

Life cycle assessment of enhanced geothermal systems : from specific case studies to generic parameterized models

Martino Lacirignola

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THÈSE

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Life cycle assessment of enhanced geothermal systems: from specific case studies to generic parameterized models

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Résumé

Cette recherche vise à étudier les impacts environnementaux d'une technologie émergente de production d'électricité basée sur une source renouvelable, les systèmes géothermiques stimulés (EGS), par l'analyse de leur cycle de vie (ACV).

Après avoir analysé plusieurs études de cas, nous avons développé un modèle ACV paramétré capable de caractériser les performances environnementales de la filière EGS. Nos résultats montrent que les émissions de gaz à effet de serre des EGS sur leur cycle de vie sont bien inférieures à celles des centrales utilisant des combustibles fossiles.

Dans un deuxième temps, nous avons mis au point un cadre méthodologique pour appliquer l'analyse de sensibilité globale (GSA) à l'ACV des technologies émergentes comme les EGS, prenant en compte les incertitudes élevées liées à leur caractère innovant. Nous avons appliqué notre nouvelle approche GSA pour développer un modèle ACV simplifié, à destination des décideurs, permettant une estimation rapide des impacts de configurations EGS spécifiques à partir de seulement cinq paramètres clefs: la capacité installée, la profondeur de forage, le nombre de puits, le débit géothermal et la durée de vie.

L'approche méthodologique développée dans cette thèse est applicable à d'autres technologies et ouvre de larges perspectives de recherche dans le domaine de l'évaluation environnementale.

Mots-clés : systèmes géothermiques stimulés, analyse du cycle de vie, impacts environnementaux, analyse de sensibilité globale

Abstract

This thesis investigates the environmental impacts of an emerging renewable energy technology, the enhanced geothermal systems (EGS), using a life cycle assessment (LCA) approach.

Following the analysis of several EGS case studies, we developed a parameterized LCA model able to provide a global overview of the life cycle impacts of the EGS technology. The greenhouse gas emissions of EGS are found comparable with other renewable energy systems and far better than those of power plants based on fossil fuels.

In a second stage, we developed a methodological framework for the application of global sensitivity analysis (GSA) to the LCA of emerging technologies like the EGS, taking into account the high uncertainties related to their description. We applied our new GSA approach to generate a simplified LCA model, aimed at decision makers, allowing a rapid estimation of the life cycle impacts of EGS from only five key parameters: installed capacity, drilling depth, number of wells, flow rate and lifetime.

The methodological approach developed in this thesis is applicable to other technologies and opens large research perspectives in the field of environmental assessment.

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

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Abbreviations and symbols

ACV: analyse du cycle de vie

CF : characterization factor

CO_2: carbon dioxide

d : amount of fuel consumed during the drilling phase (per meter)

DALY: Disability Adjusted Life Years

EGS: enhanced geothermal systems

EnR: énergies renouvelables

f : produced flow rate

GES: gaz à effet serre

GHG: greenhouse gas

GSA: Global sensitivity analysis

ICV: inventaire de cycle de vie

IPCC: Intergovernmental Panel on Climate Change

kWh: kilowatt hour

LCA: life cycle assessment

LCI: life cycle inventory

LCIA: life cycle impact assessment

LF : load factor

LT: lifetime

Nw : number of wells

ORC: Organic Rankine cycle

PDF·m^2·y: potentially disappeared fraction per square meter per year

P_{ORC} : power output of the ORC

P_p : specific power of the pumps of the geothermal loop

RE: renewable energies

SFe : factor indicating the intensity of the enhancement campaign

S_i^{First}: First order Sobol index

z : borehole depth

Extended abstract

Renewable energies (RE) systems are currently playing a major role in the electricity sector, outpacing fossil fuel technologies in terms of investment for capacity addition at a world scale. Such a strong growth is promoted by the implementation of supporting energy policies in several countries, with the aim of reducing greenhouse gas (GHG) emissions, facing the growing demand for energy and decreasing the dependency on oil, gas and coal supply. The historic COP21 agreement highlights the interest of the global community in promoting RE in the framework of the actions for mitigating climate change.

In the RE domain, the exploitation of geothermal resources represents a suitable option for the supply of cheap base load electricity and heat. However, conventional geothermal plants are located in rare locations with exceptionally favorable geological conditions (e.g. the volcanic regions in Iceland or in the Philippines). In this context, the recent development of "Enhanced Geothermal Systems" (EGS) is attracting attention as a promising solution for the valorization of geothermal resources in new “unconventional” areas.

The principle of EGS is to enhance and/or create a geothermal reservoir through hydraulic and chemical stimulation at considerable depth (usually higher than 2 km), exploiting low-medium temperature resources (generally below 175 °C in the European context). Large areas of Europe present the appropriate geological conditions, i.e. a high vertical gradient of temperature, that make EGS applications suitable: for example in France, Germany, Italy, Hungary, Spain and Turkey. A huge and still unexplored potential can be tapped with such technology and EGS can contribute to a relevant increase of the geothermal installed capacity worldwide (currently amounting to about 13 GWe). The first pilot EGS in Europe was installed in Soultz-sous-Forêts in France (Alsace region) and started operating in 2008 after two decades of R&D. Few commercial plants have been installed in Germany (Landau, Insheim) while in France the first industrial EGS was inaugurated in 2016 (Rittershoffen). Several other exploration permits in the Rhine Graben have been requested to the national authorities, thus a progressive expansion of this sector is foreseen.

Despite the absence of direct emissions in the atmosphere during the operation phase, the more elaborate realization of the wells (deep drilling, stimulation) and the surface facilities (binary plant) raised questions about the overall environmental suitability EGS. Such questions have been addressed so far by a limited number of studies presenting the Life Cycle Assessment (LCA) of few specific EGS scenarios. The LCA methodology, which has been standardized with the ISO 14 040 series, takes into account all processes related to the lifecycle of the product, such as the extraction of raw materials, manufacturing, distribution, use and disposal. In the RE domain, LCAs contribute to a better understanding of the environmental suitability of energy systems, however its application has some drawback: the complexity of the LCA process (which is time-consuming and requires expert knowledge) and the applicability of the results (which often correspond only to specific configurations of the system analyzed).

An appropriate solution to face these drawbacks is the development of stochastic parameterized LCA models (called "*simplified models*"). The latter allow investigating the life cycle impacts at two levels: (i) considering the generic "environmental profile" of the technological sector (ii) analyzing specific system configurations within the technological sector. In other words, they allow positioning the EGS technology with respect to its alternatives (like PV systems or wind turbines) and they also make possible a comparison among specific EGS configurations. However, the set-up of simplified parameterized models for EGS faces the difficulties related to the innovative character of this emerging technology. In fact, because of the limited long-term experience in the EGS sector, the characterization of the variability of the input parameters of the environmental model is a delicate operation, affected by high uncertainties. Therefore the model development must be carried out together with a critical assessment of its robustness.

Based on this context, this thesis aims at addressing the two following research questions:

[a] What is the environmental profile of the EGS sector, accounting for the heterogeneity of the possible plant configurations?
[b] How to develop simplified models for an easy estimation of the life cycle impacts of EGS, aimed at decision makers and able to take into account the high uncertainties related to such emerging technology?

The methodological approach set up in this thesis to address these research questions is structured in three sequential steps:

1. Elaboration of a **new life cycle inventory** for EGS and application of the LCA methodology to a number of case studies, in order to prepare the ground for the development of new parameterized models able to address the questions **[a]** and **[b]**.
2. Set up of a **parameterized LCA model** for EGS, able to estimate the life cycle impacts of a large panel of different EGS configurations, representative for the EGS sector in central Europe, able to address question **[a]**.
3. Elaboration of **a reduced LCA model**, aimed at decision makers and function of few key parameters, identified through a **methodological framework** of global sensitivity analysis specifically developed to deal with the high uncertainty related to an emerging technology like the EGS, addressing question **[b]**.

1. Elaboration of a new inventory and LCA of EGS case studies

The aim of this first part of our research is to produce the LCA of specific EGS configurations, using the methodology defined by the ISO standard. Considering the limited amount of data available in the literature, we elaborated **a new life cycle inventory (LCI)** for EGS through an extensive survey of the pilot power plant of Soultz-sous-Forêts. By examining the technical documentation (reports of the drilling and enhancement phases, equipment manuals, technical sheets, etc.) and interviewing several experts of the field, we collected data regarding the different inputs and outputs (materials, energy flows, waste, etc.) occurring during the life cycle of an EGS.

We defined **ten scenarios** corresponding to possible realistic EGS configurations, taking into account different options for the drilling depth, the temperature of the resource, the geothermal flow rate and the number of production and reinjection wells. We validated our choices regarding the inventory and the scenarios with scientists and experts involved in the site's construction and operation.

We calculated the environmental performances with a multi-criteria approach, considering **five indicators**: the impacts on the climate change (taking into account the emissions of greenhouse gases), on human health, on the ecosystem quality, on the depletion of finite resources and on the risk of induced **seismicity**. The latter was included for the first time as a

relevant indicator in the LCA of geothermal energy systems. We also identified the most influent processes and substances within each impact category.

Our results are coherent with the available literature and show that the construction of the wells is the most impacting process, because of the large quantity of fuel burnt during the drilling phase. We also observe that the seismicity risk increases with the environmental benefit, since high geothermal flow rates entail high energy production but also the need of massive rejection rates.

2. Set up of a parameterized LCA model for EGS, representative of the EGS sector in central Europe

The aim of this second part of our research is to develop a stochastic parameterized model, called "*Reference model*", allowing the estimation of the impacts of a **large panel of potential EGS** configurations (with a focus on the life cycle emissions of greenhouse gases). Such model aims at being as much representative as possible of the EGS sector in central Europe, characterizing its "environmental profile".

We set up the model as a function of **nine parameters** (called "model inputs"): produced flow rate, drilling depth, number of wells, fuel consumption for drilling, load factor, power demand of the pumps, enhancement's intensity, lifetime, power capacity of the ORC. These parameters allow the characterization of the size of the plant, of the inventory of materials involved and of the amount of electricity produced over the life cycle. In order to account for a large panel of possible EGS configurations, we associated a variability range and a probability distribution to each of the parameters.

We disaggregated the previously elaborated life cycle inventory (LCI) into several sub-inventories. In the *Reference model*, the nine inputs are used to scale-up such sub-inventories as well as to calculate the life cycle electricity production. Based on this computing architecture, the LCI of a **generic EGS** (whose characteristics are defined by the nine parameters) is obtained. The GHG impacts are then calculated through the characterization factors (CFs) defined by the IPCC 2013 method. Therefore the *Reference model* allows a rapid estimation of the life cycle GHG emissions of a generic EGS as a function of the abovementioned nine parameters.

Considering the description of the variability of the nine inputs, we performed a Monte Carlo analysis to calculate of the life cycle GHG impacts of **several thousand possible EGS configurations**, each of them corresponding to one random set of the nine parameters. The obtained "GHG profile" shows that most of the results lay within the 20 - 40 gCO_2eq/kWh range. This relevant figure is representative for the whole EGS sector (considering the scope of the study, i.e. in central Europe), since it encompasses a panel of thousands of possible EGS and not just a few specific configurations. Therefore it addresses the research question **[a]** and it allows a consistent comparison with other energy technologies. The environmental performances of EGS are found comparable to those of other renewable energy systems and they are much better than those of fossil fuel-based power plants. Moreover, the *Reference model* allows a rapid calculation of the environmental performances without undertaking the complex LCA procedure, preparing the ground to address the research question **[b]**.

3. Elaboration of a reduced LCA model, for the analysis of specific EGS configurations

While the *Reference model* considerably simplifies the estimation of the environmental performances with a life cycle perspective, it may still be difficult to be handled by a non-expert since it is a function of a quite large amount of parameters. The aim of this third part of the research is double: (i) to develop a **methodological framework** for the application of global sensitivity analysis to the LCA of emerging technologies, in order to identify the key parameters of the model (ii) to generate a more **simple tool**, called *Reduced model*, allowing the estimation of the life cycle environmental performances of specific EGS configurations as a function of few key parameters.

Global sensitivity analysis (GSA) allows establishing a ranking among the input parameters of a calculation model, identifying the most influential on the variability of the output. The application of GSA to LCA faces a major challenge in the EGS context, related to the innovative character of this energy technology. When conducting a GSA, the description of the variability of each input parameter (called "description of the inputs") is one of the most important steps, because it could significantly affect the results. This aspect is critical when studying new products or emerging technologies, where data regarding the model inputs are very uncertain and may cause misleading GSA outcomes, such as inappropriate input rankings. In our case, given that very few EGS installations currently exist, the description of the inputs is quite uncertain because it is only based on the few data available from the

industry, discussion with experts and literature survey. Therefore the GSA procedure must be undertaken together with a solid investigation of the robustness of its results.

In this context, we developed a methodology to **analyze the sensitivity of the GSA results** (i.e. the stability of the ranking of the inputs) **with respect to the description of such inputs** of the model (i.e. the definition of their inherent variability). Our methodology relies on the reiteration of several GSA calculations under different hypothesis regarding the description of the inputs. This allows assessing the stability of the ranking among the parameters, while considering the level of confidence of their description. We also analyzed whether the contribution of one input to the output's variance (calculated through the Sobol' indices) changes significantly from one calculation to another. We then retrieved relevant recommendations for the selection of the key parameters of the model.

The application of our methodology to the *Reference model* led us to discover that the description of the variability of the lifetime and of the drilling depth has a significant impact on the identification of the main drivers of the models. It also allowed us to identify five key parameters: the installed power capacity, the number of wells, the drilling depth, the lifetime and the geothermal flow rate. We then generated a *Reduced model*, expressing the life cycle **GHG impacts of EGS as a function of only those 5 parameters**. The developed calculation tool, aimed at decision makers, is easy to use and allows a very rapid calculation of the GHG performances of EGS: thus it addresses the question **[b]** of the thesis.

Perspectives of this research

Our research opens different paths for further studies, both in the investigation of the environmental performances of EGS and in the methodological approach for developing simplified LCA models. We explored a number of propositions, summarized as follows:

- With the investigation of new EGS operations, new data can be collected to enhance and consolidate the *Reference model*
- The scope of the *Reference model* can be extended, including for instance the cogeneration of heat and power and the use of electricity in the drilling phase
- While we focused on GHG emissions, our methodology can be applied to other impact categories, establishing a multi-criteria environmental profile for EGS

- Further investigations can be performed on the integration of the seismicity issues into an endpoint category, exploring its relation with the impacts on human health or ecosystem quality.
- Different calculation strategies to analyze the sensitivity of the GSA results can be investigated, developing new sensitivity indicators
- The integration of the environmental model with the design tools and decision-making indicators used by EGS project developers can be further investigated.

Lastly, the methodological approach presented in this manuscript can be applied to different technologies. With this research, we aim at contributing to the debate on the environmental impacts related to human activities and to the development of optimal solutions to fulfill our energy needs.

Résumé étendu

Analyse du cycle de vie des systèmes géothermiques stimulés: de l'étude de cas à la caractérisation de la filière

Cette thèse aborde des questions clefs du domaine de l'analyse environnementale des systèmes géothermiques stimulés, dits « EGS » soit « *enhanced geothermal systems* », une technologie émergente pour la production d'énergie à partir d'une source renouvelable. Ces travaux scientifiques s'inscrivent dans le débat sur l'atténuation des impacts environnementaux liés à notre approvisionnement énergétique. Ils apportent des innovations à la fois dans la compréhension des performances environnementales des EGS et dans l'application de la méthodologie d'analyse de cycle de vie (ACV) aux technologies émergentes.

Les EGS sont des systèmes géothermiques innovants qui permettent l'exploitation de la chaleur géothermale dans des zones non conventionnelles (e.g. en dehors des milieux volcaniques). Ils visent des milieux géologiques à grande profondeur, caractérisés par des anomalies thermiques (ie. températures particulièrement élevées) et un réseau de fractures naturelles. Le développement des EGS suscite un intérêt croissant comme technologie prometteuse pour la production d'électricité et/ou chaleur à partir d'une source d'énergie renouvelable. Toutefois, une promotion enthousiaste de ces systèmes est inappropriée sans une évaluation critique de leurs performances environnementales. En fait, malgré les faibles émissions de la phase d'exploitation, de grandes quantités d'énergie et de matière sont nécessaires à la construction de centrales de ce type.

L'analyse du cycle de vie (ACV) est un outil approprié pour effectuer une telle évaluation critique. Encadrée par un standard international, cette méthodologie permet de prendre en compte les impacts liés à toutes les phases de la vie du système analysé, de la construction au démantèlement. Toutefois, les résultats ACV sont en général liés à des configurations spécifiques des systèmes analysés et peuvent difficilement être appliqués à d'autres configurations. D'un autre côté, les décideurs nécessitent d'outils simples et efficaces pour

l'estimation des performances environnementales des systèmes énergétiques. Le développement de tels outils est fondamental pour soutenir la mise en œuvre de politiques environnementales cohérentes et promouvoir la généralisation de configurations optimales pour les systèmes énergétiques.

Dans ce contexte, cette thèse vise à caractériser les performances environnementales des EGS par le développement d'outils permettant (i) de comparer cette technologie à d'autres filières énergétiques (comme le photovoltaïque ou l'éolien) (ii) de comparer plusieurs configurations EGS entre eux (ayant par exemple des tailles et des caractéristiques différentes). Elle vise également à mettre au point une méthodologie d'analyse capable de faire face aux grandes incertitudes intrinsèques à une technologie émergente comme celle des EGS. Dans les prochaines sections, nous présenterons plus en détail les enjeux, les questions de recherche et la démarche scientifique utilisée dans le cadre de cette thèse.

Les EGS et l'analyse de leur cycle de vie

Les énergies renouvelables (EnR) jouent actuellement un rôle majeur au niveau mondial dans la satisfaction de nos besoins en électricité et chaleur. La forte croissance du secteur des EnR est favorisée par la mise en œuvre de politiques énergétiques favorables dans plusieurs pays, visant à réduire la dépendance des réserves de pétrole, gaz et charbon, faire face à la demande croissante d'énergie et limiter les émissions de gaz à effet de serre (GES). L'accord historique de la COP21 met en évidence la volonté de la communauté mondiale de généraliser le recours aux EnR dans le cadre des actions visant à atténuer les changements climatiques.

L'utilisation de ressources géothermales représente une option avantageuse pour la production d'électricité et chaleur, permettant une exploitation constante (non intermittente comme dans le cas du photovoltaïque et de l'éolien) et des coûts de production souvent très compétitifs. Les technologies géothermales traditionnelles exploitent des ressources en eau et vapeur à haute température situées dans des zones avec des conditions géologiques favorables (par exemple les régions volcaniques en Islande ou en Indonésie). Cependant, telles conditions sont plutôt rares à l'échelle mondiale et ceci limite le développement du secteur. Dans ce contexte, le développement récent des systèmes géothermiques stimulés (EGS) attire l'attention comme une solution prometteuse pour la valorisation des ressources géothermiques dans de nouvelles zones "non conventionnelles"

Le principe des EGS est d'améliorer et/ou de créer un réservoir géothermique par des techniques de stimulation (hydraulique, chimique, thermique) à une profondeur considérable (supérieure à 2 km en général). Depuis la première application de ce concept dans les années '70 aux États-Unis, plusieurs définitions ont été formulées pour l'encadrer, comme « *hot dry rocks* », « *hot wet rocks* », « *engineered* » or « *enhanced geothermal systems* ». Bien que le périmètre de l'appellation « EGS » ne soit pas strictement défini, les caractéristiques "typiques" d'une centrale de ce type dans le contexte européen peuvent être résumées ainsi : (i) les EGS sont des centrales binaires, i.e. la boucle géothermale est séparée, à travers un échangeur de chaleur, de l'installation de valorisation de l'énergie en surface (ii) les EGS visent des ressource à basse-moyenne enthalpie (par rapport aux centrales géothermiques traditionnelles): la température du fluide géothermal est en général inférieure à 170°C (iii) l'installation de surface est généralement un cycle de Rankine organique (ORC) (iv) des techniques de stimulation hydraulique, chimique ou thermique sont utilisées pour améliorer la perméabilité du réservoir et faciliter la circulation du fluide géothermal.

En Europe, la France est pionnière du domaine: la première centrale pilote EGS a été inaugurée à Soultz-sous-Forêts (en Alsace) en 2008, après plus de deux décennies de R&D. Des installations commerciales ont été réalisées en Allemagne (Landau, Insheim) et en France le premier EGS industriel a été inauguré en 2016 à Rittershoffen (en Alsace également). De vastes zones d'Europe présentent des conditions favorables pour la réalisation d'EGS, c'est-à-dire la présence d'un gradient de température vertical élevé dans le sous-sol: par exemple en France, en Allemagne, en Italie, en Hongrie, en Serbie, en Espagne et en Turquie. Un potentiel énorme et encore inexploré peut être exploité avec cette technologie émergente et une croissance progressive de ce secteur est prévue.

Bien que la phase d'exploitation d'un EGS n'entraîne pas d'émissions directes liées à l'utilisation de combustibles fossiles, la construction des puits (forage profond, stimulation) et des installations de surface (centrale binaire) nécessitent une grande quantité de matériaux et d'énergie. Ainsi on peut se questionner sur la pertinence, du point de vue environnemental, de cette technologie : il serait inapproprié de la promouvoir comme une alternative à l'utilisation de combustibles fossiles, sans une compréhension globale de ses impacts.

Lorsqu'on étudie les performances environnementales d'une technologie donnée et en particulière d'une filière énergétique, il est nécessaire de prendre en compte deux niveaux d'analyse pour acquérir une compréhension globale:

- L'analyse **inter**-filière : ceci consiste à caractériser le « profil environnemental » de la filière et étudier son positionnement par rapport à d'autres technologies de conversion d'énergie (e.g. comparaison entre les performances environnementales des EGS et celles des centrales à gaz, à biomasse, ou d'autres).
- L'analyse **intra**-filière : ceci consiste à caractériser les performances de différents systèmes au sein de la filière (e.g. comparaison entre les performances environnementales d'un EGS de 2 MW avec 2 puits et celles d'un EGS de 4 MW avec 3 puits).

À ce jour, la question des performances environnementales des EGS a été abordée par quelques études présentant l'analyse du cycle de vie (ACV) d'un certain nombre de scénarios EGS. La méthodologie ACV, encadrée par le standard ISO 14 040 et ISO 14 044 (ISO 2006a, 2006b), permet d'estimer les impacts d'un produit en tenant compte de tous les processus liés à son cycle de vie, tels que l'extraction des matières premières, la fabrication, l'utilisation et la fin de vie.

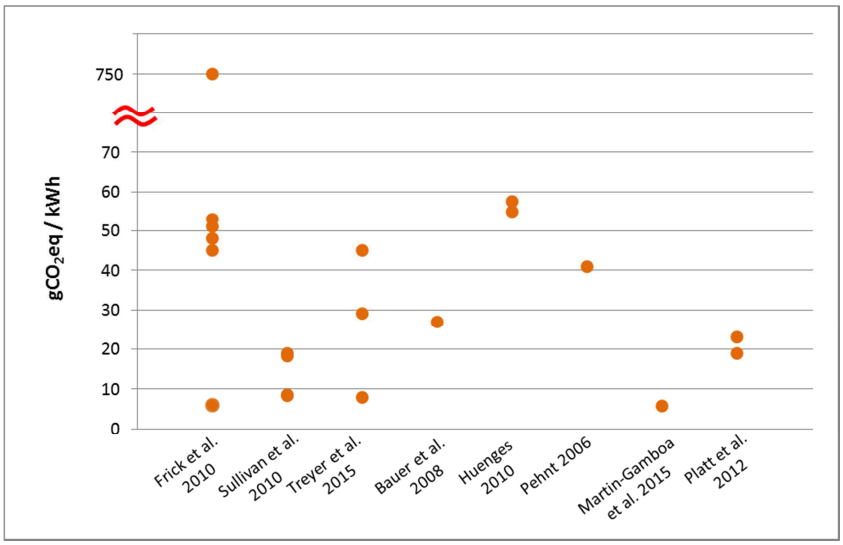


Figure i. ACV des EGS : revue de littérature (résultats d'émissions de GES)

La Figure *i* présente les résultats (impacts sur le changement climatique, prenant en compte les émissions de GES sur le cycle de vie par kWh délivré au réseau) des ACV des EGS disponibles en littérature (Frick et al. 2010, Sullivan et al. 2010, Treyer et al. 2015, Bauer et al. 2008, Huenges 2010, Pehnt 2006, Martin-Gamboa et al. 2015, Platt et al. 2012). Le

nombre d'études disponibles dans ce domaine est assez limité par rapport à d'autres secteurs EnR comme l'éolien ou le PV (une revue récente de l'IPCC identifie plus de 100 publications qui abordent chacune de ces deux dernières technologies (Moomaw et al. 2011)). En outre, les résultats disponibles ne permettent pas de caractériser les performances environnementales des EGS selon les deux niveaux mentionnés ci-dessus (inter-filière et intra-filière). En effet on observe une très grande variabilité des résultats, couvrant deux ordres de grandeur (de 6 à 750 gCO_2eq/kWh). Cet intervalle dépend strictement des études de cas de la littérature et il est potentiellement une représentation non exhaustive de la filière. Sur cette base, il est difficile de positionner les EGS par rapport à d'autres filières renouvelables (qui présentent des résultats généralement inférieures à 100 gCO_2eq/kWh) et fossiles (généralement supérieures à 500 gCO_2eq/kWh (Moomaw et al. 2011)). En outre, à partir de ces résultats, il est compliqué de comparer les performances de deux ou plusieurs EGS, car chaque publication repose sur des hypothèses et des méthodologies de calcul différentes.

