCA models and calculating the level of fitting by means of the R^2. Overall, the R^2 are above 87% for all impact categories except for minerals and resources depletion category, where the R^2 is 83%.




ILCD 2.0 2018 midpoint
resources - minerals and metals
μ = 4.73e − 07
median = 4.13e − 07
σ = 2.27e − 07
σ/μ = 0.48
p1 = 1.76e − 07
p99 = 1.2e − 06
μ = 4.87e − 07
median = 4.22e − 07
σ = 2.54e − 07
σ/μ = 0.523
p1 = 1.52e − 07
p99 = 1.33e − 06
R2= 0.829
N° of variables=3
0.0000000
0.0000005
0.0000010
0.0000015
0.0000020
kg Sb-Eq / kWh


ILCD 2.0 2018 midpoint
ecosystem quality - freshwater ecotoxicity
μ = 0.0221
median = 0.0191
σ = 0.0122
σ/μ = 0.554
p1 = 0.00611
p99 = 0.0623
μ = 0.0223
median = 0.019
σ = 0.0131
σ/μ = 0.587
p1 = 0.0056
p99 = 0.0665
R2= 0.881
N° of variables=3
0.00
0.02
0.04
0.06
0.08
0.10
0.12
CTU / kWh


ILCD 2.0 2018 midpoint
ecosystem quality - freshwater and terrestrial acidification
μ = 0.000104
median = 9.08e − 05
σ = 5.1e − 05
σ/μ = 0.489
p1 = 3.77e − 05
p99 = 0.000268
μ = 0.000104
median = 9.04e − 05
σ = 5.47e − 05
σ/μ = 0.524
p1 = 3.28e − 05
p99 = 0.000286
R2= 0.872
N° of variables=3
0.0000
0.0001
0.0002
0.0003
0.0004
mol H+-Eq / kWh


ILCD 2.0 2018 midpoint
human health - non-carcinogenic effects
μ = 4.22e − 09
median = 3.67e − 09
σ = 2.25e − 09
σ/μ = 0.534
p1 = 1.27e − 09
p99 = 1.16e − 08
μ = 4.23e − 09
median = 3.64e − 09
σ = 2.4e − 09
σ/μ = 0.566
p1 = 1.12e − 09
p99 = 1.23e − 08
R2= 0.88
N° of variables=3
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e−8
CTUh / kWh

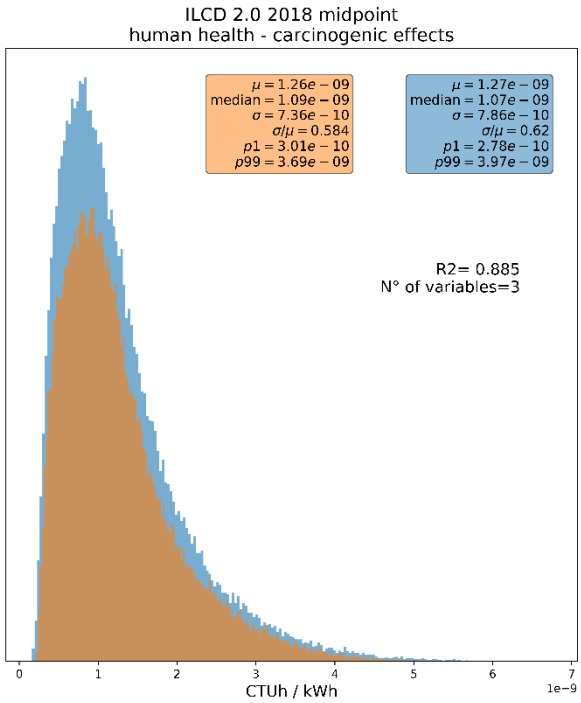


Figure 17 – Performance of the reference LCA model for HeatORC compared to the simplified models derived for the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models.

4. b. Validation of the simplified models with literature

A final validation step consists in applying the simplified models' equations to specific configurations reported by other case studies. None of the references gathered in section 2.b reported enough information to determine the variable parameters and to apply the simplified models. Therefore, this validation is not performed right now, but further research at a later stage is recommended.

5. Applicability domain of the simplified models and optional iterative adjustment of the scope of the study

The reference LCA model, and as a result the simplified models developed, are designed for:

- geothermal plants for heat generation with ORC unit for possible electricity production for self-consumption;
- very low to no direct emissions;
- located in Belgium (or in another location with a similar electricity mix as in Belgium and similar geological characteristics);
- connected to the Belgian power grid (or in another location with a similar grid mix);

- the range of values for the variable parameters as specified in Table 11.

Even though the Balmatt geothermal plant is a demonstration plant that is difficult to compare to other geothermal power plants, the Balmatt reference model is based on the reference model of Rittershoffen and can therefore be applied to similar power plants, within the above-mentioned boundaries.

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Appendixes

The Appendix gives background information for each category of geothermal installation, such as a list of the fixed parameters used for the definition of the reference LCA model, the first order Sobol indexes of the variable parameters, and the equations of the simplified models.

Appendix 1 - Background data for the EGS category

A1. A. Observed and prospective electricity mixes for the EU28 countries

Table 14 displays the shares of the different electricity sources for the EU28 countries as observed in 2010 and forecasted for 2050 (Capros et al., 2016).

Table 14 – Shares of the different electricity sources for the EU28 countries observed in 2010 and forecasted for 2050(Capros et al., 2016)

Country	Description	2010	2050
AT	Nuclear energy	0%	0%
AT	Solids	7%	0%
AT	Oil (including refinery gas)	2%	0%
AT	Gas (including derived gases)	24%	19%
AT	Biomass-waste	7%	8%
AT	Hydro (pumping excluded)	56%	51%
AT	Wind	3%	17%
AT	Solar	0%	6%
BE	Nuclear energy	51%	0%
BE	Solids	4%	0%
BE	Oil (including refinery gas)	0%	0%
BE	Gas (including derived gases)	35%	59%
BE	Biomass-waste	6%	7%
BE	Hydro (pumping excluded)	0%	1%
BE	Wind	1%	28%
BE	Solar	1%	5%
BG	Nuclear energy	33%	36%
BG	Solids	49%	21%

BG	Oil (including refinery gas)	1%	0%
BG	Gas (including derived gases)	4%	9%
BG	Biomass-waste	0%	4%
BG	Hydro (pumping excluded)	11%	7%
BG	Wind	1%	13%
BG	Solar	0%	10%
HR	Nuclear energy	0%	0%
HR	Solids	17%	0%
HR	Oil (including refinery gas)	4%	0%
HR	Gas (including derived gases)	18%	26%
HR	Biomass-waste	0%	6%
HR	Hydro (pumping excluded)	59%	37%
HR	Wind	1%	14%
HR	Solar	0%	17%
CY	Nuclear energy	0%	0%
CY	Solids	0%	0%
CY	Oil (including refinery gas)	99%	0%
CY	Gas (including derived gases)	0%	58%
CY	Biomass-waste	1%	3%
CY	Hydro (pumping excluded)	0%	0%
CY	Wind	1%	13%
CY	Solar	0%	26%
CZ	Nuclear energy	33%	54%
CZ	Solids	55%	18%
CZ	Oil (including refinery gas)	0%	0%
CZ	Gas (including derived gases)	5%	12%
CZ	Biomass-waste	3%	8%
CZ	Hydro (pumping excluded)	3%	4%
CZ	Wind	0%	2%
CZ	Solar	1%	3%
DK	Nuclear energy	0%	0%
DK	Solids	44%	0%

DK	Oil (including refinery gas)	2%	0%
DK	Gas (including derived gases)	20%	19%
DK	Biomass-waste	14%	22%
DK	Hydro (pumping excluded)	0%	0%
DK	Wind	20%	56%
DK	Solar	0%	2%
EE	Nuclear energy	0%	0%
EE	Solids	86%	15%
EE	Oil (including refinery gas)	0%	0%
EE	Gas (including derived gases)	5%	18%
EE	Biomass-waste	6%	25%
EE	Hydro (pumping excluded)	0%	1%
EE	Wind	2%	42%
EE	Solar	0%	0%
FI	Nuclear energy	28%	41%
FI	Solids	26%	1%
FI	Oil (including refinery gas)	1%	0%
FI	Gas (including derived gases)	15%	8%
FI	Biomass-waste	14%	25%
FI	Hydro (pumping excluded)	16%	16%
FI	Wind	0%	8%
FI	Solar	0%	0%
FR	Nuclear energy	76%	38%
FR	Solids	4%	0%
FR	Oil (including refinery gas)	1%	0%
FR	Gas (including derived gases)	5%	6%
FR	Biomass-waste	1%	4%
FR	Hydro (pumping excluded)	11%	12%
FR	Wind	2%	26%
FR	Solar	0%	12%
DE	Nuclear energy	22%	0%
DE	Solids	42%	21%

