Elaboration of a general protocol to generate simplified models for geothermal installations

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Author(s): I. Blanc(1), M. Douziech(1), V. Harcouët-Menou(2), R. Jolivet(1), N. Ferrara(3), P. Pérez-López(1), L. Tosti(3)
Author'(s') affiliation: (1) MINES ParisTech/ARMINES, (2) VITO, (3) CSGI

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Executive Summary

Simplified models to estimate the environmental impacts for a selection of categories of geothermal installations over their life cycle have been developed within the European project GEOENVI [Grant agreement n°818242 -- 2018-2021] (Douziech, et al., 2020). Simplified models are simple equations relying on a small number of variable parameters that are deduced per environmental impact and allow first environmental assessment estimates of geothermal installations.

The generation of these simplified models was possible thanks to the application of a protocol. This deliverable reports both the concept of the protocol and its operational implementation through relevant libraries. The concept of the protocol, initially developed to produce simplified models for wind turbines (Padey et al., 2013) and for a first type of geothermal installation, an enhanced geothermal system (EGS) generating electricity (Lacirignola et al., 2015), has been adapted to better account for uncertainty and variability sources in the environmental impact assessment of different geothermal installations. The implementation of this protocol is built on the developments of libraries from the INCER-ACV project (Jolivet et al., 2020), a project aiming at developing a general protocol for the analysis of variability and uncertainty of input parameters for life cycle assessment (LCA). This protocol is now detailed to enable future users to generate simplified models for an extended set of geothermal installations categories other than the four already generated within the GEOENVI project (Douziech, et al., 2020), namely: (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 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 Organic Ranking Cycle (ORC) producing electricity for self-consumption with very low emissions.

While simplified models resulting from the application of this protocol are tools that can easily be used by non-LCA experts to obtain estimates for their own systems, applying the protocol to obtain the simplified model itself requires extended knowledge of the LCA methodology as well as programming skills. **The protocol presented here is therefore foreseen for application by LCA experts involved in the development of geothermal LCAs.**

The protocol is structured in 5 steps: (1) definition of the scope of the study, (2) modelling and validation of a reference LCA model, (3) statistical process to identify the key input variable parameters for each impact category, (4) generation and validation of the simplified models per environmental impact, and (5) summary and range of application of the simplified models. The key variable parameters used for the definition of the simplified models (step 3) are selected by performing the following sub-steps:

(a) a Global Sensitivity Analysis (GSA) based on the estimation of the first order Sobol' indices (Saltelli, 2008) from a set of stochastic scenarios derived with a Monte Carlo simulation of the distribution functions of all variable parameters

(b) the identification of a reduced set of variable parameters covering a sufficient share of the variance of the considered environmental impact quantified when running the reference LCA model (at least 75-80%).

To ease the application of the protocol, in particular steps 3 and 4, the use of the open access libraries (based on Python language) *Brightway2* (Mutel, 2017) and *lca_algebraic* (Jolivet, 2020) is recommended.

For geothermal installations, it is proposed to focus the generation of the simplified models on the seven key impacts recommended by the LCA guidelines for geothermal installations (Blanc et al., 2020): climate change, minerals and metals resource depletion, fossil resource depletion, human carcinogenic effects, human non-carcinogenic effects, freshwater ecotoxicity, and freshwater and terrestrial acidification. The protocol could, of course, be applied to any other impact category. It is worth underlining that for the same geothermal installation category, the set of influencing variable parameters might vary depending on the environmental impact.

The definition of the applicability domain for the simplified models along the first and last step of the protocol is a critical point when applying the protocol. The user of the simplified models will be urged to carefully check the applicability domain of each simplified model prior to using it for their geothermal installations.

Finally, it is important to underline that the use of these simplified models does not replace thorough LCAs of geothermal installations but certainly gives first estimates of their environmental performances, whenever time or resources are lacking to conduct full LCAs.

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General Introduction

Life Cycle Assessment (LCA) is a standardized tool 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. Among these alternatives, geothermal energy is often considered as a renewable energy source for electricity production and heating and cooling applications with low environmental impacts (IRENA, 2018). Conducting LCAs to quantify the environmental performances of the geothermal sector is hereby essential to support this statement. Despite the advantages of being standardised, holistic, multi-criteria and widely accepted, the investment to undertake LCA might be prohibitive for most industrial actors and decision makers involved in the geothermal sector. Not only does an LCA imply a time-intensive collection of a large amount of technical and environmental data, but it also requires relevant expertise in the LCA methodology not yet widely available.

Recognising the difficulties of conducting an LCA for non-LCA experts leads to the need for the development of novel processes to allow reliable and integrated decision-making while keeping the necessary effort limited. Simplified models are a valuable alternative that estimate the environmental impact of an installation over its life cycle from a limited number of independent input variable parameters for an easy application by non-experts. Simplified models do not require final users to undertake full LCAs. Simplified models have been developed initially for wind turbines (Padey et al., 2013) and for one specific type of geothermal installation, an enhanced geothermal system generating electricity (Lacirignola et al., 2015).

