Elaboration and Discussion of Simplified Parameterized Models for Carbon Footprint of Enhanced Geothermal Systems

Martino Lacirignola[1], Bechara Hage Meany[2] and Isabelle Blanc[2]

[1] French Environment and Energy Management Agency (ADEME), Energy Networks and Renewable Energy Department, 27 rue Louis Vicat, 75737 Paris, France; [2] MINES ParisTech, Center for Observation, Impacts & Energy (O.I.E.), Rue Claude Daunesse, 06904 Sophia Antipolis Cedex, France

martino.lacirignola@ademe.fr

Keywords: simplified model, life-cycle assessment, enhanced geothermal systems, environmental impacts, global sensitivity analysis

ABSTRACT

The development of "enhanced geothermal systems" (EGS), aiming at extracting energy from deep low-enthalpy reservoirs, is attracting attention as a promising solution for the development of the geothermal sector in new areas. For the promotion of such renewable energy (RE) based technology, it is important to assess its environmental performances accounting for all phases of the life of the plant, from its construction to its dismantling. Life Cycle Assessment (LCA) is a useful tool to perform a study with such perspective. However, the application of this cradle-to-grave approach is complex and time-demanding. To overcome such drawback of traditional LCAs, this study presents and discusses a methodology to generate simplified models for the estimate of life-cycle greenhouse gases (GHG) emissions of EGS, applicable to a large sample of configurations.

An explicit detailed inventory of all input and outputs of materials and energy flows over the lifecycle of the system is generated, based on current EGS projects in central Europe. A parameterized model, called the reference model, is then established to estimate the life cycle GHG emissions from a set of parameters able to characterize current EGS configurations (size of the equipment and materials involved for example). Applying a Global Sensitivity Analysis (GSA) to this reference model allows identifying the key variables explaining most of the variability of GHG results over the considered range of input parameters. Simplified models are then established, enabling to estimate the GHG emissions of EGS as the only function of these key variables. Several simplified models are here proposed, depending on the level of reduction applied to the reference parameterized model and are compared. The results issued from our simplified models, thus avoiding the extensive application of the LCA methodology, are coherent with literature. GHG emissions of EGS are comparable to those of other RE technologies and significantly lower than those of fossil fuel-based plants. The level of simplification of the parameterized models is discussed according to the availability of input data and the level of simplicity required by the stakeholders of the EGS sector and by the decision makers. These new models contribute to the debate on the mitigation of the environmental effects caused by our current electricity mix by highlighting the environmental benefit of introducing a larger share of geothermal energy.

1. INTRODUCTION

1.1 Context

Today geothermal energy supply about 12 TWh of electricity per year in Europe, with an installed capacity of 1.85 GWe. According to the EGEC Geothermal Market report 2013, 74 new projects are under development and 144 are under investigation (EGEC 2013). In this context of growth, the enhanced geothermal systems (EGS) technologies are expected to play a major role. The principle of EGS is to create or improve artificially an underground reservoir characterized by a natural fracture system at high depth (more than 2.5 km). Its permeability is increased through hydraulic and chemical stimulation. The geothermal heat recovered from the hot crystalline rocks is then valorized through binary systems and converted to electricity. EGS concept allows going beyond traditional hydrothermal systems, producing geothermal electricity in new areas, especially in central Europe.

Enhanced geothermal systems, like most of other renewable energy (RE) technologies, do not entail direct massive emissions of pollutants during their operation. However, their complex construction phase (realization of deep deviated boreholes, stimulation of the reservoir) may raise question on their overall environmental performance. A relevant tool to address this issue and perform a cradle-to-grave environmental analysis is life-cycle assessment (LCA). LCA methodology is based on the estimation of the environmental impacts of a product considering all stages of its life cycle, from the production to the disposal, accounting for all background processes (e.g. raw material extraction). Such methodology has been standardized with the ISO 14 040 series (2006).

Currently a limited number of LCAs related to the EGS pathway are available in literature (Bayer et al. 2013, Frick et al. 2010, Lacirignola and Blanc 2013, Huenges 2010, Sullivan et al. 2013, Bauer et al. 2008, Platt et al. 2012). They propose an environmental assessment of a number of scenarios according to different hypothesis regarding the geothermal resource and the plant set-up. These LCAs are therefore representative of specific technical configurations and are related to a number of assumptions. In the current context of development of the EGS sector, the implementation of supporting environmental policies need an enlargement of the current panel of LCA studies in this field towards a better knowledge of such energy pathway.

However, to perform an LCA is a quite laborious process. In particular, the elaboration of the inventory of all input and outputs related to every stage of the life of a plant is complex and time-demanding. This paper aims at overcoming this drawback of performing additional LCAs to enlarge the sample of configurations analyzed. With the development of simplified parameterized models, it presents an alternative for the estimation of life greenhouse gas (GHG) emissions valid for a large panel of EGS power plants. The methodology to develop simplified LCAs has been initiated by Padey et al. (2013), through an application to the wind energy sector. An application of such methodology to the EGS pathway has been presented by Lacirignola et al. (2014).We now discuss in this paper different levels of simplification for the EGS pathway model within central Europe We highlight the trade-off between the accuracy of the results and the simplification of the model.

1.2 Methodology

Our study focuses on EGS power plants located in central Europe producing only electricity. The functional unit is the kWh of net electricity delivered to the grid by the EGS over its lifetime. This means that the GHG performances will be expressed in terms of gCO_2eq/kWh (carbon footprint).

The methodology presented in this paper is based on the following steps:

A. Elaboration of a reference model for the estimation of the life cycle GHG emissions of a large panel of EGS power plants (section 2):
   - A1. Compilation of all input and output (e.g. material, energy flows) related to the construction phase, the operation and the dismantling of an EGS power plant. This data list is designed to be modular and scalable in order to be applicable for the description of different plant set-ups (e.g. two-wells or three-wells plants).
   - A2. Identification of a panel of relevant parameters (e.g. produced flow rate, drilling depth) used for the characterization of the EGS plants of our sample. In our study, nine parameters have been identified. A variability range is associated to each of them to correspond to the pathway under study.
   - A3. Design of a reference parameterized model for the estimation of the GHG performances. The life cycle inventory for each plant of our sample is obtained by scaling the input/output data set with the nine parameters. These parameters also allow for the calculation of the life cycle electricity production.
   - A4. Generation of the GHG distribution profile of our sample of EGS by applying Monte-Carlo simulations.