DE	Oil (including refinery gas)	1%	0%
DE	Gas (including derived gases)	16%	19%
DE	Biomass-waste	7%	12%
DE	Hydro (pumping excluded)	3%	5%
DE	Wind	6%	30%
DE	Solar	2%	13%
GR	Nuclear energy	0%	0%
GR	Solids	54%	0%
GR	Oil (including refinery gas)	11%	0%
GR	Gas (including derived gases)	17%	21%
GR	Biomass-waste	1%	3%
GR	Hydro (pumping excluded)	13%	10%
GR	Wind	5%	38%
GR	Solar	0%	28%
HU	Nuclear energy	42%	58%
HU	Solids	17%	0%
HU	Oil (including refinery gas)	1%	0%
HU	Gas (including derived gases)	31%	23%
HU	Biomass-waste	7%	7%
HU	Hydro (pumping excluded)	1%	2%
HU	Wind	1%	7%
HU	Solar	0%	1%
IE	Nuclear energy	0%	0%
IE	Solids	22%	0%
IE	Oil (including refinery gas)	2%	0%
IE	Gas (including derived gases)	62%	41%
IE	Biomass-waste	1%	6%
IE	Hydro (pumping excluded)	2%	4%
IE	Wind	10%	49%
IE	Solar	0%	0%
IT	Nuclear energy	0%	0%
IT	Solids	13%	0%

IT	Oil (including refinery gas)	7%	0%
IT	Gas (including derived gases)	53%	34%
IT	Biomass-waste	4%	15%
IT	Hydro (pumping excluded)	17%	13%
IT	Wind	3%	15%
IT	Solar	1%	21%
LV	Nuclear energy	0%	0%
LV	Solids	0%	1%
LV	Oil (including refinery gas)	0%	0%
LV	Gas (including derived gases)	45%	29%
LV	Biomass-waste	1%	16%
LV	Hydro (pumping excluded)	53%	35%
LV	Wind	1%	19%
LV	Solar	0%	0%
LT	Nuclear energy	0%	53%
LT	Solids	0%	0%
LT	Oil (including refinery gas)	13%	0%
LT	Gas (including derived gases)	69%	18%
LT	Biomass-waste	3%	8%
LT	Hydro (pumping excluded)	11%	6%
LT	Wind	4%	13%
LT	Solar	0%	0%
LU	Nuclear energy	0%	0%
LU	Solids	0%	0%
LU	Oil (including refinery gas)	0%	0%
LU	Gas (including derived gases)	90%	82%
LU	Biomass-waste	4%	4%
LU	Hydro (pumping excluded)	3%	2%
LU	Wind	2%	11%
LU	Solar	1%	2%
MT	Nuclear energy	0%	0%
MT	Solids	0%	0%

MT	Oil (including refinery gas)	100%	0%
MT	Gas (including derived gases)	0%	78%
MT	Biomass-waste	0%	2%
MT	Hydro (pumping excluded)	0%	0%
MT	Wind	0%	3%
MT	Solar	0%	17%
NL	Nuclear energy	3%	0%
NL	Solids	19%	1%
NL	Oil (including refinery gas)	1%	0%
NL	Gas (including derived gases)	66%	56%
NL	Biomass-waste	7%	14%
NL	Hydro (pumping excluded)	0%	0%
NL	Wind	3%	25%
NL	Solar	0%	3%
PL	Nuclear energy	0%	28%
PL	Solids	87%	26%
PL	Oil (including refinery gas)	2%	0%
PL	Gas (including derived gases)	4%	17%
PL	Biomass-waste	4%	8%
PL	Hydro (pumping excluded)	2%	2%
PL	Wind	1%	18%
PL	Solar	0%	0%
PT	Nuclear energy	0%	0%
PT	Solids	13%	0%
PT	Oil (including refinery gas)	6%	1%
PT	Gas (including derived gases)	28%	3%
PT	Biomass-waste	5%	8%
PT	Hydro (pumping excluded)	30%	37%
PT	Wind	17%	37%
PT	Solar	0%	15%
RO	Nuclear energy	19%	27%
RO	Solids	34%	10%

RO	Oil (including refinery gas)	1%	0%
RO	Gas (including derived gases)	12%	15%
RO	Biomass-waste	0%	4%
RO	Hydro (pumping excluded)	33%	19%
RO	Wind	1%	19%
RO	Solar	0%	6%
SK	Nuclear energy	53%	59%
SK	Solids	13%	8%
SK	Oil (including refinery gas)	2%	0%
SK	Gas (including derived gases)	10%	9%
SK	Biomass-waste	3%	7%
SK	Hydro (pumping excluded)	19%	14%
SK	Wind	0%	1%
SK	Solar	0%	3%
SI	Nuclear energy	35%	43%
SI	Solids	33%	0%
SI	Oil (including refinery gas)	0%	0%
SI	Gas (including derived gases)	3%	13%
SI	Biomass-waste	1%	10%
SI	Hydro (pumping excluded)	28%	27%
SI	Wind	0%	2%
SI	Solar	0%	4%
ES	Nuclear energy	21%	0%
ES	Solids	9%	0%
ES	Oil (including refinery gas)	6%	0%
ES	Gas (including derived gases)	32%	13%
ES	Biomass-waste	2%	4%
ES	Hydro (pumping excluded)	14%	11%
ES	Wind	15%	39%
ES	Solar	2%	33%
SE	Nuclear energy	39%	31%
SE	Solids	1%	0%

SE	Oil (including refinery gas)	1%	0%
SE	Gas (including derived gases)	3%	6%
SE	Biomass-waste	9%	13%
SE	Hydro (pumping excluded)	45%	36%
SE	Wind	2%	14%
SE	Solar	0%	0%
UK	Nuclear energy	16%	29%
UK	Solids	28%	1%
UK	Oil (including refinery gas)	1%	0%
UK	Gas (including derived gases)	47%	30%
UK	Biomass-waste	4%	11%
UK	Hydro (pumping excluded)	1%	1%
UK	Wind	3%	26%
UK	Solar	0%	2%

A1. B. Details to the definition of the reference LCA model

Tailor-made electricity mix

The tailor-made electricity derived, is based on the ecoinvent processes listed in Table 15. RoW datasets were used since the differences in emissions between the processes for electricity production of hard coal, oil, and lignite, and wind are small. The only exception is solar power, where a dataset from Spain was used to compensate the outdated dataset currently available in ecoinvent v3.6. Geothermal energy (currently around 1% in any European electricity mix), thermal solar power (currently around 1% in any European electricity mix), wave and tidal energy (currently less than 1% in any European electricity mix) were not accounted for in this electricity mix.

The use of an electricity mix representing RoW instead of a country-specific mix was necessary to allow for such a simplification. For oil, lignite, coal, natural gas, and wind, the RoW process is derived from the other geographically specific datasets. For biomass, hydropower, and nuclear energy the inventory of the mixes modelled in ecoinvent do not vary with location.