Within the framework of the GEOENVI project, simplified models estimating the environmental impacts for four categories of geothermal installations over their life cycle have already been developed (Douziech, et al., 2020). The generation of these simplified models followed the application of a protocol designed to deliver simplified models for geothermal installations. Its rationale is to convert a reference LCA model into a range of simplified models (one per environmental impact) relying only on a limited number of key variable parameters, which influence each environmental impact the most.

Motivation and Objective

The objective of this deliverable is to present the sequence of steps, formulated as a general protocol, necessary to generate a series of simplified models, one per environmental impact, for a specific category of geothermal installation. This deliverable is reporting both the concept of the protocol and its operational implementation. **LCA experts involved in the development of geothermal LCAs are foreseen as users of this protocol.** In fact, applying the protocol requires both expertise in performing LCAs as well as programming skills, ideally in the Python programming language, for its operational implementation.

This protocol aims at generating simplified models for any category of geothermal installations. It is not restricted to the specific geothermal installations that constitute the GEOENVI case studies.

This deliverable gives a description of the protocol followed to generate simplified models per geothermal installation category for a set of environmental impacts. Taking after the LCA approach, simplified models are not restricted to the sole carbon footprint assessment and consider a multi-criteria approach. When considering geothermal installations, seven impact indicators classified as high priority in the LCA guidelines for geothermal installations (D3.2.) are considered, 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 LCA guidelines for geothermal installations recommend the use of the Environmental Footprint (EF) v3.0 (Fazio et al., 2018). However, given the current lack of implementation of the EF v3.0 in the software used when issuing this report, the ILCD 2018 impact categories (European Commission and Joint Research Centre, 2010) as available in the most recent ecoinvent v3 (Bourgault G., 2019) combined with the ecoinvent database v3.6 had to be used instead, despite the fact that it does not comply with the guidelines.

This protocol was applied to four categories of geothermal installations within GEOENVI project (Douziech, et al., 2020) 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 protocol is structured as a 5-steps sequence and displayed in Figure 1.

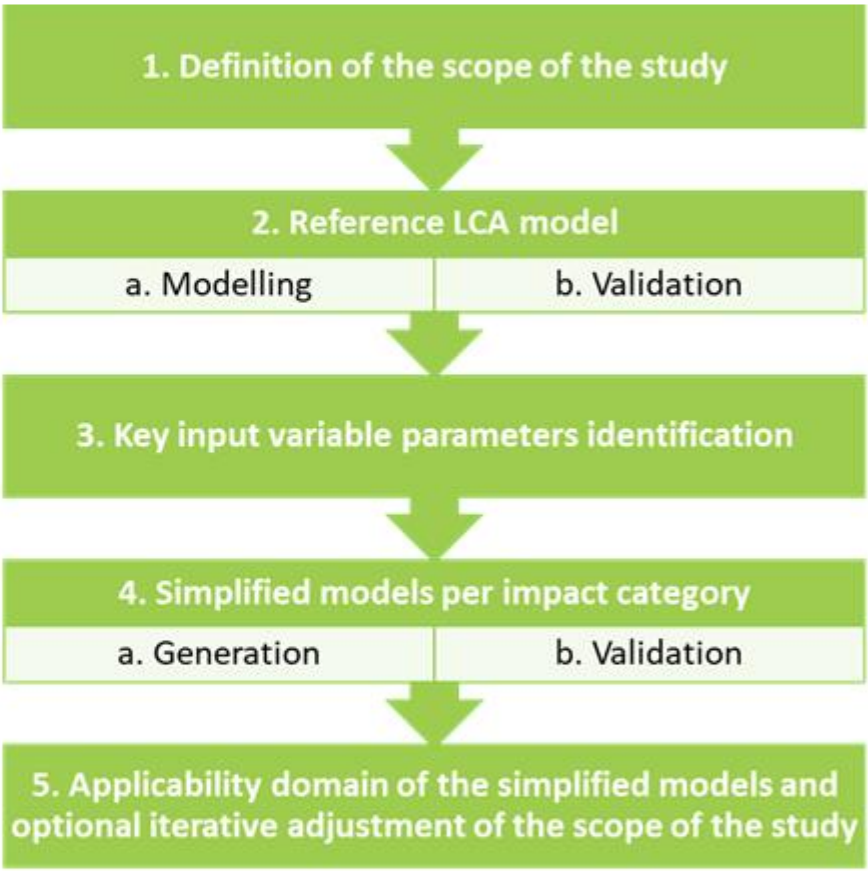

Figure 15 – The 5-steps sequence of the protocol

In the current report, each step of the protocol is detailed and its implementation illustrated by the simplified models for the specific geothermal category "EGS heat generation with very low direct emissions" (Douziech, et al., 2020).