B. Generation of the simplified models from the reference parameterized model (section 3):
   - B1. Application of a Global Sensitivity Analysis (Sobol Indices) to identify which of the nine parameters are responsible for most of the variability on GHG results.
   - B2. Elaboration of simplified models expressing the GHG performances as a function of only those key parameters. Three simplified models are presented in this study, based on two, three or four key-parameters.
   - B3. Comparison of the results of the simplified models with literature and discussion.

2. ELABORATION OF THE REFERENCE MODEL FOR THE CALCULATION OF THE GHG PERFORMANCES OF EGS POWER PLANTS

2.1 Data set for EGS binary power plants

The first step of this study is the compilation of all inputs (materials, energy flows), outputs (emissions, waste) and processes (e.g. transports, manufacturing) related to the life cycle of the EGS plant. Data have been collected through an extensive technical survey of the pilot EGS of Soutz-sous-Forêts (France), interviews with experts and a literature review. Data regarding background processes (e.g. steelmaking, extraction of raw materials) are retrieved from the ecoinvent 2.2 database.

Table 1: Overview of the materials and processes taken into account in the reference model

	Materials and processes	Main sources of data
Drilling and construction of the wells	Steel Cement Water Inorganic chemicals Bentonite Salt Silica sand Caustic soda Lubricant oil Disposal of drill. cuttings Fuel for drilling Transport of elements (rail, truck)	G.E.I.E. Exploitation minière de la chaleur (2002a; 2002b; 2002c), Southern International Inc. (2002), Degouy (2003), Gandy Inc. (2004a; 2004b)
Surface equipment (construction and operation)	Steel Copper Organic fluid ORC Lubricant oil Bentonite Mineral wood Phosphoric acid Electrical components Building components Fuel for operations Transport of elements (rail, truck) Disposal of materials Transport of waste (hazardous / non-hazardous)	Genter (2011a), Degouy (2011), Szablinski (2011), Bauer (2011), Technical sheets and equipment manuals (from the Soult-sous-Forêts site),
Enhancement campaign	Water Salt Acid Fuel Transport of elements	Hettkamp et al. (2004), Schindler et al. (2010), Nami et al. (2008), Graff and Baujard (2013)

The outcome of this mass-flow analysis is extensively discussed in Lacirignola and Blanc (2013). An overview of the materials and processes taken into account is provided in Table 1.

2.2 Design of the reference parameterized model and parameters description

Our reference model aims at calculating the GHG performances of a large sample of possible EGS configurations, in order to be representative of the EGS pathway. More details on its elaboration are provided in Lacirignola et al. (2014).

The reference model is based on nine parameters that have been identified as essential to characterize the EGS (i.e. determine the amount of material and processes involved over the lifetime) and its electricity production. These parameters are:

- *z*: drilling depth to reach the geothermal reservoir (meters)
- *f*: total produced flow rate of hot geothermal fluid (kg/s)
- *Nw*: total number of wells (for production and reinjection of the geothermal fluid)
- *d*: average amount of fuel involved in the drilling operations (energy per meter drilled)
- *LF*: load factor (a dimensionless fraction expressing the amount of equivalent operating hours at nominal power in one year)
- *LT*: lifetime of the plant (years)
- *SFe*: scaling factor for the enhancement description. Since the amount of material involved in the stimulation of the reservoir is extremely site dependent, we establish this dimensionless parameter to scale-up a set of values for a "base case" stimulation (defined according to current EGS experiences). High *SFe* means a strong enhancement campaign.
- *Pp*: Specific power of the pump of the geothermal loop (kW per kg/s). In our model we assume that all the wells are equipped with either a production or a reinjection pump that are characterized with the same power to flow rate ratio.
- P_{ORC}: Installed power capacity of the ORC (kW). This variable represents the power output of the organic Rankine cycle of the binary system. It is calculated as the power output of the electrical generator minus the internal power demand of the ORC (e.g. air cooler, ORC circulation pump).

The nine parameters are used to scale-up the input/output dataset described in section 2 and to calculate the life cycle electricity output of the EGS, as presented in Figure 1.

The GHG performances of EGS power plants can be expressed by Equation 1:

$$GHG_{EGS}\left[gCO_2eq/kWh\right] = \frac{GHG_{wells} + GHG_{geoth\_pumps} + GHG_{ORC} + GHG_{enhancement}}{(P_{ORC} - f \cdot P_p) \cdot 8760 \cdot LF \cdot LT} \quad (1)$$

Where 8760 is the number of hours of one year.
The GHG emissions of the system are calculated as the sum of the contributions of the four parts of the model: the wells (GHG_{wells}), the surface elements (GHG_{ORC}), the pumps of the geothermal loops (GHG_{geoth_pumps}), the enhancement campaign ($GHG_{enhancement}$). Each GHG contribution is calculated from the life-cycle inventory previously elaborated and using the IPCC GHG characterization factors (Bernstein et al. 2008).
Developing Equation 1, we obtain the formula of our reference model (2) allowing for an estimation of the GHG emissions of an EGS power plant as a function of the nine parameters listed above.

$$GHG_{EGS\_REF}\left[gCO_2eq/kWh\right] = \frac{z \cdot Nw \cdot (\alpha_1 + \alpha_2 \cdot d) + LT \cdot f \cdot \alpha_3 + P_{ORC} \cdot LT \cdot \alpha_4 + Nw \cdot SFe \cdot \alpha_5}{LT \cdot LF \cdot (P_{ORC} - f \cdot P_p) \cdot 8760} \quad (2)$$

Where α_1= 567014.8 gCO_2eq/m; α_2=86.49 gCO_2eq/MJ; α_3=411384 $gCO_2eq \cdot s/(kg \cdot y)$; α_4=43139 $gCO_2eq/(kW \cdot y)$; α_5=65017978.7 gCO_2eq

The α_i constants correspond to the amount of the life-cycle GHG emissions of each part of the model.

Based on this parameterized model, we then can generate the environmental profile of the EGS pathway by applying Monte Carlo simulations over the input variables range. The boundaries of the variability intervals of the input parameters and their statistical distributions are reported in Table 2. They have been defined in accordance with:

- Current EGS experiences in central Europe, namely the geothermal plants located in:
  - Soultz-sous-Forêts (France): Genter (2011b), LabEx G-EAU-THERMIE PROFONDE (2013)
  - Landau (Germany): Hettkamp et al. (2011), Geox GmbH (2007)
  - Insheim (Germany): Baumgärtner (2011), Bestec (2012)
  - Rittershoffen (France): Perret(2011), Schmittbuhl (2013)
- Other EGS case studies analyzed in LCAs from literature: Frick et al. (2010), Huenges (2010), Platt et al. (2012), Bauer et al. (2008), Lacirignola and Blanc (2013), Sullivan et al. (2013)
- Literature review and discussion with experts (references mentioned in Table 1).

