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Simplified Parameterized Models for a Multi-Criteria Environmental Impact Assessment of Four Types of Geothermal Installations

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ABSTRACT

Life cycle assessment (LCA) is a standardized, multi-criteria environmental assessment methodology for products or systems over their entire life cycles. Applying LCA to energy systems provides a robust basis to fully grasp their environmental performances but is data-intensive, time-consuming, and requires expert knowledge to handle all methodological aspects. As a result, the potential of LCA to support decision-making on new energy systems development is not exploited to its fullest. Alternatives to detailed LCAs, such as simplified models, are increasingly relevant and currently available to estimate the global warming potential of wind energy and enhanced geothermal systems (EGS) for electricity generation. These simplified models are deduced from comprehensive reference parameterized LCA models by identifying a number of key parameters using variance-based global sensitivity analysis. Their development and use are however rare and models for the multi-criteria assessment of other energy generating pathways are lacking. In this paper, we present simplified models for the environmental assessment of four geothermal installation types: (1) 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 non-condensable gases (mostly CO_2), (3) combined heat and power geothermal plant with low direct emissions, and (4) heat production plant including a demonstration organic Rankine cycle producing electricity for self-consumption with very low direct emissions. For each geothermal installation type, seven simplified models were developed to estimate impacts on climate change, minerals and metals resource depletion, fossil resource depletion, human toxicity carcinogenic and non-carcinogenic effects, freshwater ecotoxicity, and freshwater and terrestrial acidification using only two to six installation-specific parameters. Applying these simplified models is useful to give quick and reliable first estimates of the life-cycle related environmental impacts of installations that fall into the applicability domain of the considered model.

1. INTRODUCTION

In 2018, the electricity and heat generation from the combustion of coal, gas, and oil were responsible for 10,104 Mt CO_2, thus approximately one third of the worldwide CO_2 emissions (33,513 Mt CO_2) (International Energy Agency, 2018). High CO_2 concentrations in the atmosphere increase the greenhouse gas effect, thus contributing to the global climate change. Renewable energy generating techniques are alternatives to fossil-fuels and emit little CO_2 during their operational phase. Geothermal energy is one example: the heat stored in the Earth's underground can either be used directly and/or transformed to electricity.

However, before staking everything on renewable energies, two additional aspects need to be considered. First, over their entire life cycle, not only the operational phase of these technologies might emit CO_2. CO_2 as well as other gases can also be emitted during the construction, maintenance, and end of life phases and need to be considered to get a complete picture of the potential environmental impacts of the considered technology. Second, the consideration of CO_2 emissions alone ignores other potential environmental impacts, such as human health effects (Treyer et al., 2014), land use (Fthenakis and Kim, 2009), or resource depletion (Kouloumpis et al., 2015). A multi-criteria analysis of the potential environmental impacts of energy generating technologies over their entire life cycles is therefore essential to ensure complete and robust comparisons among energy-generating pathways. Life Cycle Assessment (LCA) is a standardized methodology that fulfills exactly this task. LCA quantifies all emissions and resources used over the entire life cycle of a system or product and estimates their potential environmental impacts. Although LCA is a powerful tool, its implementation can be difficult. LCA is time-intensive because of the large amount of data that needs to be gathered to describe the system's emissions and resources use. LCA also requires expert knowledge to correctly cover all methodological aspects. As an alternative, simple non-expert tools are needed to support an energy transition towards lower environmental impacts. Arithmetic equations based on a small number of installation-specific parameters and estimating the environmental impacts of a system or product are an alternative to full LCAs. These simplified models are derived from extensive parametrized LCA models of the system of interest by identifying the most influencing parameters using a Global Sensitivity Analysis (GSA). Up to now, one simplified model for electricity generation from an enhanced geothermal system (EGS) exist (Lacirignola et al., 2014), but is not sufficient to cover the variety of geothermal installations currently installed worldwide. Within the European GEOENVI project (Nb 818242)

(GEOENVI, 2020), European partners of different institutions in Belgium, France, Iceland, and Italy came together to develop simplified models estimating the environmental impacts of four typical geothermal installation types: (1) Enhanced Geothermal System (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 non-condensable gases (mostly CO_2), (3) combined heat and power geothermal plant with low direct emissions, and (4) heat production plant including a demonstration organic Rankine cycle producing electricity for self-consumption with very low emissions. Per installation type, seven simplified models were developed. One simplified model was developed per impact category: climate change, minerals and metals resource depletion, fossil resource depletion, human toxicity carcinogenic and non-carcinogenic effects, freshwater ecotoxicity, and freshwater and terrestrial acidification using only two to six installation-specific parameters. As long as applied within their defined applicability domain, these simplified models can be very useful for first multi-criteria environmental assessments of geothermal plants falling within one of the four installation types presented.