Au cours des dernières années, différentes approches d'analyse environnementale prenant en compte le cycle de vie ont été développées. Certains sont orientés vers l'analyse de cas d'études spécifiques, comme les ACV classiques (e.g. Frick et al. 2010) et les ACV paramétrés (e.g. Zimmermann 2012). D'autres visent plutôt la caractérisation de la filière dans son ensemble, comme les Meta-ACV (e.g. Lenzen 2008) ou les revues de littérature (e.g. Tomasini-Montenegro et al. 2016). Une approche intermédiaire, proposée par Padey et al. (2013), consiste dans la mise au point de « **modèles simplifiés** » ACV : il s'agit de modèles paramétrés stochastiques, prenant en compte la variabilité des paramètres d'entrée, de manière à représenter l'hétérogénéité de configurations existantes au sein de la filière. Ensuite l'application de l'analyse de sensibilité globale (GSA) permet d'identifier les paramètres clefs et de développer des formules simples de calcul ACV, qui expriment les impacts environnementaux en fonction de seulement ces paramètres.

Le développement de modèles simplifiés dans les cas des EGS comporte un défi supplémentaire. En effet, s'agissant d'une technologie émergente, la description de la variabilité des paramètres d'entrée est une opération délicate et caractérisée par de grandes incertitudes. Ces incertitudes peuvent affecter les résultats, par conséquent le développement d'un modèle simplifié pour les EGS doit être accompagné par une analyse critique de sa robustesse.

Les questions de recherche et la démarche scientifique

L'analyse du contexte et de l'état de l'art en matière d'analyse environnementale des EGS ont permis de définir la problématique scientifique de cette recherche, qui vise à adresser les deux questions suivantes:

> **[a]** Quel est le profil environnemental de la filière EGS, prenant en compte l'hétérogénéité des configurations existantes au sein de la filière?
> **[b]** Comment développer des modèles simplifiés, à destination des décideurs, permettant une estimation rapide des impacts des EGS et prenant en compte les incertitudes liées à cette technologie émergente?

La question **[a]** porte sur la nécessité d'obtenir une vision globale des performances environnementales de la technologie EGS, en vue d'une comparaison avec d'autres options pour la production d'électricité (positionnement *inter-filière*). La question **[b]** met l'accent sur la nécessité, pour les décideurs, d'avoir accès à des outils pratiques pour l'analyse de configurations EGS spécifiques (analyse *intra-filière*), capables d'estimer rapidement les performances environnementales sans entreprendre la complexe méthodologie ACV.

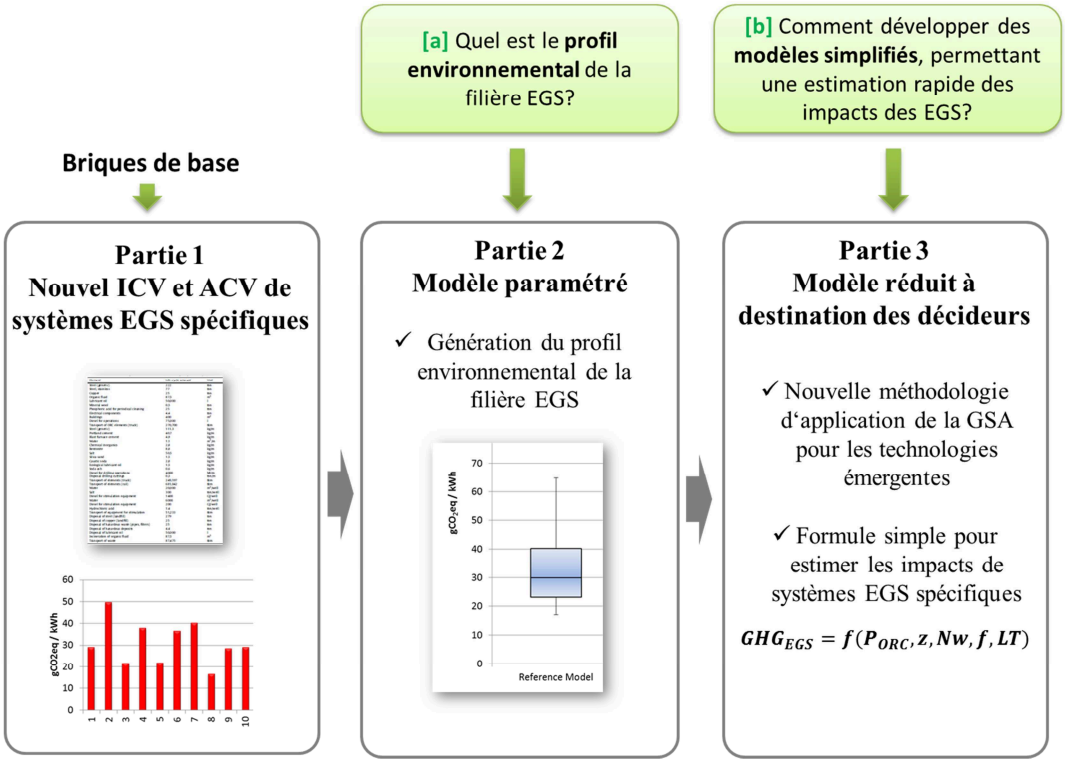


Figure ii. Questions de recherche et plan de la thèse

L'approche méthodologique mise en place dans cette thèse pour aborder ces questions de recherche est structurée en trois étapes successives, détaillées dans les trois parties du présent manuscrit (Figure *ii*).

1. L'élaboration d'un nouvel inventaire de cycle de vie (ICV) et l'application de la méthodologie ACV à un certain nombre de scénarios EGS, afin de préparer le terrain pour le développement de nouveaux modèles paramétrés capables de répondre aux questions **[a]** et **[b]**.
2. Le développement d'un modèle d'ACV paramétré pour les EGS, permettant d'estimer les impacts d'un large panel de centrales, représentatif de la filière EGS électrique en Europe centrale (capable de répondre à la question **[a]**).
3. L'élaboration d'un modèle réduit de calcul ACV, destiné aux décideurs et fonction de quelques paramètres clefs, identifiés grâce à une méthodologie d'analyse de sensibilité globale, spécifiquement développée pour faire face à la grande incertitude intrinsèque à une technologie émergente comme l'EGS (capable de répondre à la question **[b]**).

Partie 1. Nouvel ICV et ACV de systèmes EGS spécifiques

Dans cette première partie, nous réalisons l'analyse du cycle de vie d'un certain nombre d'études de cas EGS. Ceci nous permettra de (i) compiler une nouvelle base de données avec les flux de masse et d'énergie qui interviennent au cours du cycle de vie d'un EGS (ii) tester sa robustesse par la comparaison de nos résultats d'ACV avec la littérature et (iii) identifier les sources principales d'impacts (processus et substances).

La démarche scientifique détaillée dans cette partie consiste dans les phases suivantes:

(1) définition des études de cas, représentant différentes configurations EGS possibles
(2) élaboration d'un modèle ACV, selon le standard ISO;
(3) discussion des résultats de l'ACV.

(1) Définition des dix études de cas

Compte tenu de la variété de paramètres de conception interdépendants qui déterminent la taille de l'installation et la quantité finale d'énergie livrée au réseau, dix scénarios EGS ont été élaborés. Leurs caractéristiques sont définies sur la base des opérations EGS en cours en

Europe centrale. Les dix scénarios (Figure *iii*) se distinguent par des choix différents concernant :

- le nombre de puits : deux (« doublet ») ou trois (« triplet ») ;
- la profondeur de forage : 2.5 ou 4 km ;
- la température du fluide géothermal, fixée en fonction de la profondeur sur la base des études menées à Soultz-sous-Forets et Landau ;
- le débit de production : deux possibilités sont considérées (débit élevé ou bas) pour chaque profondeur et en fonction de la profondeur ;
- le débit de réinjection : plus ou moins élevé selon le nombre de puits de réinjection ;
- le risque de sismicité induite : une fonction empirique, élaborée sur la base des récentes expériences EGS, est établie en relation avec le débit de réinjection. Un risque plus faible est associé à un plus bas débit dans un puits de réinjection.

Pour calculer la production annuelle d'électricité, des hypothèses sont établies quant à l'efficacité de conversion et la puissance requise par les équipements auxiliaires. Le scénario no. 6 est sélectionné comme "cas de base" en raison de sa similarité avec l'EGS installé à Soultz-sous-Forêts. En effet, cette installation pilote prévoyait dans les conditions initiales d'exploitation (en 2008) une production de 35 kg/s par un puits, réinjecté dans deux puits (les trois ayant une profondeur d'environ 5 km).

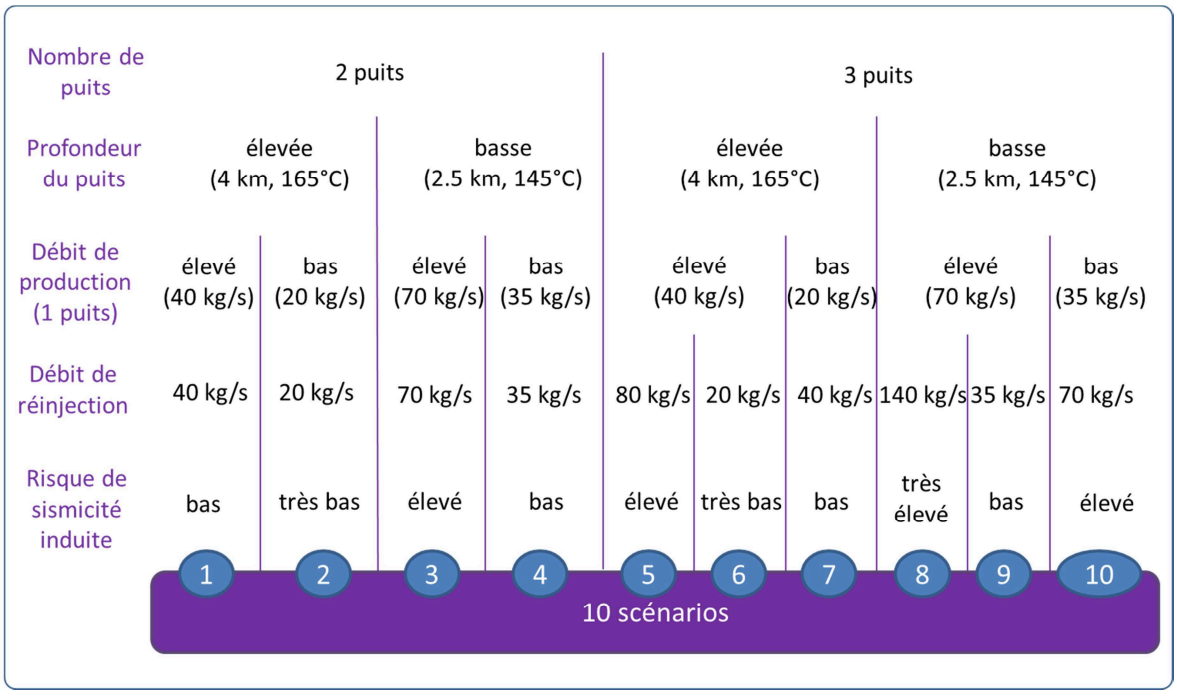


Figure iii. Dix scénarios EGS analysés

(2) Élaboration du modèle ACV

Le standard ISO 14 040 encadre la méthodologie ACV en quatre phases, détaillées ci-après: définition des objectifs et du champ de l'étude, analyse de l'inventaire, évaluation des impacts, interprétation.

Définition des objectifs et du champ de l'étude. L'objectif de cette étude est d'évaluer les impacts environnementaux des systèmes géothermiques stimulés en Europe centrale, en comparant dix études de cas réalistes élaborées sur la base des opérations actuellement en cours dans le fossé rhénan et prenant en compte des contraintes techniques et économiques. Les limites des systèmes analysées incluent les équipements du cycle organique de Rankine (ORC), les éléments souterrains relatifs à la boucle du fluide géothermal (puits, boue de forage, etc.) et les différents flux de matière et d'énergie liés aux phases de construction, d'opération et de démantèlement. La référence temporelle est l'année 2012. L'unité fonctionnelle est le kWh d'énergie nette produite sur une période de fonctionnement de 25 ans. Cela signifie que toutes les émissions calculées font référence à l'unité d'énergie livrée au réseau électrique national. La puissance nette correspond à la sortie électrique brute de la turbine ORC moins la puissance nécessaire pour les équipements auxiliaires de l'ORC (aérocondenseur, etc.) et de la boucle géothermique (pompes de production et de réinjection).

Élaboration de l'inventaire : L'élaboration de l'inventaire de cycle de vie (ICV) se base sur la compilation des flux dits « d'entrée » (matériels, combustibles, ressources, électricité, chaleur) et flux dits « de sortie » (émissions, déchets) qui interviennent lors des différentes phases de la vie de la centrale. Il s'agit de la phase la plus chronophage de l'ACV, nécessitant la récolte d'un grand nombre d'informations. Nous avons élaboré un nouvel ICV pour les EGS: cette tâche a été particulièrement difficile au vu du faible nombre d'opérations EGS en cours et de l'expérience relativement limitée de la communauté scientifique dans ce secteur. Les données d'inventaire ont été calculées et collectées à partir de :

- une enquête détaillée sur le site de l'EGS de Soultz-Sous-Forêts: nous avons travaillé sur le site de la centrale et analysé à la documentation technique disponible (rapports journaliers de forage, rapports de construction des puits, rapports finaux des travaux, manuels des équipements, etc.). Nous avons également interviewé l'équipe de recherche scientifique ainsi que les opérateurs de la centrale ;

- une revue de littérature, afin de récolter toutes les données publiques disponibles: études sur la phase de stimulation, retour d'expérience d'autres sites EGS, etc. ;
- le recours à la base de données Ecoinvent 2.2 (ecoinvent centre, 2010) pour les données de background comme l'extraction de matières premières, l'approvisionnement en énergie, le transport, le traitement des déchets, etc.

Nos hypothèses et estimations ont été discutées et validées avec des experts du monde scientifique, académique et industriel impliqués dans la construction et la gestion de la centrale EGS. La base de données résultant de ce travail (tableau 1.4 dans le manuscrit) constitue un résultat majeur de cette étude et servira également comme base pour les travaux présentés dans les prochaines parties de la thèse.

Évaluation des impacts. Pour le calcul des impacts, parmi les différentes méthodologies disponibles en littérature, nous avons choisi IMPACT2002+ (Jolliet et al. 2003), qui considère les quatre catégories d'impact suivantes:

- **Santé humaine**, mesurée en DALY (années équivalentes de vie perdue)
- **Qualité des écosystèmes**, mesurée en en PDF· m^2·y (fraction d'espèce disparue sur un mètre carré pour une année)
- **Changement climatique**, exprimé en gCO_2eq (quantité « équivalente » de CO_2, ayant le même impact sur le changement climatique des émissions des différents gaz à effet de serre liées au cycle de vie du produit)
- **Ressources,** mesurées en kJ (cette unité prend en compte l'énergie primaire non renouvelable dissipée et l'énergie additionnelle qui sera nécessaire dans le futur pour l'extraction des minerais, en raison de la baisse des teneurs en minerai dans les mines)

Nous avons considéré le **risque de sismicité induite**, évoqué précédemment, comme une cinquième catégorie d'impact au vu de sa criticité dans la réalisation d'opérations EGS. En effet en 2006, sur le site EGS de Bâle (Suisse), des événements sismiques ont atteint la magnitude ML 3.4 six jours après la stimulation principale, créant des dégâts (> 6M CHF) et beaucoup d'inquiétude dans la population : ceci a entraîné la suspension du projet (Weimer et al. 2015). En 2009, des séismes de magnitude 2.7 ont été enregistrés à Landau (Allemagne) pendant la circulation (Groos et al. 2013), entraînant une obligation à réduire le débit de

réinjection. Au vu de son importance en phase de conception, nous avons donc intégré l'appréciation du risque sismique dans le cadre de l'évaluation environnementale.

Interprétation. Tout au long de l'étude, les valeurs concernant les flux de matière et d'énergie ont été comparées avec les références disponibles en littérature. Nous avons ensuite validé notre inventaire en comparant nos résultats d'impact avec une étude de référence (Frick et al. 2010) avec des hypothèses harmonisées. Nous avons analysé en détail les résultats du cas de base, mettant en évidence les processus et les substances responsables de la majorité des impacts. Enfin, nous avons comparé les résultats des dix scénarios entre eux et avec la littérature, analysé leurs différences relatives et confirmé la pertinence de la prise en compte du risque sismique. La compilation de l'inventaire ainsi que le calcul des impacts ont été réalisés avec le logiciel SimaPro v7.2.4.

(3) Discussion des résultats de l'ACV

Les résultats pour le cas de base (scénario 6) sont les suivants: 6.78E-08 DALY/kWh (santé humaine), 1.17E-02 PDF·m^2·y/kWh (Qualité des écosystèmes), 36.7 gCO_2eq/kWh (Changement climatique), 579 kJ/kWh (Ressources), bas risque de sismicité. La construction des puits a une forte incidence sur les performances environnementales, étant la cause d'environ 80% des impacts sur le changement climatique, la santé humaine et les ressources et d'environ 60% des effets sur la qualité de l'écosystème.

La Figure *iv* présente un extrait des résultats de cette première partie de notre recherche et montre la grande quantité d'informations obtenues (cf. section 1.4 du manuscrit pour la présentation de l'ensemble des graphiques). Le graphique en secteurs en haut montre les processus responsables des impacts sur la santé humaine. La même représentation est obtenue pour les autres catégories d'impacts ainsi que pour illustrer les substances (NOx, chromium, etc.) qui affectent les performances environnementales. L'utilisation de générateurs diesel pour alimenter la machine de forage est identifiée comme le processus ayant le plus d'impact sur la santé humaine et le changement climatique et est également très influent sur la qualité des écosystèmes et la consommation de ressources. L'histogramme en bas à droit présente la comparaison des résultats dans la catégorie « changement climatique » entre les dix scénarios et la littérature (points orange), montrant une cohérence avec les estimations proposées par les autres auteurs. Des diagrammes radar (en bas à gauche) ont également été réalisés pour effectuer une comparaison multicritère entre les scénarios et évaluer les avantages et

inconvénients des différentes configurations. On observe que le risque sismique augmente, avec les bénéfices environnementaux : en effet, des débits plus élevés comportent une production énergétique plus importante et des impacts plus faibles (par kWh) mais impliquent la nécessité de réinjecter une grande quantité de fluide géothermal à haute pression, ce qui augmente le risque sismique.

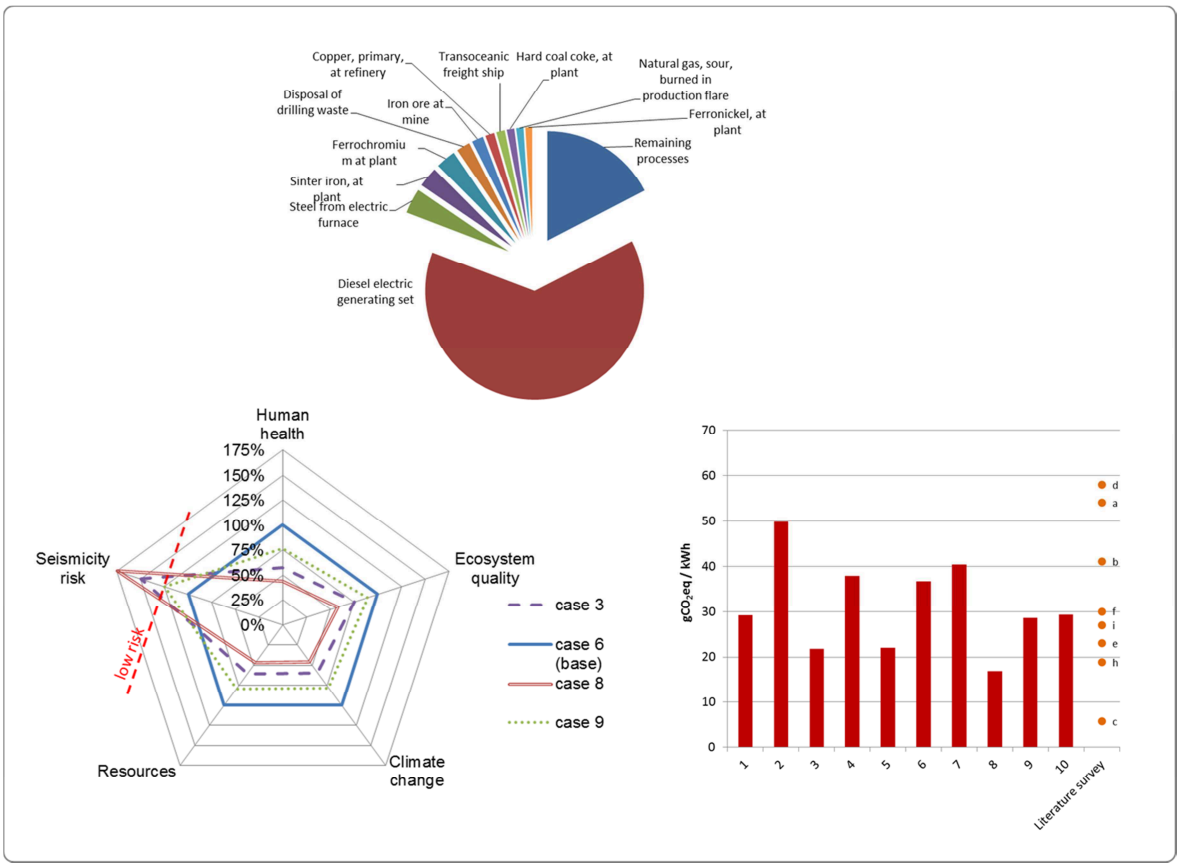


Figure iv. Extrait des résultats d'ACV des dix scénarios : cf. section 1.4 du manuscrit pour la présentation de l'ensemble des résultats.

En conclusion, dans cette première partie de notre recherche nous avons discuté en détail les performances environnementales de plusieurs scénarios et nous avons apporté deux innovations majeures dans le domaine de l'ACV des EGS :

- L'élaboration d'une nouvelle base de données présentant les principaux flux de matières et d'énergie qui interviennent au cours du cycle de vie d'un EGS. Très peu d'inventaires de ce type existent actuellement, et les informations disponibles sont souvent caractérisées par de fortes incertitudes. Ainsi, cette étude apporte une

contribution importante à la communauté scientifique travaillant sur la modélisation environnementale des EGS.

- La prise en compte du risque de sismicité induite dans le cadre d'une analyse du cycle de vie : cet aspect n'avait jamais été abordé auparavant en littérature. Notre recherche met en évidence l'importance de cet indicateur et la nécessité de trouver le bon compromis avec les autres catégories d'impact.

Les résultats de cette étude ont été publiés dans le journal *Renewable Energy* (Lacirignola and Blanc 2013) et présentés lors de plusieurs colloques internationaux (Lacirignola and Blanc 2012a, 2012b, 2012c). Cet article a été récemment reconnu dans la revue de littérature proposée par Menberg et al. (2016) comme une des publications de référence dans le domaine de l'ACV des EGS.

Les éléments produits dans cette première partie de notre recherche constituent des briques de base essentielles pour le développement de modèles paramétrés, présentés dans les deux autres chapitres, permettant d'adresser les questions de recherche **[a]** et **[b]**.

Partie 2. Développement d'un modèle paramétré représentatif de la filière EGS

L'objectif de cette deuxième partie de notre recherche est de développer un modèle ACV paramétré, représentatif de la filière EGS en Europe centrale, capable d'estimer les impacts d'un large panel de systèmes EGS différents. Ce modèle adresse la première question de recherche **[a]**, en identifiant le «profil environnemental» de la filière EGS. L'approche scientifique pour développer le modèle paramétré, basé sur le protocole proposé par Padey et al. (2013), repose sur les étapes suivantes:

(1) Définition des objectifs et du périmètre du modèle paramétré
(2) Mise au point du modèle paramétré, dit "*Modèle de référence*". Cette phase comporte l'identification des paramètres nécessaires à caractériser le système, la description de leur variabilité, la compilation de bases de données modulaires nécessaires à calculer l'inventaire des entrées et sorties sur le cycle de vie
(3) Génération du profil environnemental
(4) Discussion et validation du profil environnemental

Nous focalisons l'attention sur la catégorie d'impact «changement climatique», évaluée en termes gCO_2 équivalents par kWh. Ce choix est motivé par le grand intérêt de la communauté scientifique pour cet indicateur, les effets du changement climatique étant au centre du débat public sur l'environnement. Néanmoins, le cadre méthodologique mis en place dans cette partie de la recherche peut également s'appliquer à d'autres catégories d'impacts. Par abus de langage, souvent on se réfère aux résultats de la catégorie d'impact "changement climatique" en termes de "*émissions de gaz à effet de serre*". Néanmoins il faut préciser qu'un gCO_2eq n'est pas une *émission* physique: derrière cette unité se cache un modèle d'impact des différents gaz à effet de serre, qui sont normalisés par rapport à celui d'un gramme de CO_2 à l'aide de facteurs de caractérisation.

(1) Définition des objectifs et du périmètre du modèle paramétré

L'objectif du modèle de référence est de générer le profil environnemental (en termes d'impacts des GES sur le cycle de vie) de la filière EGS, définie par la caractérisation suivante:

- caractérisation technologique: les EGS considérés ont 2 ou 3 puits d'une profondeur entre 2 et 6 km et sont équipés d'un cycle ORC en surface. Le système génère uniquement de l'électricité (pas de cogénération). La stimulation hydraulique et chimique sont également considérées ;
- caractérisation géographique: l'étude se focalise sur les EGS en Europe centrale ;
- caractérisation temporelle: le modèle considère des technologies courantes pour tous les équipements. Il considère la possibilité de forer jusqu'à 6 km de profondeur, dans l'hypothèse qu'une exploitation à cette grande profondeur deviendra viable dans un futur proche grâce aux améliorations dans les techniques de forage ;
- caractérisation méthodologique: les données d'inventaire sont issues des travaux présentés dans la première partie de cette recherche et d'ecoinvent. Les facteurs de caractérisation utilisés pour calculer les émissions GES sont issus des travaux de l'IPCC (IPCC 2013).