Figure 2 presents the EGS GHG distribution profile generated through the Monte Carlo simulations, accounting for 50 000 different scenarios (each one corresponding to a random set of values for the nine parameters). These results are compared with other LCA regarding EGS and other renewable energy-based technologies (Moomaw et al. 2011). The median of our GHG distribution profile lies around 30 gCO_2eq/kWh. We observe that the results from literature are comparable with those of our reference model, assessing its robustness. Moreover, the GHG performances are similar to those of other renewable energy technologies. For comparison, the average GHG performances of fossil fuel based power plants are 469 gCO_2eq/kWh for natural gas, 840 gCO_2eq/kWh for oil, 1000 gCO_2eq/kWh for coal (Moomaw et al. 2011).

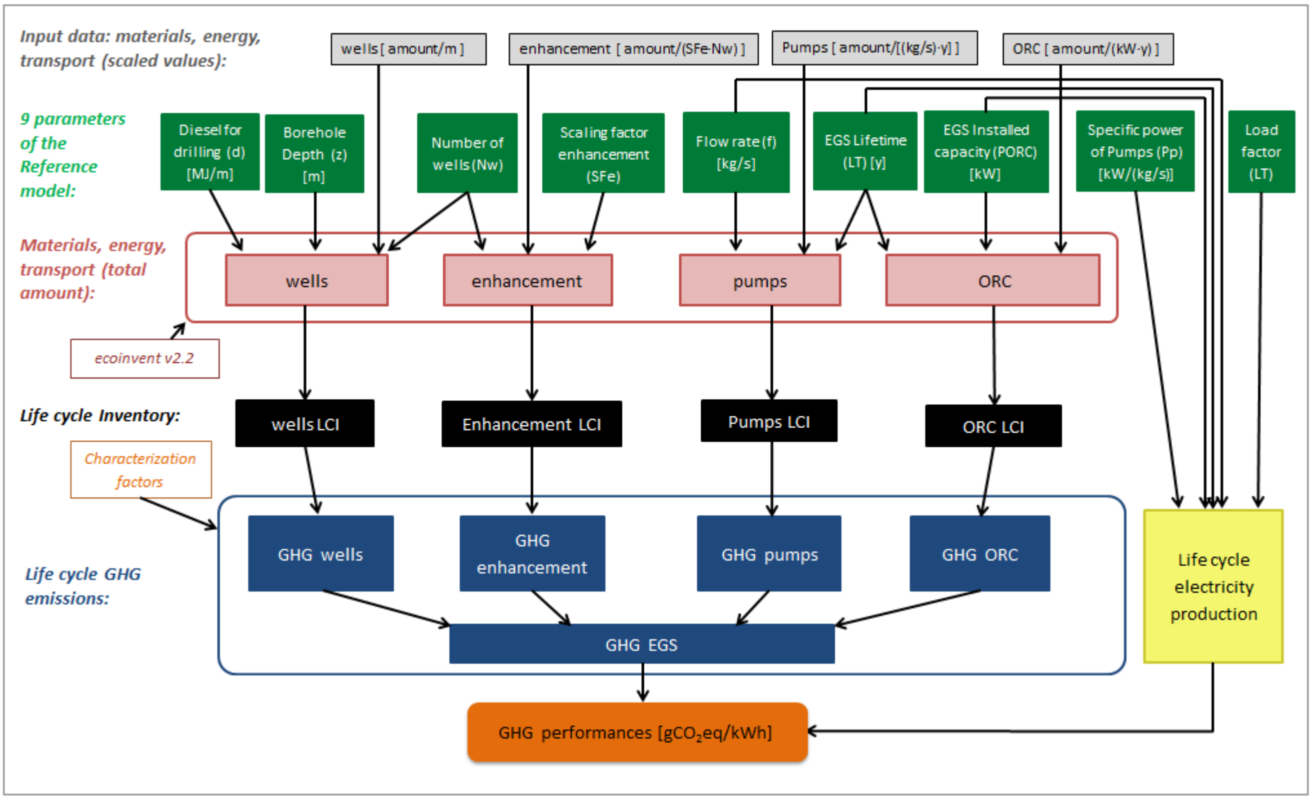

Figure 1: Reference model for the estimation of the life cycle GHG emissions of EGS power plants

Table 2: Description of the nine parameters of our reference model

Symbol	Parameter	Value range	Unit	Probability distribution in the value range	Main references
z	Borehole depth	2000 – 6000	m	Equiprobability	Current EGS projects, Frick et al. (2010), Bauer et al. (2008)
f	Produced flow rate	25 – 100	kg/s	Equiprobability	Current EGS projects, Frick et al. (2010)
Nw	Number of wells	2 – 3	adimensional	Equiprobability	Current EGS projects, Huenges (2010), Bauer et al. (2008), Schmidt et al. (2010)
d	Fuel for drilling	3000 – 7000	MJ/m	Equiprobability	Drilling reports from Soultz-sous-Forêts, Bauer et al. (2008), Frick et al. (2010)
LF	Load factor	0,85 - 0,95	adimensional	Equiprobability	Lund (2003), Huenges (2010), Platt et al. (2012)
LT	Lifetime	20 – 40	years	normal distribution centered on LT = 30 y with σ=3.25	Frick et al. (2010), Platt et al.(2012), Bauer et al. (2008), Huenges (2010)
SFe	Enhancement Scaling factor	0,5 – 10	adimensional	lognormal distribution with σ=1, μ=0 and peak on SFe = 1	Schindler et al. (2010), Hettkamp et al. (2004), Nami et al. (2008), Graff and Baujard (2013)
Pp	Specific power of pumps	3,6 - 8,6	kW/(kg/s)	Equiprobability	Frick et al. (2010), Lacirignola and Blanc (2013), Graff and Baujard(2013)
P_{ORC}	Installed capacity ORC	1250 – 3500	kW	Equiprobability	Current EGS projects, Huenges (2010), Bauer et al. (2008)