In the following sections, we will first describe the protocol used to generate the simplified models. Second, the geothermal installation types for which the simplified models were derived will be presented and their modelling shortly discussed. Finally, the simplified models will be presented for all geothermal installation types and their applicability domain and representativeness will be discussed.

2. PROTOCOL TO GENERATE SIMPLIFIED MODELS

The simplified models presented in this paper rely on the application of a five-step protocol, illustrated in Figure 1 and briefly described below.

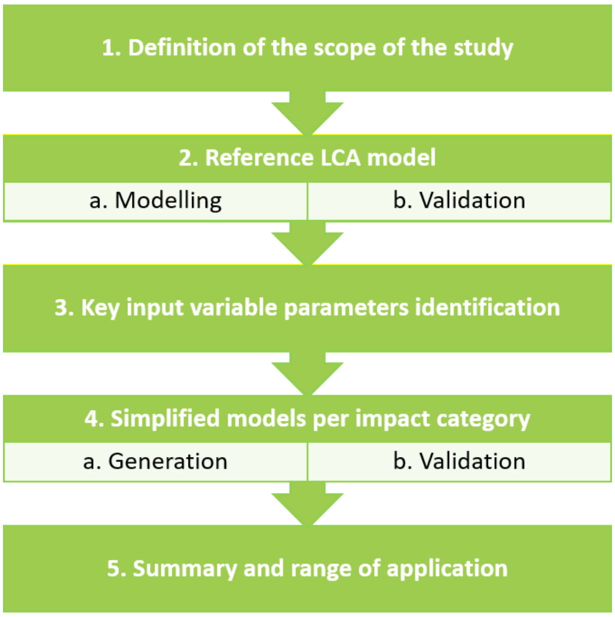

Figure 1: Scheme representing the five-steps protocol used to derive the simplified models for the four types of geothermal installation.

2.1. Definition of the scope of the study

The scope of the study describes the type of geothermal installation for which one aims at developing a simplified model. In this first step, the type of geothermal installation studied is defined based on a “representative geothermal system” (RGS). The RGS is either an existing installation or a hypothetical installation with average values obtained from a set of existing installations of the chosen type. The LCA-specific methodological choices made in this step are based on the published guidelines to conduct LCAs of geothermal systems (Parisi et al., 2020). They include the selection of a functional unit, the system boundaries, as well as the environmental impact categories. However, some deviations from the LCA guidelines were required and reported in Sections 3 and 4.

2.2. Reference Life Cycle Assessment model

The second step consists of the creation of the reference LCA model, based on the chosen RGS. The reference LCA model relies on parametrized inventory flows, defined by either fixed or variable parameters. Fixed parameters are assigned a representative value for the geothermal installation type chosen. Variable parameters, on the other hand, are defined with a probability distribution function covering the range of possible values for the given geothermal installation type. The environmental profile of the reference LCA model is then simulated for the chosen environmental impact categories with the Monte Carlo method. This profile is compared to results of published LCAs for geothermal installations of the chosen type to investigate the representativeness of the reference LCA model.

2.3. Identification of the key input variable parameters

A Global Sensitivity Analysis is at the heart of the protocol’s third step to identify the variable parameters explaining most of the variance of the evaluated environmental impact categories from first order Sobol’ indices. These key parameters define the simplified models and are chosen from a trade-off between covering a sufficient share of the variance and reducing their number. We recommend reducing the number of parameters ideally by 70% compared to the initial number, while still explaining at least 75% of the variance. In practice, the analysis is easily conducted in Python using the libraries Brightway2 (Mutel, 2017) and lca_algebraic (Jolivet, 2020).

2.4. Simplified models per impact category

One simplified model is derived per chosen impact category by setting the non-key variable parameters to the median of the Monte Carlo simulation and rounding float values. The performance of the simplified models is first compared to the reference model using the coefficient of determination, R^2 (Draper and Smith, 1998), and, second, to published literature. When assessing the performance of the simplified model compared to published literature, the values of the key parameters from the published study are used as input to the simplified model and the outcome of the simplified models compared to the one published to validate the simplified model.