The implementation of the protocol presented in this deliverable is based on the use of two open-access libraries developed in the Python environment:

- *Brightway2* (Mutel, 2017) an open-source framework enabling the implementation of the calculation steps necessary to conduct LCA in Python language
- *lca_algebraic,* a layer above Brightway2, developed within the INCER-ACV project, that implements the statistical part of the protocol for the fast identification of the key input variables and the generation of the simplified models themselves (Pérez-López et al., 2020). The operational guidance for its implementation based on the *lca_algebraic* library[1] is provided in a supplementary section for each step.

For each step of the protocol, an example of its implementation for the specific geothermal category "EGS heat generation with very low direct emissions" is given in purple and followed, whenever applicable, by details of the implementation using the *lca_algebraic* library. More

[1] Available on https://oie-mines-paristech.github.io/lca_algebraic/doc/

guidance on the application of the protocol in the Python environment (using Jupyter Notebook) is available in an online video tutorial (https://youtu.be/kZHB--NFe50). An example Jupyter Notebook is further provided on the GEOENVI website (https://www.geoenvi.eu/lca-for-geothermal/).

Protocol to generate simplified models per category of geothermal installation

1. Definition of the scope of the study

First, the category of geothermal installation analysed must be precisely described, hence, describing the range of application of the models. The category of geothermal installation can be defined with the support of a representative geothermal system (RGS). A RGS is defined based on 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), whether there is or not a Non-Condensable Gas abatement system and other key features as identified in the GEOENVI LCA guidelines for geothermal installations (Blanc et al., 2020). An RGS is also defined by default values for some fixed parameters (pump efficiency or transport distance for example) and value ranges for variable parameters (range of drilled depth for example). Within the GEOENVI project, four RGS specific to four categories of geothermal installations were studied. In addition, the chosen functional unit and the system boundaries must be clearly stated. We recommend to set these two aspects following the guidelines, meaning either kWh of heat or kWh of electricity produced and system boundaries according to Figure 16. Additional recommendations of the guidelines should also be followed if applicable (e.g. allocation in case of multi-output processes). The database used in the modelling of the background processes (e.g. ecoinvent) should also be stated together with its version, if applicable.

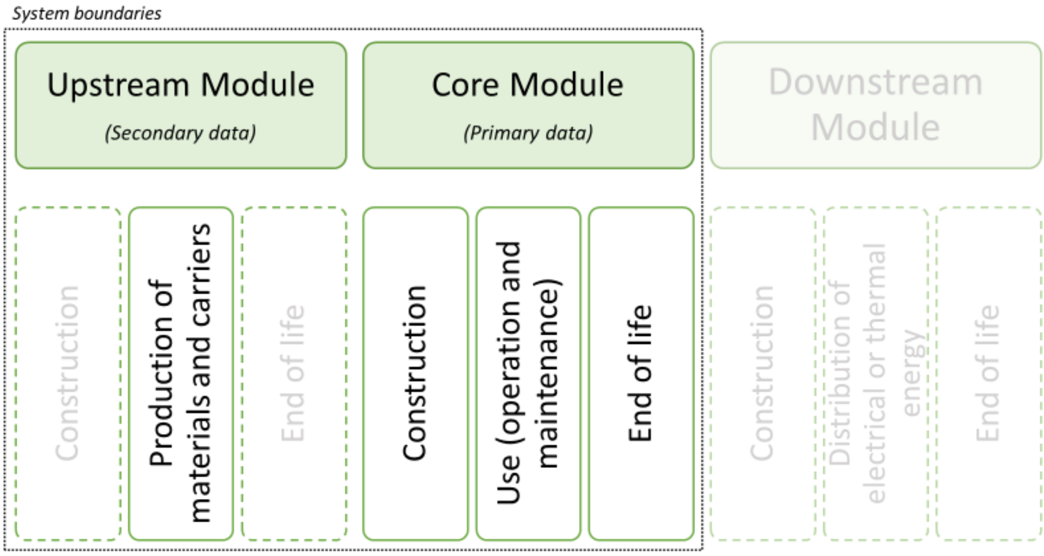

Figure 16 – System boundaries to be included in the definition of the scope of the study (Blanc et al., 2020)

Application to EGS category with very low direct emissions

The category of geothermal installation given as an illustration of the application of the protocol is an EGS for heat generation with very low direct emissions. The geothermal heat plant of Rittershoffen (France) shown in Figure 17, being a typical example of this geothermal installation category, served as a basis for the development of the reference LCA model [step 2 of the protocol]. The plant has been developed to supply heat to the industrial processes of a starch plant. This industrial user, located in Beinheim, totals 100 MW_{th} of thermal needs. The geothermal heat plant, with an installed capacity of 27.5 MW_{th}, provides an average of 22.5 MW_{th} and 180 GWh/year of heat to this starch plant since June 2016.