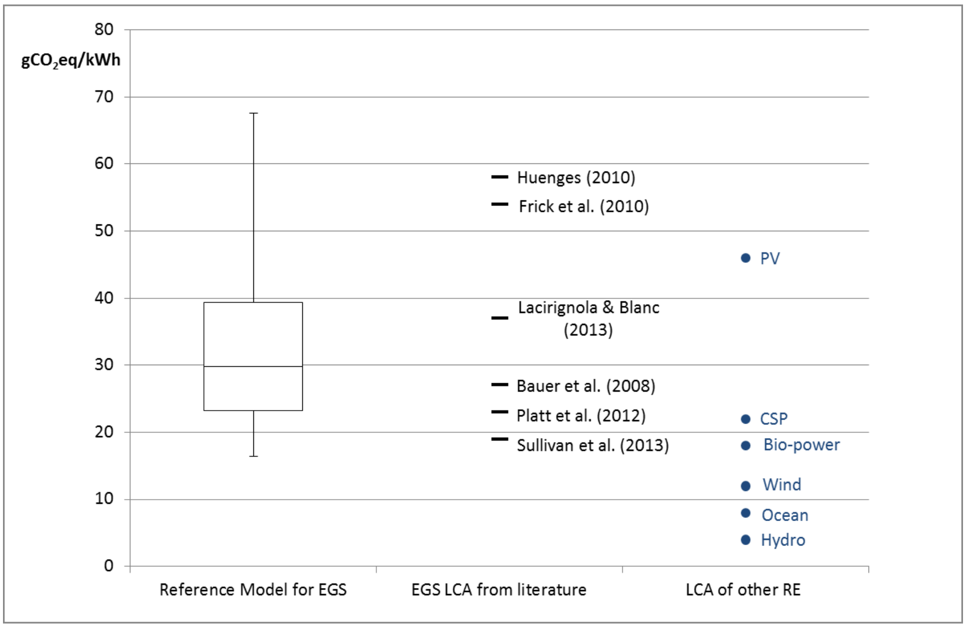

Figure 2: Results of the reference model (GHG profile) compared with LCA results from literature regarding EGS and other renewable energy technologies. Whiskers indicate the 5th and 95th percentiles. The box indicates the 25th and 75th percentiles.

3. GENERATION OF SIMPLIFIED MODELS FROM THE REFERENCE PARAMETRIZED MODEL

3.1 Application of global sensitivity analysis

We here discuss the possibility of further simplifications for the reference model, by reducing the number of input parameters for the estimations of the GHG performances of EGS. A global sensitivity analysis (GSA) is performed to identify the parameters that are responsible for most of the variability of the GHG results within a defined scope of study of the pathway. The GSA calculation (Sobol 2001, Iooss 2011) is based on the variance decomposition and the main output is the estimation of the Sobol Indices (SI). The first order SI indicates the contribution of each parameter alone to the overall variability of the GHG results. A necessary condition for the application of GSA is that the parameters of the model are independent. In our model no dependence relation is established among the nine parameters: each of them can assume a value within its variability range independently from the values assumed by the other eight. Hence, GSA is applicable. The first order Sobol Indices of the nine parameters of our model are shown in Figure 3. We observe that the installed capacity alone is responsible for about half of the variance of GHG results, having a SI close to 0.5. Note that this does not mean that the size of the ORC is the main cause of the GHG emissions: it means that, according to the scope and the architecture of our model, it has a very high influence on the variability of the GHG performances. The second highest SI is the one of the borehole depth, followed by the number of wells and the produced flow rate.

Figure 3: First order Sobol indices of the nine parameters of the reference model.

3.2 Generation of simplified models relying on the key-parameters

Based on this results providing the ranking of the parameters of our reference model, we now propose to discuss three possible simplified models (Equations 3, 4, 5), expressing the GHG performances of EGS as a function of only two, three or four key-parameters. These formulas are obtained by doing a regression analysis on the sample generated from Equation 2, by setting the other non-key parameter to the value corresponding to the median of their respective variability intervals (presented in Table 2). Those median values are d=5000 MJ/m, LF=0.9, LT=30 y, SFe=1.7, Pp=6.1 kW/(kg/s), f=62.5 kg/s.

$$GHG_{EGS\_Simpl2} = f(P_{ORC}, \mathrm{z}) = \frac{\gamma_1 \cdot \mathrm{z} + \gamma_2 \cdot P_{ORC} + \gamma_3}{P_{ORC} - \gamma_4} \tag{3}$$

Equation 3 reports a 2-variables model with γ_1= 10.564 gCO$_2$eq/(m·h); γ_2=5.472 gCO$_2$eq/kWh; γ_3=4429.5 gCO$_2$eq/h ; γ_4=381.2 kW

$$GHG_{EGS\_Simpl3} = f(P_{ORC}, z, Nw) = \frac{Nw \cdot (\beta_1 \cdot z + \beta_2) + \beta_3 \cdot P_{ORC} + \beta_4}{P_{ORC} - \beta_5} \tag{4}$$

Equation 4 reports a 3-variables model with β_1=4.226 gCO$_2$eq/(m·h) β_2=467.3 gCO$_2$eq/h; β_3=5.472gCO$_2$eq/kWh β_4=3261.2 gCO$_2$eq/h; β_5=381.2 kW

$$GHG_{EGS\_Simpl4} = f(P_{ORC}, z, Nw, f) = \frac{Nw \cdot (\theta_1 \cdot z + \theta_2) + \theta_3 \cdot P_{ORC} + \theta_4 \cdot f}{P_{ORC} - \theta_5 \cdot f} \tag{5}$$

Equation 5 reports a 4-variables model with: θ_1=4.226 gCO$_2$eq/(m·h) θ_2=467.3 gCO$_2$eq/h; θ_3=5.472gCO$_2$eq/kWh θ_4=53.18 (gCO$_2$eq·s)/(h·kg); θ_5=6.10 kW·s/kg

A comparison between the results of the reference model and those of the simplified models is provided in Figures 4, 5, 6. Each dot represents one of the 50 000 Monte Carlo simulations (namely one random set of the key variables).

The GHG performances obtained with the 2-variables formula (Figure 4) lie on a more restricted range of the x-axis (compared to those obtained with the 4-variables formula, Figure 6). This can be explained by the fact that the results of 2-variables formula depend on the variability of only two parameters (P_{ORC} and z). The 4-variables formula, accounting also the variability of Nw and f, allows obtaining higher GHG results (higher values on the x-axis).