L'unité fonctionnelle est le kWh électrique livré au réseau. Dans le reste du document, lorsqu'on parlera (pour concision) de "filière EGS en Europe centrale" on fera référence au périmètre défini ci-dessus (filière EGS électrique, avec telle caractérisation temporelle, etc.).

(2) Mise au point du modèle de référence

Le *Modèle de référence* a été construit sur la base de neuf paramètres (appelés «paramètres d'entrée»): la profondeur des puits (***z***), le débit géothermal produit (***f***), le nombre de puits (***Nw***), la consommation de carburant par mètre de forage (***d***), le facteur de charge indiquant le nombre d'heures à fonctionnement nominal sur l'année (***LF***), la puissance spécifique des pompes (P_p), un paramètre indiquant l'intensité de la campagne de stimulation (***SFe***), la durée de vie (***LT***) et la puissance de sortie de l'ORC (P_{ORC}), dite aussi « puissance installée », i.e. celle à la sortie du générateur moins celle demandée par les équipements auxiliaires de l'ORC. Ces neuf paramètres (présentés dans le tableau *i*) ont été choisis car ils permettent de caractériser la taille de l'installation, de déterminer l'inventaire de cycle de vie (ICV) et de calculer la quantité d'électricité produite. De manière générale, le choix des paramètres et de l'architecture du modèle est fait par le modeleur (sur la base des données disponibles, d'avis d'experts, etc.) et se base sur un compromis entre simplicité et précision.

Les neuf paramètres sont définis comme mathématiquement indépendants. P_{ORC} dépend de nombreux facteurs, dont le débit, la température du fluide ou l'efficacité thermique, ces facteurs étant également corrélés entre eux. Généraliser toutes les relations entre tels facteurs interdépendants avec des équations génériques valables en toute l'Europe centrale est une opération délicate et complexe. Ainsi dans notre modèle P_{ORC} est introduit comme paramètre indépendant, qui intègre les différentes variables thermodynamiques et leurs corrélations.

Les intervalles de variabilités et les distributions de probabilités ont été établis sur la base des opérations EGS en cours, discussions avec des experts ainsi que sur la littérature disponible (cf. le chapitre 2 du manuscrit pour l'ensemble des références).

Tableau i. Paramètres du *Modèle de référence*

Paramètre	**Intervalle de variabilité**	**Distribution de probabilité**	**Paramètre**	**Intervalle de variabilité**	**Distribution de probabilité**
Profondeur des puits (***z***)	2000 – 6000 m	Uniforme	Durée de vie (***LT***)	20 – 40 ans	Gaussienne avec μ=30 et σ=3.25
Débit géothermal (***f***)	25 – 100 kg/s	Uniforme	Intensité de la stimulation (***SFe***)	0.5 – 10	lognormale avec σ=1, μ=0 et pic sur SFe = 1
Nombre de puits (***Nw***)	2 – 3	Uniforme	Puissance spécifique des pompes (P_p)	3.6 – 8.6 kW/(kg/s)	Uniforme
Carburant pour le forage (***d***)	3000 – 7000 MJ/m	Uniforme	Puissance de sortie de l'ORC (P_{ORC})	1250 – 3500 kW	Uniforme
Facteur de charge (***LF***)	0.85 – 0.95	Uniforme			

Les informations concernant les flux de matières et énergies, basées sur l'ACV présenté dans la première partie de la recherche, ont été intégrées dans des bases de données modulaires. Les données d'ecoinvent concernant les processus en arrière-plan (extraction de matières premières, transport, etc.) sont également intégrées dans le calcul. Les neuf paramètres permettent de compiler l'ICV par l'interaction avec ces bases des données modulaires (par exemple, la valeur en *mètres* du paramètre z va multiplier les masses de matière exprimées en termes de *quantité/mètre*). Les résultats en gCO_2eq sont ensuite calculés à partir de l'ICV en utilisant les facteurs de caractérisation de l'IPCC (IPCC 2013). Le code de calcul du *Modèle de référence* a été développé avec le logiciel *R* et les données d'inventaire ont été extraites avec SimaPro v7.2.4. La formule du *Modèle de référence* (équation *i*), obtenue à partir des données d'inventaire, des facteurs de caractérisation IPCC et de l'architecture de calcul décrite ci-dessus, est la suivante :

$$GHG_{EGS_Ref} = \frac{z \cdot Nw \cdot (\alpha_1 + \alpha_2 \cdot d) + LT \cdot f \cdot \alpha_3 + P_{ORC} \cdot LT \cdot \alpha_4 + Nw \cdot SFe \cdot \alpha_5}{LT \cdot LF \cdot (P_{ORC} - f \cdot P_p) \cdot 8760} \qquad \text{(eq. i)}$$

$\alpha_1 =$ 498 761.36 $[gCO_2eq/m]$; $\alpha_2 =$ 90.56$[gCO_2eq/(MJ \cdot m)]$; $\alpha_3 =$ 487 363.03 $[gCO_2eq \cdot s/(kg \cdot y)]$;

$\alpha_4 =$ 50 603.13$[gCO_2eq/(kW \cdot y)]$; $\alpha_5 =$ 25 757 089.05$[gCO_2eq]$;

(3) Génération du profil environnemental

La formule paramétrée du modèle de référence permet de calculer très rapidement les émissions des GES sur le cycle de vie sans devoir entreprendre la longue et complexe procédure ACV. Il suffit d'attribuer une valeur à chaque parcmètre (e.g. nombre de puits = 2, débit géothermal = 50 kg/s, etc.) pour générer un nouvel ICV: chaque nouveau jeu de valeurs pour les neuf paramètres correspond à un scénario EGS différent. Sur cette base, nous avons utilisé la méthode de Monte-Carlo pour générer 500 000 scénarios EGS aléatoires et estimer leurs émissions de GES.

Ceci nous permet d'obtenir le **profil environnemental** (concernant les impacts des GES) de la filière EGS en Europe centrale. En effet, le processus d'échantillonnage aléatoire prend en compte les intervalles de variabilité et les distributions de probabilité précédemment définies pour les neuf paramètres d'entrée (tableau *i*), qui reflètent l'hétérogénéité de configurations possibles pour un EGS dans le champ de notre étude (compte tenu des installations existantes et des opérations futures qui pourraient être développées). La figure *v* (à gauche) présente le

profil environnemental obtenu: la boite indique la médiane, le 25ème et le 75ème percentile, tandis que les moustaches indiquent le 5ème et le 95ème percentile.

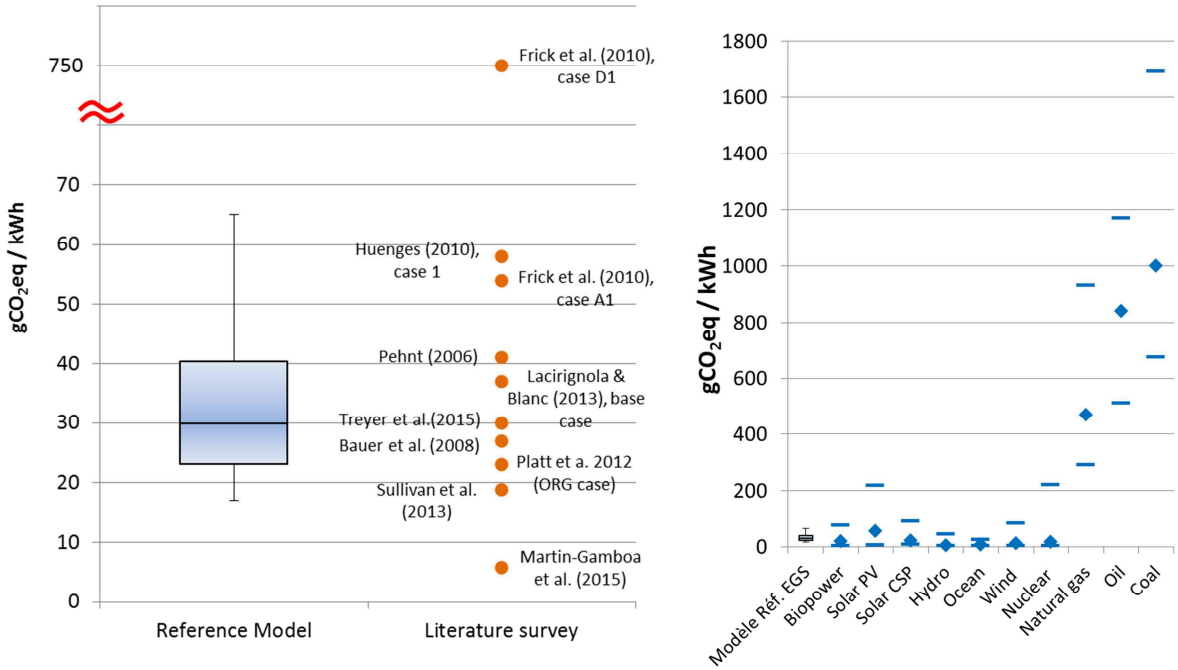


Figure v. Profil environnemental de la filière EGS en Europe centrale, comparé avec des ACV d'EGS de la littérature (à gauche) et avec des ACV d'autres technologies énergétiques (Moomaw et al. 2011)

(4) Discussion et validation du profil environnemental

La validation du *Modèle de Référence* est effectuée par comparaison avec les résultats d'ACV d'EGS disponibles en littérature (Figure *v*, gauche). On observe que les résultats du profil environnemental sont cohérents avec les données de la littérature. Deux études de cas (celui proposé par Martin-Gamboa et al. 2015 et le scénario D1 de Frick et al. 2010) se placent en dehors de notre intervalle de résultats: ceci est dû au fait que ces deux scénarios ne rentrent pas dans le périmètre de notre modèle. Martin-Gamboa et al. considère un EGS en Espagne avec des puits très peu profonds (~700m) alors que Frick et al. propose ici un scénario très pessimiste avec une productivité extrêmement faible: ces deux cas de figure ne sont pas pris en compte par notre modèle, qui est développé pour être représentatif d'opérations EGS viables en Europe centrale. En conclusion, la comparaison avec la littérature est jugée satisfaisante.

Le *Modèle de référence* développé dans cette deuxième partie de la thèse permet d'adresser la question de recherche **[a]**, qui porte sur la nécessité d'obtenir une vision globale des performances environnementales de la technologie EGS. Le profil environnemental obtenu est représentatif de la filière EGS en Europe centrale et montre que les résultats d'impact sur le changement climatique d'une centrale de ce type sont généralement compris entre 20 et 40 gCO_2eq/kWh. Ceci nous donne une vision beaucoup plus claire par rapport à la revue de littérature (qui présentait un intervalle de résultats bien plus large) et permet de positionner les EGS par rapport à d'autres technologies énergétiques, comme montré dans la Figure *v* (à droite). On observe que les performances environnementales, en termes d'impacts sur le changement climatique, sont comparables avec celles d'autres systèmes EnR et sont bien meilleures de celles de centrales alimentées par des combustibles fossiles.

Les résultats de cette partie de notre recherche ont été publiés dans le journal *Geothermal Energy* (Lacirignola et al. 2014) et présenté lors du World Geothmal Congress 2015 à Melbourne (Lacirignola et al. 2015).

La formule du *Modèle de référence* adresse partiellement la question **[b]** de recherche également, car elle permet l'analyse de configurations EGS spécifiques à partir d'un set de valeurs pour les paramètres d'entrées. Néanmoins, une formule à neuf variables pourrait être difficile à utiliser, en particulier pour les non spécialistes du domaine de l'EGS. Dans la dernière partie, nous travaillerons sur le développement d'une formule plus simple, basée uniquement sur les paramètres « clefs » du modèle.

Partie 3. Développement d'un modèle réduit, à destination des décideurs, pour l'analyse de configurations EGS spécifiques

L'analyse de sensibilité globale (soit « global sensitivity analysis » ou « GSA ») a été identifiée par plusieurs auteurs comme une méthode très pertinente pour identifier les paramètres "clefs" d'un modèle de calcul (Wei et al. 2015, Bisinella et al. 2016). La GSA permet d'établir un classement parmi les paramètres d'entrée et d'identifier les plus influents sur la variabilité de la sortie du modèle.

L'application de l'analyse de sensibilité globale à l'ACV, initiée par Padey et al. (2013), comporte un défi supplémentaire dans le contexte EGS, lié au caractère innovant de cette

technologie émergente. En effet lors de la réalisation de la GSA, la description de la variabilité des paramètres d'entrée (appelée «description des entrées») est l'une des étapes les plus importantes, car elle peut affecter de façon significative les résultats. Cette opération est très délicate dans l'étude de nouveaux produits ou de technologies émergentes, car les données concernant les entrées du modèle sont souvent très incertaines et peuvent entraîner des résultats erronés, i.e. un mauvais classement entre les paramètres. Dans le cas de l'EGS, au vu du faible nombre d'opérations en cours, la description des entrées du modèle ACV est assez incertaine, car elle est basée uniquement sur les quelques données disponibles en littérature et sur l'avis d'experts du secteur. Par conséquent, l'application de la GSA au domaine des EGS doit être accompagnée d'une analyse critique de la robustesse de ses résultats.

Dans ce contexte, l'objectif de cette troisième partie de notre recherche est double:

(1) développer un cadre méthodologique pour l'application de l'analyse de sensibilité globale à l'ACV des technologies émergentes, caractérisées par de grandes incertitudes. Cette nouvelle méthodologie devra permettre d'apprécier l'influence de la description des paramètres d'entrée (i.e. la caractérisation de leur domaine de variabilité) sur les résultats de la GSA (i.e. sur le classement entre ces paramètres) ;
(2) mettre au point un *Modèle réduit* de calcul ACV, à destination des décideurs, permettant d'estimer facilement les impacts de configurations EGS spécifiques en fonction de quelques paramètres clefs. À partir du *Modèle de référence* développé précédemment, l'application du cadre méthodologique évoqué ci-dessus devra permettre d'identifier les paramètres les plus influents.

(1) Méthodologie d'application de la GSA à l'ACV de technologies émergentes

Notre nouvelle méthodologie spécifiquement développée pour appliquer la GSA à l'ACV de technologies émergentes repose sur les étapes suivantes :

Étape 1: *Identification du modèle ACV*, i.e. l'architecture de calcul utilisée pour estimer les impacts à partir de *N* paramètres d'entrée indépendants, ainsi que son champ d'application.

Étape 2: *Description des N entrées du modèle*. Une description « *de base* » est établie pour chaque paramètre, indiquant son intervalle de variabilité et la distribution de probabilité associée, en cohérence avec le périmètre du modèle ACV.

Étape 3a: *Réalisation d'une analyse de sensibilité globale « de base »* en fonction des descriptions établies dans l'étape précédente, par le calcul des indices de Sobol'. Pour un modèle donné $z = f(x_1, x_2, \dots, x_N)$, l'indice de Sobol du premier ordre S_i^{First} indique la contribution de la variance du paramètre d'entrée x_i à la variance globale de la sortie z (Sobol' 2001).

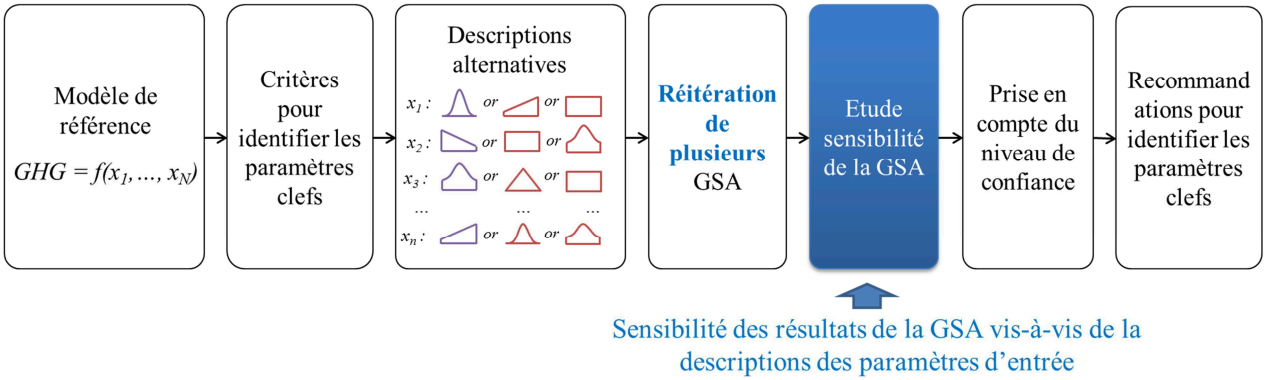


Figure vi. Schéma de l'étape 3b

Étape 3b: *Analyse de l'influence de la description des entrées sur les résultats de la GSA* (Figure *vi*). Tout d'abord, le critère pour identifier les paramètres clefs est défini : un seuil minimum est fixé concernant la contribution cumulée de tels paramètres à la variance de la sortie du modèle. Ensuite, des descriptions « *alternatives* » des paramètres d'entrées sont établies (différentes de celles « de base » de l'étape 2). Le choix des alternatives est laissé au développeur du modèle: en tout cas elles doivent être réalistes, en fonction de la connaissance du système analysé et du périmètre de l'ACV. Ensuite la GSA est réitérée plusieurs fois à partir de conditions initiales différentes, c'est-à-dire en considérant les différentes descriptions possibles pour les entrées. L'analyse des résultats permet de comprendre si la description d'un ou plusieurs paramètres a une influence significative sur l'identification des variables clefs. Le niveau de confiance associé à chaque description est également pris en compte. Ensuite des recommandations sont formulées pour affiner le modèle et pour sélectionner les paramètres clefs.

Étape 4. *Évaluation globale*, afin de vérifier la cohérence des résultats des différentes étapes.

Étape 5. *Identification des paramètres clefs du modèle ACV*, prenant en compte les résultats des étapes précédentes.

(2) Application à l'analyse environnementale des EGS

La méthodologie détaillée ci-dessus est appliquée au *Modèle de référence* EGS présenté précédemment, dans le but de mettre au point un *Modèle réduit* fonction uniquement des paramètres clefs.

Étapes 1, 2 et 3a. Les entrées du *Modèle de référence* sont les 9 paramètres discutés auparavant (profondeur des puits, débit géothermal, etc.), la sortie est l'estimation des émissions de GES sur le cycle de vie. La description *de base* de la variabilité des entrées est présentée dans le Tableau *i*. Les résultats de la GSA *de base* montrent que les paramètres responsables de la majorité de la variabilité des émissions GES sont la puissance installée $\boldsymbol{P_{ORC}}$ (S_i^{First}=0.46), la profondeur des puits $\boldsymbol{z}$ (S_i^{First}=0.18) et le nombre de puits ***Nw*** (S_i^{First}=0.09). Ces résultats dépendent strictement de la description de la variabilité des entrées: par exemple si on considère pour la durée de vie (***LT***) une distribution uniforme au lieu d'une gaussienne (pour avoir une approche plus conservative) on obtient un classement différent (le S_i^{First} de ***LT*** dépasse celui de ***Nw***). L'approche systématique proposée dans l'étape 3b, détaillée ci-après, nous permettra d'identifier les descriptions des entrées qui ont une grande influence sur les résultats de la GSA.

Étape 3b. Le seuil minimum de contribution cumulée des paramètres clefs est fixé à 66%: cela signifie que ces paramètres doivent être responsables d'au moins deux tiers de la variabilité des émissions de GES (et que la somme de leurs S_i^{First} doit dépasser 0.66). Un seuil assez élevé permet d'assurer une représentativité suffisante du *Modèle réduit* (en outre, plus le seuil est élevé plus grand sera le nombre de paramètres du *Modèle réduit*).

Pour chacun des neuf paramètres d'entrée, plusieurs descriptions alternatives sont identifiées. Nous considérons au total cinq types de distribution de probabilité continue (gaussienne, uniforme, lognormale, etc.) par paramètre, à l'exception du nombre de puits ***Nw*** (trois distributions discrètes). Pour chaque paramètre, les bornes de son intervalle de variabilité restent inchangées, car ils représentent les valeurs minimum et maximum que chaque variable peut assumer en cohérence avec le périmètre du modèle ACV. À titre d'exemple pour la durée de vie (***LT***), en ajout à la description de base (une gaussienne centrée sur 30 ans) on

considère, avec les quatre alternatives, la possibilité réaliste que la description la plus appropriée soit une distribution uniforme, ou une distribution donnant plus de poids aux valeurs aux bornes de l'intervalle (Figure *vii*).

Paramètre	Intervalle de variabilité	Description de base	Descriptions alternatives			
			type 2	type 3	type 4	type 5
Durée de vie (***LT***)	20 - 40 [ans]	 *gaussienne* *μ: 30* σ: *3.3*	 Δμ: 0% Δσ: 76%	 Δμ: -7% Δσ: 62%	 Δμ: 7% Δσ: 62%	 Δμ: 0% Δσ: 51%

Figure vii. Descriptions alternatives de la variabilité du paramètre ***LT***

Ensuite la GSA est réitérée plusieurs fois, en modifiant les descriptions des paramètres avec une approche « *one factor at a time* » (OAT). Cela signifie que pour chaque GSA on choisit parmi une des 5 alternatives pour un seul paramètre, tandis que pour les autres huit paramètres la description *de base* est fixée (cf. Tableau 3.2 du manuscrit). Cette approche comporte dans notre cas (9 paramètres, 3 ou 5 distributions par paramètre) la réalisation de 35 GSA ; en plus, chacune étant répétée 100 fois (avec une technique de bootstrapping), au total 3500 classements entre les neuf paramètres sont enregistrés.

Plusieurs remarques peuvent être formulées à partir de ces calculs. On observe que la somme des S_i^{First} des trois premiers paramètres du classement est toujours supérieure à 0.66. Lorsqu'on modifie la description de certaines variables comme ***d*** ou ***SFe***, le classement ne subit presque aucune variation. Au contraire, on observe que la description de la variabilité de z et ***LT*** est très influente sur l'identification des paramètres clefs, car elle comporte des variations importantes dans le classement. Globalement (Figure *viii*) on remarque que les trois premières positions du classement peuvent être couvertes par 5 paramètres différents. Le niveau de confiance associé aux descriptions de z et ***LT*** est faible, en outre ces descriptions ne peuvent pas être améliorées, car elles reflètent les meilleures connaissances actuelles (elles pourraient être consolidées dans le futur, lorsque de nouvelles données seront disponibles).

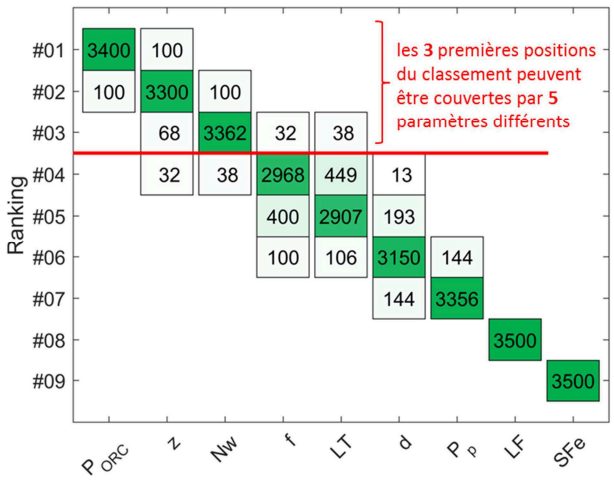


Figure viii. Résultats agrégés des 3500 GSA

Étapes 4 et 5. Un contrôle de cohérence a été effectué tout au long de l'application de la méthodologie et aucun résultat contre-intuitif n'a été repéré. Les résultats agrégés de l'étape 3b sont cohérents avec ceux de la GSA de base (étape 3a) et permettent d'améliorer notre compréhension du modèle ACV. Étant donné que les descriptions de certains paramètres sont très influentes sur les résultats de la GSA et sont également incertaines, on décide de sélectionner comme paramètres clefs tous les cinq qui sont susceptibles de couvrir une des trois premières positions classement : $\boldsymbol{P_{ORC}}$, ***z***, ***Nw***, ***f*** et ***LT***. Les autres quatre paramètres sont donc fixés à leurs valeurs médianes, on obtient ainsi la formule du *Modèle réduit* (eq. *ii*):

$$GHG_{EGS_Reduced}\left[\frac{gCO_2eq}{kWh}\right] = \frac{Nw\cdot(\omega_1\cdot z+\omega_2)+LT\cdot(\omega_3\cdot f+\omega_4\cdot P_{ORC})}{LT\cdot(P_{ORC}-f\cdot\omega_5)} \pm e \qquad \text{(eq. ii)}$$

With $\omega_1 = 120.70\ [gCO_2eq/(m\cdot h/y)]$; $\omega_2 = 5\,161.87\ [gCO_2eq/(h/y)]$;

$\omega_3 = 61.82\ \left[gCO_2eq\cdot\frac{s}{kg\cdot h}\right]$; $\omega_4 = 6.42\ \left[\frac{gCO_2eq}{kWh}\right]$; $\omega_5 = 6.10\ [(kW\cdot s)/kg)]$;

$e = 4.69\ gCO_2eq/kWh$

Cette formule permet d'estimer très rapidement les impacts sur le changement climatique d'un EGS à partir de seulement 5 paramètres : la puissance de sortie de l'ORC, la profondeur du puits, le nombre de puits, le débit géothermal et la durée de vie. La figure *ix* montre l'utilisation du *Modèle réduit* pour certaines configurations EGS analysées en littérature (cf. Tableau 3.3 du manuscrit pour les données d'entrée). Les résultats calculés avec notre formule sont très proches des estimations obtenues par différents auteurs en appliquant la longue et complexe procédure ACV.