2.5. Summary and applicability domain of the simplified model

In the fifth step of the protocol, the derived simplified models are displayed and their applicability domains are clearly stated. This protocol allows an iterative adjustment of the model's scope by either setting variable parameters to fixed ones or adjusting the variable parameters' ranges to broaden or narrow the simplified model's applicability domain. Adjusting the parameter ranges implies to re-run all steps of the protocol.

3. GEOTHERMAL INSTALLATION TYPES AND LCA FRAMEWORK

As explained in the introduction, four geothermal installation types were considered in this study: (1) EGS for heat generation with very low direct emissions (EGS), (2) geothermal flash power plant (Flash), (3) CHP geothermal plant (CHP), and (4) a heat production plant including a demonstration ORC (HeatORC). Details on the geothermal installation types, such as the geothermal source type, the RGS used, or geographical specificities, are given in Table 1.

The ecoinvent v3.6 database was used to model background processes, such as the steel manufacturing or the electricity production. The functional unit is detailed per type in Table 1. The ILCD 2018 impact assessment method was used to generate the environmental profile and simplified models of each installation type for these seven impact categories: climate change, freshwater and terrestrial acidification, freshwater ecotoxicity, human toxicity carcinogenic and non-carcinogenic impacts, mineral and metals resource depletion, and fossil resource depletion. These impact categories correspond to the ones labelled as high priority in the published LCA guidelines (Parisi et al., 2020). However, unlike the recommendations in (Parisi et al., 2020), the EF v3.0 methodology could not be used since it was not available in the Brightway2 library when the models were developed.

Table 1 – Description of the geothermal installation types. RGS stands for representative geothermal system, NCG for non-condensable gases. DHC stands for District Heating and Cooling applications, CHP for Combined Heat and Power, P for Power production. For more information on the clusters, please refer to (Rocco et al., 2020).

	(1) EGS	(2) Flash	(3) CHP	(4) HeatORC
Geothermal source type	Liquid	Vapor	Liquid/Vapor	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
Direct emissions	0.1-2% of the flow rate of the geothermal fluid direct emissions with very small amounts of CO_2 (0-1%) and CH_4 (0-0.01%)	7% in mass of the flow rate of the geothermal fluid Average gas fraction and constituted of 92% CO_2	0.12-0.23% CO2 of the flow rate of the geothermal fluid 0.00021% CH4 of the flow rate of the geothermal fluid	None
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)
Functional unit	1 kWh heat	1 kWh electricity	1 kWh electricity	1 kWh heat
Reference cluster in (Rocco et al., 2020)	2DHC	3P CHP	1P CHP	7P CHP
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

4. REFERENCE LCA MODEL

The reference LCA models of all installation types considered the construction, operation and maintenance, and end of life phases. In accordance with the guidelines on LCAs of geothermal systems, the end of life only accounted for the well abandonment and the disposal of wastes generated during drilling and maintenance operations (Parisi et al., 2020). The inventory flows of the processes describing each life cycle stage were modelled either using primary data, regression equations (Rocco et al., 2020), or scaling relationships (e.g. building size proportional to the electrical capacity, or heat exchanger mass proportional to flow rate).

The geothermal power plants producing heat (EGS and HeatORC) require electricity input during operation to power the production and injection pumps. While for HeatORC the electricity is partly self-produced by the ORC and partly taken from the Belgian electricity grid, the electricity needed for the operation of EGS is taken entirely from the grid. To guarantee the applicability of the reference model for EGS to different locations in continental Europe and allow testing the influence of a potential decarbonization of future electricity mixes, the electricity was modelled as a tailor-made mix consisting of: oil, coal, natural gas, wind, hydropower, solar power, biomass, and nuclear power.

In the end, each reference LCA model relied on several variable parameters: 35 for EGS (among which, eight describe the tailor-made electricity mix), 24 for Flash, 14 for CHP, and 19 for HeatORC.

Figure 2 compares the mean and standard deviation of the climate change impact category results of the four reference LCA models to published values. The comparison focuses on climate change impacts because it is the most studied impact category and LCA results for other impact categories are rarely reported in literature. Results for other impact categories for the four reference LCA models can be found in the detailed report published on the GEOENVI website (Douziech et al., 2020; GEOENVI, 2020).