We also observe that the results of the simplified and the reference models are similar (close to the black diagonal line) for low GHG values (higher concentration of dots, highlighted in red). The affinity between the reference and the simplified model increases with the number of selected key-variables as shown in Table 3: the R^2 increases while the root-mean-square error (RMSE) is divided by two (from 12.10 to 6.14 gCO$_2$eq/kWh). The percentage of the final GHG variance that is covered accounting for the selected key-variables is expressed by the sum of their first order Sobol Indices.

Table 3: Affinity between the reference model and three different simplified models, based on two, three or four key-variables

Number of key-variables of the simplified model	Key-variables	% of the final variance explained by the key-variables	R^2	RMSE
2	P_{ORC}, z	~65%	52%	12.10 gCO$_{2eq}$/kWh
3	P_{ORC}, z, Nw	~75%	70%	8.17 gCO$_{2eq}$/kWh
4	P_{ORC}, z, Nw, f	~79%	81%	6.14 gCO$_{2eq}$/kWh

A comparison between the GHG performances of EGS case studies from literature and the results of our models has been performed. Table 4 presents the selected case studies and the values of the four key-parameters for each of them. Results are shown in Figure 7. For every case study, we propose three different boxplots ("2-var", "3-var", "4-var") respectively related to the simplified model based on two (P_{ORC},z), three (P_{ORC}, z, Nw) or four (P_{ORC}, z, Nw, f) key-parameters. For example, the "FA1 – 2 var" boxplot is obtained as follows: we set P_{ORC} and z to the value proposed by Frick et al. (2010) in its case study A1 (1240 kW and 3 800 m respectively), then we run our reference model (based on nine variables) over 10 000 simulations (the other seven parameters are set to random values within their variability range). The numerical result of the simplified model (Equation 3, where the seven non-key parameters are set to their median values) is indicated by the middle line of the box (60 gCO$_2$eq/kWh in this case). The results interval (described by the boxplot) represents the variability of the seven non-key parameters when running Monte-Carlo simulations. The box indicates the interquartile range and whiskers correspond to the 5th and 95th percentile. The red point indicates the estimation proposed by Frick et al. (2010) (54 gCO$_2$eq/kWh in this case).

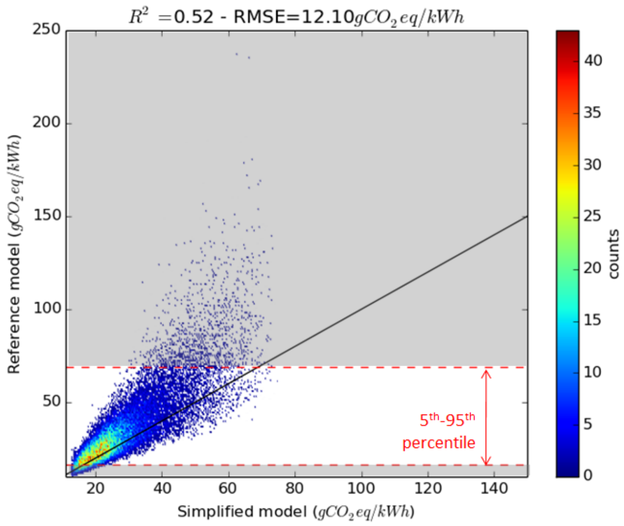

Figure 4: Affinity between the reference model and the two-variables simplified model (Equation 3) (50 000 simulations)

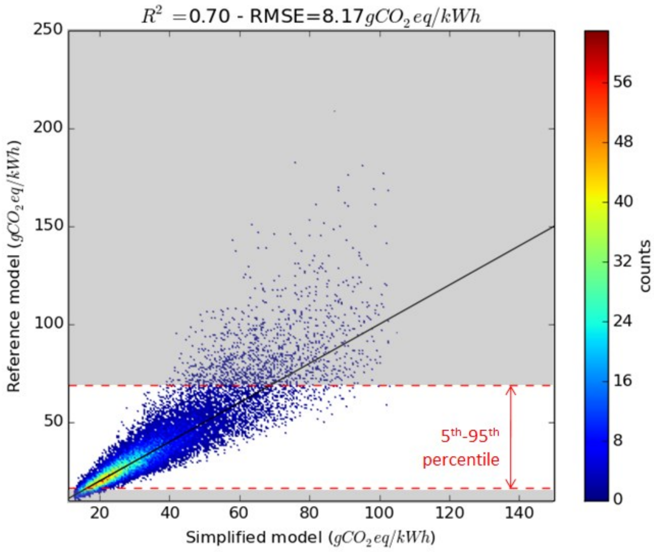

Figure 5: Affinity between the reference model and the three-variables simplified model (Equation 4) (50 000 simulations)

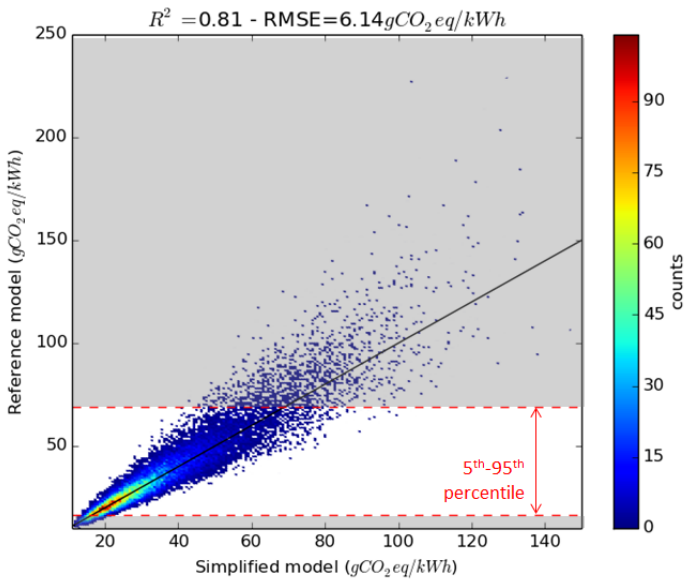

Figure 6: Affinity between the reference model and the four-variables simplified model (Equation 5) (50 000 simulations)