Figure 17 – View of the Rittershoffen geothermal heat plant (ES-Géothermie)

The functional unit is the production of 1kWh of heat delivered. The system boundaries include the upstream, meaning the secondary data, and the core module including the infrastructure, the operation and maintenance of the installation, and its end of life. The activities of the upstream module are derived from the ecoinvent database v3.6.

2. Modelling and validation of the reference LCA model

a) Modelling of the reference LCA model

The definition of a reference LCA model is an important step in the protocol as the scope, boundaries and applicability domain of the simplified models are directly derived from the ones defined for this reference LCA model. Such a reference LCA model, corresponding to a geothermal installation category, is defined along two sub-steps:

1. **A parametrisation of the life cycle model** for the category defined with relevant input variable parameters:

A computational structure based on a parametrisation of the life cycle model for the geothermal installation category is designed to estimate the life cycle inventory according to a set of *N* independent input variable parameters. Such detailed description is referred to as “the reference LCA model” and should be representative of the category of geothermal installation defined in step 1. Instead of using actual numbers for the different inventory flows, the LCA practitioner should identify parameters that can be used instead. These parameters can either represent the inventory flow directly (e.g. the mass of a certain material), or a specific property which is related to the inventory flow through a known equation. For example, the amount of drilling fluid is directly proportional to the well length, which can be therefore set as a parameter. Once all inventory flows have been described and parameters defined, sorting the parameters to be set, so-called fixed parameters, and the ones to vary, variable parameters, is essential.

Several strategies are possible to generate this reference LCA model: (a) either start from an existing life cycle inventory model and adapt it through the identification of relevant variable parameters to best represent the targeted category. Its modelling can hereby rely on a generalisation of the identified RGS, (b) or construct a new life cycle inventory taking advantage of a systematic technological review to build coherent foreground data.

For both options, it is necessary to make certain assumptions concerning background data such as setting the energy mix, for example.

The choice of the input variable parameters should also fulfil the criteria of their mutual independence. This is a necessary condition for applying the global sensitivity step of the protocol (step 3). Furthermore, only input variable parameters for which information on their distributions is accessible should be used. In case of missing information, alternative variable parameters should be preferred.

2. **The definition of the probability ranges of the input variable parameters**

The applicability range of the reference LCA model is partly set through the definition of the probability range for the input variable parameters. At this stage, the LCA modeller has to allocate a probability distribution (triangular, uniform, or any other) to the defined range of variability of each input variable. This process should be based on expert opinions, literature survey or even better on field data in relation with the selected geothermal installation category. The coverage of this variability range can also be extended to include prospective configurations to account for emerging technologies (for example new drilling technologies). The choice of the probability distributions should be done according to the following criteria:

- Whenever sufficient data on the variable parameter is available, it is recommended to choose the distribution function describing the observed data as much as possible.
- On the contrary, when no specific information is known, a uniform distribution by default is recommended from our experience to ensure the same probability for all values within of the variable parameter’s validity domain. It is the least risky option but the least precise one as well as it can imply a low technological relevance for example
- When designing simplified models for current situation for which future developments are already foreseen and quantified, the choice of a triangular or Gaussian distribution is recommended: such distributions will associate a higher weight to the current situation (top of the triangle or mean value for the Gaussian distribution) and a much lower weight to emerging technologies for example.
- The Beta distribution is a continuous probability distribution relying on two parameters that can be used to estimate random variables between 0 and 1. It is a very flexible distribution function and can represent proportions, percentages, or probability outcomes (Lehoczky, 2001)
- Discrete distributions are also another possibility whenever several different options are available for the variable parameter, for example when investigating the sensitivity of the choice of a type of material (recycled or not) on the environmental impacts. A statistical weight could also be associated to the values of these discrete distributions, for example for diesel or electric drilling knowing that the latter is less common than diesel drilling.

As reported by Lacirignola et al (2017), the influence of the probability distribution on the relative importance of these variable parameters is fairly high and affects the generation of the simplified models which relies on this ranking.

Once the reference LCA model is defined through these two sub-steps, scenarios from the probability distribution functions defined for the input variable parameters are generated stochastically, referred to as Monte Carlo simulations (MC). When performing the Monte Carlo scheme, several thousand simulations are recommended to ensure results stability. Such stability is reached when very little variation of the MC results occur while increasing the number of stochastic samples.