Most studies publish results within the range defined by the mean and standard deviation. The observed differences are likely due to the impact assessment methodology used, the choice of the system boundaries or the allocation method. Overall, the comparison in Figure 2 and the continuous interactions with geothermal experts when defining the reference LCA models give a good confidence in the representativeness of the reference LCA models.

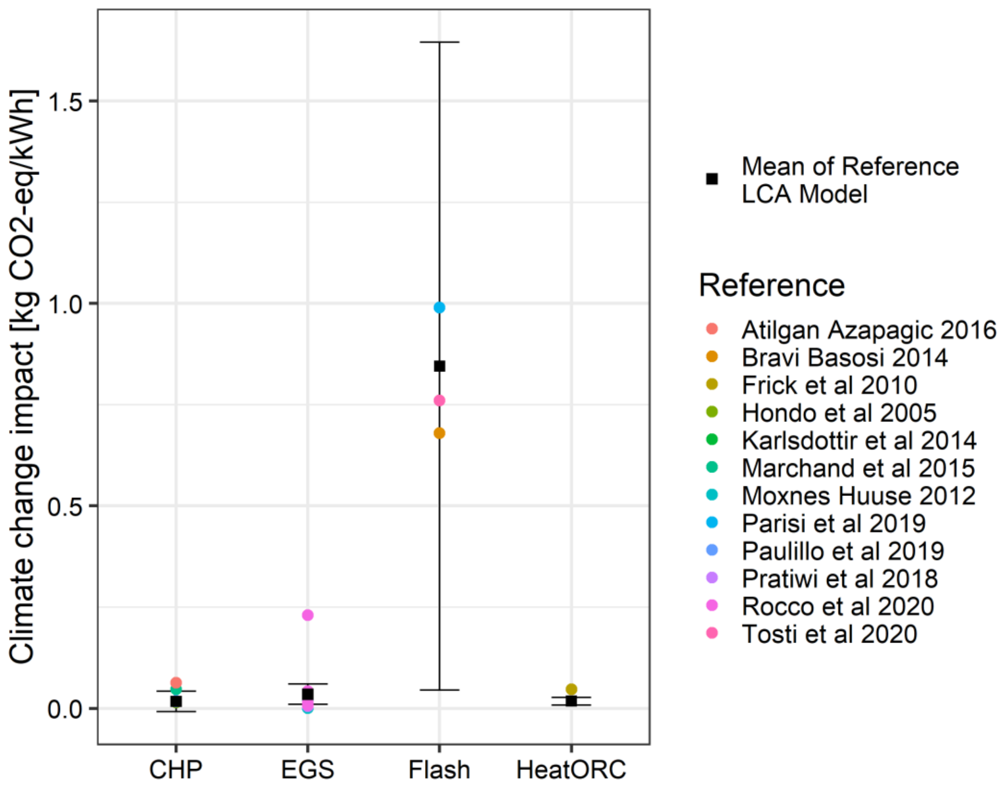

Figure 2: Comparison of the mean ± standard deviation of the climate change impact category results for the four reference LCA models to published literature results.

4. SIMPLIFIED MODELS

The technological parameters used for the simplified models, their value range, and the models' applicability domains are listed in Table 2.

Table 2 – Applicability domains of the simplified models and their key variable parameters and value ranges derived for all four geothermal installation types [1].

Name	Applicability Domain	Key variable parameters and value ranges
EGS	• Enhanced geothermal systems 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.	• Thermal output [10-40 MW] • Power of the production pump [200 - 1200 kW] • Power of the injection pump [0 - 500 kW] • Number of production and injection wells [1 - 2] • Average well length [1300 - 5500 m] • Shares of electricity (coal, natural gas, nuclear, oil, hydropower, wind power, biomass, solar power) [0 - 1]
Flash	• Flash or dry steam power plant exploiting high enthalpy field; • producing only electricity, or electricity and heat for industrial purposes whereby heat must be less than 50% of the electricity produced; • geothermal sources showing low to a high content of NGCs; • diesel-powered drilling rig; • No electricity demand for auxiliaries from the electric network.	• Electrical capacity [20 000 - 120 000 kW] • Fraction of NCGs [0.006 - 0.12] • Flow rate [110000 - 1E6 kg/h] • Fraction of NH_3 on NCGs composition [0.0012 - 0.032] • Make-up wells ratio [0 - 0.76] • Average well length [586 - 4727 m]
CHP	• Hydrothermal liquid/vapor geothermal source; • natural flow; • single or double flash system producing both heat and electricity; • no abatement system; • diesel-powered drilling rig.	• CO_2 content in the geothermal fluid [0.0012 - 0.0023] • Power output [300 - 500 MW] • Lifetime [20 - 40 years] • Well depth [1394 - 3323 m] • Capacity factor [0.6 - 1] • Diesel required for the drilling [1022 - 3632 MJ/m drilled] • Number of production wells [28.2 - 65.8]
HeatORC	• Geothermal plants for heat generation with ORC unit for electricity production for self-consumption; • very low to no direct emissions; • located in Belgium (or another location with a similar electricity mix and similar geological characteristics); • connected to the Belgian power grid; • electricity-powered drilling rig.	• Installed thermal power [6.6 - 25 MW] • Power of the reinjection pump [0 - 500 kW] • Power of the production pump [200 - 1200 kW] • Yearly operating hours of the plant [5000 - 8500 h] • Number of injection wells [1 - 2]