Table 4: Case studies from literature used for comparison with our results

Code	Case study from literature	Depth (z) [m]	Number of wells (Nw)	Installed capacity (P_{ORC}) [kW]	Flow rate (f) [kg/s]	Estimate of GHG performances (literature) [gCO_2eq/kWh]
FA1	Frick et al.(2010)- Site A1	3800	2	1 240	69.4	54
FB1	Frick et al. (2010) – Site B1	4700	2	1 290	43.1	53
Hu1	Huenges (2010) - case 1	4000	2	1 440	69,4	58
Hu2	Huenges (2010) - case 2	4000	2	1 440	33,3	55
Su	Sullivan et al. (2013)	6000	10	20 000	60	18,9

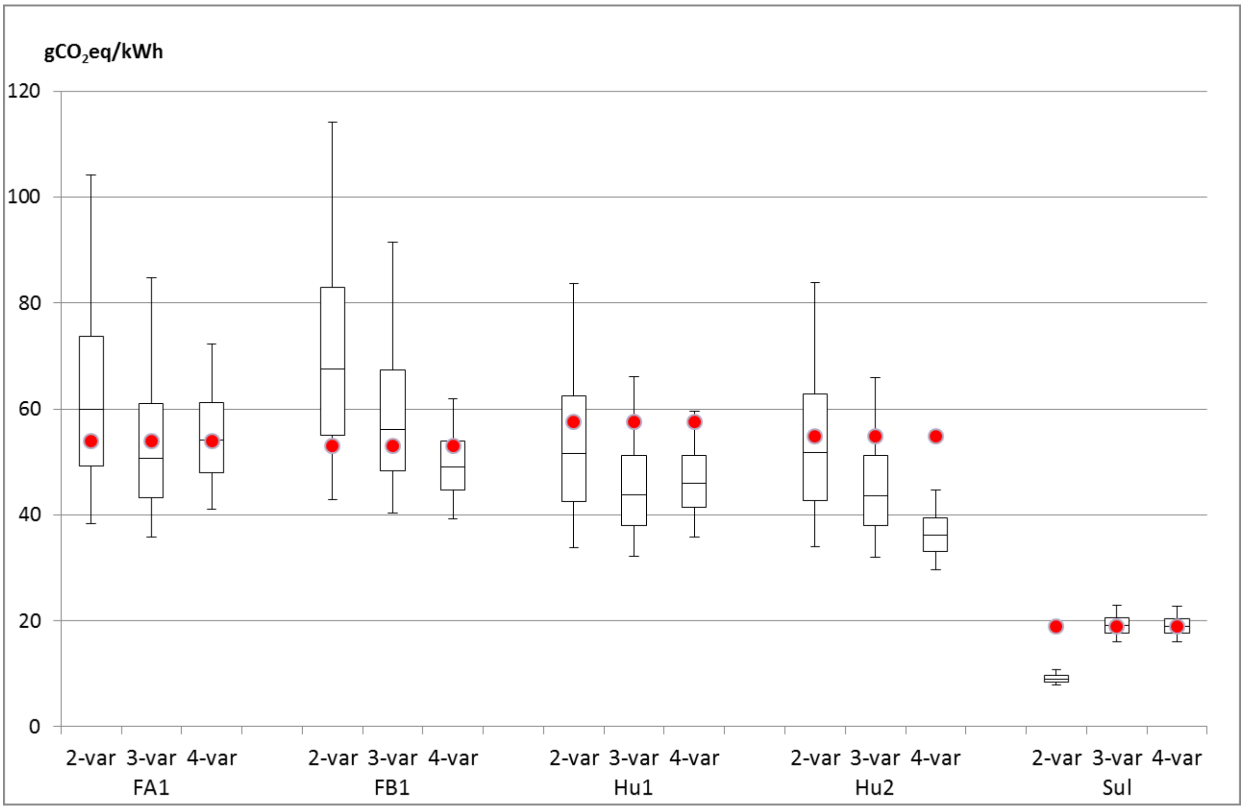

Figure 7: Comparison of the results of our parameterized models with literature. The middle line of the boxplot (median of the distribution) indicates the result of the simplified model. The box and the whiskers indicate the result of the reference model (Equation 2) over 10 000 simulations with fixed values of the key parameters. Whiskers indicate the 5th and 95th percentile. Boxes indicate the 25th and 75th percentile. The red points correspond to the literature values.

3.3 Discussion

Two of the case studies selected for comparison are coherent with the parameters description that we established (Table 2): the FA1 and FB1 scenarios from Frick et al. (2010). We also propose a comparison with two case studies with characteristics at the edge of the scope our reference model (Hu1 and Hu2 from Huenges 2010) and one case study outside the scope of our analysis (Su from Sullivan et al. 2013). This section presents a point to point discussion of these comparisons.

A more general discussion on the methodology and the differences between the simplified models (Equations 3, 4 and 5) is also proposed.

<u>3.3.1 Case studies coherent with the scope of our reference model: FA1 and FB1</u>

The comparison with the FA1 case study is satisfactory. In particular, the result of the 4-variables model (median of the boxplot) is nearly equal to the estimation proposed by the author.
Comparing with the FB1 case, the 2-variables model overestimates the result. This can be explained by our characterization of the variability ranges for the number of wells and the flow rate. In fact, their median values are respectively Nw=2.5 and f=62.5 kg/s while FB1 is characterized by two wells and a flow rate of 43.1 kg/s. A higher number of wells causes higher emissions because of the complex construction process. Moreover in our model the size of the pumps of the geothermal loop is directly proportional to the flow rate: larger pumps generate higher GHG emissions for the EGS, contributing in Equation 2 with the terms GHG_{geoth_pumps} at

the numerator and *(-f·Pp)* at the denominator. Therefore, the GHG estimation of the 2-var model is higher than the value proposed by Frick et al. (2010). However, when the user can also set the number of wells (in the 3-var model) and the flow rate (in the 4-var model) our estimation of the GHG performances progressively decrease and get close to the result proposed by the author.

3.3.2 Case studies at the edge of the scope of our reference model: Hu1 and Hu2

Huenges (2010) assumes a lifetime of 20 years in both Hu1 and Hu2 cases. In our reference model the boundaries of the *LT* variability interval are 20 and 40 years, but most of the scenarios are characterized by about 30 years (a normal distribution centered on *LT*=30 years with σ=3.25 years has been established). The lifetime is not responsible for a high share of the variability of results (it has a low Sobol Index) but it is influent on the GHG performance itself (being related to the overall electricity production). The life cycle GHG emissions of the plant are lower if the lifetime is higher. Hence, our simplified models underestimate the results proposed by Huenges (2010): this is especially obvious in the 4-var calculation for the Hu2 case.
Such overestimation is partially compensated in the 2-var model, since in this case the Monte-Carlo calculation accounts also the three-wells configurations (characterized by higher GHG emissions), while Hu1 and Hu2 cases have only 2 wells.
Hu1 and Hu2 are characterized by the same installed capacity and drilling depth. They differ from the flow rate (69.4 kg/s and 33.3 kg/s respectively). Their equal power output is explained by the hypothesis of a higher temperature of the produced geothermal fluid in the second case. The different flow rate explains the gap between the 4-var results for the Hu1 and Hu2 cases.