Table 15 – Ecoinvent processes used to represent each energy flow in the tailor-made electricity mix

Electricity type	Name in ecoinvent
Hydro	'electricity production, hydro, run-of-river' (kilowatt hour, RoW, None)
Wind	'electricity production, wind, 1-3MW turbine, onshore' (kilowatt hour, RoW, None)
Biomass	'heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014' (kilowatt hour, RoW, None)
Solar	'electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted' (kilowatt hour, ES, None)
Nuclear energy	'electricity production, nuclear, pressure water reactor' (kilowatt hour, RoW, None)
Coal and lignite	40% 'heat and power co-generation, hard coal' (kilowatt hour, RoW, None), 60% 'heat and power co-generation, lignite' (kilowatt hour, RoW, None),
Natural gas	'electricity production, natural gas, combined cycle power plant' (kilowatt hour, RoW, None)
Oil	'electricity production, oil' (kilowatt hour, RoW, None),

The data published as part of the EU Reference scenario 2016 were used (Capros et al., 2016) to choose and estimate the distribution functions representing best the shares of each electricity source. This dataset describes the gross electricity generation by source for 28 EU

countries for the years 2000, 2005, 2010 and predictions for the years 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050. The electricity sources covered are: nuclear energy, solid fossil fuels, oil, gas, biomass, hydro, wind, solar, geothermal and other renewables, as well as other fuels. Other fuels were assigned a value of 0 for all the years of interest and were therefore not considered.

The share of gross electricity production by source was described with a probability distribution function derived from the values for the 28 EU countries for the years 2000, 2005, 2010 (observed) and 2030, 2040, and 2050 (forecasted). The scenarios presented in (Capros et al., 2016) do not account for the 2030 climate and energy targets for which the scenarios EUCO3232.5 were developed (European Commission, 2019). However, it appeared that the forecasted shares for 2050 were often close to the values forecasted by the EUCO3232.5 for 2030, so that the chosen years are expected to be representative of future developments.

The Beta distribution was chosen to represent the share of gross electricity production by source and the parameters are displayed in Table 16 for each electricity source.

Table 16 – Parameters a and b of the Beta distribution fitted to the observed and forecasted electrical sources shares for the 28 European countries.

	Shape1 (=a)	Shape2 (=b)
Nuclear energy	1.97	3.17
Solids (coal)	0.51	1.66
Oil (including refinery gas)	0.26	2.59
Gas (including derived gases)	0.97	2.66
Biomass-waste	0.82	13.28
Hydro (pumping excluded)	0.51	2.84
Wind	0.47	3.93
Solar	0.27	6.16

The deterministic results for the reference model relying on the tailored-made electricity mix were compared to the ones of the same reference model relying on the ecoinvent electricity mix for France. The shares of each electricity source were 2% coal, 6% natural gas, 75% nuclear energy, 0% oil, 0% biomass, 13% hydropower, 4% wind, and 0% solar.

The differences between both results vary between 0 to 46% (Table 17) as a result of the simplifications necessary to model the tailor-made electricity mix. For example, hydropower is modelled with three different processes in ecoinvent, while only one process is included in the tailor-made mix.

Table 17 – Comparison of the reference model for EGS relying on the tailor-made electricity mix with default values set to the ones of the French electricity mix of ecoinvent to the reference model using the electricity mix of ecoinvent directly.

Impact category (ILCD 2018)	Tailor-made Electricity mix with default set to FR electricity mix	French electricity mix	Unit	Δ
ecosystem quality, freshwater ecotoxicity	4.18E-03	4.35E-03	CTU	-4%
human health, non-carcinogenic effects	7.62E-10	8.25E-10	CTUh	-8%
human health, carcinogenic effects	1.98E-10	2.01E-10	CTUh	-1%
resources, minerals and metals	1.38E-07	1.37E-07	kg Sb-Eq	1%
climate change, climate change biogenic	1.93E-05	2.34E-05	kg CO_2-Eq	-21%
climate change, climate change fossil	4.29E-03	4.54E-03	kg CO_2-Eq	-6%
climate change, climate change land use and land use change	1.67E-05	1.67E-05	kg CO_2-Eq	0%
climate change, climate change total	4.33E-03	4.58E-03	kg CO_2-Eq	-6%
ecosystem quality, freshwater and terrestrial acidification	3.92E-05	3.96E-05	mol H+Eq	-1%
ecosystem quality, freshwater eutrophication	2.05E-06	1.44E-06	kg P-Eq	30%
ecosystem quality, marine eutrophication	7.12E-06	7.32E-06	kg N-Eq	-3%
ecosystem quality, terrestrial eutrophication	6.69E-05	7.06E-05	mol N-Eq	-6%
human health, ionising radiation	1.39E-02	1.35E-02	kg U235-Eq	3%
human health, ozone layer depletion	1.37E-09	1.55E-09	kg CFC-11.	-13%
human health, photochemical ozone creation	2.04E-05	2.14E-05	kg NMVOC-.	-5%
human health, respiratory effects, inorganics	2.16E-10	2.15E-10	disease i.	0%
resources, dissipated water	3.55E-03	4.02E-03	m3 water-.	-13%
resources, fossils	3.05E-01	3.25E-01	megajoule	-7%
resources, land use	3.10E-02	4.66E-02	points	-50%

Construction

Retention basins

The construction of the retention basins was modelled using the indications of the GREET model and dimensions taken from the aerial vision of the geothermal power plant taken from Google Maps.

For a basin of width W and length L, the internal surface area can be calculated using Equation (18). Assuming a berm height of 0.9 m, a pond liner thickness of 40mm, and using proportionality constants derived for the different materials required, Equations (19) to (22) can be used to estimate the amounts of concrete, HDPE (with density 970 kg/m3), polypropylene and excavation necessary.

$$A_{internal} = (L - W) * W + \frac{\pi}{4} * W^2 \quad (18)$$

$$M_{concrete} = 0.0013 * A_{internal} \quad (19)$$

$$M_{HDPE} = 1.22 * A_{internal} * \frac{40}{1000} * 0.0254 * 970 \quad (20)$$

$$M_{polypropylene} = 1.22 * A_{internal} * 0.203 \quad (21)$$

$$Excavation\ Volume = A_{internal} * 0.9 \quad (22)$$

Well drilling

The inventory flows necessary for the drilling of the wells are all derived from the Equations (23) to (26) (Rocco et al., 2020).

$$E_{drilling} = 10\text{^}(0.000319 * MD + 2.04) \quad (23)$$

Where $E_{drilling}$ is given in MWh, and MD stands for the meters drilled in m. If the energy is provided by a diesel generator, a conversion efficiency of 40% is assumed.

$$V_{cement} = 10\text{^}(1.23 * \log(MD) - 2.15) \quad (24)$$

Where V_{cement} is the volume of cement [m^3] and using a density of cement of 3,150 kg/m^3.

$$M_{steel} = 10\text{^}(1.22 * \log(L_w) - 1.78) \quad (25)$$

Where M_{steel} is given in tons and L_w stands for the well length in m.

$$V_{drilling\ mud} = 0.157 * MD \quad (26)$$

Where $V_{drilling\ mud}$ is the volume of drilling mud [m^3] and using a density of the mud of 1,300 kg/m^3.

In addition, the amount of drilling cuttings to be de disposed-off was estimated from Equation (27).

$$V_{cuttings} = 0.0948 * MD^{1.046} \quad (27)$$

Where $V_{cuttings}$ is the volume of cuttings produced [m^3] and using a density of 2,400 kg/m^3.

Filter

The filters' masses are assumed to be proportional to the mass of the filters at Rittershoffen according to the pipe radius ratio (Equation (29)). The radius of the pipes is hereby calculated from Equation (28).

$$r_{pipe} = \left(\frac{Q}{\pi * 3600 * 1.5}\right)^{0.5} \quad (28)$$

Where Q is a variable parameter describing the flow rate in t/h and assuming a water density of 1000kg/m^3 so that r_{pipe} is in m.

$$M_{Filter,new} = \frac{r_{new}}{r_{known}} * M_{Filter,known} \quad (29)$$

Where r_{known} is the radius of the pipes at the Rittershoffen plant (calculated from Equation (4) using 306 t/h flow rate), r_{new} the radius of the pipes at the powerplant under study (calculated from Equation (4) using the variable parameter Q as flow rate), and $M_{Filter,known}$ the mass of the filter in Rittershoffen, namely 931kg.

Valve

The valves consist up to 82% of unalloyed steel and 18% of chromium steel. The mass of these valves is estimated similarly to the one of the filters, using Equation

$$M_{Valve,new} = \frac{r_{new}}{r_{known}} * M_{Valve,known} \quad (30)$$

Where r_{known} is the radius of the pipes at the Rittershoffen plant (calculated from Equation (4) using 306t/h flow rate), r_{new} the radius of the pipes at the powerplant under study (calculated from Equation (4) using the variable parameter Q as flow rate), and $M_{Valve,known}$ the mass of the valve in Rittershoffen, namely 18 106kg.