[1] NCG stands for non-condensable gases and ORC for organic Rankine cycle. “EGS” describes installations 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 non-condensable gases (mostly CO_2), “CHP” combined heat and power geothermal plant with low direct emissions, and “HeatORC” heat production plant including a demonstration organic Rankine cycle producing electricity for self-consumption with very low emissions

Table 3 lists the simplified models per installation type and impact category. The key parameters chosen explained between 65% (freshwater and terrestrial acidification for Flash) and 92% (freshwater and terrestrial acidification for CHP) of the variance of each impact category, relied on two to six installation-specific parameters, and showed an R^2 ranging from 78 to 99%. All simplified models are defined by a ratio reflecting the normalization of the results per kWh of produced heat or electricity.

The same set of key parameters is used for all simplified models of the EGS installation type. On the one hand because no large difference was observed in the ranking of the key parameters between impact categories and, on the other hand, to ease the data collection. Besides the number and length of the wells, the electricity needed during operation and maintenance represented by the pump powers and the characteristics of the electricity mix influenced the environmental impacts greatly.

For the Flash installation type, it is interesting to note the different key parameters identified for the climate change, acidification, and human health impact categories. In those cases, the direct emissions represented by the emitted fraction of non-condensable gases, Hg, and H_2S are predominantly explaining the impacts’ variability. On the contrary, the well length and the make-up wells’ ratio are explaining most of the impacts’ variability for the other impact categories.

The results for the CHP installation type follow a similar trend than for the Flash, as the fraction of CO_2 in the geothermal fluid is one key parameter for the climate change impact category but not for the others, where the well length and the plant’s lifetime are more relevant.

The simplified models for the HeatORC type show similarities to the ones for EGS with the number of wells and the power of the pumps identified in most models as driving the impacts’ variability.

Table 3 – Simplified models for the seven impact categories and the four types of geothermal installations. The parameters found in the simplified models for each installation type are explained in the first row.