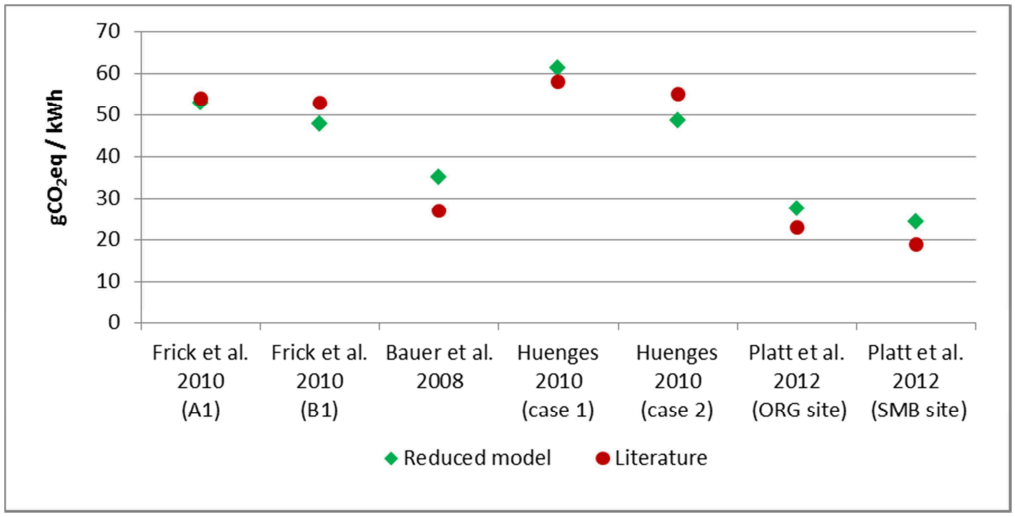


Figure ix. Comparaison des résultats de notre *Modèle réduit* avec la littérature

Le cadre méthodologique spécifiquement développé pour l'application de la GSA à l'ACV des technologies émergentes ainsi que l'application au cas EGS ont été publiés dans le journal *Science of the Total environnement* (Lacirignola et al. 2017). Ces avancements nous permettent d'adresser la question **[b]** de recherche. Le *Modèle réduit* a été développé prenant en compte les incertitudes liées au caractère innovant de la technologie EGS et il est très simple à utiliser. Ce modèle peut être utilisé par différents types de décideurs (agences publiques, décideurs politiques, développeurs de projets) et permet d'effectuer une évaluation immédiate de configurations EGS spécifiques sans devoir entreprendre la démarche ACV, qui s'avère chronophage et nécessite l'intervention d'experts.

Partie 4. Perspectives de recherche

Ce travail de thèse ouvre plusieurs pistes pour des recherches futures à la fois dans le domaine de l'analyse environnementale des EGS et dans l'application de la méthodologie ACV aux technologies émergentes. Des propositions sont listées ci-après:

(I). *Améliorer le Modèle de référence EGS en rassemblant de nouvelles données.* Avec l'étude de nouvelles opérations EGS, plus d'informations peuvent être collectées afin de consolider les bases de données modulaires du *Modèle de référence* (flux de matières et d'énergie) et les descriptions de la variabilité des paramètres.

(II). *Élargir le périmètre du Modèle de référence et développer ultérieurement son architecture*. Le périmètre du *Modèle de Référence* peut être élargi, par exemple en prenant en

compte la cogénération de chaleur et électricité ainsi que l'utilisation d'électricité du réseau pendant le forage à la place des générateurs diesel. Un profil environnemental actualisé, représentatif du secteur EGS, peut être ainsi généré. D'autres recherches peuvent se focaliser sur l'architecture du modèle, explorant par exemple la possibilité d'exprimer la puissance installée comme variable dépendante et fonction de plusieurs paramètres thermodynamiques.

(III). *Établir un profil environnemental multicritères pour les EGS, prenant en compte plusieurs catégories d'impact*. Les parties 2 et 3 de cette thèse se focalisent sur les émissions de gaz à effet de serre. La même méthodologie peut être appliquée à d'autres catégories d'impact, par exemple la demande de ressources énergétiques non renouvelables ou l'impact sur les écosystèmes.

(IV). *Étudier la possibilité d'intégrer la sismicité dans une catégorie de dommage*. Nous avons discuté l'importance de prendre en compte le risque de sismicité dans la phase de conception des EGS. Des recherches peuvent être menées pour étudier comment prendre en compte les problèmes de sismicité lors de l'estimation des impacts sur la santé humaine ou sur la qualité des écosystèmes.

(V). *Étudier d'autres stratégies de calcul pour appliquer la GSA dans l'ACV des technologies émergentes*. Notre stratégie pour évaluer la robustesse des résultats de l'analyse de sensibilité globale repose sur la réitération de plusieurs GSA avec une approche OAT ("one factor at a time"). D'autres stratégies de calcul peuvent également être étudiées, par exemple en faisant varier les descriptions de tous les paramètres en même temps.

(VI). *Étudier comment intégrer les modèles environnementaux dans les outils de conception des développeurs de projets EGS*. Une catégorie d'utilisateurs potentiels des modèles ACV paramétrés est celle des développeurs d'EGS, qui utilisent plusieurs indicateurs (taux de rentabilité, acceptabilité sociale, etc.) et différents outils de calcul pour dimensionner la centrale. De nouvelles recherches peuvent se focaliser sur l'intégration de notre modèle paramètre à ces outils, en étudiant l'interaction entre les critères environnementaux et d'autres indicateurs de décisions.

Conclusions

En conclusion, cette thèse propose une étude détaillée des performances des systèmes géothermiques stimulés, une technologie qui suscite un intérêt croissant au niveau mondial. Notre recherche prend en compte la nécessité de considérer à la fois l'analyse inter-filière et intra-filière pour acquérir une compréhension globale des performances environnementales.

Nous avons développé un modèle paramétré représentatif du secteur EGS, permettant une comparaison avec d'autres technologies énergétiques. Ce modèle montre que les performances environnementales des EGS, en termes d'émissions de GES, sont comparables avec celles d'autres systèmes EnR et sont bien meilleures de celles de centrales alimentées par des combustibles fossiles.

Nous avons mis au point une formule de calcul simplifié, destiné aux décideurs, permettant une estimation très rapide des impacts de configurations EGS spécifiques à partir de cinq paramètres clefs. Nous avons également développé un protocole pour l'application de l'analyse de sensibilité globale dans l'ACV des technologies émergentes, capable de faire face aux difficultés liées aux incertitudes élevées.

Cette thèse vise également à alimenter les études environnementales d'autres secteurs énergétiques. En fait, l'approche méthodologique présentée dans ce manuscrit peut être également appliquée à des technologies différentes. Avec cette recherche, nous souhaitons contribuer aux efforts de la communauté globale pour le développement des solutions respectueuses de l'environnement répondant à nos besoins énergétiques.

Introduction
and outline of the thesis

Foreword

This research addresses key issues related to the environmental assessment over the life cycle of enhanced geothermal systems (EGS), an emerging technology for electricity production based on a renewable energy source. Such issues are of high interest especially in the context of the public debate regarding the mitigation of the negative effects on the environment related to our energy supply. This thesis presents innovations both in the understanding of the environmental performances of EGS and in the methodology for a wise application of Life Cycle Assessment (LCA) to energy pathways. In this introductive chapter, we present the main drivers of this study, we identify the research questions and we formalize the methodological approach to address them.

Section I.1 provides a brief overview of the geothermal sector among the different options for producing electricity from a renewable energy source, pointing at the recent development of the enhanced geothermal systems (EGS) as a promising emerging technology.

Section I.2 introduces the main features of EGS, detailing the evolutions in its concept from the first experiments in the US to the ongoing operations in central Europe. The question of the environmental impacts of this kind of power plants is also formulated, and the life cycle assessment (LCA) methodology is presented as a relevant tool to address this issue.

Section I.3 presents the state of the art regarding the LCA of EGS and the limited amount of research currently available on this topic. The drawbacks of the LCA methodology are also discussed, in particular from the perspective of the final users of such studies (e.g. public bodies, decision-makers).

Section I.4 introduces the different tools for the environmental analysis based on LCA, discussing the need for obtaining a global overview of the analyzed sector, as well the importance of being able to analyze specific plant configurations with a generic approach.

Section I.5 presents the research questions, based on the context and the challenges previously discussed.

Section I.6 briefly describes the methodological approach set up to address such research questions, providing an overview of the structure of this manuscript.

I.1 Geothermal power in the panorama of renewable energies

Renewable energy (RE) technologies are currently facing an exponential growth, becoming a mainstream solution for electricity and heat supply. In 2014, about 19% of the world final energy consumption was provided through RE sources. Close to 150 GW of new power capacity was installed in 2015, allowing to achieve about 1850 GW worldwide. For the last six years, the total amount of yearly investments in RE outpaces the one of the fossil fuel sector for power capacity additions. At the end of 2015, RE-based plants were able to cover an estimated 23.7% of the global demand of electricity (REN21, 2016).

Such an unprecedented development is supported by the implementation of supporting energy policies in several countries. On the occasion of the 21st Conference of the Parties (COP21) in 2015 in Paris, 195 countries agreed on the need to limit the global warming effects caused by human activities. In November 2016, a few days before the COP22 conference in Marrakesh, the threshold for the entry into force of the Paris Agreement was achieved, since the parties accounting for at least 55 % of the total global greenhouse gas emissions had ratified their engagement (UNFCCC 2016). In this framework, different countries are implementing ambitious environmental plans and the exploitation of RE sources is seen as a key factor in mitigating the environmental effects caused by our current energy supply.

One of the biggest limitations of renewable technologies, especially wind farms and solar plants, is the intermittent nature of their resource: its irregular availability leads to a variable power output, a relatively low capacity factor and affects the life cycle cost of the kWh delivered (Skea et al. 2008). In this context, the exploitation of geothermal resources, namely the energy contained in underground aquifer reservoirs, is an advantageous option. In fact, given the potential for a continuous extraction of hot geothermal fluid and the use of well-known thermodynamic processes such as the Rankine cycle, geothermal technologies are characterized by a great reliability and a high capacity factor. Since the latter is frequently over 90% (Lund 2003), these plants are suitable for supplying constant base-load power (Williamson 2010), thus overcoming the key restriction of intermittent RE technologies. These essential factors make conventional geothermal technologies one of the cheapest means of producing electricity, with a levelized cost of energy (LCOE) ranging from 2.5 to 22 €cent/kWh (REN21 2016).

The geothermal installed capacity is currently about 12.7 GWe worldwide, mostly shared among a few countries such as the US (3.45 GW), the Philippines (1.9 GW), Indonesia (1.3 GW), Mexico (1 GW) and Italy (0.9 GW), as shown in Figure I.1 (Bertrani et al. 2015). Clearly, producing electricity with these systems is highly dependent on the availability of geothermal hot water or steam, which represents a limiting factor for the generalization of this technology. Most of these power plants are located in areas with exceptionally favorable geological conditions, characterized by high-enthalpy reservoirs, but this favorable condition is quite rare.

On the other hand, outside these particular sites, large geological areas show the presence of low to medium-temperature resources, which represent a huge and still unexplored geothermal potential. The recent development of "enhanced" or "engineered" geothermal systems (EGS) is attracting attention as a promising solution for the valorization of geothermal resources in such new "unconventional" areas.

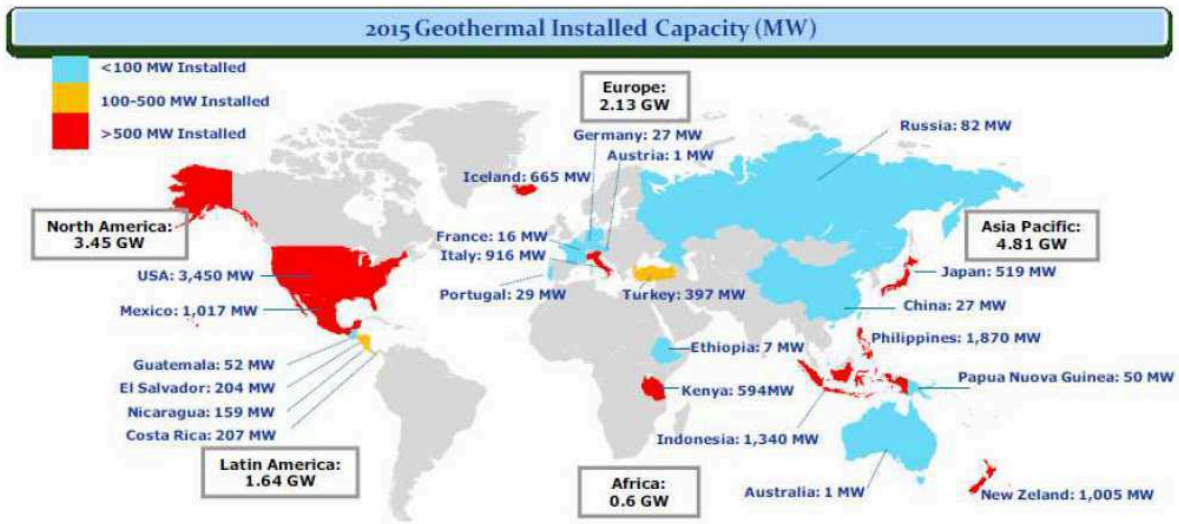


Figure I.1 Geothermal installed capacity in 2015 (image from Bertrani et al. 2015)

I.2 EGS: an emerging technology. A brief state of the art

The general principle of EGS is to enhance and/or create a geothermal resource through reservoir stimulation at great depth (higher than 2 km) in considerably hot geological formations. This concept was applied for the first time in the 1970s in the US with the Fenton Hill project, referred as “Hot Dry Rock” (HDR) system. The idea was to reach impermeable crystalline formations at a depth of 3-4 km (characterized by a temperature of at least 200 °C), to create artificially a system of fractures through hydraulic fracking and use such reservoir as an enormous heat exchanger, suitable to warm up the water pumped from the surface. When the same principle was applied for the first time in Europe (France, Germany, Sweden, UK) in the 1980s in few operations in the Rhine Graben on the French-German border, the presence of some pre-existing natural fluid was found in the deep fractured rocks: the term “Hot Wet Rock” (HWR) than appeared.

Baugmartner (2011) refers to “Hot Fractured Rock” (HFR) for the project in Soultz-sous-Forêts (France) and to “Hot Wet Rocks” for the operations in Landau and Insheim (Germany). Despite their differences, all the projects mentioned above are also referred, in general terms, as “enhanced” or “engineered” geothermal systems (EGS). Indeed, being a relatively young technology, the term EGS may cover a pretty broad range of geothermal configurations. For instance as reported by Breede et al. (2013), the Massachusetts Institute of Technology (MIT), the Australian Geothermal Reporting Code Committee and the German ministry for the Environment (BMU), propose slightly different perimeters for the definitions of EGS, depending on temperature, rock type or pre-existing geothermal exploitation (MIT et al. 2006, AGRCC 2010, BMU 2011).

Results from deep drilling in the recent geothermal project in Rittershoffen (France), located less than 10 km from Soultz-sous-Forets, also raised questions and debates about the EGS definition. Two boreholes have been drilled to a depth of 2.6 km: the first was stimulated for enhancing its injectivity index by a factor 4 (Baujard et al. 2017) whereas the second was purely a hydrothermal well (it was producing enough and it didn’t need to be stimulated thermally, chemically nor hydraulically). For the geothermal developers in the Upper Rhine Graben, stimulation represents a technique which allows achieving viable hydraulic performance by improving the connection between the borehole and the fractured reservoir (Genter et al. 2015).

In this context, despite the lack of a universal definition, we can generally refer to EGS as “unconventional geothermal systems", where artificial means (i.e. the “stimulation” of the reservoir) are used to make possible an economical exploitation of the resource.

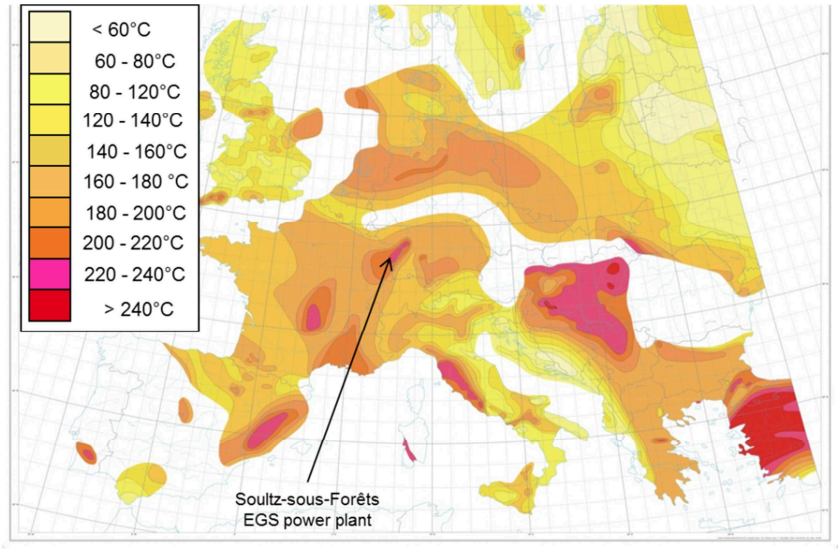


Figure I.2. Map of the temperature extrapolated at 5 km depth in Europe (from Hurtig et al, 1992)

Figure I.2 presents the map of the temperature extrapolated at a depth of 5 km in Europe (from Hurtig et al. 1992): while the normal increase of temperature with depth is about 2-3 °C / 100 m, some area presents a so-called "geothermal anomaly" with a gradient reaching 10 °C / 100 m in the first kilometer. In one of these regions, close to the village of Soultz-sous-Forêts (east of France), the first European EGS power plant was installed and started operating in 2008, after two decades of R&D. The map shows that large areas of Europe are characterized by geothermal conditions that make EGS applications suitable.

Although a description embracing any configuration is not possible as previously discussed, the general characteristics of a "typical" EGS in central Europe can be resumed as follows (see also Figure I.3):

- EGS are **binary** plants, namely the underground loop where the geothermal fluid circulates (from the production to the reinjection wells) is separated through an heat exchanger from the surface loop used for the electricity production.
- EGS target **low-medium enthalpy** resources (compared to conventional geothermal plants): the targeted temperature of the produced geothermal fluid is generally around 150-175°C
- The surface loop is generally an **Organic Rankine Cycle** (ORC), which exploits a working fluid with appropriate thermodynamic characteristics (namely a low vaporization temperature), like isobutane or propane, to convert the geothermal power into electricity. The use of a Kalina cycle (which uses a mixture of two substances, like ammonia and water) is also possible.
- Different techniques are used to "**enhance**" the reservoir, increasing its permeability: *hydraulic* stimulation (injection of high-pressure water to produce a hydroshearing

phenomenon on pre-existing fractures or fracking in case of the creation of an artificial heat exchanger), *chemical* stimulation (injection of acids to dissolve the hydrothermal deposits that obstruct the natural fractures) or *thermal* stimulation (injection of cold fluid to induce a thermal stress in the fracture system).

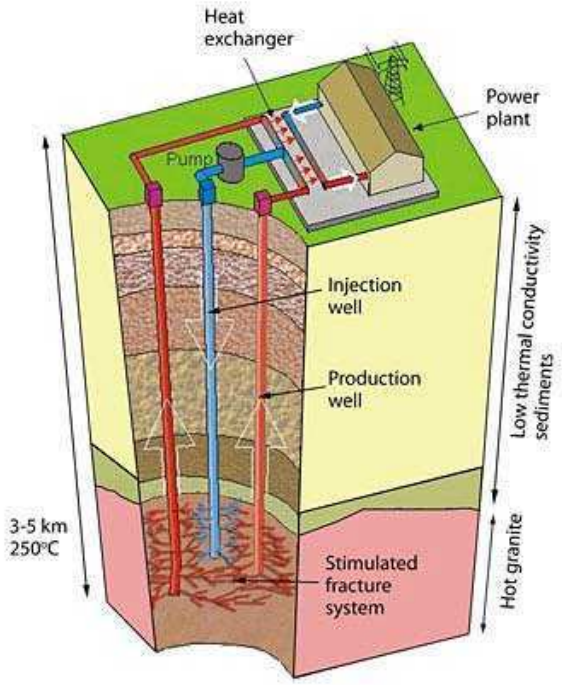


Figure I.3 Conceptual scheme of an EGS (from geothermalworldwide, 2016). In this picture two wells are used for production and one for reinjection, but other circulation schemes based on 2 or 3 wells are also possible as discussed in the manuscript.

Since the first operation in Fenton Hill in the 1970s to recent years, the development of the EGS sector was pretty slow worldwide. This was principally caused by the high investment costs of the deep drilling operations and by the uncertainty related to the success of the reservoir stimulation, which make EGS financially more risky than conventional geothermal plants.

In central Europe, based on the lesson learnt from the pilot plant of Soultz-sous-Forêts, the first commercial EGS was realized in Landau, followed by the one in Insheim (both in Germany). In France, the first commercial operation was inaugurated in 2016 in Rittershoffen, with an EGS aimed at supplying thermal power for industrial processes (no electricity production). The principal features of these plants, that in this manuscript are taken as reference EGS in central Europe, are presented in Table I.1. Also in the Rhine valley, it is worth mentioning the EGS project in Basel (Switzerland), which was cancelled after the seismic events that followed the stimulation phase in 2006 (more details will be provided in chapter 1).

In the review performed by Breede et al. (2013), the power plants in Bruchsal (which uses a kalina cycle) and Neustadt-Glewe (both in Germany) are indicated as EGS, however no information are found regarding the stimulation techniques used in these sites. In the same article, the use of acidizing is reported for the sites of Unterhaching (Germany) and Altheim (Austria), however the use of acids is a common practice also in conventional geothermal site, thus we may argue about labeling as EGS a power plant where only chemical stimulation has been performed.

The Italian site of Larderello is also referred as an EGS by Capetti (2006). This site differs from the ones above since Larderello is also one of the most renowned areas for the "conventional" geothermal exploitation (high enthalpy hydrothermal reservoir). The enhancement techniques (hydraulic, thermal and chemical stimulation) were used only in a second stage to compensate the decline of productivity induced by decades of intensive exploitation of the resource.

Outside Europe, other ongoing EGS projects are reported (Breede et al., 2013) in Desert Peak (USA), Coso (USA), Berlin (El Salvador), Copper Basin (Australia) and Hijiori (Japan).

Table I.1 EGS power plants in central Europe taken as reference in this manuscript

	Country	**Installed capacity**	**Depth [km]**	**Temperature [°C]**	**Produced flow rate [l/s]**	**Surface cycle**	**Comments**
Soultz-sous-Forêts	France	1.7 MW_{el}	5	160	30	ORC	First EGS in Europe
Rittershoffen	France	24 MW_{th}	2.6	170	70	Only heat exchange	Only thermal power production
Landau	Germany	3.6 MW_{el}	3.1-3.3	160	70	ORC	First EGS in Germany
Insheim	Germany	4.8 MW_{el}	3.6-3.8	165	65-85	ORC	Commercial plant

Although the EGS technology is still on its learning curve, its deployment is accelerating and new projects or test facilities are planned or under development in several countries such as the USA, Canada, France, Iceland, Germany, China, Hungary, Turkey, and Australia (Menberg et al. 2016, Breede et al. 2013). In France, 15 exploration licenses have been recently approved for different territories in Alsace, Auvergne, Provence and Aquitaine regions and 4 other exploration applications are currently under review (MEEM 2016). In conclusion, EGS is considered a promising option for electricity and heat production from a renewable energy source, and a progressive development of the sector is foreseen.

I.3 Investigating the environmental performances of EGS through LCA

Although the operation phase of most RE-based systems doesn't entail direct emissions related to the combustion of fossil fuels, the industrial processes related to the manufacturing or the installation of such devices may have significant impacts on the environment (Varun et al. 2009, Ardente et al. 2008, Pacca et al. 2007). In the case of EGS, despite the absence of direct emission in the atmosphere during the operation phase, the more elaborate realization of the wells (deep drilling, stimulation) and of the surface facilities (binary plant), both requiring a large amount of materials and resources, can legitimately rise questions about the overall environmental suitability EGS. Indeed, it would be inappropriate to enthusiastically promote EGSs as a relevant alternative to fossil fuels without a solid understanding of their environmental benefits and considering all the stages of the life cycle of the plant.

When investigating the environmental performances of a given technology, the most consistent way to gain a comprehensive understanding is to consider two different levels for the analysis:

- The positioning of the **technological sector as a whole**, comparing its "**environmental profile**" with other options for energy production. This means for instance being able to make a general comparison of the environmental impacts of the EGS technology with respect to the wind or photovoltaic technologies.
- The comparison of several **specific system configurations within the same technological sector:** this means being able to compare one particular EGS (for instance, with two wells and a power capacity of 2 MW) with another EGS (for instance, characterized by thee wells and a power capacity of 4 MW).

We define "**environmental profile**" the representation of the variability of the life cycle impacts of a system, accounting for the heterogeneity of its possible configurations. An environmental profile is produced considering a large panel of system configurations and a boxplot is a smart and concise way to represent it, because it displays the overall variability of the impacts (from the minimum to the maximum estimates) as well as their median value and the inter-quartile range.