Operation and maintenance

The amount of corrosion inhibitor and scaling inhibitor necessary during the operation and maintenance phases can be estimated from the flow rate assuming a weight% of 5ppm for each of them (Equations (31) and (32))

$$M_{corrosion\ inhibitor,per\ year} = Q * OH * 5ppm * 1000 \quad (31)$$

$$M_{scaling\ inhibitor,per\ year} = Q * OH * 5ppm * 1000 \quad (32)$$

With the flow Q in t/h and OH the operating hours per year.

The corrosion inhibitor was modelled with 20% ethylene glycol, 10% butyl glycol, 5% ammonium quaternaire, and 10% fatty acid. Butyl glycol is not modelled as such in ecoinvent (ethyl tert-butyl ether is), so it was modelled as ethylene glycol. The closest available in ecoinvent for quaternary ammonium chloride is ammonium chloride production

The scaling inhibitor is assumed to be a polymer with less than 0.05% 1,2-benzoisothiazolinone. It was modelled as benzo[thia]diazole-compound

The lubricating oil requirement is derived from Equation (33).

$$M_{lubricating\ oil,per\ year} = 20\frac{l}{day} * 365 * 0.9\frac{kg}{l} \quad (33)$$

6670kg of salt and 700m^3 water, modelled as water from unspecified origin, were assumed necessary for the operation and maintenance of the plant per year.

Direct gas emissions during operation of the plant are accounted for as CO_2 and CH_4 releases, calculated with Equation(34) and (35).

$$M_{CO2,operation} = Q * Operating\ hours * f_{CO2} * f_{direct} * 1000 \quad (34)$$

$$M_{CH4,operation} = Q * Operating\ hours * f_{CH4} * f_{direct} * 1000 \quad (35)$$

Where Q is the flow rate in t/h, f_{CO_2} the fraction of CO_2 in the geothermal fluid, f_{CH_4} the fraction of CH_4 in the geothermal fluid, and f_{direct} the fraction of direct emissions from the geothermal fluid.

End of life

Only the cuttings produced during well drilling and scalings removed during operation and maintenance are treated in the end of life. The cuttings were treated using the ecoinvent process 'treatment of drilling waste, residual material landfill' and the scalings with the ecoinvent process 'treatment of low-level radioactive waste, surface or trench deposit'.

A1. C. Fixed parameters used in the reference LCA model

Table 18 – Fixed parameters used in the reference LCA model.

Phase	Parameter Name	default	unit
Drilling	Content bentonite drilling mud	0.11	-
Drilling	Content barite drilling mud	0	-
Drilling	Content calcium carbonate drilling mud	0.1	-
Drilling	Content carboxymethyl cellulose drilling mud	0.08	-
Drilling	Content chemical inorganic drilling mud	0.27	-
Drilling	Content citric acid drilling mud	0.01	-
Drilling	Content monoethanolamine drilling mud	0	-
Drilling	Content sodaash drilling mud	0.01	-
Drilling	Content sodium chloride drilling mud	0.03	-
Drilling	Content sodium hydroxide drilling mud	0.01	-
Drilling	Content triethanolamine drilling mud	0	-
Drilling	Content water drilling mud	0.36	-
Drilling	Length retention basin 1	27.5	m
Drilling	Length retention basin 2	73	m
Drilling	Width retention basin 1	21	m
Drilling	Width retention basin 2	44.5	m
Drilling	Content silica in cement	0.31	-

Exploration	Distance travelled exploration	880	km
General	Loss	0.000833333	-/y
General	Content bentonite in cement	0.03	-
Operation and maintenance	Mass salt	6,670	kg
Operation and maintenance	Volume water blasting	700	m3
Operation and maintenance	Fraction heat exchanger replaced	0.05	-
Operation and maintenance	Fraction line shaft pump replaced	0.0714286	-
Operation and maintenance	Fraction pump replaced	0.05	-
Operation and maintenance	Fraction valve replaced	0.05	-
Operation and maintenance	Fraction filter replaced	0.05	-
Operation and maintenance	Fraction pipe replaced	0.025	-
Power plant	Mass of cables	19,017	kg
Power plant	Thickness aluminium	0.002	m
Power plant	Thickness rockwool	0.08	m
Stimulation	Pressure difference	40	bar
Stimulation	Pump efficiency	0.75	-
Stimulation	Content organic chemical	0.25	-
Stimulation	Content KCl	0.25	-
Stimulation	Content water	0.5	-
Transport	Distance chemical stimulation	500	km
Transport	Distance for the transport of drilling equipment	500	km
Transport	Transport pipes	500	km
Transport	Transport heat exchanger	500	km
Transport	Transport line shaft pump	7,600	km
Transport	Transport line shaft pump across the sea	44,200	km
Transport	Transport pump	500	km
Transport	Transport filter	500	km
Transport	Transport valve	500	km
Transport	Transport air cooler	500	km
Transport	Transport scaling	293.667	km

A1. D. Comparison with literature

The adjustments made to the “Pratiwi Model” and the “GEOENVI Model” to reduce their differences were partly made prior to starting the comparison, and partly after analysing the contributing flows to each impact category. At first, only (1) the specific equipment for the heat user (transport pipes, treatment of heat at the users’ site) was removed from the “Pratiwi Model”; (2) the lifetime of the powerplant was set to 25 years in the “GEOENVI Model”; (3) the

"GEOENVI Model" was modified to rely on the French electricity mix available in ecoinvent and not the tailor-made electricity mix; and (4) the ILCD 2016 impact assessment methodology was used for both models. Table 19 shows that the "GEOENVI Model" then underestimates by approximately 20% most of the impacts compared to the "Pratiwi Model". For both models, the diesel requirements during well drilling (9.4% for the "GEOENVI Model" and 12.9% for the "Pratiwi Model") and the electricity need during the operation and maintenance phase (38.1% for the "GEOENVI Model" and 46.5% for the "Pratiwi Model") contribute the most to the climate change impact category. However, the modelled inventory flows for both processes in the "GEOENVI Model" are smaller than in the "Pratiwi Model", which led us to adjust these values to increase the comparability of both models.

Table 19 – Comparison of the ILCD 2016 impacts for the "Pratiwi Model" and "GEOENVI Model" of the Rittershoffen geothermal heat plant over its life time.

Impact category (ILCD 2016)	Unit	Pratiwi Model	GEOENVI Model	(GEOENVI-Pratiwi)/ GEOENVI
climate change - GWP 100a	kg CO_2-Eq	2.46E+07	2.13E+07	-15.7%
ecosystem quality - freshwater and terrestrial acidification	mol H+-Eq	2.07E+05	1.90E+05	-9.1%
ecosystem quality - freshwater ecotoxicity	CTUh.m3.yr	2.86E+08	6.49E+08	56.0%
ecosystem quality - freshwater eutrophication	kg P-Eq	7.22E+03	7.01E+03	-2.9%
ecosystem quality - ionising radiation	mol N-Eq	1.21E+02	1.06E+02	-13.7%
ecosystem quality - marine eutrophication	kg N-Eq	4.68E+04	3.58E+04	-31.0%
ecosystem quality - terrestrial eutrophication	mol N-Eq	4.59E+05	3.51E+05	-30.8%
human health - carcinogenic effects	CTUh	2.44E+00	3.02E+00	19.1%
human health - ionising radiation	kg U235-Eq	6.71E+07	5.93E+07	-13.1%
human health - non-carcinogenic effects	CTUh	1.02E+01	1.04E+01	1.3%
human health - ozone layer depletion	kg CFC-11-Eq	1.25E+01	1.08E+01	-15.8%
human health - photochemical ozone creation	kg ethylene-Eq	1.33E+05	1.01E+05	-30.9%
human health - respiratory effects, inorganics	kg PM2.5-Eq	1.90E+04	1.61E+04	-18.4%
resources - land use	kg Soil Organic Carbon	4.61E+07	4.08E+07	-12.8%
resources - mineral, fossils and renewables	kg Sb-Eq	1.46E+03	1.38E+03	-5.7%

The difference between the results of the freshwater ecotoxicity impact category between both models was also investigated. The main contributing flows for the "GEOENVI Model" were the cable production (39.1%), the heat exchanger (15.1%), the electricity required during operation

(12.1%), and the steel manufacturing process (6.44%) and drilling mud (5.43%) required for the well drilling process. On the contrary, the process of cable production contributed only up to 9% in the "Pratiwi Model", which is however not related to differences in the modelled cable weights in both models: 11.5t in the "Pratiwi Model" versus 19.0t in the "GEOENVI Model". In fact, Table 20 still shows differences between both models after reducing the cable weight in the "GEOENVI Model" to match the value of the "Pratiwi Model".