	EGS	Flash	CHP	ORC
Parameters	N_{in}: number of injection wells, N_{prod}: number of production wells, P_{pump}: power of the injection pump [kW], P_{LSP}: power of the production pump [kW], P_{th}: thermal output [MW], L_W: average well length [m], f_{XX}: fraction of the different electricity inputs	$ElecCapacity$: electrical capacity [kW], $FlowRate$: flow rate [kg/h], f_{NCG}: fraction non condensable gases, f_{H2S}: fraction of H_2S, f_{Hg}: fraction of Hg, $MakeUpWellsRatio$: ratio of make up wells, l: average well length [m]	CO_2: CO2 in geofluid, $Power_{output}$: power output [MW], $Lifetime$: lifetime of the plant [years], $Well_{depth}$: average well depth [m], $Capacity_{Factor}$, $Diesel_{drilling}$: diesel used for drilling [MJ/m]	$Operating_{hours}$: operating hours [h], $power_{pumpkW}$: power of the injection pump [kW], $power_{ESPkW}$: power of the production pump [kW], $MWth$: thermal output [MW], $N_{wellinjection}$: number of injection wells,
Climate Change [kg CO_2-eq/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\begin{bmatrix}0.0588f_{biomass}+1.28f_{coal}\\ +0.00426f_{hydro}+0.434f_{NG}\\ +0.0115f_{nuclear}+0.917f_{oil}\\ +0.0624f_{solar}+0.0137f_{wind}\end{bmatrix}+5.08\cdot 10^{-9}[2.47\cdot 10^{3}P_{th}+2.42\cdot 10^{5}N_{in}+3.28\cdot 10^{3}N_{prod}\cdot P_{LSP}+16.6P_{pump}+(N_{in}+N_{prod})\cdot\left(790.0\cdot 10^{0.000399\cdot L_W+2.04}+277.0L_W+27.9L_W^{1.05}+58.5L_W^{1.22}+26.1L_W^{1.23}\right)+7.06\cdot 10^{6}]}{P_{th}}$	$\frac{2.56\cdot 10^{-7}ElecCapacity^2+1.18\cdot FlowRate\cdot f_{NCG}+4.14\cdot 10^3}{ElecCapacity}$	$\frac{3.63\cdot 10^3 CO_2}{Power_{output}}+1.4\cdot 10^{-6}Power_{output}+0.000625+\frac{1.02}{Power_{output}}+\frac{77.1}{Power_{output}^2}$	$\frac{0.000326\cdot Operating_{hours}\cdot power_{pumpkW}+0.957\cdot power_{ESPkW}+423.0}{MWth\cdot Operating_{hours}}$
Resources, fossil [MJ/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\begin{bmatrix}0.689f_{biomass}+15.4f_{coal}\\ +0.0458f_{hydro}+7.81f_{NG}\\ +13.4f_{nuclear}+11.1f_{oil}\\ +0.915f_{solar}+0.204f_{wind}\end{bmatrix}+5.04\cdot 10^{-9}[3.56\cdot 10^{4}P_{th}+3.25\cdot 10^{6}N_{in}+4.65\cdot 10^{4}N_{prod}\cdot P_{LSP}+221.0P_{pump}+(N_{in}+N_{prod})\cdot\left(1.05\cdot 10^{4}\cdot 10^{0.000398\cdot L_W+2.04}+3.83\cdot 10^{3}L_W+484.0L_W^{1.05}+839.0L_W^{1.22}+126.0L_W^{1.23}\right)+5.21\cdot 10^{7}]}{P_{th}}$	$\frac{3.8\cdot 10^{-6}ElecCapacity^2+0.0509\,ElecCapacity+4.73\,MakeUpWellsRatio\cdot l+3.54\,MakeUpWellsRatio\cdot l^{1.2}+0.178\,MakeUpWellsRatio\cdot l^{1.23}+4.03\cdot 10^4 MakeUpWellsRatio+0.0582\,l^{1.2}+9.29\cdot 10^3}{ElecCapacity}$	$\frac{0.000514Lifetime+0.000216\,Well_{depth}+0.534}{Capacity_{Factor}\cdot Lifetime}$	$\frac{0.0112\cdot N_{wellinjection}\cdot power_{pumpkW}+0.167\,N_{wellinjection}+1.93}{MWth}$