Application to EGS category with very low direct emissions

The reference LCA model developed is a parameterised representation of an EGS for heat generation with very low direct emissions possibly implemented in a wide set of European countries with specific electricity mix. It was developed starting from the existing life cycle inventory generated for the Rittershoffen EGS installation (Pratiwi et al., 2018). Its parametrisation was performed mostly following the recommendations of the guidelines for the life cycle assessment of geothermal energy systems, except that equations reported in literature were used instead of primary data for some of the inventory flows to ease the parametrisation (Blanc et al., 2020). This allowed a parametrisation with 47 fixed parameters and 35 variable parameters as reported in Figure 2. Besides plant-specific variable parameters, the shares of electricity sources were also added as variable parameters to include country-specific information on the type of electricity used during the plant's operation phase. These electricity shares are described with eight variable parameters reporting the share of electricity from wind, solar, hydropower, biomass, oil, natural gas, coal and lignite, and nuclear energy.

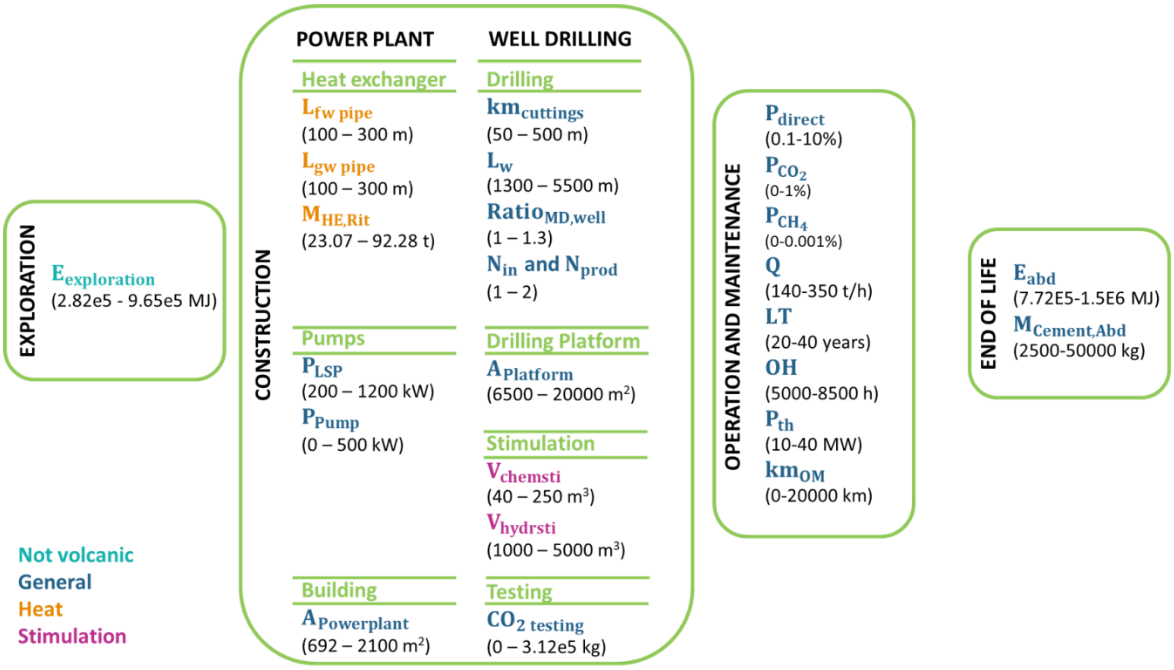

Figure 18 – Flow chart and input variable parameters for the Representative Geothermal System for Enhanced Geothermal System (EGS)

Implementation in lca_algebraic

The modelling of the reference LCA model for the EGS category was based on the functions provided in the lca_algebraic library[2]*. In a first step, the variable and fixed parameters were defined using the function newFloatParam(). Fixed parameters were set as such with the argument distrib=DistributionType.FIXED and the variable parameters were assigned a uniform distribution (DistributionType.LINEAR) except for the electricity shares, which were assigned a beta distribution based on observations collected in (Capros et al., 2016). Within the lca_algebaric library normal, triangular, beta and uniform distributions are available*[3]*. An example of the application of this function is shown in* Figure 19*. More examples can be found in the example Jupyter Notebook provided on the GEOENVI website (https://www.geoenvi.eu/lca-for-geothermal/).*

```
In [10]: ## (1) Drilling platform
A_platform = newFloatParam(
    'A_platform', # short name
    default=20000.0, # default values
    min=6500.0, # minimum value of the parameter range
    max=20000.0, # maximum value of the parameter range
    distrib=DistributionType.LINEAR, # distribution assigned to the parameter, uniform (linear) by default
    group="Drilling", # when listing the parameters, grouped according to this group
    label_fr = 'Area drilling platform', # long label
    unit="m2", # unit
    description="Area of the drilling platform in m2")
```

Figure 19 – Code snippet taken from the example Jupyter notebook (https://www.geoenvi.eu/lca-for-geothermal/) describing how the platform area of the drilling platform is defined as a parameter.