Table 20 – Comparison of the ILCD 2016 impacts for the "Pratiwi Model" and "GEOENVI Model" of the Rittershoffen geothermal heat plant. The mass of the cables was adapted in the "GEOENVI Model" to match the one modelled in the "Pratiwi Model":

Impact category	Reference unit	Pratiwi Model	GEOENVI Model	(GEOENVI-Pratiwi)/ GEOENVI
climate change - GWP 100a	kg CO_2-Eq	2.46E+07	2.36E+07	-4.5%
ecosystem quality - freshwater and terrestrial acidification	mol H+-Eq	2.07E+05	2.11E+05	1.5%
ecosystem quality - freshwater ecotoxicity	CTUh.m3.yr	2.86E+08	5.63E+08	49.3%
ecosystem quality - freshwater eutrophication	kg P-Eq	7.22E+03	6.87E+03	-5.0%
ecosystem quality - ionising radiation	mol N-Eq	1.21E+02	1.19E+02	-1.6%
ecosystem quality - marine eutrophication	kg N-Eq	4.68E+04	4.57E+04	-2.5%
ecosystem quality - terrestrial eutrophication	mol N-Eq	4.59E+05	4.54E+05	-1.0%
human health - carcinogenic effects	CTUh	2.44E+00	3.06E+00	20.0%
human health - ionising radiation	kg U235-Eq	6.71E+07	6.63E+07	-1.2%
human health - non-carcinogenic effects	CTUh	1.02E+01	1.00E+01	-2.1%
human health - ozone layer depletion	kg CFC-11-Eq	1.25E+01	1.22E+01	-2.8%
human health - photochemical ozone creation	kg ethylene-Eq	1.33E+05	1.28E+05	-3.6%
human health - respiratory effects, inorganics	kg PM2.5-Eq	1.90E+04	1.76E+04	-8.2%
resources - land use	kg Soil Organic Carbon	4.61E+07	4.49E+07	-2.7%
resources - mineral, fossils and renewables	kg Sb-Eq	1.46E+03	1.42E+03	-3.1%

A1. E. Contribution of stimulation processes

The reference LCA model was developed to represent EGS for heat generation with very low direct emissions. However, the hydraulic and chemical stimulation contribute only slightly to the outcomes of the different impact categories as shown in Table 21 for the reference LCA model and the French electricity mix.

Table 21 – Contribution in % of the hydraulic and chemical stimulation to the impacts calculated for ILCD2018 impact categories for the reference LCA model and the electrical shares from the French electricity mix.

	Chemical stimulation	Hydraulic stimulation
ecosystem quality freshwater ecotoxicity	0.12%	0.00%
human health non-carcinogenic effects	0.07%	0.00%
human health carcinogenic effects	0.04%	0.00%
resources minerals and metals	0.10%	0.00%
climate change climate change biogenic	0.05%	0.00%
climate change climate change fossil	0.14%	0.02%
climate change climate change land use and land use change	0.02%	0.00%
climate change climate change total	0.14%	0.02%
ecosystem quality freshwater and terrestrial acidification	0.07%	0.03%
ecosystem quality freshwater eutrophication	0.05%	0.00%
ecosystem quality marine eutrophication	0.07%	0.07%
ecosystem quality terrestrial eutrophication	0.09%	0.08%
human health ionising radiation	0.00%	0.00%
human health ozone layer depletion	0.06%	0.01%
human health photochemical ozone creation	0.13%	0.07%
human health respiratory effects inorganics	0.13%	0.01%
resources dissipated water	0.12%	0.00%
resources fossils	0.06%	0.00%
resources land use	0.05%	0.00%

A1. F. Key variable parameters

Table 22 displays the first order Sobol indexes for the seven impact categories of interest and the 35 variable parameters included in the reference model.

Table 22 – First order Sobol indexes for the seven impact categories of interest and the 35 variable parameters included in the reference model. EQ stands for ecosystem quality, HH for human health, and R for resources. The sum of all electrical shares sums P Ele Oil, P Ele Bio, P Ele Hydro, P Ele NG, P Ele Wind, P Ele Coal, P Ele Solar, P Ele Nuclear.

		EQ - freshwater ecotoxicity	HH - non-carcinogenic effects	HH - carcinogenic effects	R - minerals and metals	climate change total	EQ - freshwater and terrestrial acidification	R - fossils
4	MWth	37.8%	36.0%	59.0%	60.5%	33.2%	28.2%	46.4%
19	power_LSP_kW	10.0%	12.0%	12.0%	4.5%	11.8%	7.8%	19.9%
10	well_length	3.1%	1.0%	5.7%	4.4%	2.4%	5.8%	1.1%
2	Operating_hours	1.5%	0.6%	5.2%	4.5%	0.2%	0.5%	0.1%
13	N_well_production	3.0%	3.4%	4.7%	2.4%	3.0%	2.4%	4.9%
3	LT_years	0.7%	0.4%	2.7%	5.2%	0.1%	0.1%	0.0%
12	N_well_injection	0.6%	0.4%	0.8%	0.6%	0.6%	0.5%	0.6%

20	power_pump_kW	1.3%	1.7%	0.4%	0.6%	2.7%	1.9%	4.8%
1	Flow_rate_tph	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
18	M_heatexchanger_Rittershoffen_kg	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
34	P_Ele_Bio	0.8%	19.0%	0.1%	0.0%	0.1%	0.0%	0.5%
33	P_Ele_Wind	0.0%	0.3%	0.1%	0.1%	1.0%	0.7%	1.6%
31	P_Ele_Oil	22.4%	-0.1%	0.1%	0.0%	2.7%	6.2%	0.1%
28	P_Ele_Coal	-0.1%	2.2%	0.1%	1.2%	20.0%	20.2%	3.1%
30	P_Ele_Nuclear	0.7%	2.1%	0.1%	0.3%	2.5%	1.6%	1.2%
32	P_Ele_Hydro	0.5%	1.2%	0.1%	0.2%	1.4%	1.0%	2.7%
11	Ratio_MD_well_length	0.2%	0.0%	0.1%	0.2%	0.2%	0.8%	0.1%
35	P_Ele_Solar	-0.1%	0.1%	0.1%	3.8%	0.1%	0.0%	0.4%
29	P_Ele_NG	0.8%	1.2%	0.0%	0.3%	0.1%	0.7%	0.1%
15	A_powerplant_m2	0.0%	0.0%	0.0%	1.2%	0.0%	0.0%	0.0%
14	km_cuttings	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
17	L_gw_pipe_m	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5	E_exploration_MJ	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
24	M_scaling_kgpyear	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6	M_CO2_release_welltesting_kg	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
21	P_CH4_gf	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
22	P_CO2_gf	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
23	P_direct_emissions	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
26	M_cement_abd_kg	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
8	V_hydraulic_sti_m3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
27	E_abd_diesel_MJ	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	V_stimulated_m3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9	A_platform	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
16	L_fw_pipe_m	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25	km_passenger_OM_pday	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Sum P Elec	25.1%	25.9%	0.8%	5.9%	27.9%	30.5%	9.7%
	Sum 4, 19, 13, 20, 10, 12	55.7%	54.4%	82.5%	73.0%	53.7%	46.6%	77.8%
	Total	80.8%	80.4%	83.3%	78.9%	81.6%	77.0%	87.4%

A1. G. Simplified models

The equations for the simplified models based on these 14 variable parameters are listed below per impact category.