Resources, minerals [kg Sb-eq/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\begin{bmatrix}7.07\cdot 10^{-7}f_{biomass}+2.56\cdot 10^{-6}f_{coal}\\ +1.92\cdot 10^{-7}f_{hydro}+1.03\cdot 10^{-7}f_{NG}\\ +2.24\cdot 10^{-7}f_{nuclear}+5.01\cdot 10^{-7}f_{oil}\\ +8.54\cdot 10^{-6}f_{solar}+1.6\cdot 10^{-6}f_{wind}\end{bmatrix} +5.01\cdot 10^{-9}[0.0415P_{th}+11.2N_{in} +0.105N_{prod}\cdot P_{LSP}+0.00416P_{pump} +(N_{in}+N_{prod})\cdot\begin{pmatrix}0.000727\cdot 10^{0.000396\cdot L_W+2.04}+0.0233L_W\\ +0.000734L_W^{1.05}+0.00097L_W^{1.22}+0.000137L_W^{1.23}\end{pmatrix} +416.0]}{P_{th}}$	$\frac{6.4\cdot 10^{-12}ElecCapacity^2 +3.14\cdot 10^{-7}ElecCapacity +7.5\cdot 10^{-6}MakeUpWellsRatio\cdot l +3.95\cdot 10^{-6}MakeUpWellsRatio\cdot l^{1.2} +9.79\cdot 10^{-8}MakeUpWellsRatio\cdot l^{1.23} +0.0885MakeUpWellsRatio +6.7\cdot 10^{-8}\cdot l^{1.2}+0.0223}{ElecCapacity}$	$\frac{9.91\cdot 10^{-10}Lifetime +2.77\cdot 10^{-10}Well_{depth} +5.94\cdot 10^{-7}}{Capacity_{Factor}\cdot Lifetime}$	$\frac{1.7\cdot 10^{-7}Operating_{hours} +3.0\cdot 10^{-5}power_{ESPkW} +0.0211}{MWth\cdot Operating_{hours}}$
Ecosystem quality – Freshwater ecotoxicity [CTUe/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot\begin{bmatrix}0.309f_{biomass}+0.0891f_{coal}\\ +0.00554f_{hydro}+0.0114f_{NG}\\ +0.0251f_{nuclear}+0.671f_{oil}\\ +0.0937f_{solar}+0.0374f_{wind}\end{bmatrix} +4.98\cdot 10^{-9}[2.85\cdot 10^{3}P_{th}+8.14\cdot 10^{5}N_{in} +7.97\cdot 10^{3}N_{prod}\cdot P_{LSP}+236.0P_{pump} +(N_{in}+N_{prod})\cdot\begin{pmatrix}131.0\cdot 10^{0.0004\cdot L_W+2.04}+332.0L_W+206.0L_W^{1.05}\\ +66.4L_W^{1.22}+2.8L_W^{1.23}\end{pmatrix} +5.53\cdot 10^{6}]}{P_{th}}$	$\frac{5.76\cdot 10^{-7}ElecCapacity^2 +0.0129ElecCapacity +10.7MakeUpWellsRatio\cdot l +0.342MakeUpWellsRatio\cdot l^{1.2} +1.37\cdot 10^{4}MakeUpWellsRatio +0.174\cdot l +1.24\cdot 10^{4}}{ElecCapacity}$	$\frac{2.38\cdot 10^{-5}Lifetime +5.98\cdot 10^{-5}Well_{depth} +0.118}{Capacity_{Factor}\cdot Lifetime}$	$\frac{0.014\,Operating_{hours} +2.29\,power_{ESPkW} +486.0}{MWth\cdot Operating_{hours}}$
Ecosystem quality – Freshwater and terrestrial acidification [mol H+-eq/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot\begin{bmatrix}0.00211f_{biomass}+0.00949f_{coal}\\ +2.19\cdot 10^{-5}f_{hydro}+0.000241f_{NG}\\ +7.09\cdot 10^{-5}f_{nuclear}+0.00888f_{oil}\\ +0.000511f_{solar}+9.08\cdot 10^{-5}f_{wind}\end{bmatrix} +5.19\cdot 10^{-9}[10.9P_{th}+6.28\cdot 10^{3}N_{in} +25.6N_{prod}\cdot P_{LSP}+0.768P_{pump} +(N_{in}+N_{prod})\cdot\begin{pmatrix}11.2\cdot 10^{0.000402\cdot L_W+2.04}+1.84L_W\\ +0.155L_W^{1.05}\\ +0.256L_W^{1.22}+0.0671L_W^{1.23}\end{pmatrix} +6.25\cdot 10^{4}]}{P_{th}}$	$\frac{FlowRate\cdot f_{NCG}\cdot(1.54\cdot f_{H2S}+0.00822)}{ElecCapacity}$	$\frac{2.7\cdot 10^{-11}Diesel_{drilling}\cdot Well_{Depth} +3.15\cdot 10^{-7}Lifetime +7.62\cdot 10^{-8}Well_{depth} +0.000275}{Capacity_{Factor}\cdot Lifetime}$	$\frac{0.000138\,Operating_{hours} +0.00733\,power_{ESPkW} +3.35}{MWth\cdot Operating_{hours}}$