*In a second step, background activities from ecoinvent 3.6. used in the reference LCA model were retrieved with findTechAct() (e.g., unalloyed steel, lorry transport). The function findBioAct() was necessary to retrieve biosphere activities (*Figure 20*).*

```
In [18]: # Drilling platform
concrete = findTechAct('concrete production 40MPa',loc='RoW')
excavation = findTechAct('excavation, hydraulic digger',loc='RER')
land_occupation = findBioAct('Occupation, industrial area')
# Drilling
steel_unalloyed = findTechAct('steel production, converter, unalloyed',loc='RER')
steel_unalloyed_manufacturing = findTechAct('metal working, average for steel product manufacturing',loc='RER')
cement = findTechAct('cement production, Portland',loc='Europe without Switzerland')
diesel = findTechAct('diesel, burned in diesel-electric generating set, 10MW')
transport_lorry = findTechAct('transport, freight, lorry 16-32 metric ton, EURO4',loc='RER')
# Drilling mud
water = findBioAct('Water, unspecified natural origin',categories=('natural resource', 'in water'))
bentonite = findTechAct('activated bentonite production',loc='RoW')
calciumcarbonate = findTechAct('calcium carbonate production, precipitated',loc='RER')
carboxymethylcellulose = findTechAct('carboxymethyl cellulose production, powder',loc='RER')
citricacid  = findTechAct(code='7a678cd8026b10484159dcc3d0cc889a')
chemical_inorganic = findTechAct('chemical production, inorganic')
sodaash = findTechAct('soda ash, dense, to generic market for neutralising agent',loc='GLO')
sodiumchloride = findTechAct('sodium chloride production, powder',loc='RER')
sodiumhydroxide = findTechAct('sodium hydroxide to generic market for neutralising agent')
# Well testing
CO2_alt = findBioAct('Carbon dioxide, fossil',categories= ('air',))
# Operation and maintenance
electricity = findTechAct('market group for electricity, high voltage',loc="Europe without Switzerland")
```

Figure 20 - Code snippet taken from the example Jupyter notebook (https://www.geoenvi.eu/lca-for-geothermal/) describing how the functions findBioAct() and findTechAct() can be used to retrieve background activities.

*In a third step, the different building blocks of the reference LCA model (*Figure 18*) were modelled based on combinations of the fixed and variable parameters with the identified background activities. This was done either by creating new activities with the function*

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[2] Available on https://github.com/oie-mines-paristech/lca_algebraic/blob/master/README.md

[3] https://oie-mines-paristech.github.io/lca_algebraic/doc/params.html#lca_algebraic.params.DistributionType

*newActivity() (*Figure 21*) or by adapting existing activities found in ecoinvent 3.6. with copyActivity() combined with deleteExchanges() and addExchanges(). As an example, the hydraulic stimulation was modelled by copying the ecoinvent activity "stimulation of deep well, for geothermal power", deleting the electricity input, and adding a diesel input. The final model was simply a new activity with the different building blocks as exchanges.*

```
In [19]: drilling_platform = newActivity(db_name= USER_DB, #name of the database
                                         name = "onshore platform production, geothermal, tailor made",
                                          # name of the new activity
                                         unit= "m2", #unit
                                         exchanges={ # what are the technosphere and biosphere flows defining the activity
                                             concrete:0.3, # defined using a dictionary activity key : amount
                                             excavation:0.3,
                                             land_occupation: 1
                                         })
```

Figure 21 - Code snippet taken from the example Jupyter notebook (https://www.geoenvi.eu/lca-for-geothermal/) describing how to use the function newActivity() to create a user-defined activity.

b) 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. The comparison can be somehow tricky to undertake as it is usually difficult to find published LCAs fitting the same applicability domain with similar technological and methodological assumptions. Whenever possible, adjusting the reference LCA model to obtain a consistent set of methods and assumptions, similar to the harmonization step required when dealing with Meta LCA (Heath & Mann, 2012) is necessary to proceed with the validation step. Such adjustments relate to the boundaries of the study, the metrics used for the impact characterisation factors, or the values for some input parameters such as the life time of an installation.

Application to EGS category with very low direct emissions

LCA results of three published studies (Karlsdottir et al., 2014) (Pratiwi et al., 2018) (Rocco et al., 2020) showed a good overlap with the Monte Carlo results of the reference LCA model, except for differences related to the use of different impact assessment methodologies between the studies. A more thorough validation of the reference LCA model was done by comparing the modelling framework shared by Pratiwi et al. (2018) for the Rittershoffen geothermal heat plant to the reference LCA model. After adapting the reference LCA model to better match the assumptions made by Pratiwi et al. (2018), the differences in the outcomes could easily be linked to the use of different ecoinvent versions, the approximation of inventory flows with equations instead of direct inputs in the reference LCA model, and the simplification of the modelling of equipment pieces. Overall, this comparison supports the statement that the reference LCA 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.