Climate change, total

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[0.0588f_{biomass}+1.28f_{coal}+0.00426f_{hydro}\\+0.434f_{NG}+0.0115f_{nuclear}+0.917f_{oil}+0.0624f_{solar}+0.0137f_{wind}]\\+5.08\cdot 10^{-9}[2.47\cdot 10^{3}P_{th}+2.42\cdot 10^{5}N_{in}+3.28\cdot 10^{3}N_{prod}\cdot P_{LSP}+16.6P_{pump}\\+(N_{in}+N_{prod})\cdot\begin{pmatrix}790.0\cdot 10^{0.000399\cdot L_W+2.04}+277.0L_W\\+27.9L_W^{1.05}+58.5L_W^{1.22}+26.1L_W^{1.23}\end{pmatrix}\\+7.06\cdot 10^{6}]\end{gathered}}{P_{th}} \tag{36}$$

Resources, fossil

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[0.689f_{biomass}+15.4f_{coal}+0.0458f_{hydro}\\+7.81f_{NG}+13.4f_{nuclear}+11.1f_{oil}+0.915f_{solar}+0.204f_{wind}]\\+5.04\cdot 10^{-9}[3.56\cdot 10^{4}P_{th}+3.25\cdot 10^{6}N_{in}+4.65\cdot 10^{4}N_{prod}\cdot P_{LSP}+221.0P_{pump}\\+(N_{in}+N_{prod})\cdot\begin{pmatrix}1.05\cdot 10^{4}\cdot 10^{0.000398\cdot L_W+2.04}+3.83\cdot 10^{3}L_W+484.0L_W^{1.05}\\+839.0L_W^{1.22}+126.0L_W^{1.23}\end{pmatrix}\\+5.21\cdot 10^{7}]\end{gathered}}{P_{th}} \tag{37}$$

Resources, minerals

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[7.07\cdot 10^{-7}f_{biomass}+2.56\cdot 10^{-6}f_{coal}\\ +1.92\cdot 10^{-7}f_{hydro}+1.03\cdot 10^{-7}f_{NG}+2.24\cdot 10^{-7}f_{nuclear}\\ +5.01\cdot 10^{-7}f_{oil}+8.54\cdot 10^{-6}f_{solar}+1.6\cdot 10^{-6}f_{wind}]\\ +5.01\cdot 10^{-9}[0.0415P_{th}+11.2N_{in}+0.105N_{prod}\cdot P_{LSP}+0.00416P_{pump}\\ +(N_{in}+N_{prod})\cdot\begin{pmatrix}0.000727\cdot 10^{0.000396\cdot L_W+2.04}+0.0233L_W+0.000734L_W^{1.05}\\ +0.00097L_W^{1.22}+0.000137L_W^{1.23}\end{pmatrix}\\ +416.0]\end{gathered}}{P_{th}} \tag{38}$$

Ecosystem quality – Freshwater ecotoxicity

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[0.309f_{biomass}+0.0891f_{coal}+0.00554f_{hydro}\\ +0.0114f_{NG}+0.0251f_{nuclear}+0.671f_{oil}+0.0937f_{solar}+0.0374f_{wind}]\\ +4.98\cdot 10^{-9}[2.85\cdot 10^{3}P_{th}+8.14\cdot 10^{5}N_{in}+7.97\cdot 10^{3}N_{prod}\cdot P_{LSP}+236.0P_{pump}\\ +(N_{in}+N_{prod})\cdot\begin{pmatrix}131.0\cdot 10^{0.0004\cdot L_W+2.04}+332.0L_W+206.0L_W^{1.05}\\ +66.4L_W^{1.22}+2.8L_W^{1.23}\end{pmatrix}+\ 5.53\cdot 10^{6}]\end{gathered}}{P_{th}} \tag{39}$$

Ecosystem quality – Freshwater and terrestrial acidification

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[0.00211f_{biomass}+0.00949f_{coal}+2.19\cdot 10^{-5}f_{hy}\\ +0.000241f_{NG}+7.09\cdot 10^{-5}f_{nuclear}+0.00888f_{oil}+0.000511f_{solar}+9.08\cdot 10^{-5}f_{win}\\ +5.19\cdot 10^{-9}[10.9P_{th}+6.28\cdot 10^{3}N_{in}+25.6N_{prod}\cdot P_{LSP}+0.768P_{pump}\\ +(N_{in}+N_{prod})\cdot\begin{pmatrix}11.2\cdot 10^{0.000402\cdot L_W+2.04}+1.84L_W+0.155L_W^{1.05}\\ +0.256L_W^{1.22}+0.0671L_W^{1.23}\end{pmatrix}+\ 6.25\cdot 10^{4}]\end{gathered}}{P_{th}} \tag{40}$$

Human health – Non-carcinogenic effects

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[3.37\cdot 10^{-7}f_{biomass}+6.23\cdot 10^{-8}f_{coal}\\ +9.67\cdot 10^{-10}f_{hydro}+2.68\cdot 10^{-9}f_{NG}+3.97\cdot 10^{-9}f_{nuclear}+2.14\cdot 10^{-8}f_{oil}\\ +2.94\cdot 10^{-8}f_{solar}+7.09\cdot 10^{-9}f_{wind}]+5.0\cdot 10^{-9}[0.000496P_{th}+0.192N_{in}\\ +0.00141N_{prod}\cdot P_{LSP}+6.64\cdot 10^{-5}P_{pump}\\ +(N_{in}+N_{prod})\cdot\begin{pmatrix}1.74\cdot 10^{-5}\cdot 10^{0.000401\cdot L_W+2.04}+4.1\cdot 10^{-5}L_W+3.56\cdot 10^{-5}L_W^{1.05}\\ +1.18\cdot 10^{-5}L_W^{1.22}+1.33\cdot 10^{-6}L_W^{1.23}\end{pmatrix}\\ +1.2]\end{gathered}}{P_{th}} \tag{41}$$

Human health – Carcinogenic effects

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[3.37\cdot 10^{-9}f_{biomass}+2.01\cdot 10^{-9}f_{coal}\\ +3.83\cdot 10^{-10}f_{hydro}+5.28\cdot 10^{-10}f_{NG}+5.95\cdot 10^{-10}f_{nuclear}+2.08\cdot 10^{-9}f_{oil}\\ +2.21\cdot 10^{-9}f_{solar}+2.21\cdot 10^{-9}f_{wind}]\\ +5.16\cdot 10^{-9}[0.000172P_{th}+0.0511N_{in}+0.000501N_{prod}\cdot P_{LSP}+1.05\cdot 10^{-5}P_{pump}\\ +(N_{in}+N_{prod})\cdot\begin{pmatrix}1.2\cdot 10^{-6}\cdot 10^{0.000396\cdot L_W+2.04}+9.63\cdot 10^{-6}L_W+9.74\cdot 10^{-6}L_W^{1.05}\\ +4.13\cdot 10^{-6}L_W^{1.22}+6.38\cdot 10^{-8}L_W^{1.23}\end{pmatrix}\\ +0.231]\end{gathered}}{P_{th}} \tag{42}$$

Appendix 2 - Background data for the Flash category

A2. A. Key variable parameters

Figure 18 displays the first order Sobol indexes for the seven impact categories of interest and the 24 variable parameters included in the reference LCA model.