It is important to highlight the two levels mentioned above, because (i) it is necessary to take them both into account for a thorough understanding of the environmental performances and (ii) the available "tools" to address these two levels are not necessarily the same, as we will detail in the next section.

To date, the question of the environmental suitability of EGS has been addressed by few studies presenting the **Life Cycle Assessment** (LCA) of a number of different configurations for this kind of power plants. The LCA methodology is based on the estimation of the impacts of a product taking into account all processes related to its life cycle, such as the extraction of raw materials, the manufacturing, distribution, use and disposal. The LCA methodology considers several impact categories, and it has been standardized with the ISO 14 040 series (ISO 2006a, ISO 2006b). It is widely considered as a relevant approach to investigate the overall environmental impacts of an energy technology from a "cradle to grave" perspective (Ness et al. 2007).

However, when comparing with other energy technologies such as biomass plants or wind turbines, the number of LCAs focused on geothermal energy is still relatively limited. This is highlighted by the results (Figure I.4) of a review published in 2011 by the IPCC (Moomaw et al. 2011) based on the collection of about one thousand LCA studies, selected through a number of qualitative screening and considering the '"Climate change" impact category. Less than ten studies were focused on geothermal plants (of all kinds, from EGS to hydrothermal), while more than one hundred were addressing other technologies like biopower, PV, wind, nuclear or coal power plants. Since this IPCC review, a few more LCAs focused on geothermal have been published, but globally the environmental performances of this sector received so far less attention with respect to other renewable energy technologies (especially those that are recently facing an exponential development like PV or wind turbines).

The impacts on the climate change are expressed in terms of gCO2-*equivalent* per functional unit (eg. 20 gCO_2eq/kWh). In literature, values of gCO_2eq are also usually referred as "*emissions of greenhouse gases*" (eg. Moomaw et al. 2011, Frick et al. 2010). However, it is worth to underline that a figure like *20 gCO_2eq* doesn't actually represent a "physical emission" of carbon dioxide: it is the result of an impact model which aggregates the impacts of many different greenhouse gases according to their global warming potential (GWP).

For the sake of brevity, in this manuscript we will also sometimes refer to the values of gCO_2eq (ie. results on the "Climate change" impact category) as “GHG emissions”.

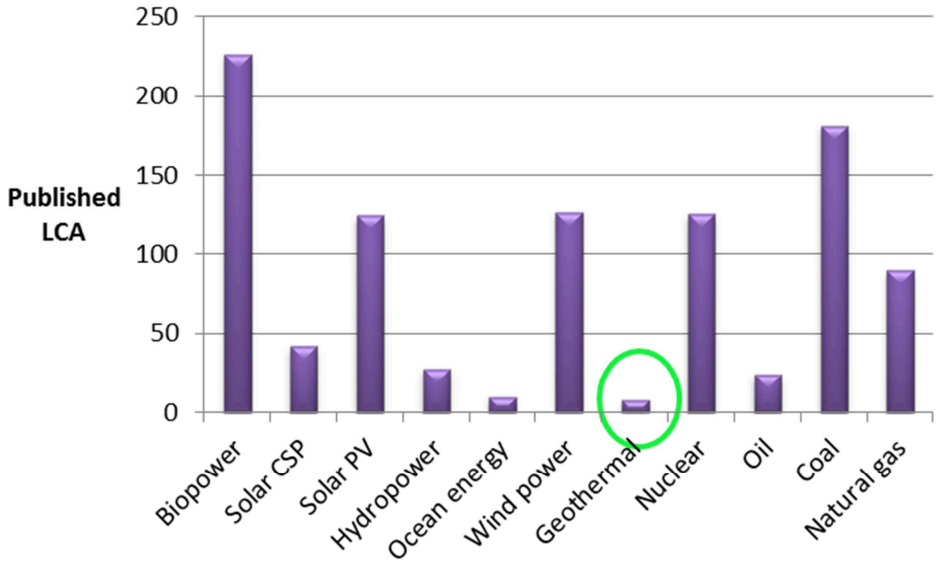


Figure I.4 Survey of the available LCAs of energy technologies, performed by the IPCC (Moomaw et al., 2011). 984 LCAs are taken into account, focused on the estimation of GHG emissions and selected through a number of quality criteria.

Table I.2 and Figure I.5 present an overview of the currently available life cycle assessments that analyze EGS (sometimes among other technological options), excluding the LCA that we published in the framework of this thesis and that we’ll present in chapter 1 (Lacirignola and Blanc 2013). The following observations can be formulated:

- most of the studies are quite recent (published from 2010 on);
- it is difficult to find original datasets (issued from mass flow analysis) regarding the amount of materials and energy flows occurring during the life cycle of the plants: the studies use to refer to each other;
- moreover, EGS being an emerging technology, such few available datasets are usually characterized by high uncertainties;
- all these publications present the results of specific case studies, corresponding to particular EGS configurations;
- all studies present an estimation of the impacts on the climate change, highlighting the interest of the scientific community on this impact category;

- the LCA results proposed by the different authors for such impact category are presented in Figure I.5. A very high variability is observed, with estimates ranging from 6 to 750 gCO_2eq/kWh;
- different methodologies are used for the impact assessment, for instance ReCiPe (Goedkoop et al. 2008), Ecoindicator 99 (Goedkoop and Spriensma 2000) or CML (Guinée et al. 2002);
- the most detailed LCA, whose data are frequently cited or retrieved by other studies, is the one proposed by Frick et al. (2010).

Table I.2 Review of the published LCA of EGS. See also Menberg at al. (2016)

Authors	Publication date	Geogr. reference	Description	Impact categories
Frick et al.	2010	Germany	LCA of 4 EGS scenarios, with several variants. Includes a dataset of mass and energy flows over the life cycle	Climate change, Energy demand, Acidification, Eutrophication
Sullivan et al.	2010	USA	LCA of 2 EGS scenarios, compared with other technologies. Includes a dataset of mass and energy flows over the life cycle	Climate change, Energy ratio (based on demand)
Treyer et al.	2015	Switzerland	LCA of 3 EGS scenarios. Includes a dataset of mass and energy flows over the life cycle.	Climate change + 15 midpoints categories (*ReCiPe method*)
Bauer et al.	2008	Switzerland	LCA of 1 EGS scenario compared with other technologies, two temporal scales (2005, 2030).	Climate change + 9 other categories (*Eco-indicator 99, CML, CED methods*)
Huenges et al.	2010	n.s.	LCA of 2 EGS scenarios	Climate change, Energy demand, Acidification, Eutrophication
Pehnt	2006	Germany	Dynamic LCA comparing "future" (2010) energy technologies including "HDR"	Climate change, Acidification, Eutrophication, Energy demand
Martin-Gamboa et al.	2015	Spain	LCA of an enhanced binary system operating a shallow depth and of a heating generation system. Input/output dataset mainly based on Frick et al. 2010	Climate change + other categories (*CML method*)
Platt et al.	2012	Germany	LCA of 3 EGS scenarios in three areas of Germany	Climate change
Gerber and Marechal	2012	Switzerland	Environomic analysis of future geothermal EGS configurations in Switzerland. No specific figures provided regarding the impacts.	Focus on climate change (*IPCC 2007 and Eco-indicator99 methods*)

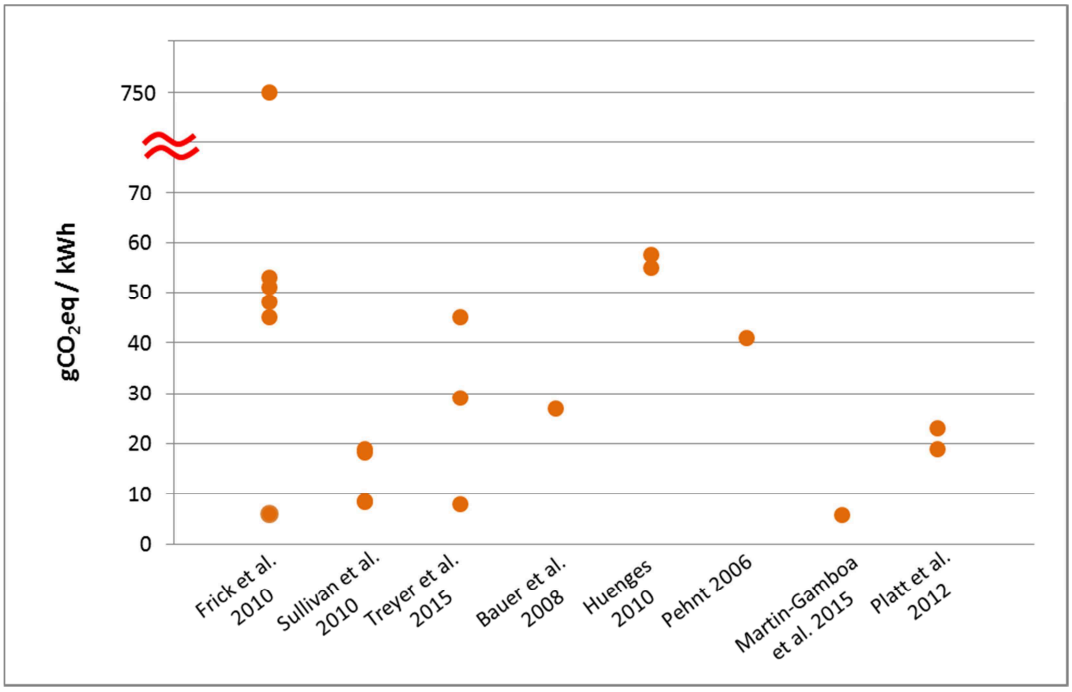


Figure I.5 Literature review of the LCA of EGS: results on the "Climate change" impact category

Based on this state of the art, we are in the position to question whether such available knowledge is sufficient or not for a thorough understanding of the environmental performances of EGS:

1. *Are we able to compare the environmental performances of EGS with other energy technologies, like for instance photovoltaics or coal power plants?*

   Typical estimates of life cycle GHG emissions of renewable energy-based technologies are below 100 gCO_2eq/kWh, while for power plants based on fossil fuels they are frequently higher than 500 gCO_2eq/kWh (Moomaw et al. 2011). When observing the very large range of estimates for EGS shown in Figure I.5 (from 6 to 750 gCO_2eq/kWh), it is hard to decide whether EGS perform better or worse than other technologies. This range of estimated impacts strictly depends on the specific case studies analyzed by few authors and is potentially an unfair picture of the environmental performances of a generic EGS. Indeed the stand-alone higher estimate (750 gCO_2eq/kWh), which is proposed by only one author (scenario "D1" in Frick et al. 2010), is not very representative of the EGS sector: Frick et al. present it as a "worst case" scenario characterized by very unfavorable conditions for a viable exploitation. All the other estimates available from other authors are lower than 60 gCO_2eq/kWh. In conclusion, based on the current knowledge, it is not possible to have

a consistent understanding of the environmental performances of the EGS sector as a whole.

2. *Are we able to estimate the life cycle impacts of one (or more) EGS with given characteristics without performing a new LCA study?*

   Let's take the example of a project developer (or any other decision-maker) willing to identify the most suitable option, from an environmental point of view, between two alternative EGS configurations in a given site (considering, as a simplified example, three wells drilled at 2.5 km depth versus two wells drilled at 3 km). It may be impossible to find in literature a study addressing exactly those two configurations. Or, similar configurations could be found in the scenarios proposed by two different authors while using different methodologies and assumptions, making a consistent comparison unfeasible. Therefore the decision maker would be obliged to command a new LCA tailored on his needs. However, the realization of a LCA is quite complex and requires expert knowledge. It is also pretty time consuming, especially the collection of data regarding the input and outputs of materials and energy flows over the lifecycle of the assessed system.

   In conclusion, based on the current knowledge, it is not possible to have "on demand" a rapid access to the environmental results of specific EGS configurations.

Based on this analysis, we can summarize the first main challenge related to the environmental analysis of EGS:

> **Challenge #1:** gaining a thorough understanding of the life cycle environmental performances of EGS <u>at two levels</u>: considering the global performances of the sector, and the ones of specific EGS configurations.

I.4 Beyond LCAs: environmental tools for a thorough understanding of the environmental performances of EGS

In recent years, different approaches have been developed to promote the understating of the life cycle environmental performances of energy systems and to enhance the decision-making process. Figure I.6 proposes an outlook of the available methodologies, highlighting whether they are more appropriate for providing an overview of the whole technological sector or for investigating specific system configurations within the sector (Padey 2013).

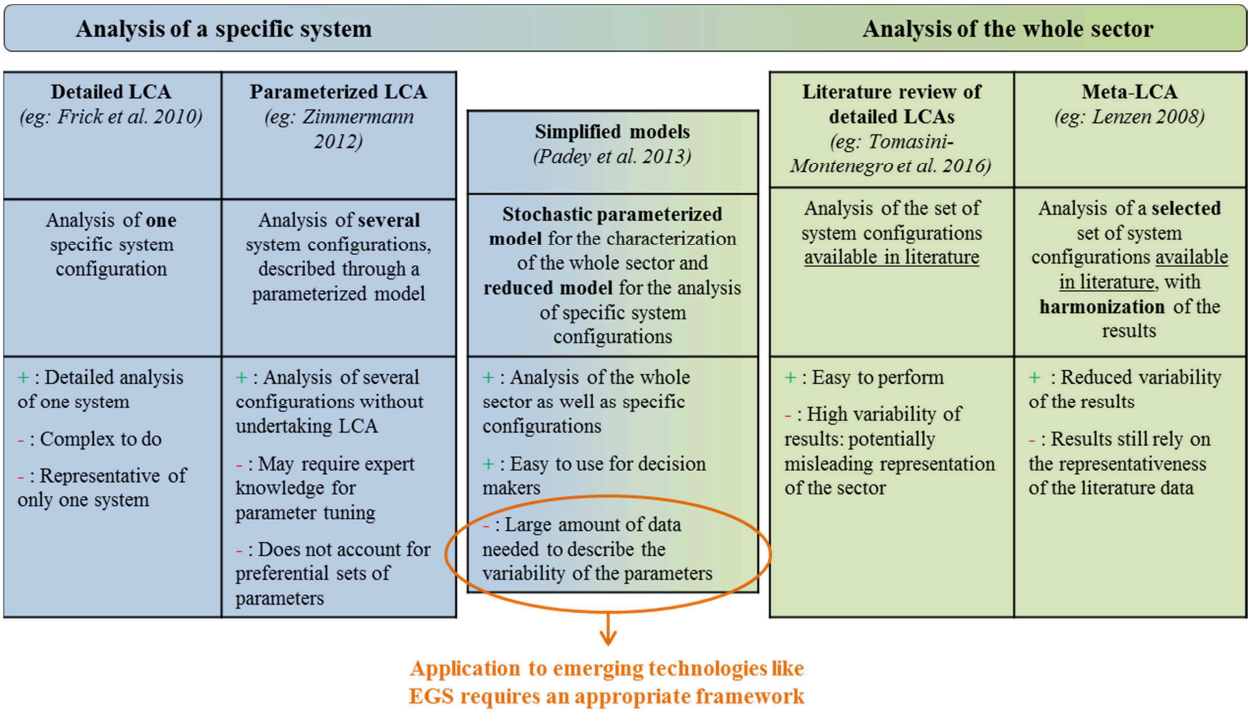


Figure I.6 Tools for environmental analysis: advantages and disadvantages (after Padey 2013)

The "traditional" **detailed LCAs**, like those listed in the previous section (Table I.2) have the advantage of allowing a very deep analysis of the environmental impacts of a given system. For instance they support the identification of the specific processes that are responsible for most of the pollutant emissions, taking into account the different phases of the production chain of the equipment that compose the system. They also allow the identification of specific substances that are responsible for the impacts in the different damage categories considered. Nevertheless, as previously discussed, LCA results frequently correspond only to specific case studies: in general they can't be applied to other configurations of the system analyzed and they can't be considered representative for the whole sector. Moreover, as discussed in

the previous section, the application of the LCA methodology requires expert knowledge and is costly in term of time and resources.

Parameterized LCAs provide a partial response to the abovementioned drawbacks. In such models, the life cycle inventory is disaggregated in several modules that are embedded in the computational structure: the user has just to specify the appropriate value for a number of pre-defined parameters (for instance: lifetime, capacity factor, etc.) to obtain the LCA results. Examples of this approach can be found in Zimmermann (2012) or in the recent initiative of the French Environment and Energy Management Agency (ADEME) of developing a parameterized tool for the LCA of wind turbines. In the latter example, the user can obtain the LCA results by specifying, on a user-friendly interface, the features of the machine from pre-defined lists of options, for instance regarding the type of turbine (onshore or offshore), the type of tower (steel or concrete-made) or the rotor diameter. The development of this tool was driven by the need of ADEME to enhance its understanding of the suitability of wind power generation through the realization of in-house environmental calculations, for instance comparing the impacts of different types of machines in a given site, without undertaking long and complex LCAs (Bellini 2016). This example highlights the need for decision-makers and public entities to have simplified and easy-to-use tools for environmental assessment.

Parameterized models allow the analysis of several different system configurations, but are not able to characterize the environmental profile of the whole technological sector under study. In fact, despite being potentially able to take into account all the possible existing system design, they do not account for the existence of "preferential" configurations (like for instance the fact that most of the wind turbines in France have a given design lifetime, or a particular widely-used rotor architecture). In conclusion, parameterized models are not conceived for the analysis of one energy sector as a whole and they don't allow a systematic comparison with other power technologies.

The more "basic" approach that is commonly used to understand the environmental performances of an energy technology is the **literature review of detailed LCAs,** like the one proposed in Figure I.5. However, as discussed in the previous section, given that the available publications are generally based on different sets of assumptions and different calculation methodologies, it is not possible to perform a consistent comparison of the impacts of specific configurations proposed by different authors. On the other hand, in principle the collection of

several dozens of results from literature should help to get a global overview of the analyzed technology: the problem is that the overall variability of the results observed through this kind of review may be fairly high. For instance, in the review proposed by Menberg et al. (2016) we observe a range of estimated life cycle GHG emissions of 4 to 1100 gCO_2eq/kWh for hydropower, and in the review performed by Moomaw et al. (2011) we observe an interval of 5 to 217 gCO_2eq/kWh for solar PV installations. Considering the average values of these ranges is also tricky, since they depend on the case studies addressed in literature, which may not reflect consistently the heterogeneity of the possible system configurations.

The **meta-LCA** methodology tried to face these drawbacks when considering the energy pathways globally (i.e. a set of systems instead of a single one) and has been widely used in the energy field over the last few years (Warner et al. 2010). The meta-LCA is based on the cross comparison of literature sources: the selected studies are harmonized into a common framework (e.g. same lifetime, same characterization factors, etc.). The variance induced by each parameter is assessed one factor at a time and its relative contribution to the environmental performances is measured. Two outcomes are possible: a reduced range of emissions' estimation (compared to a generic literature review of single LCAs) and in some case meta-models (Lenzen 2008) which enable to estimate the environmental impacts of the literature using a simple linear regression model. However, in both cases, the results rely only on the representativeness of literature and cannot compensate for the lack of data or specific case studies in the literature.

In this context, Padey et al. (2013) developed an intermediate solution between the detailed LCAs and the Meta-LCAs (Blanc et al. 2013), aimed at quantifying the overall environmental profile of the energy pathways while also enabling to estimate the environmental impacts of their embedded systems through so-called **simplified models**. Their methodology (Figure I.7) relies on the set-up of a reference parameterized LCA model (1) coupled with a description of the variability of the parameters (2), reflecting the existence of preferential system configurations. Then, the use of uncertainty propagation methods allows the generation of the environmental profile of the analyzed sector (3), suitable for comparison with other technologies. Furthermore, the application of global sensitivity analysis (GSA) leads to the identification of a restricted number of key parameters that are responsible for most of the variability on the environmental performances (4). A reduced model (5) is then developed, expressing the environmental impacts as a function of these few key variables. This approach

allows generating a simple tool, aimed at non experts and decision-makers, for the environmental assessment of specific configurations of the energy system. Padey et al. (2013) presented an application of this new methodology to the wind electricity pathway. Such protocol appears to be the most appropriate strategy to investigate the environmental performances of EGS, nevertheless the application of global sensitivity analysis (4) faces **an additional difficulty** in the EGS context, related to the **innovative character** of this energy technology and the high uncertainty related to its characterization.

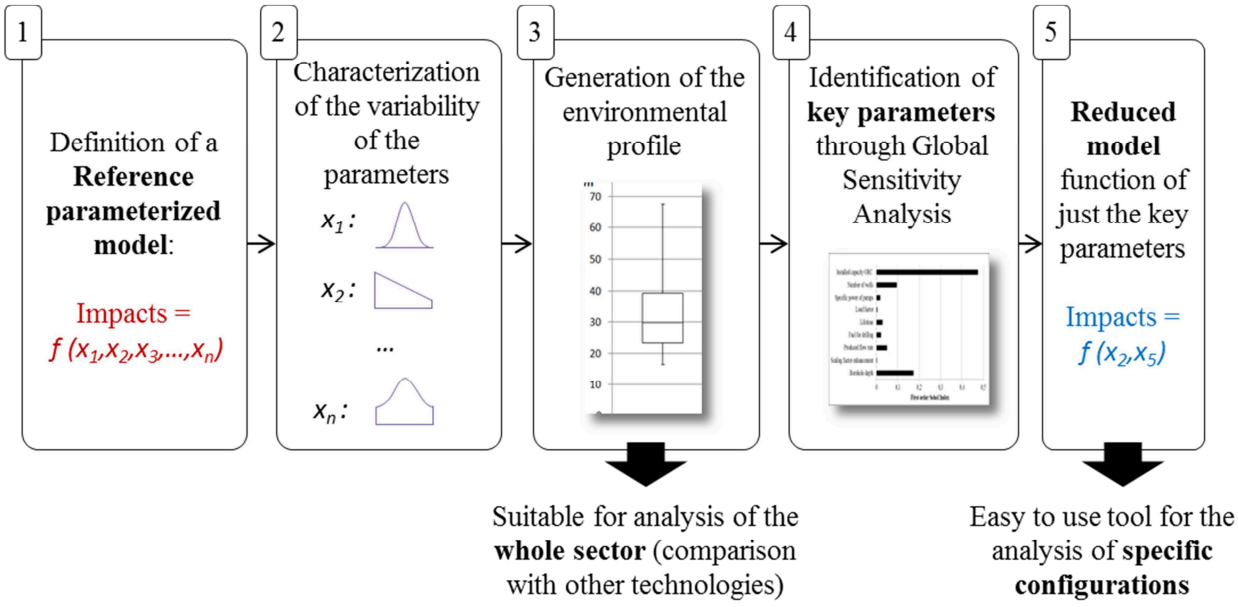


Figure I.7 Synthesis of the methodology proposed by Padey et al. (2013) to generate *simplified models*

In fact, when conducting a GSA (4), the characterization of the variability of each input parameter (2) is one of the most important steps, because it could significantly affect the results. This aspect is critical when studying new products or emerging technologies, where data regarding the model inputs are very uncertain and may cause misleading GSA outcomes, such as the identification of an inappropriate set of key parameters for the reduced model. In the case of EGS, because of the limited long-term experience in this sector, it is difficult to establish a stochastic description of the principal features of these power plants, i.e. identifying the most probable geothermal flow rate of an EGS, or the most appropriate variability range of its lifetime. Therefore in this context the GSA procedure must be undertaken together with a solid investigation of the robustness of its results.

Based on these remarks, we can highlight our second main challenge:

> **Challenge #2:** Face the high uncertainties related to the innovative character of the EGS technology when setting up calculation models aimed at investigating its environmental performances**.**

I.5 The research questions

In section I.1 to I.3 we highlighted the challenge of acquiring a consistent understanding of the environmental performances of power technologies, in the context of a rapid development of renewable energies and within the framework of the implementation of supporting policies. The interest of public authorities and decision makers on the environmental assessment methods is constantly growing, especially with the international engagements of the different countries to reduce their impacts on our ecosystems. In occasion of the last Conference of the Parties (COP22), LCA was highlighted as a relevant approach for understanding the impacts related to our energy supply (LIST, 2016).

Considering the EGS sector, we underlined the importance of considering two levels of investigation in the framework of their environmental analysis: (1) the comparison of EGS with other energy technologies and (2) the comparison of different plant configurations within the EGS sector. We assessed that the LCA results available in literature are not sufficient to understand the environmental performances of EGS according to these two levels of investigation.

In section I.4 we presented the different available environmental tools that could help addressing this lack of knowledge, pointing out their advantages and limitations, in particular from the perspective of a decision-maker as a final user of these tools. Thus we identified the development of "simplified models" (Padey et al. 2013) as a suitable methodology for a thorough environmental investigation with a life cycle perspective. However, we highlighted the challenge related to the application of such methodology, which needs to be further developed in order to account for the high uncertainties related to the innovative character of an emerging technology such as the EGS.

These elements of context allowed us to define the scope of our investigation, which aims at addressing the following two general research questions:

[a] What is the environmental profile of the EGS sector, accounting for the heterogeneity of the possible plant configurations?
[b] How to develop simplified models for an easy estimation of the life cycle impacts of EGS, aimed at decision makers and able to take into account the high uncertainties related to such emerging technology?

Question **[a]** addresses the need of obtaining a **global overview** of the environmental performances of the **EGS technology**, for a comparison with its alternatives for electricity production. Question **[b]** focuses on the need, for decision makers, to have access to practical tools for the analysis of **specific EGS configurations**, able to estimate rapidly the life cycle performances without undertaking the long and complex LCA methodology.

I.6 Methodological approach and outline of the thesis

The methodological approach set up in this thesis to address these research questions is structured in three sequential steps and is detailed in the three parts of the present manuscript (Figure I.8).