3.3.3 Case study outside the scope of our reference model: Su

The case study proposed by Sullivan et al. (2013) is characterized by 10 boreholes and a power output of 20 MW. Such values lie outside the variability intervals considered in our reference model (Table 2). Hence, the estimation produced by the 2-var model is far below the one proposed by the author, since our simulations account for a maximum of three wells per plant and 3.5 MW installed capacity. However, the results of the 3-var and 4-var models are much more accurate. This is explained by the fact that, in those calculations, both P_{ORC} and *Nw* are input variables (i.e. set to the values proposed by Sullivan et al.). Therefore the model is able to estimate the high electricity output of this plant and to account for the high emission related to construction of ten boreholes: the resulting GHG estimation is then more accurate.

3.3.4 General observations

1. The range of GHG results (represented by the size of the boxplot) tends to be smaller for case studies presenting lower GHG emissions (e.g. Su case). This is also observed from Figure 4, 5 and 6: the results of the Monte-Carlo simulations applied to the reference model are closer to the simplified model value (i.e. smaller boxplot) for lower GHG results.

2. In general, the GHG results variability range associated to the simplified models decreases with the number of key parameters. In fact, for the 2-var model the size of the boxplot depends on the variability of the other seven non-key parameters, while for the 4-var model it depends on the variability of "only" five of them. The Su case is an exception, since the 2-var estimations lies within very low-GHG values (see observation no. 1).

3. The accuracy of the results of the simplified models (compared to literature) increases with the number of key parameters, as can be observed for the FA1 case. Only for the Hu2 case the estimation of the 4-var model is less accurate than the one of the 3-var model: this is explained by the values of the lifetime and the flow rate, as discussed in section 3.3.2. However, when using a 5-variables model that include also the lifetime as an input variable (set to 20 years), the result is much closer to literature (we obtain 50 gCO_2eq/kWh).

4. The application of GSA requires that the nine parameters for the reference model are independent. From a physical point of view, the installed capacity P_{ORC} depends on many factors, including the flow rate of geothermal fluid and the number of production wells. However, in our model P_{ORC} is set as independent from the other eight parameters. Such simplified modelling is due to the impossibility of generalizing all the physical relations with simple equations widely valid in central Europe (e.g. the flow rate is also related to the drilling depth depending on the reached geological layer). The random sampling process may generate some unlikely scenarios, for example an EGS with a very high power output despite a very low production rate of geothermal fluid: in this case the GHG emissions per kWh will be fairly high (see Figures 4, 5, 6). However, such results belong to the tails of the statistical distribution: in facts, most of the results of the GHG profile shown in Figure 3, 4, 5 and 6 lie on a restricted range (16-69 gCO2eq/kWh).

5. It is worth to note that our results depend on the architecture of the reference model, the dataset collected for the life cycle inventory and the parameters description (variability ranges and probability distributions) necessary to run the Monte-Carlo simulations for the reference model. Therefore these operating and technological conditions may not be applicable to power plants outside the scope of our analysis.

4. CONCLUSIONS

This research presents a relevant tool for the estimate of the life cycle GHG emissions of EGS power plants located in central Europe. It provides easy-to-use formulas allowing for a rapid calculation without undertaking detailed LCAs.

Starting from a reference parameterized model based on nine parameters, which encompass a very large panel of possible technical configurations of EGS, we presented and discussed more simplified models, based on two to four key-parameters. The comparison with the GHG results proposed in several case studies from literature is satisfactory.

The simplified models, based on 2, 3 or 4 variables, allow for a fast estimation of the GHG performance and require the input of a limited number of easy accessible parameters. In case the values of the other five non-key parameters are also known, a more precise estimation can be performed by using directly the reference model equation (unknown values are set to the median of the variability intervals shown in Table 2). In fact, the accuracy of the results increases with the number of customized parameters.

We recommend to perform the calculation with the reference model formula by using as much input variables as possible. The outcome of the global sensitivity analysis (Sobol indices) indicates the ranking of key parameters and therefore which ones (when few of them are available) are to be set in priority (installed power capacity, drilling depth, number of wells, produced flow rate) to run the simplified models.

Therefore the choice of the number of input parameters results on a trade-off between accuracy (a satisfactory estimation of the GHG results) and simplification (use of a limited number of easily-accessible parameters). It is important to note that if the EGS analyzed has characteristics at the edge or outside the variability ranges that we established (i.e. the lifetime for the Hu2 case, the power capacity and the number of wells for the Su case) it is necessary to include such parameters in the calculation and choose accordingly the simplified model.

Our study provides a set of useful simplified tools for decision makers and environmental analysts of the EGS pathway. It confirms the interest of developing such simplified models using Global Sensitivity Analysis for an energy pathway following the methodology elaborated by Padey et al. (2013). It aims at contributing to the debate on the environmental performance of geothermal systems.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Camille Marini and Dr. Pierryves Padey for their valuable comments and support.

REFERENCES

Bauer, C., Dones, R., Heck, T., and S. H.: Environmental assessment of current and future Swiss electricity supply options. *Proceedings*, International Conference on the Physics of Reactors "Nuclear Power: A Sustainable Resource", Interlaken, Switzerland, (2008).

Bauer, C.,Paul Scherrer Institut: *personal communication*, July 2011.

Baumgärtner, J.: Geothermie-Projekt Insheim, *Proceedings*, Soultz geothermal conference, Soultz-sous-Forêts, France, 5-6 October 2011.

Bayer, P., Rybach, L., Blum, P., and Brauchler, R.: Review on life cycle environmental effects of geothermal power generation, *Renewable and Sustainable Energy Reviews*, **26**, (2013), 446-463.

Bernstein, L., Pachauri, R.K, Reisinger, A., Intergovernmental Panel on Climate Change: Climate change 2007: synthesis report, Geneva (2008).