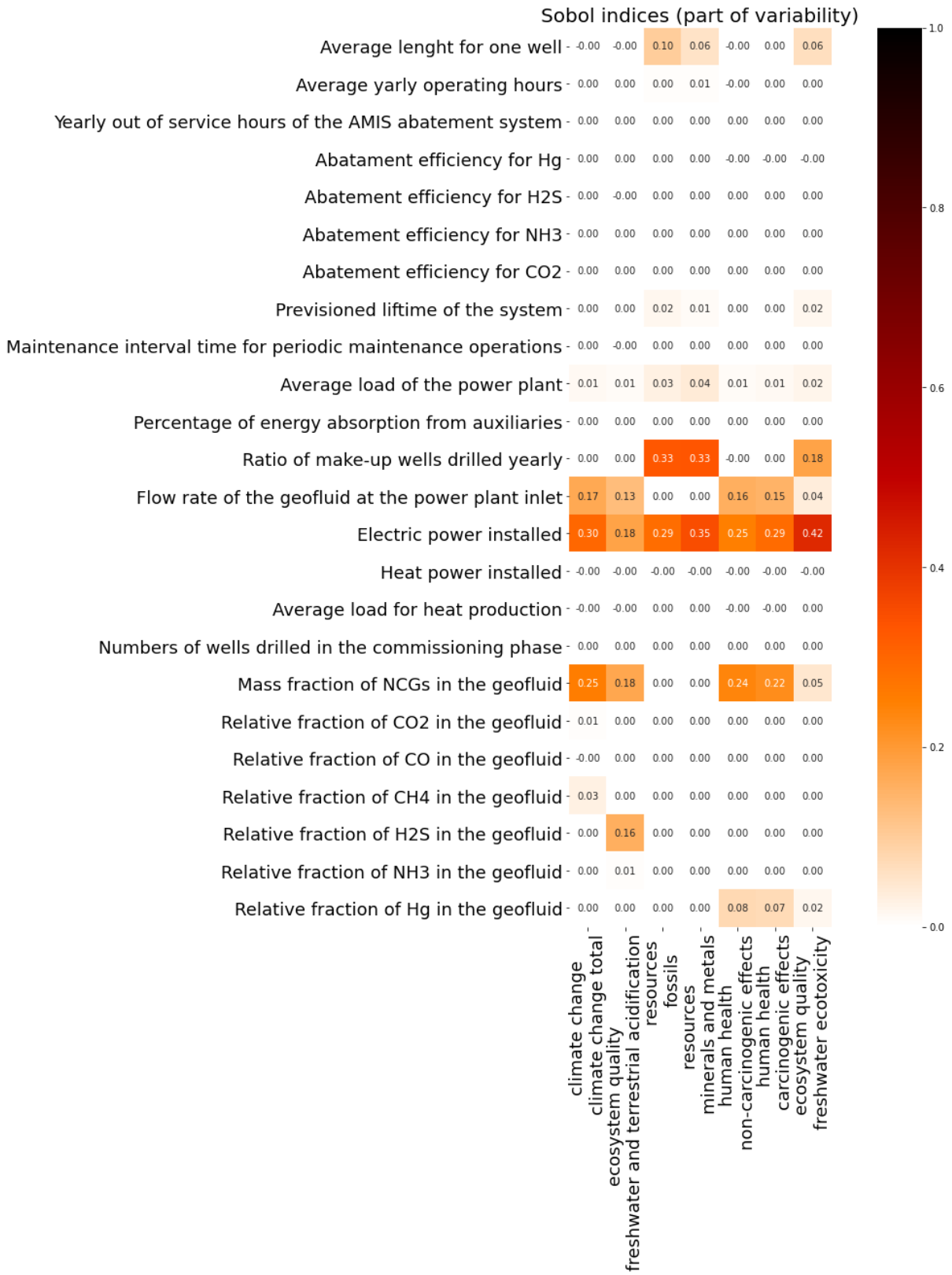

Figure 18 – First order Sobol indexes derived for the reference model for Flash

A2. B. Simplified models

The equations for the simplified models for the Flash category are listed below per impact category.

Climate change, total

$$\frac{2.56 \cdot 10^{-7} ElecCapacity^2 + 1.18 * FlowRate * fNCG + 4.14 \cdot 10^3}{ElecCapacity} \quad (43)$$

Resources, fossil

$$\frac{\begin{gathered} 3.8 \cdot 10^{-6} ElecCapacity^2 + 0.0509 * ElecCapacity + \\ 4.73 * MakeUpWellsRatio * l + 3.54 * MakeUpWellsRatio * l^{1.2} + \\ 0.178 MakeUpWellsRatio * l^{1.23} + 4.03 \cdot 10^4 MakeUpWellsRatio + \\ 0.0582 * l^{1.2} + 9.29 \cdot 10^3 \end{gathered}}{ElecCapacity} \quad (44)$$

Resources, minerals

$$\frac{\begin{gathered} 6.4 \cdot 10^{-12} ElecCapacity^2 + 3.14 \cdot 10^{-7} ElecCapacity + \\ 7.5 \cdot 10^{-6} MakeUpWellsRatio * l + 3.95 \cdot 10^{-6} MakeUpWellsRatio * l^{1.2} + \\ 9.79 \cdot 10^{-8} MakeUpWellsRatio * l^{1.23} + 0.0885 MakeUpWellsRatio + \\ 6.7 \cdot 10^{-8} * l^{1.2} + 0.0223 \end{gathered}}{ElecCapacity} \quad (45)$$

Ecosystem quality – Freshwater ecotoxicity

$$\frac{\begin{gathered} 5.76 \cdot 10^{-7} ElecCapacity^2 + 0.0129 ElecCapacity + \\ 10.7 MakeUpWellsRatio * l + 0.342 MakeUpWellsRatio * l^{1.2} + \\ 1.37 \cdot 10^4 MakeUpWellsRatio + 0.174 * l + 1.24 \cdot 10^4 \end{gathered}}{ElecCapacity} \quad (46)$$

Ecosystem quality – Freshwater and terrestrial acidification

$$\frac{FlowRate * fNCG * (1.54 * fH2S + 0.00822)}{ElecCapacity} \quad (47)$$

Human health – Non-carcinogenic effects

$$\frac{0.978 * FlowRate * fHg * fNCG}{ElecCapacity} \quad (48)$$

Human health – Carcinogenic effects

$$\frac{4.14 \cdot 10^{-14} ElecCapacity^2 + 0.00827 * FlowRate * fHg * fNCG + 0.000731}{ElecCapacity} \quad (49)$$

Appendix 3 - Background data for the CHP category

A3. A. Fixed parameters used in the reference LCA model

Table 23 show the fixed parameters used in the definition of the reference LCA model for the CHP category. The process of fixing parameters was only done when having first assigned a distribution and when the Sobol index was close to 0 it was fixed.

Table 23 – Fixed parameters used in the modelling of the reference LCA model for the CHP category

Fixed parameter	Value	Unit
Steel use in buildings	990	kg/MW
Replacement rate	105	%
End of life Cement	25,000	kg/well
Silica in well construction	13.5	kg/meter
Bentonite in well construction	28.4	kg/meter
Perlite in well construction	0.7	kg/meter
Retardant in well construction	0.08	kg/meter
Binder in well construction	0.2	kg/meter
Soap in well construction	0.5	kg/meter
Caustic Soda in well construction	1.3	kg/meter
CH4 in geofluid	0.0021/1000	kg/kg
H2S in geofluid	0.37/1000	kg/kg
H2 in geofluid	0.015/1000	kg/kg
Land occupation of power plant area	15	m2/Well
Land transformation of power plant area	90	m2/Well
Excavation for pipelines	18	m3/meter
Concrete in pipelines	0.3	m3/meter
Aluminium in pipelines	6.3	kg/meter
Aluminium in buildings	577	kg/MW
Aluminium in machinery	255	kg/MW
Stone wool in pipelines	594	kg/MW
Stone wool in buildings	264	kg/MW
Copper in building	150	kg/MW
Copper in machinery	377	kg/MW
Plastics in buildings	729	kg/MW
Plastics in machinery	9	kg/MW
Asphalt in building	36,108	kg/MW
Titanium in machinery	465	kg/MW
GRP in machinery	2,142	kg/MW
Lubrication oil in machinery	683	kg/MW
Sodium hypochlorite for maintenance	700	kg

Sea transportation of material for wells	103	kg/meter
Sea transportation of material for pipelines	246	kg/meter
Sea transportation of material for building and machinery	67,277	kg/MW
Land transportation of material for wells	103	kg/meter
Land transportation of material for pipelines	246	kg/meter
Land transportation of material for building and machinery	67,277	kg/MW
Sea transport distance	2,178	km
Land transport distance	1,000	km

A3. B. Key variable parameters

Figure 19 displays the first order Sobol indexes for the seven impact categories of interest and the 14 variable parameters included in the reference LCA model.