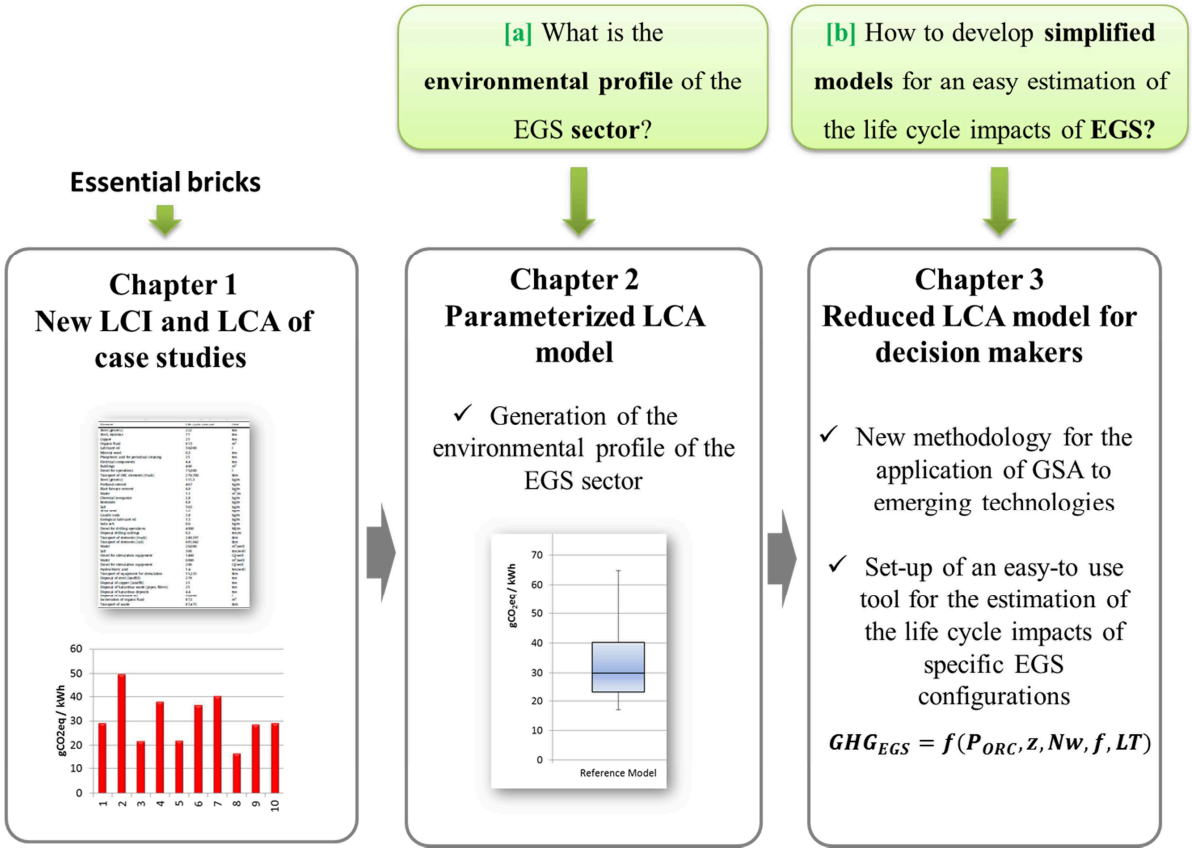


Figure I.8 Research questions and outline of the thesis

1. The elaboration of a **new comprehensive life cycle inventory for EGS** and the application of the **LCA** methodology to a number of case studies, in order to prepare the ground for the development of new parameterized models able to address the questions **[a]** and **[b]**.

As an important preliminary step for the investigation of the environmental performances of EGS, we start with the realization of the LCA of a number of case studies. This allows us (i) to elaborate a new dataset of the mass and energy flows occurring during the life cycle of an EGS and test its robustness through the comparison of our LCA results with literature and (ii) to identify the most relevant processes and the main sources of life cycle impacts. The new datasets elaborated in this part of the research will constitute the basis for the set-up of parameterized models

tailored on the EGS technology and developed in the following chapters. The scientific approach of this chapter consists in the following phases:

(I) definition of the case studies, establishing the features of a number of relevant scenarios reflecting different design options;

(II) application of the LCA methodology according to the ISO standard (ISO 2006a, 2006b);

(III) discussion of the LCA results to validate the setting of our model.

→ *In **chapter 1** we present the elaboration of the new life cycle inventory for EGS, developed through an extensive on-site survey and data collection performed on the EGS site of Soultz-sous-Forêts. We define ten scenarios corresponding to possible realistic EGS configurations, taking into account different possibilities for the drilling depth, the geothermal flow rate and temperature, the number of wells and the reinjection strategy. We estimate the environmental performances with a multi-criteria approach, considering five indicators: the impact on the climate change, on the human health, on the ecosystem quality, on the depletion of finite resources and the risk of induced seismicity. The latter is included for the first time as a relevant indicator in the LCA of geothermal energy systems. We also identify the most influent processes and substances in each impact category.*

2. The development of a **parameterized LCA model** for EGS, able to estimate the life cycle impacts of a large panel of different EGS configurations, **representative for the EGS sector** in central Europe, able to address question **[a]**.

In this step a parameterized LCA model is developed, following the methodological framework proposed by Padey et al. (2013). The scientific approach consists in the following phases:

(I) The formalization of the objective and scope of the parameterized model, expressing its technological, geographical, temporal and methodological characterization.

(II) The design of a parameterized model called "*Reference model*" through (i) the identification of a panel of relevant input parameters (ii) the description of their variability (range of variation and associated probability distribution) (iii) the set-up of modular and scalable datasets of the materials and energy flows occurring during the life cycle: the latter are based on the dataset developed in the first part of this research.

(III) The generation of the "environmental profile": the use of a Monte Carlo method allows the calculation of the life cycle impacts of a large sample of configurations, randomly generated according to the established laws of variability of the parameters.

(IV) The comparison of the produced environmental profile with results from literature to check for its robustness and representativeness.

The elaboration of such environmental profile addresses question **[a]**, since it is representative for the EGS sector, accounting for the variability of the possible plant configurations within to the scope of the model.

→ ***Chapter 2*** *presents the elaboration of our Reference model and the generation of the environmental profile considering the life cycle emissions of greenhouse gases. Our model is based of nine parameters (called "model inputs"): produced flow rate, drilling depth, number of wells, fuel consumption for drilling, load factor, power demand of the pumps, enhancement's intensity, lifetime and power output of the ORC. These inputs allow for the characterization of the size of the plant, of the inventory of materials involved and of the amount of electricity produced. The Reference model expresses the life cycle GHG emission of a generic EGS as a function of the abovementioned nine parameters, whose variability is described through appropriate probability distributions (Gaussian, uniform, etc.). The use of a Monte Carlo technique allows us to estimate the GHG emissions of several thousands of possible EGS configurations and to generate the "environmental profile" representative for the EGS sector in central Europe and allowing a consistent comparison with other energy technologies.*

3. The elaboration of **a reduced LCA model**, aimed at decision makers and function of few key parameters, identified through a methodological framework of global sensitivity analysis **specifically developed** to deal with the high uncertainty related to an emerging technology like the EGS, addressing question **[b]**.

In this step we develop a methodological framework for the application of global sensitivity analysis to the LCA of emerging technologies and we apply it to the EGS case. The proposed scientific approach consists in the following phases:

(I) Identification of the LCA model, namely the parameterized computational structure used to estimate the life cycle impacts according to a set of input variables.

(II) Identification of a "baseline" *description of the inputs* of the model, that establishes their ranges of variability and the probability distribution applied to such ranges.

(III) Realization of a "baseline" *global sensitivity analysis* through the calculation of the Sobol' indices. GSA allows establishing a ranking among the input parameters, identifying the ones that are responsible for most of the variability of the output of the model, called "*key parameters*".

(IV) Analysis of the influence of the *description of the inputs* (c.f. point (II)) on the GSA results. A set of realistic "alternative" descriptions of the inputs is established (different from the "baseline" descriptions made in point (II)). Then the GSA is reiterated several times under different initial conditions, namely considering different combinations for the alternative descriptions of the inputs. This allows generating a number of potentially different rankings and studying if and how the description of the inputs has an influence on the identification of the key parameters. Indeed, for an emerging technology it may be difficult or impossible to identify with high confidence the "baseline" description of one or more inputs: thus the robustness of the hypothesis made by the modeler is here investigated.

(V) Identification of the key input parameters, following the results of the "baseline" GSA (point (III)) and of the "alternative" GSAs (point (IV)). Such identification takes

into account the sensitivity of the GSA results with respect to the description of the inputs, as well as the level of confidence associated to each description.

(VI) Generation of a reduced parameterized model, expressing the life cycle impacts as a function of only the key parameters.

The resulting *Reduced model* is an easy-to-use tool, aimed at decision makers, for a rapid estimation of the life cycle impacts of specific system configurations without undertaking the whole LCA procedure. Thus it addresses question **[b]** of our research.

→ ***Chapter 3*** *presents in detail our new methodological framework for the application of GSA to the LCA of emerging technologies as well as its application to the EGS case, considering the Reference model developed in chapter 2. In addition to the "baseline description" of the nine parameters (established in chapter 2 as well), we account for two to four "alternative descriptions". We reiterate the global sensitivity analysis 3500 times (using Sobol indices) and we observe the stability of the ranking among the nine parameters, while considering the level of confidence of their description. This new protocol allows us to identify five key inputs of the Reference model: the installed power capacity, the number of wells, the drilling depth, the lifetime and the geothermal flow rate. We then establish the Reduced model, expressing the life cycle GHG emissions of EGS as a function of only those 5 parameters. The developed calculation tool, aimed at decision markers, is easy to use and allows a very rapid calculation of the GHG performances of specific EGS configurations.*

Chapter 1
Life cycle assessment of EGS case studies

1.1 Methodology for the LCA of EGS

In this chapter, we start our investigation of the environmental performances of EGS with the elaboration of a new life cycle inventory (LCI) and the analysis of a panel of relevant configurations for this kind of power plants. This will prepare the ground for the development of parameterized models, presented in the other two chapters, allowing us to enhance our understanding of the life cycle impacts of EGS.

The methodology applied in this Chapter can be resumed as follows (Figure 1.1).

1. **Definition of the case studies**: ten scenarios are established (box "A" in Figure 1.1) based on current EGS operations in central Europe, to explore combinations of interdependent factors that determine the size of the installation (number of wells, reinjection strategy, seismicity risk, drilling depth, temperature and flow rate). Then, the annual electricity output of the ten power plants corresponding to these different sets of parameters is calculated (box "C"). A detailed description of this first step is presented in section 1.2.

2. **Elaboration of the LCA model**. The life cycle assessment of these ten power plants is to be performed in accordance to the ISO 14040 standard (ISO 2006a, ISO 2006b). This requires the elaboration of a new relevant life cycle inventory for EGS (box "D" in Fig. 1.1) based essentially on data collected through a technical survey (box "B") on the pilot EGS of Soultz-sous-Forêts (France) and by retrieving information about background processes from the ecoinvent database (box "E") (ecoinvent centre 2010). The impact assessment method (box "F") to be used for the LCA calculation is selected according to the scope of the analysis. An additional environmental indicator is included: the risk of induced seismicity. The latter is identified as a relevant supplementary impact category to assess the environmental performances, in addition those traditionally used in LCAs. This new life cycle model is described in section 1.3.

3. **Analysis of the results**. The robustness of our LCI is validated by comparing the impact results, through harmonized assumptions, with those of one of the most detailed available LCA of EGS (Frick et al. 2010). The LCA results of the base case are analyzed in detail in section 1.4.1, observing the most influent processes and substances on the different

impact categories. In section 1.4.2 the ten scenarios are compared (i) among each other and (ii) with other case studies from literature. Recommendations are retrieved regarding the best design options from an environmental perspective.

4. **Conclusions and step forward.** Based on the results, section 1.5 discusses the contribution of these detailed LCAs in the framework of the general investigation defined in the Introduction chapter. The coherence of our results being assessed, the datasets elaborated in this chapter will constitute the basis for the set-up of parameterized models representative of the EGS sector (to be developed in the following chapters).

The methodology and the contents of this chapter have been published in the following paper:

> Lacirignola, M., Blanc, I. Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment. *Renewable Energy*, 2013, 50, 901-914. doi: http://dx.doi.org/10.1016/j.renene.2012.08.005

They have also been presented in several international conferences (Lacirignola and Blanc 2012a, 2012b, 2012c).

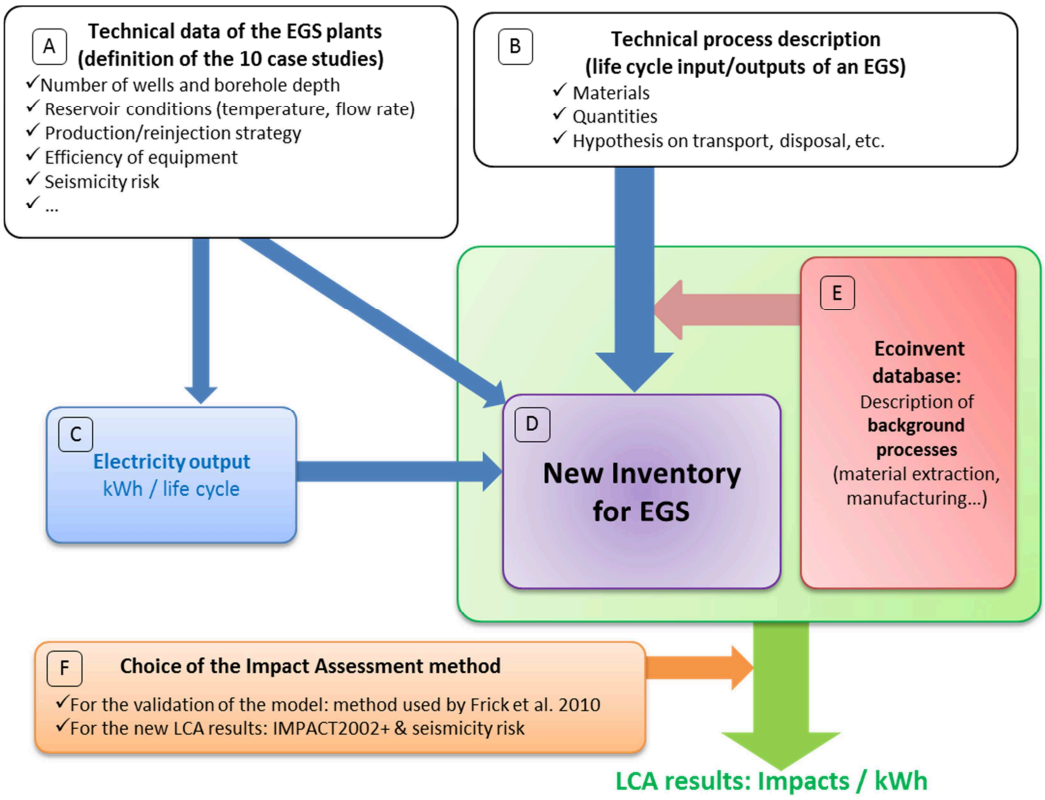


Figure 1.1 Methodology applied in this chapter for the detailed LCA of EGS

1.2 Definition of the ten case studies

Depending on the geology and the geothermal resource conditions, a range of production flow rates and fluid temperatures can be expected from a targeted reservoir. Moreover, technical and economic considerations are essential for the choice of the drilling depth and the number of wells to be realized. Given the variety of interdependent design factors that determine the size of the installation and the final amount of energy delivered to the grid, different parameters are defined to identify ten possible configurations for an EGS plant in central Europe, in the area where the first European EGS installations were developed.

The case studies are distinguished by different choices regarding the number of wells, the borehole depth, the production flow rate and the geothermal fluid temperature (Figure 1.2). All of them are binary plants, equipped with an organic ranking cycle (ORC) on the surface and data are set within reasonable ranges, based on the experiences of current EGS installations (sections 1.2.1 to 1.2.3). Moreover, an additional environmental indicator has been added to characterize each case: the potential risk of induced seismicity. This factor is particularly relevant at design stage, especially since the suspension of the EGS project in Basel (Switzerland) and the problems encountered in Landau (Germany) (Breede et al. 2013), as detailed in section 1.2.4. As for other industrial installations, different risks are connected to the operation of the plant (fire, explosion, electrical shortage, etc.); however in this study we are referring to normal EGS running conditions not considering accidental failures. To evaluate the annual electricity production, hypotheses are made as to the efficiency of the plants and the power required by auxiliary equipment, as reported in section 1.2.5.

Case no. 6 is selected as “base case” because of its similarity to the EGS installed in Soultz-sous-Forêts. Under the initial operating conditions (in 2008), such pilot plant was designed to produce ~35 kg / s from a 5 km borehole, reinjecting the flow rate into two wells at about the same depth and inducing a very low seismic activity. The choice of the values selected for the parameters defining the ten case studies is now discussed, focusing on their technical representativeness.

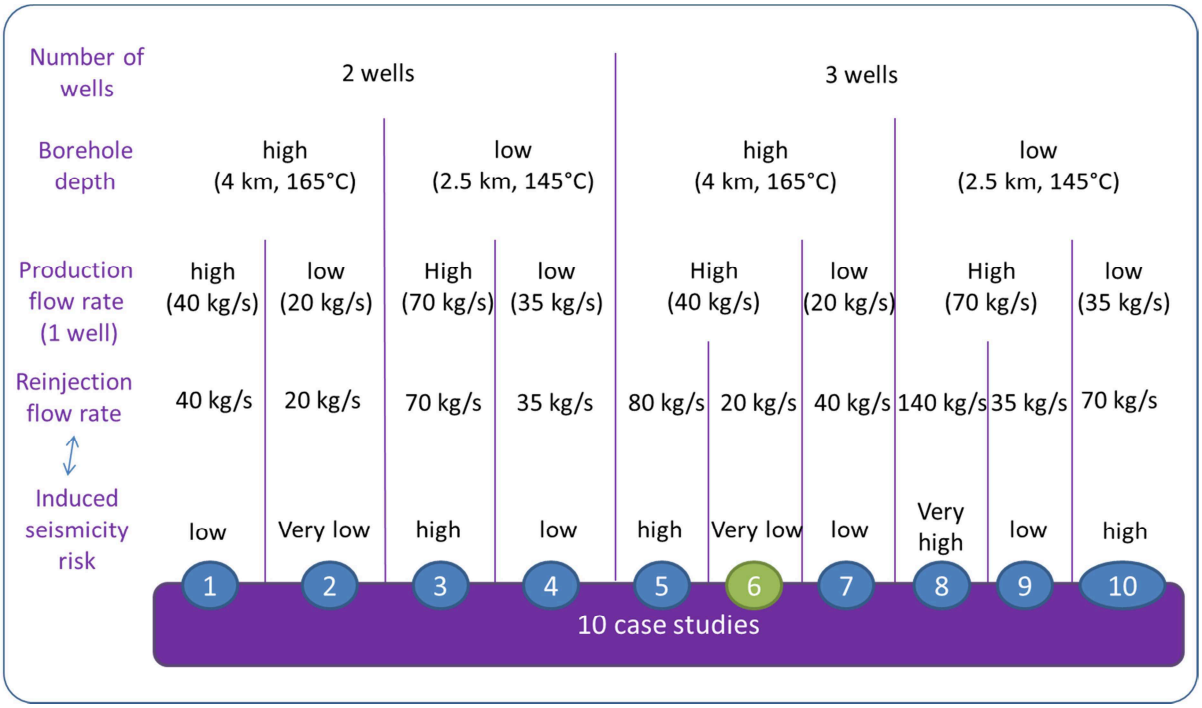


Figure 1.2 Features of the 10 case studies. Case no. 6 is selected as “base case”

1.2.1 Drilling depth and temperature

The energy content of the geothermal resource is site dependent. Basically the temperature increases with depth, but it is not possible to define a widely applicable law, since it depends on the presence of heat transfer phenomena (such as conduction or convection) in relation to the site’s geology and the presence of hydrothermal resources.

Figure 1.3 shows the increase of the temperature with depth observed in two locations in the Rhine Graben (from Schindler et al. 2010). In the area of Soultz-sous-Forêts, the subsurface vertical temperature gradient in the first 1000 m is around 100°C/km, decreasing to 10 °C/km until a depth of 3500 m and then rising to about 30°C/km below 4000 m. A temperature of 200°C is reached at 5000 m. In Landau's area (only 40 km from Soultz-sous-Forêts), where the first European commercial EGS was installed, the granite formation is encountered about 1000 m deeper, hence a very high temperature gradient is registered in the first 2000 m. During production, the geothermal fluid is subjected to cooling of about 5-15°C, which increases with the depth of the borehole and is inversely proportional to the flow rate. Production temperature also depends on the borehole diameter, which is considered to vary from top to bottom of the well from 24″ to 8 1/2″ (steel casing from 20″ to 9 5/8″).

For the set-up of ten case studies, two different drilling depths are considered: 2.5 and 4 km. The production temperature at wellhead (i.e. including the vertical cooling effect during production) is estimated accordingly, as shown in Figure 1.3: 145°C for the 2.5 km wells and 165°C for the 4 km wells.

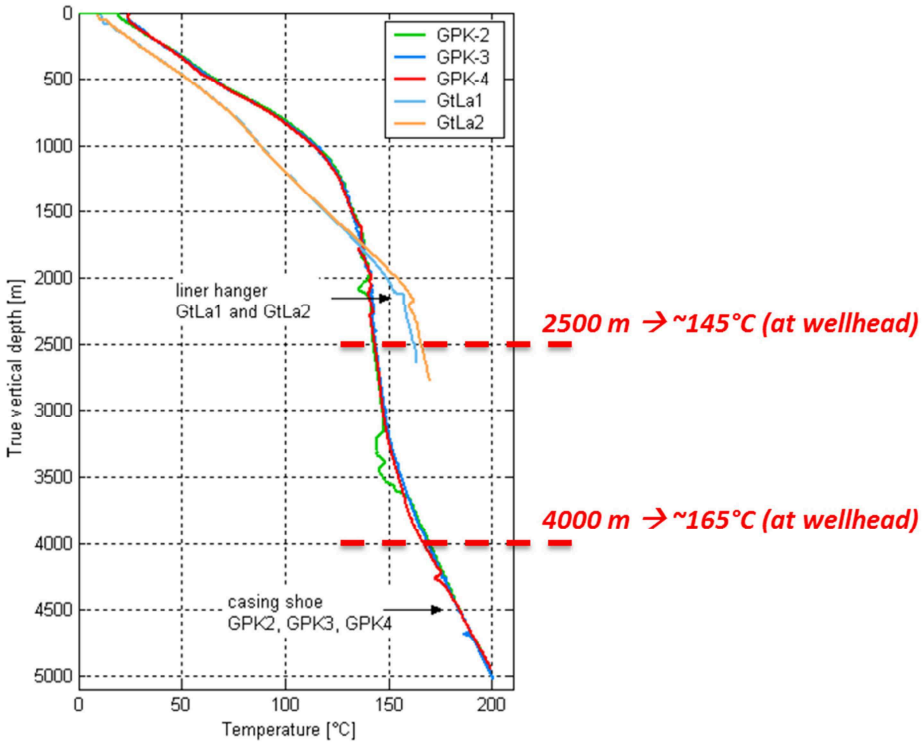


Figure 1.3 Temperature logs in Soultz-sous-Forêts (GPK-2, GPK-3, GPK-4 wells) and Landau (GtLa1, GtLa2 wells), adapted from Schindler et al. (2010)

1.2.2 Flow rate

The produced flow rate depends both on the geology and on the increase in the well's productivity after the enhancement operations. Current experiences show that targeting the fractured granite zone deeper than 4000 m leads to lower production of geothermal flow. On the contrary, drilling at a lower depth and reaching geological layers characterized by the natural convection of thermal fluid can lead to a higher production rate (Schindler et al. 2010). However, higher flows also generate a greater amount of deposits in the filters over the plant's lifespan. Large accumulations of deposits, which are periodically removed, could require stricter safety measures on site because of their radioactive content resulting from the water's circulation through a granite reservoir.

In presented the case studies, two possible production rates are associated with each drilling depth, indicated as “high” or “low” in Figure 1.2. In the case of the 4 km borehole, a flow rate of respectively 40 or 20 kg/s per well is assumed, reflecting the design conditions in Soultz (35 kg/s, Breede et al. 2013). For the 2.5 km boreholes, the production rate is set at 70 or 35 kg/s, reflecting (for the “high” value) the design condition in Landau and Rittershoffen (Breede et al. 2013; Baujard et al. 2015).

1.2.3 Number of wells

As for other renewable energy technologies, the life cycle emissions of binary plants and are mostly related to the construction of the facility while those related to the operation phase are practically negligible. Results from literature (Menberg et al. 2016, Tomasini-Montenegro et al. 2016) show that most of the life cycle impacts of EGS are caused by the drilling operations. This is essentially due to the combustion of hundreds thousands liters of fossil fuel in electric generators that drive the drilling rigs for several weeks. Hence, designing a system with either two or three wells (respectively called “doublet” and “triplet”) has non-negligible consequences on the life cycle emissions. However, even though the first choice might seems favorable from an economic and environmental point of view, the second allows higher flexibility, in particular regarding the reinjection strategy. In fact, in the triplet case, two boreholes can be used for the reinjection of the geothermal fluid, thus decreasing the working pressure and flow rate and reducing the risk of induced seismicity. Conversely, in the case of unfavorable reservoir conditions, allocating two wells for the geothermal production (and one for the reinjection) allows doubling the available thermal power to be converted into electricity. Four case studies are associated with a two-borehole system, while the remaining six are characterized by three boreholes.