Implementation in lca_algebraic

Two functions of the *lca_algebraic* library were useful in this second step: first *multiLCAAlgebric()* which takes as input the reference LCA model, the impact categories to be considered, and the values of the variable parameters to run the LCA. The function then generates deterministic outcomes of the model. Second, with *incer_stochastic_dashboard()* the Monte Carlo simulation using the defined variable parameters can be launched and the stochastic LCA results displayed as well as the first order Sobol indexes.

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

The key variable parameters used for the definition of the simplified models (step 3) are selected via a Global Sensitivity Analysis (GSA). Performing GSA in an LCA context has been addressed quite recently and was proved useful to identify the most influent variable parameters (Padey et al., 2013, Cucurachi et al., 2016, Andrianandraina et al., 2015, Wei et al., 2015, Bisinella et al., 2016). GSA establishes a ranking among the input variable parameters and identifies the most influential ones on the model output's variability. The identification of the key variable parameters is fundamental to design simplified models. In fact, based on the GSA results, the environmental impacts' variability of the reference LCA model can be related only to a few key input variable parameters while fixing the others to average values. Identifying the most influent variables allows therefore to develop simplified parameterized LCA models (Padey et al., 2013).

The identification of the key variable parameters is done with the following two steps:

(a) by performing a GSA calculating the first order Sobol' indices (Saltelli, 2008) from the set of stochastic scenarios derived in step 2 of the protocol from a Monte Carlo simulation of the distribution functions of all variable parameters and

(b) by choosing the variable parameters covering a sufficient share of the variance of the considered environmental impact quantified when running the reference LCA model (at least 75-80%) and keeping the number of variable parameters to a minimum, preferably less than 10.

By applying a GSA for each impact indicator may well lead to a different hierarchy for the key variable parameters or even with different sets of variable parameters. One option would be to select a set covering all combinations of variable parameters and generate the simplified models for all impact categories with the same set. Another option to avoid such a large selection would be to differentiate each set of variable parameters for each simplified model.

Application to EGS category for heat generation with very low direct emissions

The following six variable parameters explained between 53.1% and 83.7% of the total variance of all seven impact categories of interest:

- **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 combined with the eight variable parameters describing the electricity sources' shares explained between 77.0% and 85.1% of the total variance. The simplified models for the seven impact categories rely on these 14 variable parameters.

Implementation in lca_algebraic

The outcome of the function *incer_stochastic_dashboard()* allows to identify manually the variable parameters influencing the variance the most.

4. Generation and validation of the simplified models per impact category

a) Generation of the simplified models per impact category

Each simplified model is generated using the selected key variable parameters as input parameters and by setting the other non-key variable parameters to the median of 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)).

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

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 values obtained with the reference LCA model.

Application to EGS category for heat generation with very low direct emissions

The seven simplified models (one per environmental impact) relying on the 14 variable parameters identified in Step 3 represented well the outcomes of the reference LCA model with R^2 values ranging from 85% to 99.1%. Figure 3 displays the distribution profiles for two environmental indicators, *Climate change total* and *Resources fossil* from ILCD 2.0 2018, when using the reference LCA model (blue colour) and the simplified model (orange colour).

As an illustration Equation 2 gives the simplified model for the environmental impact “Climate change”:

$$\frac{\begin{gathered}0.00113(N_{in}\cdot P_{pump}+N_{prod}\cdot P_{LSP})\cdot[0.0588f_{biomass}+1.28f_{coal}+0.00426f_{hydro}\\ +0.434f_{NG}+0.0115f_{nuclear}+0.917f_{oil}+0.0624f_{solar}+0.0137f_{wind}]\\ +4.99\cdot 10^{-9}[2.47\cdot 10^{3}P_{th}+2.45\cdot 10^{5}N_{in}+3.31\cdot 10^{3}N_{prod}\cdot P_{LSP}+16.6P_{pump}\\ +(N_{in}+N_{prod})\cdot\begin{pmatrix}790.0\cdot 10^{0.000384\cdot L_W+2.04}+274.0L_W\\ +24.1L_W^{1.05}+58.5L_W^{1.22}+27.5L_W^{1.233}\end{pmatrix}\\ +7.49\cdot 10^{6}]\end{gathered}}{P_{th}} \quad (2)$$

Features in lca_algebraic

The simplified models can be generated in two alternative ways: either automatically using *sobol_simplify_model()* where only the variable parameters explaining a certain threshold of the variance, set by default to 80% in *lca_algebraic*, are kept, or using *simplifiedModel()* which allows to manually fix the variable parameters that should not be included in the simplified model. In both cases, the variable parameters not included were set to the median value of their Monte Carlo simulations with the function’s argument fixed_mode= FixedParamMode.MEDIAN. For the EGS category, *simplifiedModel()* was used so that a combination of *evalf()* and *round_expression()* was then necessary to display the model equation with numbers up to the third digit only.