Bestec: The Insheim Geothermal Project, available at http://www.bestec-for-nature.com/j_bestec/index.php/en/projects/insheim, (2012), Accessed December 2013

Degouy, M.: Fluids MI. GPK-4-rapports journaliers et Boue. Soultz-sous-Forêts, France (2003).

Degouy, M., BRGM: *personal communication*, Soultz-Sous-Forêts, France, October 2011.

Ecoinvent centre: ecoinvent data v2.2. In: ecoinvent reports No.1-25. Available at http://www.ecoinvent.org, Accessed December 2013.

European Geothermal Energy Council, Geothermal Market Report 2013/2014, Brussels, Belgium (2013)

Frick, S., Kaltschmitt, M., and Schröder, G.: Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs, *Energy*, **35**, (2010), 2281-2294.

G.E.I.E. Exploitation Minière de la Chaleur: GPK-3 daily drilling report, Soultz-sous-Forêts, France, (2002a).

G.E.I.E. Exploitation Minière de la Chaleur: GPK-3 daily mud report, Soultz-sous-Forêts, France, (2002b).

Gandy Inc.: GPK-4 final drilling report, Soultz-sous-Forêts, France, (2004a)

Gandy Inc.: GPK-4-rapports journaliers de Forage, Soultz-sous-Forêts, France (2004b).

G.E.I.E. Exploration Minière de la Chaleur : Rapport sommaire de fin de forage de GPK-3 [in French], Soultz-Sous-Forêts, France, (2002c).

Genter, A.: Overview of the scientific and technical research program done at Soultz during geothermal exploitation, *Proceedings*, Soultz geothermal conference, Soultz-sous-Forêts, France, 5-6 October 2011.

Genter, A., G.E.I.E. Exploitation minière de la Chaleur: *personal communication*, Soultz-sous-Forêts, France, August 2011.

Geox GmbH: projektinfo 14/07: Geothermische stromerzeugung in Landau, Available at http://www.geox-gmbh.de/media/Downloadbereich/projekt_1407internet-x.pdf, (2007), Accessed December 2013.

Graff, J.J., and Baujard, C., Electricité de Strasbourg Géothermie: *personal communication*, Paris, July 2013.

Hettkamp, D., Teza, D., Michelet, S., Baumgartner, J., and Baria, R.: Technical report on the 2003 hydraulic testing and stimulation program, Soultz-sous-Forêts, France, (2004)

Hettkamp, T., Baumgärtner, J., Teza, D., Gandy, T., and Frost, J.: Production pump technology in the Landau and Insheim geothermal projects, *Proceedings*, Soultz geothermal conference, Soultz-sous-Forêts, France, 5-6 October 2011.

Huenges, E.,: Economic performance and environmental assessment, in: *Geothermal Energy Systems: Exploration, development and utilization*, Wiley-VCH, (2010).

Iooss, B.: Revue sur l’analyse de sensibilité globale de modèles numériques, *Journal de la Société Française de Statistique*, **152**, (2011), 3-25.

ISO 14040: Environmental management - Life cycle assessment - Principles and framework, International Standard Organization, (2006).

ISO 14044: Environmental management - Life Cycle Assessment - Requirements and guidelines, International Standard Organization, (2006).

LabEx G-EAU-THERMIE PROFONDE: La géothermie profonde EGS - l’exemple de Soultz-sous-Forêts, Available at http://labex-geothermie.unistra.fr/article200.html, (2013), Accessed December 2013

Lacirignola, M., and Blanc, I.: Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment, *Renewable Energy*, **50**, (2013), 901-914.

Lacirignola, M., Hage Meany, B., Padey, P., and Blanc, I.: A simplified model for the estimation of life-cycle greenhouse gases emissions of enhanced geothermal systems, *Geothermal energy*, (2014), doi: 10.1186/s40517-014-0008-y.

Lund, J.W.: The USA geothermal country update, *Geothermics*, **32**, (2003), 409-418.

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., and Verbruggen, A.: Annex II: Methodology, in: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, (2011).

Nami, P., Schellschmidt, R., Schindler, M., and Tischner, T.: Chemical stimulation operations for reservoir development of the deep crystalline HDR/EGS system at Soultz-sous-Forêts (France), *Proceedings*, Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, USA, 28-30 January 2008.

Padey, P., Girard, R., Le Boulch, D., and Banc, I.: From LCAs to Simplified Models: A Generic Methodology Applied to Wind Power Electricity. *Environmental Science & Technology*, **47**, (2011), 1231-1238.

Perret, E.: ECOGI, L'alliance de la géothermie et de l'industrie, *Proceedings*, Soultz geothermal conference, Soultz-sous-Forêts, France, 5-6 October 2011.

Platt, M., Balon, B., Appelhans, K., and Bracke, R.: Ökobilanzdaten der geothermischen Strom- und Wärmeerzeugung in Deutschland im Bereich Treibhausgase [in German], *Proceedings*, German Geothermal Congress, Karlsruhe, Germany, 13–16 November 2012.

Schlinder, M., Baumgartner, J., Gandy, T., Hauffe, P., Hettkamp, T., Menzel, H., Penzkofer, P., Teza, D., Tischner, T., and Wahl, G.: Successful Hydraulic Stimulation Techniques for Electric Power Production in the Upper Rhine Graben, Central Europe, *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.

Schmidt, B., Rogulic, B., Ritter, J.: Relationship between reduced injection rates and reduced induced seismicity e 3 years of field data from the commercial geothermal power plant of Landau (Germany), *Proceedings*, Workshop on induced seismicity, Luxembourg, 15-17 November 2010.

Schmittbuhl, J.: Géothermie, EOST Université de Strasbourg, Available at http://labex-geothermie.unistra.fr/IMG/pdf/presentation_geothermie_3a_2013.pdf, (2013), Accessed December 2013.

Sobol, I.M.: Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates, *Mathematics and Computers in Simulation*, **55**, (2001), 271-280.

Southern International Inc.: GPK-3 final report, Soultz-sous-Forêts, France, (2002).

Sullivan, J.L., Clark, C., Han, J., Harto, C., and Wang, M.Q.: Cumulative energy, emissions and water consumption for Geothermal Power Production, *J. Renew. Sustain. Energy*, **5**, (2013), 023127, http://dx.doi.org/10.1063/1.4798315.

Szablinski, D., Pfalzwerke Geofuture GmbH: *personal communication*, Landau, Germany, October 2011.