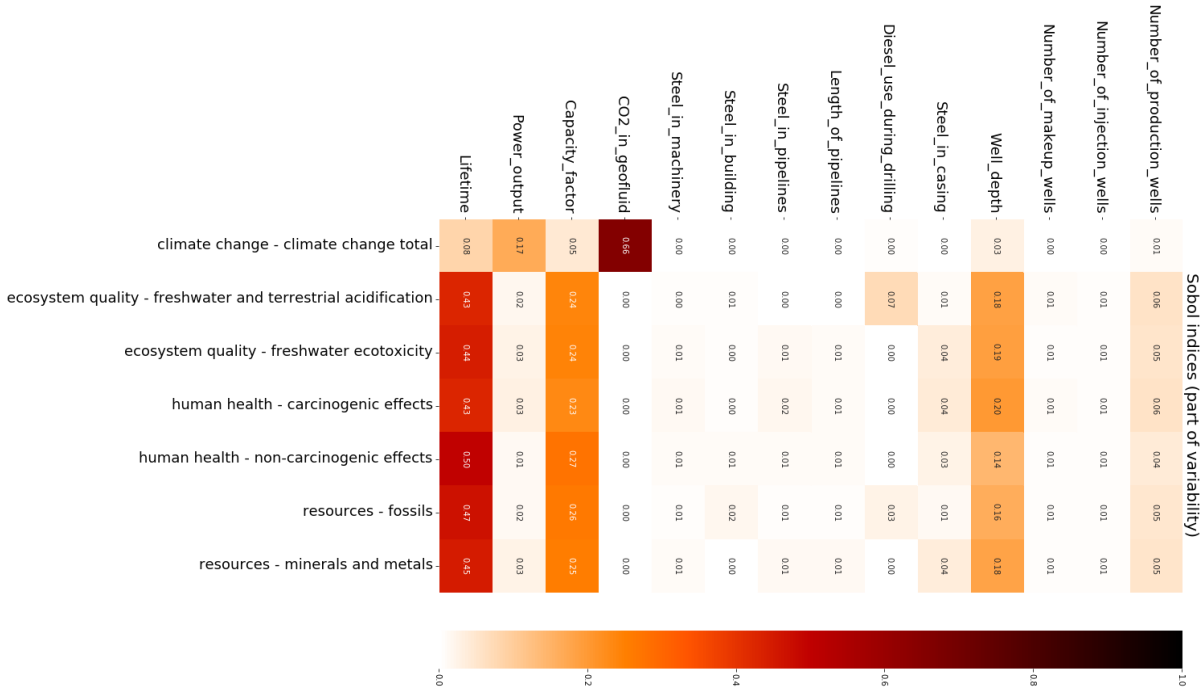

Figure 19 – First order Sobol indexes derived for the reference LCA model for the CHP category

A3. C. Simplified models

The equations for the simplified models are listed below per impact category per kWh of electrical output.

Climate change, total

$$\frac{3.63 \cdot 10^{3} CO_{2ingeofluid}}{Power_{output}} + 1.4 \cdot 10^{-6} Power_{output} + 0.000625 + \frac{1.02}{Power_{output}} + \frac{77.1}{Power_{output}^{2}} \quad (50)$$

Resources, fossil

$$\frac{0.000514 Lifetime + 0.000216 Well_{depth} + 0.534}{Capacity_{factor} Lifetime} \quad (51)$$

Resources, minerals

$$\frac{9.91 \cdot 10^{-10} Lifetime + 2.77 \cdot 10^{-10} Well_{depth} + 5.94 \cdot 10^{-7}}{Capacity_{factor} Lifetime} \quad (52)$$

Ecosystem quality – Freshwater ecotoxicity

$$\frac{2.38 \cdot 10^{-5} Lifetime + 5.98 \cdot 10^{-5} Well_{depth} + 0.118}{Capacity_{factor} Lifetime} \quad (53)$$

Ecosystem quality – Freshwater and terrestrial acidification

$$\frac{2.7 \cdot 10^{-11} Diesel_{useduringdrilling} Well_{depth} + 3.15 \cdot 10^{-7} Lifetime + 7.62 \cdot 10^{-8} Well_{depth} + 0.000275}{Capacity_{factor} Lifetime} \quad (54)$$

Human health – Non-carcinogenic effects

$$\frac{8.35 \cdot 10^{-12} Lifetime + 5.99 \cdot 10^{-12} Well_{depth} + 1.81 \cdot 10^{-8}}{Capacity_{factor} Lifetime} \quad (55)$$

Human health – Carcinogenic effects

$$\frac{8.23 \cdot 10^{-13} Lifetime + 2.36 \cdot 10^{-14} Number_{ofproductionwells} + 5.67 \cdot 10^{-14} Well_{depth} \left(Number_{ofproductionwells} + 40.1\right) + 8.77 \cdot 10^{-9}}{Capacity_{factor} Lifetime} \quad (56)$$

Appendix 4 - Background data for the HeatORC category

A4. A. Key variable parameters

Table 24 shows the first order Sobol indexes for the seven impact categories of interest and all variable parameters included in the reference LCA model.

Table 24 – First order Sobol indexes for the seven impact categories of interest and all variable parameters included in the reference model for HeatORC. EQ stands for ecosystem quality, HH for human health, and R for resources.

	Length well	Ratio meters drilled and well length	Number injection wells	Number production wells	Distance for the cuttings	Flow rate	Power ESP	Power pump	Operating hours	Lifetime	Fraction of direct emissions	CO2 content gas release	CH4 content gas release	Mass scaling	Energy for well abandonment	Mass cement for well abandonment	Mass Balmatt heat exchanger	Thermal power	CO2 released	Volume hydraulic stimulation	Area drilling platform	Area of the power plant
climate change - climate change total	8	2	9	7	1	0	16	19	10	4	0	0	0	0	3	1	0	39	0	0	0	0
ecosystem quality - freshwater and terrestrial acidification	6	2	4	9	1	1	21	6	14	5	0	0	0	0	6	0	2	39	0	0	0	0
resources - fossils	4	1	14	1	1	0	9	38	5	2	0	0	0	0	2	0	0	39	0	0	0	0
resources - minerals and metals	10	3	3	9	1	0	19	2	15	10	0	0	0	0	0	0	0	39	0	0	0	5
human health - non-carcinogenic effects	6	2	4	12	1	0	26	6	14	5	0	0	0	0	1	0	0	40	0	0	0	0
human health - carcinogenic effects	6	1	2	14	0	0	32	1	15	4	0	0	0	0	0	0	1	40	0	0	0	0
ecosystem quality - freshwater ecotoxicity	7	2	3	13	1	0	28	3	15	5	0	0	0	0	1	0	0	40	0	0	0	0

A4. B. Simplified models

The equations for the simplified models based on the selected variable parameters are listed below per impact category

Climate change, total

$$\frac{0.000326 * Operating_{hours} * power_{pumpkW} + 0.957 * power_{ESPkW} + 423.0}{MWth * Operating_{hours}} \quad (57)$$

Resources, fossil

$$\frac{0.0112 * N_{wellinjection} * power_{pumpkW} + 0.167 * N_{wellinjection} + 1.93}{MWth} \quad (58)$$

Resources, minerals

$$\frac{1.7 \cdot 10^{-7} * Operating_{hours} + 3.0 \cdot 10^{-5} * power_{ESPkW} + 0.0211}{MWth * Operating_{hours}} \quad (59)$$

Ecosystem quality – Freshwater ecotoxicity

$$\frac{0.014 * Operating_{hours} + 2.29 * power_{ESPkW} + 486.0}{MWth * Operating_{hours}} \quad (60)$$

Ecosystem quality – Freshwater and terrestrial acidification

$$\frac{0.000138 * Operating_{hours} + 0.00733 * power_{ESPkW} + 3.35}{MWth * Operating_{hours}} \quad (61)$$

Human health – Non-carcinogenic effects

$$\frac{6.85 \cdot 10^{-9} * Operating_{hours} + 3.98 \cdot 10^{-7} * power_{ESPkW} + 9.05 \cdot 10^{-5}}{MWth * Operating_{hours}} \quad (62)$$

Human health – Carcinogenic effects

$$\frac{3.28 \cdot 10^{-10} * Operating_{hours} + 1.46 \cdot 10^{-7} * power_{ESPkW} + 2.04 \cdot 10^{-5}}{MWth * Operating_{hours}} \quad (63)$$

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