Human health – Non-carcinogenic effects [CTUh/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot\begin{bmatrix}3.37\cdot10^{-7}f_{biomass}+6.23\cdot10^{-8}f_{coal}\\+9.67\cdot10^{-10}f_{hydro}+2.68\cdot10^{-9}f_{NG}\\+3.97\cdot10^{-9}f_{nuclear}+2.14\cdot10^{-8}f_{oil}\\+2.94\cdot10^{-8}f_{solar}+7.09\cdot10^{-9}f_{wind}\end{bmatrix}+5.0\cdot10^{-9}[0.000496P_{th}+0.192N_{in}+0.00141N_{prod}\cdot P_{LSP}+6.64\cdot10^{-5}P_{pump}+(N_{in}+N_{prod})\cdot\left(1.74\cdot10^{-5}\cdot10^{0.000401\cdot L_W+2.04}+4.1\cdot10^{-5}L_W+3.56\cdot10^{-5}L_W^{1.05}+1.18\cdot10^{-5}L_W^{1.22}+1.33\cdot10^{-6}L_W^{1.23}\right)+1.2]}{P_{th}}$	$\frac{0.978\cdot FlowRate\cdot f_{Hg}\cdot f_{NCG}}{ElecCapacity}$	$\frac{8.35\cdot10^{-12}Lifetime+5.99\cdot10^{-12}Well_{depth}+1.81\cdot10^{-8}}{Capacity_{Factor}\cdot Lifetime}$	$\frac{6.85\cdot10^{-9}\,Operating_{hours}+3.98\cdot10^{-7}\,power_{ESPkW}+9.05\cdot10^{-5}}{MWth\cdot Operating_{hours}}$
Human health – Carcinogenic effects [CTUh/kWh]	$\frac{0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot\begin{bmatrix}3.37\cdot10^{-9}f_{biomass}+2.01\cdot10^{-9}f_{coal}\\+3.83\cdot10^{-10}f_{hydro}+5.28\cdot10^{-10}f_{NG}\\+5.95\cdot10^{-10}f_{nuclear}+2.08\cdot10^{-9}f_{oil}\\+2.21\cdot10^{-9}f_{solar}+2.21\cdot10^{-9}f_{wind}\end{bmatrix}+5.16\cdot10^{-9}[0.000172P_{th}+0.0511N_{in}+0.000501N_{prod}\cdot P_{LSP}+1.05\cdot10^{-5}P_{pump}+(N_{in}+N_{prod})\cdot\left(1.2\cdot10^{-6}\cdot10^{0.000396\cdot L_W+2.04}+9.63\cdot10^{-6}L_W+9.74\cdot10^{-6}L_W^{1.05}+4.13\cdot10^{-6}L_W^{1.22}+6.38\cdot10^{-8}L_W^{1.23}\right)+0.231]}{P_{th}}$	$\frac{4.14\cdot10^{-14}ElecCapacity^2+0.00827\cdot FlowRate\cdot f_{Hg}\cdot f_{NCG}+0.000731}{ElecCapacity}$	$\frac{8.23\cdot10^{-13}Lifetime+2.36\cdot10^{-14}N_{prod}+5.67\cdot10^{-14}Well_{depth}\cdot(N_{prod}+40.1)+8.77\cdot10^{-9}}{Capacity_{Factor}\cdot Lifetime}$	$\frac{3.28\cdot10^{-10}\,Operating_{hours}+1.46\cdot10^{-7}\,power_{ESPkW}+2.04\cdot10^{-5}}{MWth\cdot Operating_{hours}}$

The validation of the simplified models with literature was difficult since it implied to find literature studies matching the applicability domains and parameter ranges listed in Table 2, estimating impacts using the same impact categories, and reporting the values for the chosen key parameters. For EGS, the comparison with the values for climate change reported by (Pratiwi et al., 2018) shows a relatively good overlap with values derived from the simplified model, namely 4.2 g CO_2-eq/kWh vs. 5.6 g CO_2-eq/kWh reported. For Flash, none of the study presented in Figure 2 used the same impact categories. Tosti et al., (2020) report results based on the same power plant of the reference model but using ILCD 2011 Midpoint+ method v1.0.9 which has for example a lower characterization factor for CH_4 a greenhouse gas with a large influence on the climate change impact category, than ILCD 2018. Still, applying the simplified model for climate change on the values reported in Tosti et al., (2020) leads to 0.71 kg CO_2-eq/kWhe compared to 0.63 kg CO_2-eq/kWhe reported. Applying the simplified models' equations for climate change for CHP to the configuration reported by Paulillo et al., (2019) resulted in 21.6 g CO_2/kWh 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. CONCLUSION

In this paper, we presented simplified tools for the multi-criteria environmental assessment of deep geothermal energy systems that can be used by non-LCA experts. These tools were developed by identifying the key parameters explaining most of the variance of the impact categories and deriving simple equations from them. The simplified equations presented for four types of geothermal installations can be used for their multi-criteria environmental assessments as long as the applicability domain is respected and the parameters fit into the specified ranges. These equations represent very useful tools for first assessments and comparisons of energy generating alternatives but do not aim at replacing complete LCAs of geothermal systems.

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