1.2.4 Seismicity

The reinjection of the geothermal fluid in the underground reservoir may cause micro-seismicity phenomena that can be felt by the local communities. In 2006, on the site of the Basel EGS plant, seismic events reached the Richter magnitude ML 3.4 six days after the main stimulation, creating damages (> 6M CHF) and much concern among the population, resulting in the project’s suspension. The reinjection flow rate in Basel was about 60 kg/s, with the pressure achieving 295 bar. In St. Gallen, another Swiss site, a seismic event of ML 3.5 occurred in 2013 (Weimer et al. 2015). In 2009, earthquakes of magnitude ML 2.7 were

registered in Landau during circulation, causing complaints from residents (Groos et al. 2013). Landau's doublet was designed to generate 3 MWe with a reinjection flow of about 70 kg/s at a pressure of 80 bars (Baumgartner et al. 2010). But after 2009 the German authorities defined strict limitations to prevent future seismic events on the site (Schmidt et al. 2010).

An obligation to reduce the reinjection parameters, in order to mitigate unexpected seismicity, entails running the plant outside the design conditions. This can have significant consequences on the project's profitability, therefore today the seismic risk is an increasingly important parameter in plant design. Reinjection pressure also play an important role, since for a well with given characteristic of injectivity it increases together with the flow rate. In this study, to analyze directly the correlation between the electricity produced and the induced seismicity, we focus only on the reinjection flow rate.

No fixed correlation between reinjection parameters and seismic phenomena can be defined, but empiric experiments show that a relevant decrease of the reinjection flow rate strongly decreases the risk. This is highlighted by Cuenot et al. (2011a) after many years of observation in Soultz-sous-Forêts. Rothert and Shapiro (2007) show that fixing the reinjection pressure, the probability of induced seismicity increases with the cumulative volume of the reinjected fluid. This feature seems site independent. Moreover Shapiro et al. (2010) show that the increase of the flow rate enhances the seismic activity. In Landau, after having imposed a lower flow rate (because of the concern created by the earthquakes in 2009), the micro seismic activity became acceptable (LGB-RLP, 2012).

For the ten case studies, according to the reinjection flow rate, a 4-grade scale has been set-up, based on the above identified empirical relation, to quantify the potential seismic risk according to the current limited knowledge on EGS. A very low grade is assumed for a 20 kg/s flow rate. In 2011 in Soultz-sous-Forêts two wells were used for the reinjection of 12 kg/s in each of them and no relevant seismicity was registered. A low grade is chosen for a 35-40 kg/s flow rate (the design conditions in Soultz-sous-Forêts). A high grade is associated to a 70 kg/s flow rate, which is the condition that generated the seismic events in 2009 in Landau. When doubling the flow rate to 140 kg/s we logically obtain an extreme case, associated with a much higher grade of risk (Table 1.1). In other words, we assume that reinjecting a flow rate as high as 140 kg/s in one single well entails a high probability of inducing relevant seismic events, which may provoke damages on surface and possibly lead to the suspension of the operations or even the abandon of the EGS project (as in Basel).

The risk of triggering induced seismicity may also depend of other factors, like for instance the geological structure of the reservoir. However, considering the geographical scope of our LCA (central Europe) and the limited knowledge of the scientific community on the relation between seismicity and EGS, we based our empirical scale (Table 1.1) only on the reinjection flow rate. The robustness of our empirical scale may be improved when further studies on induced seismicity will be available.

Table 1.1 Empirical relation between the seismicity risk and the reinjection flow rate. The percentages in the last column will be used for the radar representation of the results.

Reinjection flow rate	Seismicity risk	Representation
20 kg/s	Very low	100%
35-40 kg/s	Low	125%
70 kg/s	High	150%
140 kg/s	Very high	175%

1.2.5 Annual energy production

For all case studies, it is assumed that the geothermal fluid is reinjected at a temperature T_{reinj}=70°C, after having transferred the thermal power necessary for heating the organic fluid of the binary cycle. Experiences in Rittershoffen and Soultz-sous-Forets show that reinjecting at a temperature lower than ~70°C may generate challenging operational issues, due to the formation of hydrothermal deposits (scaling) in the geothermal loop. The specific heat capacity *HC* of the geothermal fluid is generally in the range of 3.8-4.12 kJ/(kg·K) depending on its temperature and mineral content; for the ten cases it is fixed at an average value of 4 kJ/(kg ·K).

The conversion efficiency of the plant is defined as the ratio between the gross power output of the turbine and the thermal power available from the geothermal resource P_{Therm} (P_{Therm} can be estimated as $P_{Therm} = f \cdot HC \cdot (T_{prod_wh} - T_{reinj})$ where f is the total production flow rate and T_{prod_wh} is its temperature at the production wellhead). For EGS power plants, the conversion efficiency is unavoidably low, because of the low temperatures that characterize the cycle, and is assumed to be 15% or 13% when T_{prod_wh} is 165°C and 145°C respectively (following discussions with experts and the extrapolation proposed by Tester and coworkers in a study published by the MIT (2006b)). These assumptions lead to an estimation of the gross power output P_{gross} between 1.14 MW (case 2) and 5.46 MW (case 8).

Based on discussions with the operators in Soultz-sous-Forêts, it is also assumed that the auxiliary elements of the organic Rankine cycle (circulation pump, air cooler and other minor equipment) globally require 20% of the turbine gross power output. Specifically, 8% is assumed to be related to the pump, around 8% to the air cooler and 4% to other auxiliary devices. Thus the estimated ORC power output P_{ORC} varies from 0.91 to 4.37 MW.

The power absorbed by the downhole pump depends on many interdependent parameters (productivity of the well, borehole depth, flow rate, etc): the simplified hypothesis of 1.5 kW per m^3/h of geothermal fluid is made. For the reinjection pump, 1 kW/(m3/h) is assumed. Deducting the power demand of these pumps, we obtain a final power output P_{NET} of 0.8 to 3.1 MW in the ten case studies.

Geothermal plants are characterized by an extremely high capacity factor (Lund 2003), so the number of annual operating hours at full capacity is considered to be 8 000 for all cases. The annual net energy production, calculated from the parameters detailed above and reported in Table 1.2, varies from 6.24 GWh per year (case 4) to 24.88 GWh per year (case 8). The lifetime of all configurations is assumed to be 25 years.

Table 1.2 Characteristics of the 10 EGS case studies

	Unit	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6 (base)	Case 7	Case 8	Case 9	case 10
Number of wells	ad.	2	2	2	2	3	3	3	3	3	3
Reservoir depth	km	4	4	2.5	2.5	4	4	4	2.5	2.5	2.5
Geoth. fluid temp. T_{prod_wh} (at wellhead)	°C	165	165	145	145	165	165	165	145	145	145
Geoth. fluid temp. T_{reinj} (at wellhead)	°C	70	70	70	70	70	70	70	70	70	70
Total production flow rate	kg/s	40	20	70	35	80 (40x2)	40	40 (20x2)	140 (70x2)	70	70 (35x2)
Total Reinjection flow rate	kg/s	40	20	70	35	80	40 (20x2)	40	140	70 (35x2)	70
Hazardous deposits in filters	kg/y	160	80	280	140	320	160	160	560	280	280
Gross power output P_{gross}	MW	2.28	1.14	2.73	1.36	4.56	2.28	2.28	5.46	2.73	2.73
Auxiliary power ORC	kW	456	228	546	273	912	456	456	1092	546	546
ORC power output P_{ORC}	MW	1.82	0.91	2.18	1.1	3.65	1.82	1.82	4.37	2.18	2.18
Auxiliary power downhole pump	kW	216	108	378	189	432	216	216	756	378	378
Auxiliary power reinjection pump	kW	144	0	252	126	288	0	144	504	252	252
Final power output P_{NET}	**MW**	**1.46**	**0.80**	**1.55**	**0.78**	**2.93**	**1.61**	**1.46**	**3.11**	**1.55**	**1.55**
Annual net energy production	**GWh/y**	**11.68**	**6.4**	**12.4**	**6.24**	**23.44**	**12.88**	**11.68**	**24.88**	**12.4**	**12.4**

1.3 Elaboration of the LCA model

Following the definition of the 10 EGS scenarios, we now apply the LCA methodology in accordance with the ISO 14040 series, that recommend four different phases: goal and scope definition, inventory analysis, impact assessment and critical step-by-step interpretation (Figure 1.4).

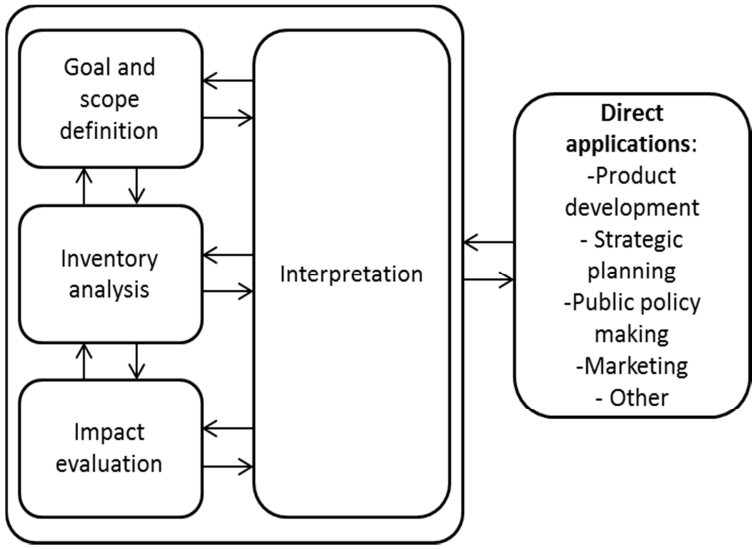


Figure 1.4 Framework of the LCA (ISO 14040, ISO 14044)

1.3.1 Goal and scope definition

Our goal is to evaluate the environmental impacts of enhanced geothermal systems in central Europe, comparing ten realistic plant configurations based on current operations in the Rhine Graben and taking into account technical and economic constraints.

The system's boundaries include the ORC's surface equipment and the sub-surface elements related to the geothermal loop: material and energy flows related to their installation, operation (lubricant oil, organic fluid replacement, fuel consumption, equipment replacement) and disposal are accounted for. The temporal reference is the year 2012. The functional unit is the kWh of net energy produced by the plant for an operating period of 25 years. The net energy production is defined as the gross energy output of the turbine minus the energy required by all auxiliary elements of the ORC and the pumps of the geothermal loop.

1.3.2 Inventory analysis: elaboration of a new LCI for EGS

The life cycle inventory elaboration (LCI) is the compilation of all inputs (material, fuels, resources, electricity, heat) and outputs (emissions, waste) occurring during the several stages of the product's life cycle. In our case this is a particularly challenging task, since very few EGS applications exist today and the long-term experience of the scientific community is relatively limited.

In this study we elaborated a new inventory, based on the technical processes involved in the life cycle of the system (Table 1.4). The necessary information (type of material used, quantities, supply process) were obtained through a detailed mass-flow analysis conducted on the site of the EGS plant of Soultz-sous-Forêts (see Annex 1 for some pictures of the plant). In this framework, we examined the available technical documentation (reports of the drilling and enhancement phases, equipment manuals, technical sheets, scientific publications) we interviewed several experts of the field, we conducted a thorough literature review and we established a number of assumptions. Our hypothesis and estimations were discussed and validated with scientists and industrial actors involved in the site's construction and operation. The main references and sources of information are reported in Table 1.3.

Data regarding the background processes such as raw materials extraction and manufacturing, transport and waste treatment, were retrieved from the ecoinvent database v2.2 (ecoinvent centre, 2010).

Table 1.3 References for the elaboration of the LCI

	Main sources of data
Drilling and construction of the wells	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)	Degouy (2011), Szablinski (2011), Bauer (2011), Technical sheets and equipment manuals (from the Soultz-sous-Forêts site),
Enhancement campaign	Hettkamp et al. (2004), Schindler et al. (2010), Nami et al. (2008), Baujard et al. (2017)

The systems analyzed in the ten scenarios are binary: hence some of the equipment is related to geothermal fluid loops (wells, production and reinjection pumps, etc.) and other elements are related to the ORC (turbine, air cooler, etc). A diagram of the system is presented in Fig. 1.5, showing the system's boundaries and the elements considered in the inventory.

Surface elements. Geothermal water is produced from one or two wells through a long-shaft pump and, before being reinjected underground, it flows into a heat exchanger where it releases the thermal power necessary for the organic fluid to reach a sufficient enthalpy level. The vaporized fluid, which circulates in a separate loop, drives a turbine connected to the electricity generator. It then condenses in an air-cooler, which enhances the heat exchange with the ambient air via a series of fans; before this device, the presence of a regenerator is assumed. Filters are placed on the surface geothermal loop and deposits may contain radioactive elements, which naturally occur in low concentrations during normal reactions between water and rocks. Observations in Soultz-sous-Forêts showed an average value of the dose rate in the ambient of the plant of about 0.4 μSv/h with a maximum of 1.8 μSv/h. For such limited levels, normal precautionary measures are taken by the operators (Cuenot et al. 2011b). However, accumulations of such deposits need to be periodically removed from filters and properly stocked in specific monitored sites, managed by dedicated agencies. Normally their annual amount increases with the geothermal flow, therefore a rough estimation of 4 kg/(kg/s) of total flow rate is made (see Table 1.2). Use of anti-scale agents is not considered. In case of maintenance of the ORC loop, the geothermal water produced is deviated to a backup system including a pool, where it can cool down before being reinjected. The presence of steam separators (particularly useful in the starting operations) is also accounted for.

Sub-surface elements. The most energy-demanding process is the realization of the boreholes. This requires a large amount of material, such as water and chemicals to produce the mud (which is used to facilitate the removal of the drilling cuttings), steel and cement for the well casing and fuel to supply the electric generators that drive the rig. The use of diesel in this process is one of the main causes of environmental issues; an amount of 4 GJ per meter has been identified through calculations based on the data from the drilling reports (GEIE 2002a, Southern International Inc. 2002, Gandy Inc. 2004a, Gandy Inc. 2004b) and comparison with literature.

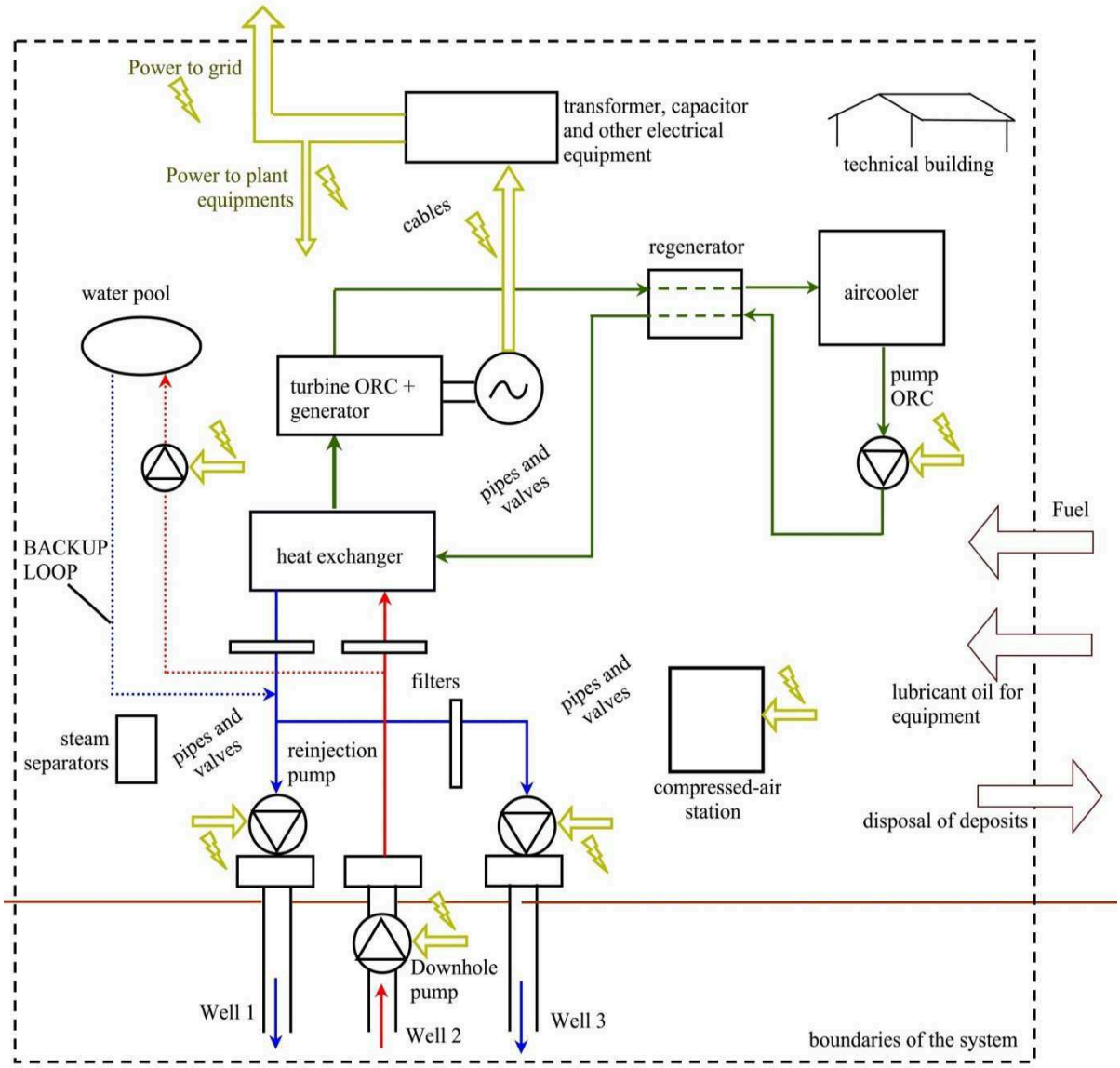


Figure 1.5 System boundaries for the analyzed EGS (base case)

Stimulation. As discussed in the Introduction, enhancement techniques are used to increase the productivity of the wells. Hydraulic stimulation is performed by injecting water at high pressure while chemical treatment is done by injecting several types of acids in the borehole. For example in Soultz-sous-Forêts hydrochloric acid, regular mud acid (RMA), nitrilotriacetic acid and organic clay acid have been used (Nami et al. 2008). In the ecoinvent database there is lack of inventory data regarding the latter three chemical compounds. Moreover, they haven't been used to stimulate all the wells, while HCl has been injected in each of the three boreholes (GPK-2, GPK3 and GPK-4). Hence for simplicity only hydrochloric acid is considered in this study. To estimate the amount of materials involved in the chemical stimulation, we referred to Nami et al. (2008). For the calculation of the material and energy

flows related to the realization of the boreholes we used GPK3 as a main reference, since it is considered a successful well, showing after stimulation in 2003 an injectivity of 0.3 l/s/bar.

Transports. Regarding the transport of materials, equipment is transported by truck or train, and different delivery distances are evaluated according to assumptions on the supply process.

End of life. At the end of the plant's lifetime it is assumed that most of the surface elements are disposed in landfill, except for parts in contact with radioactive deposits, which are stored in appropriate sites for hazardous materials. The wells are filled with cement, following the current practices in geothermal installations. We didn't model the materials for casing and cementation as a long-term emission in soil: given the high depth of the boreholes, we considered that there isn't a direct exposure of humans and the ecosystem to such emissions. The same methodological choice has been done in other datasets available in literature (Frick et al. 2010, Bauer et al. 2007, Treyer et al. 2015). Moreover, the modeling of the impacts of long-term emissions in soil is still the object of studies in the LCA community. A discussion of the LCA results obtained by modeling the end of life of the wells as a long-term emission is proposed in Annex 4.

Table 1.4 presents the results of this long and complex work of estimation of the mass and energy flows occurring during the life cycle of EGS. Data in this table correspond to case 6, (which is considered as "base case" as discussed in section 1.2). Equipment quantities include their replacement during the operation phase. For the other nine scenarios, the variation in the amount of materials (related to the different size of the surface equipment) is accounted for through mass extrapolation. Such mass extrapolation is possible because of the slight difference between the equipment size in the presented case studies.

The uncertainties related to the "foreground processes" (i.e. the values calculated in this study) are based on simplified qualitative evaluations (third column of Table 1.4). In fact, given the limited availability of inventory information (because of the small number of existing EGS) such intervals can't be based on a large data sample. This qualitative evaluation takes into account the quantity and the completeness of the available sources (see notes below Table 1.4). On the other hand, uncertainty intervals related to the "background processes" (e.g. material and processes for steelmaking, energy required for the fabrication of equipments, etc) have been retrieved from ecoinvent. Even if the uncertainty estimations for the foreground processes (the last column of Table 1.4) are quite approximate, we observed

that the final confidence range of the results of a given scenario (presented in section 1.4) is not highly affected (Lacirignola and Blanc 2012c). In other words, when performing two Monte-Carlo calculations, respectively including and excluding the uncertainties of the last column of Table 1.4, we obtain almost the same confidence ranges on the results. Therefore, the uncertainty on the impacts is essentially due to the description of the background processes made in the ecoinvent database. However, it is worth to note we may come to a different conclusion, if ever the uncertainty on the foreground processes increases (which may happen in the future, when new data will be available).

Before proceeding to the impact assessment of our 10 case studies, we validated the robustness of our dataset (Table 1.4) through a comparison (with harmonized assumptions) with one of the case studies presented by Frick et al. (2010). Namely we verified that applying our dataset to Frick et al.'s scenario we obtained similar results: this simulation is presented in Annex 2.

Table 1.4 Materials, processes and energy flows occurring during the life cycle of an EGS plant. Data refer to the base case (1.61 MW final power output)

Phase	Element	Life-cycle amount	Unit	Uncertainty [%]
Surface elements [a]	steel (generic)	222	ton	+/-20 [e]
	steel, stainless	77	ton	+/-20 [e]
	copper	25	ton	+/-20 [e]
	organic fluid	87.5	m^3	+/-20 [e]
	lubricant oil	50000	l	+/-20 [e]
	mineral wool	0.5	ton	+/-20 [e]
	phosphoric acid for periodical cleaning	25	ton	+/-20 [e]
	electrical components	4.4	ton	+/-20 [e]
	buildings	400	m^2	+/-20 [e]
	diesel for operations	75000	l	+/-20 [e]
	transport of ORC elements (truck)	270700	tkm	+/-30 [g]
drilling, casing, cementation, closing [b]	steel (generic)	111.3	kg/m	+/-10 [d]
	portland cement	40.7	kg/m	+/-10 [d]
	blast furnace cement	4.9	kg/m	+/-10 [d]
	water	1.1	m^3/m	+/-10 [d]
	chemical inorganics	2.8	kg/m	+/-10 [d]
	bentonite	8.8	kg/m	+/-10 [d]
	salt	50.5	kg/m	+/-10 [d]
	silica sand	1.5	kg/m	+/-10 [d]
	caustic soda	2.8	kg/m	+/-10 [d]
	ecological lubricant oil	1.5	kg/m	+/-10 [d]
	soda ash	0.6	kg/m	+/-10 [d]
	diesel for drilling operations	4000	MJ/m	+/-20 [d]
	disposal drilling cuttings	0.3	ton/m	+/-10 [d]
	transport of elements (truck)	249197	tkm	+/-20 [g]
	transport of elements (rail)	681042	tkm	+/-20 [g]
hydraulic stimulation [c]	Water	20000	m^3/well	+/-40 [f]
	Salt	300	ton/well	+/-40 [f]
	diesel for stimulation equipment	1400	GJ/well	+/-40 [f]
chemical stimulation [c]	Water	6000	m^3/well	+/-40 [f]
	diesel for stimulation equipment	200	GJ/well	+/-40 [f]
	Hydrochloric acid	1.4	ton/well	+/-40 [f]
	Transport of equipment for stimulation	51233	tkm	+/-40 [g]

Decommissioning and disposal	Disposal of steel (landfill)	279	ton	+/-20 [e]
	Disposal of copper (landfill)	25	ton	+/-20 [e]
	Disposal of hazardous waste (pipes, filters)	25	ton	+/-20 [e]
	Disposal of hazardous deposits	4.4	ton	+/-20 [e]
	Disposal of lubricant oil	50000	l	+/-20 [e]
	Incineration of organic fluid	87.5	m^3	+/-20 [e]
	Transport of waste	87475	tkm	+/-30 [g]

Notes:

[a] A different lifespan is associated with each surface element. Energy for industrial production of the equipment is accounted for using data from general manufacturing included in ecoinvent.

[b] Data related to a 5000 m borehole with diameter varying from 24" to 8 1/2" and casing from 20" to 9 5/8". Lifespan of well's elements is supposed to be equal to the lifetime of the plant. Drilling mud essentially based on water and salt; higher content of viscosifying agents can be expected.

[c] Estimation of materials for enhancement based on the references previously cited.

[d] Uncertainty of +/- 10% is estimated for data related to the boreholes (since very detailed reports about drilling, casing and cementation of the wells have been consulted in Soultz-sous-Forêts), except for the quantity of diesel because it's a very sensible data (site dependent).

[e] A value of +/- 20% is set for the uncertainty on the materials related to surface equipment (and their disposal). Size and mass of the equipment have been retrieved from manuals or technical sheets. However, because of the assumptions about their lifetime, the variability of their characteristics (depending on the supplier) and the lack of information about their fabrication, we assumed a higher uncertainty compared to the boreholes.

[f] Uncertainty of +/- 40% is estimated for the materials related to the well stimulation, because such operations are extremely site-dependent and the quantity of water and chemicals may largely change from site to site.

[g] Higher uncertainty for transports because of the additional hypothesis on the supply distance.