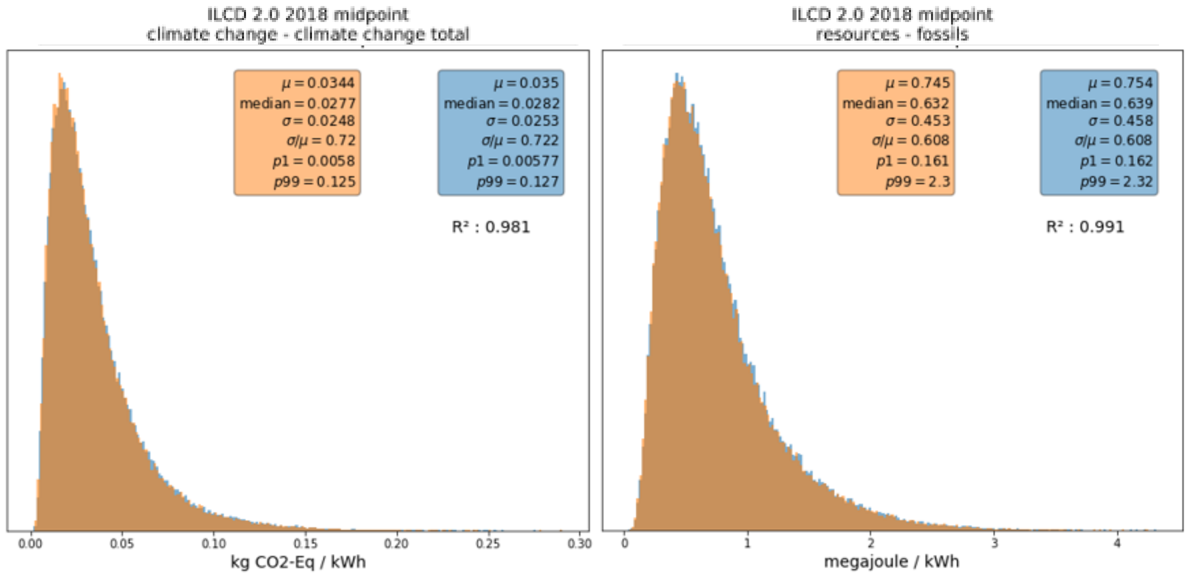

Figure 22 – Performance of the reference LCA model for EGS compared to the simplified models derived for two of the ILCD 2018 impact categories. Blue represents the distribution of the reference LCA model results and orange of the simplified models

b) 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.

1) For each relevant literature case study, the values for the key variable parameters required to run the simplified models are identified.
2) The simplified model is then run with this specific set of values for the key variable parameters.
3) 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.

Undertaking such comparison could be difficult because of missing published LCAs with the same applicability domain and similar technological and methodological assumptions than the one specified for the simplified models. Similar to Step 2b) adjusting to a consistent set of methods and assumptions is necessary. However, one can face the issue of ending with very small consistency with any published literature. Whenever adjustments are not possible and no validation of the simplified models with literature is possible, the simplified models should be used with a lot of caution and with all assumptions fully and transparently reported as explained in step 5. As more literature on LCAs of geothermal projects becomes available, the validation of the reference LCA model and the simplified models will get easier and more robust. LCA practitioners are therefore encouraged to publish their LCA results in a transparent and reproducible way, ideally following the LCA guidelines developed within GEOENVI (Blanc et al., 2020) to ease this validation process.

Application to EGS category for heat generation with very low direct emissions

Due to the lack of literature values available, only the performance of the simplified model for climate change could be compared to published results (Pratiwi et al., 2018) with an estimation of 4.2 g CO_2-eq/kWh when applying the simplified model vs. 5.5 g CO_2-eq/kWh reported.

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

An additional action in the protocol might be necessary if the results from the step 4 are not fully satisfactory. An adjustment of the definition of the applicability domain might be required. It implies to redefine 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 must be summarised for the user to be fully informed on how and when to apply these simplified models to avoid any misuse.

Application to EGS category for heat generation with very low direct emissions

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 Appendix 1 from (Douziech et al., 2020);
- value ranges for the variable parameters as specified in Table 4 from Appendix (Douziech et al., 2020).

It is further important to stress that additional comparisons with other geothermal heat plants are necessary to fully validate the developed models.

Conclusions

This protocol gives the possibility to generate simplified models that allow to estimate the environmental impacts of any geothermal installation type. The indications provided in this document together with the developed programming library *lca_algebraic* and the online video tutorial (https://youtu.be/kZHB--NFe50) make its application by LCA experts with some programming skills to other geothermal installation types possible. These simplified models are powerful tools to increase the use of LCA by non-LCA experts as they only require knowledge on a few parameters.

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