1.3.3 Impact assessment

This phase aims at evaluating the environmental impacts starting from the LCI information. From the several impact assessment methods available from literature, we opted for IMPACT2002+ (Jolliet et al. 2003 and Annex 3), that considers the following impact categories (Figure 1.6):

- Impacts on the **Climate Change**, measured in **gCO_2eq** : this is an estimation of the equivalent mass of carbon dioxide which have the same impact of the different GHG emitted in the atmosphere over the life cycle.

- Impacts on the **Human Health**, measured in "Disability Adjusted Life Years" (**DALY**), which is an estimation of the total amount of healthy life lost, to all causes, whether from premature mortality or from some degree of disability during a period of time.

- Impacts on the **Ecosystem quality**, measured in "potentially disappeared fraction of species over a certain area and during a certain time" (**$PDF \cdot m^2 \cdot y$**), which is an estimation of the percentage of animal species due to the environmental load.

- Impacts on the **Resources,** measured in terms of **MJ**. This unit takes into account both the consumption of non-renewable energy resources and the additional energy that will be required in the future for the extraction of mineral resources (due to the lower concentration of minerals in the mines).

Moreover, the risk of **induced seismicity** is added as a fifth impact category to be taken into account for the evaluation of the environmental performances of the EGS plant.

All the calculations have been performed with the software SimaPro v7.2.4.

1.3.4 Interpretation

After an initial validation of our model, carried out by comparing it with the results of one of the scenarios presented by Frick et al. (2010) (Annex 2), we explored in detail the impacts for the base case, highlighting the most relevant processes and substances. Then we compared the results of the ten case studies, analyzing their relative differences and observing the induced

seismicity as another important parameter to be considered at design stage. These figures are presented in the next section.

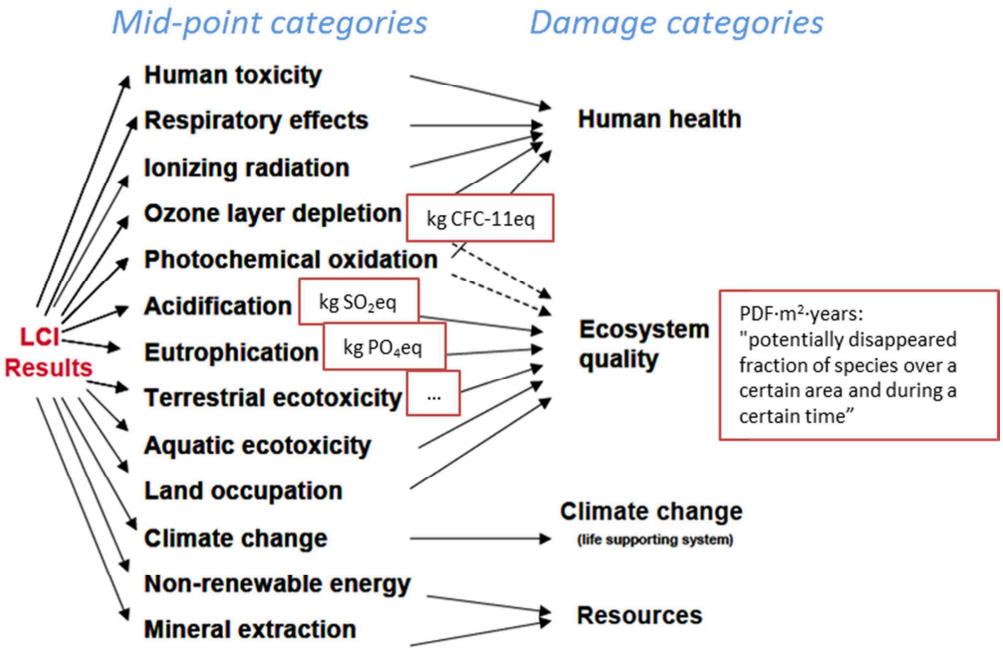


Figure 1.6 Scheme of the IMPACT2002+ methodology (see Annex 3 for further details)

1.4 Results and discussion

1.4.1 Results on base case

The environmental performances of the base case, which has a final power output of 1.61 MW and is equipped with a 4 km-deep triplet, are presented in Figure 1.7, 1.8 and Table 1.5.

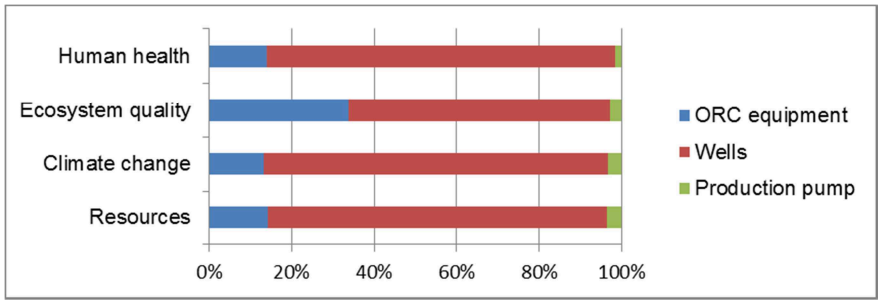


Figure 1.7 Contribution of the system elements to the four impact categories (base case)

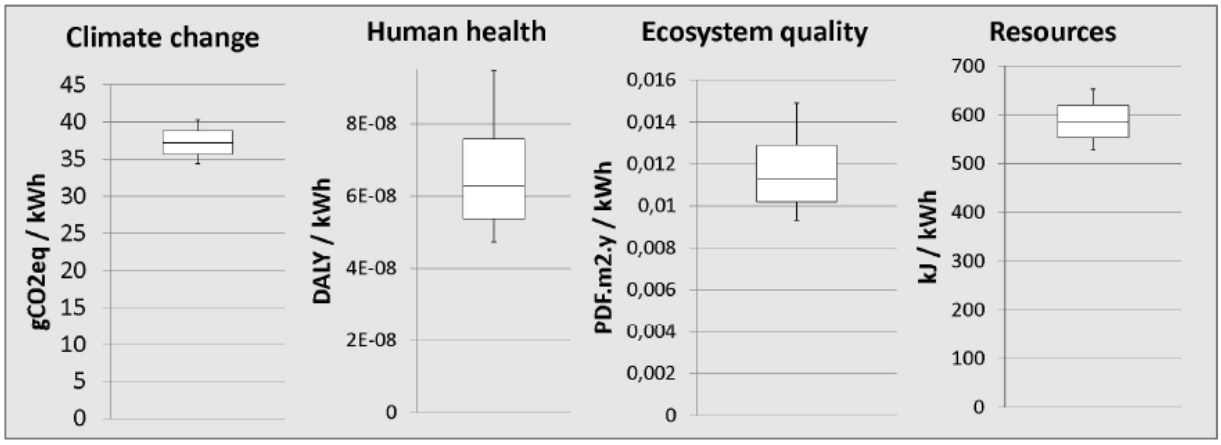


Figure 1.8 LCA results for the base case. Uncertainties calculated with Monte Carlo analysis. The central line indicates the median after 5000 simulations. Bottom and top of the box: 25th and 75th percentile. Whiskers: 10th and the 90th percentile.

Table 1.5 LCA results for the base case (median)

Damage category	Unit / kWh	Result (median)
Human health	DALY	6.78E-08
Ecosystem quality	PDF·m^2·y	1.17E-02
Climate change	gCO_2eq	36.7
Resources	kJ	579
Seismicity risk	very low	

Since there is a single production well (40 kg/s) and a double reinjection at low flow rate, the seismic risk is expected to be very low. The impacts on the Climate change are lower compared to some analogous results from literature (Frick et al. 2010, Huenges 2010): this is essentially due to our estimation regarding the quantity of diesel necessary for the drilling phase (4 GJ/m). The creation of the wells has the highest impact (see Fig. 1.7), covering a share of ~80% of the impact on climate change, human health and resources and ~60% of the effects on ecosystem quality. The latter is also considerably influenced by the construction of surface equipment, essentially because of the large amount of steel required for producing the ORC installations. The use of alternative power supply solutions in the drilling phase, such as connecting to the national grid, could produce relevant improvements in the environmental performance. However the use of diesel generator is still the most common solution. The use of electrical drilling in the LCA is discussed in the conclusive chapter of this manuscript.

Fig. 1.9 to 1.12 show the **most relevant processes** that are responsible for the impacts in the four categories The use of diesel generators in the drilling phase is by far the process with the highest impact on human health (Fig. 1.9) and climate change (Fig. 1.11). For ecosystem quality (Fig. 1.10), the environmental repercussions of blasting operations when extracting raw materials (especially iron for steel production) and disposing the drilling waste (during oil production) are also relevant. Onshore and offshore production of crude oil is the main cause for finite energy resources depletion (Fig. 1.12).

In the Annex 4, the **most influent substances** on the four categories are also presented. The results shows that the impacts on human health are principally caused by the emissions of NOx and particulates in the atmosphere (both related to the use of diesel generators). Ecosystem quality is also particularly influenced, beyond nitrogen oxides, by the pollutant effect of aluminum (dispersed in air during blasting operations and in soil when disposing drilling waste) and zinc (whose emissions are particularly related to the steel making process in the electric arc furnace). Impacts on climate change are mainly caused by carbon dioxide emissions. Depletion of non-renewable resources is essentially related to the consumption of oil, coal and gas to supply the energy demand of industrial processes. In Annex 4, we also discuss the results of a simulation carried out with a possible alternative modeling of the end of life of the wells as a long term emission in soil.

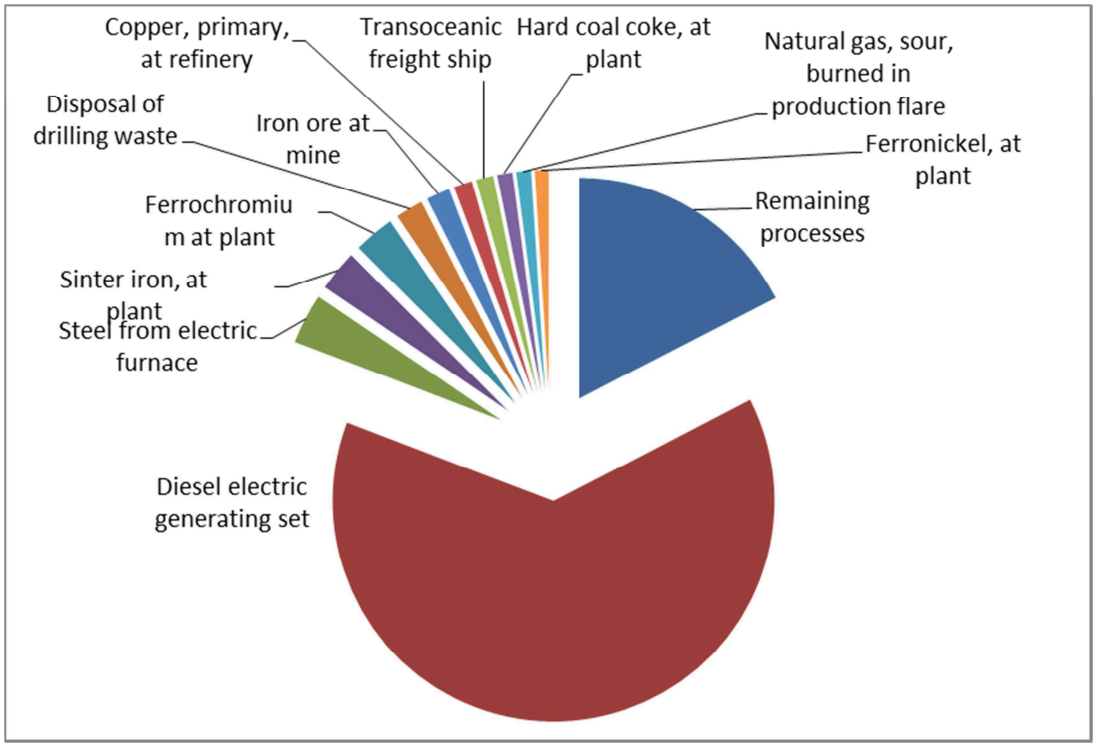


Figure 1.9 Processes responsible for the life cycle impacts on human health (base case)

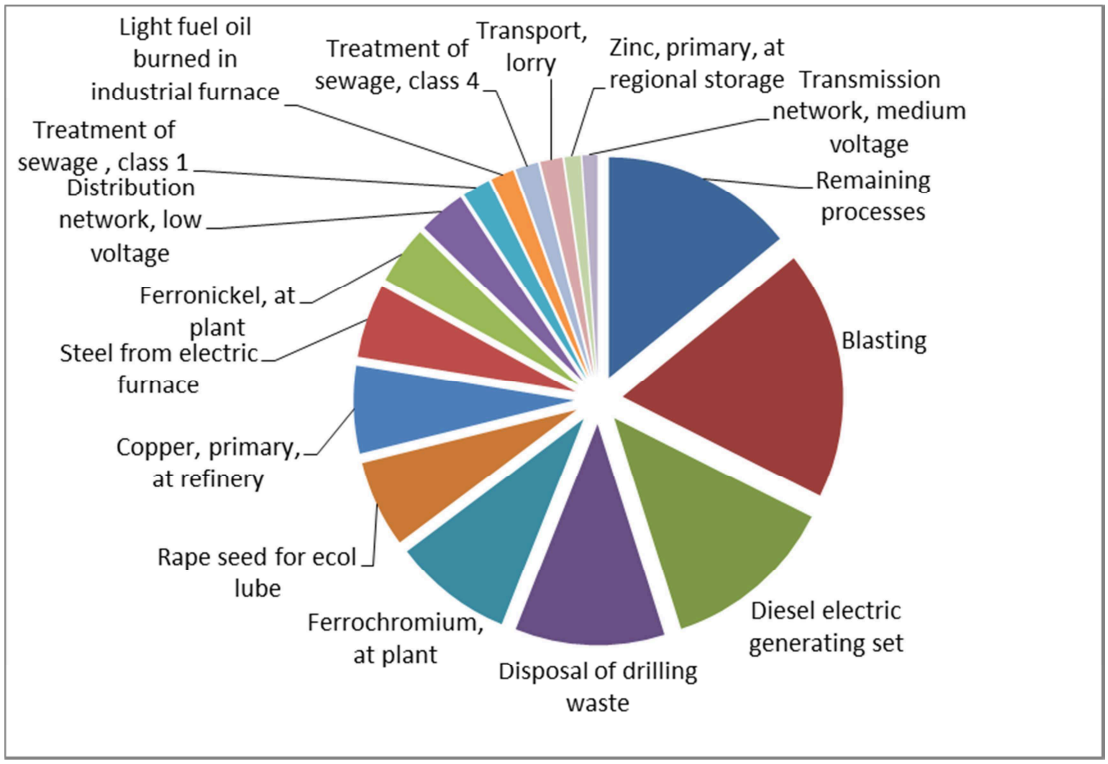


Figure 1. 10. Processes responsible for the life cycle impacts on ecosystem quality (base case)

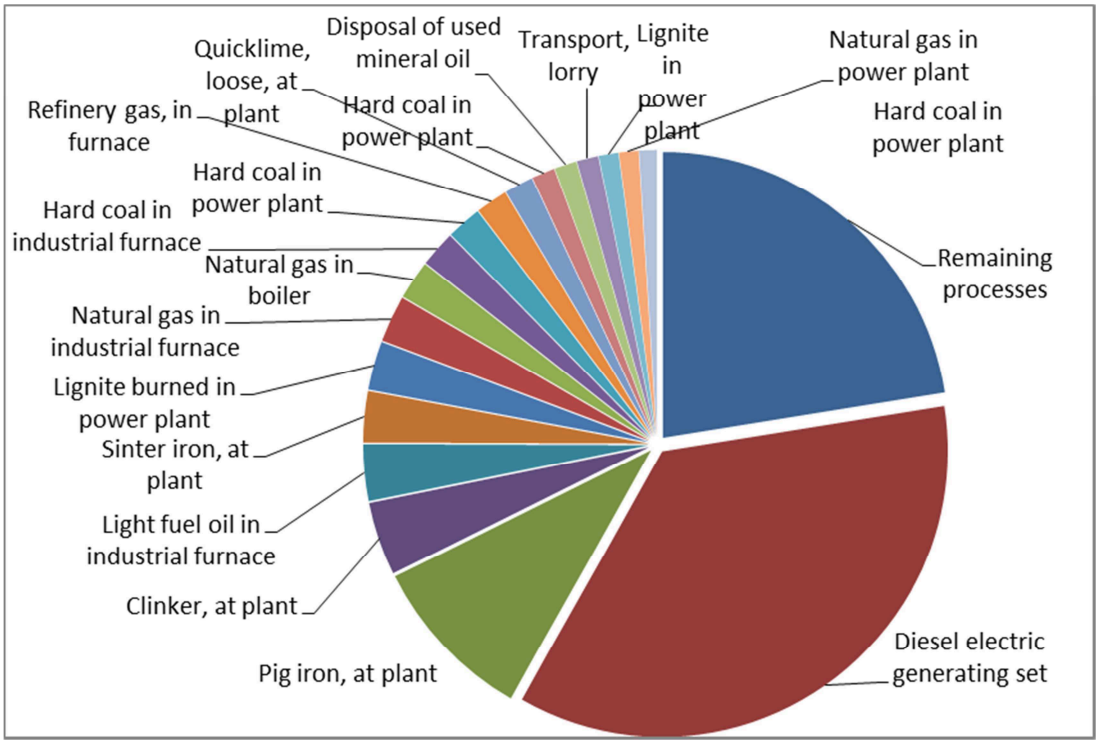


Figure 1.11 Processes responsible for the life cycle impacts on climate change (base case)

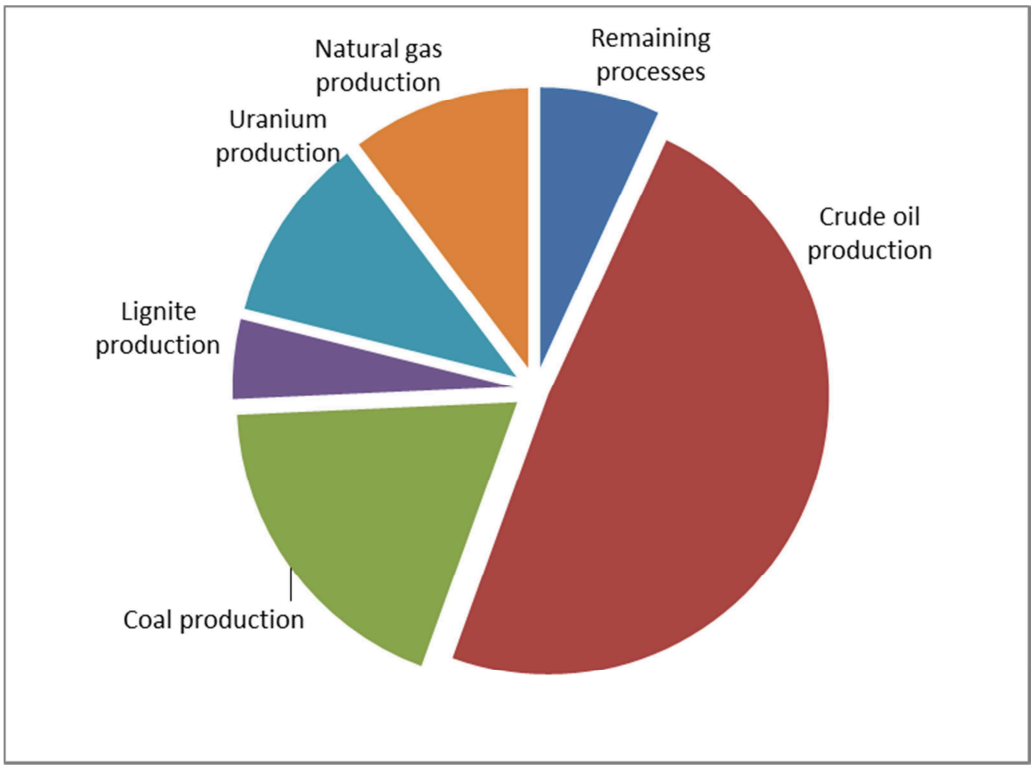


Figure 1.12 Processes responsible for the life cycle impacts on the depletion of resources (base case)

1.4.2 Comparing the ten case studies

Table 1.6 shows the LCA results of the ten case studies described. Impacts on the climate change are in the range of 16.9 – 49.8 gCO_2eq/kWh, while the impacts on resources varies between 272 and 785 kJ/kWh. Such results are comparable to those currently available in literature, as shown in Figure 1.13 and 1.14 (Frick et al. 2010, Sullivan et al. 2010, Treyer et al. 2015, Bauer et al. 2008, Huenges 2010, Pehnt 2006, Martin-Gamboa et al. 2015, Platt et al. 2012). Figures 1.15 and 1.16 respectively show the results on the human health and on the ecosystem quality: no comparison with literature is proposed, since none of the other authors has produced estimates for the latter two impact categories.

Table 1.6 LCA results for the ten scenarios

Damage category	Unit/ kWh	case 1	case 2	case 3	case 4	case 5	case 6	case 7	case 8	case 9	case 10
Human health	DALY	5.35 E-08	9.28 E-08	3.92 E-08	6.98 E-08	3.98 E-08	6.78 E-08	7.45 E-08	2.96 E-08	5.21 E-08	5.26 E-08
Ecosystem quality	PDF·m^2·y	1.02 E-02	1.65 E-02	8.82 E-03	1.39 E-02	7.53 E-03	1.17 E-02	1.29 E-02	6.78 E-03	1.05 E-02	1.07 E-02
Climate change	gCO_2eq	29.2	49.8	21.8	37.9	22	36.7	40.4	16.9	28.6	29.3
Resources	kJ	462	785	349	603	349	579	636	272	456	466

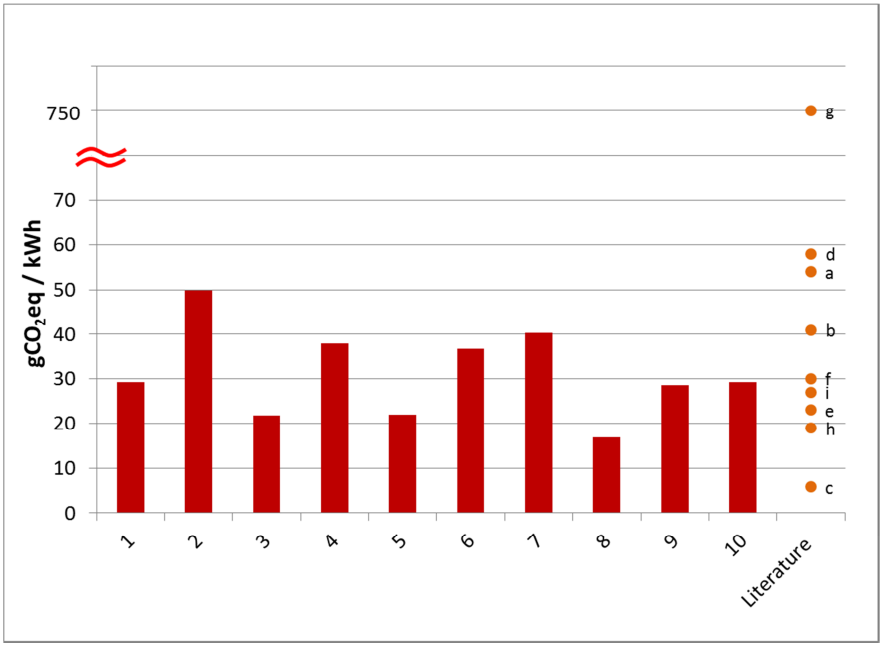


Figure 1.13 Results of the ten case studies (Climate change) compared with literature. a: Frick et al. (2010) site A1; b: Pehnt (2006); c: Martin-Gamboa et al. (2015); d: Huenges (2010) case 1; e: Platt et al. (2012); f: Treyer et al. (2015); g: Frick et al. (2010) case D1 (which is confirmed to be a "stand alone" estimate); h: Sullivan et al. (2010); i: Bauer et al. (2008)

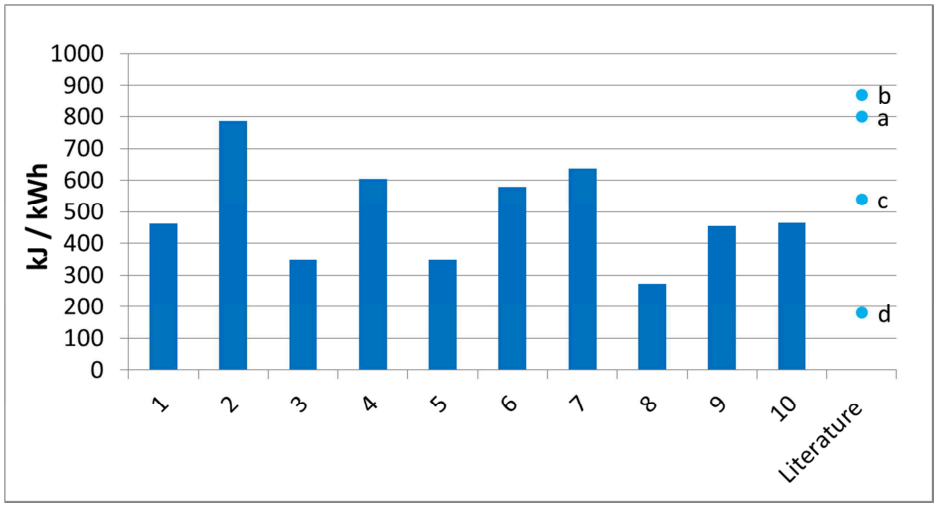


Figure 1.14 Results of the ten case studies (Resources) compared with literature. a: Frick et al. (2010) site A1; b: Huenges (2010) case 1; c: Pehnt (2006); d: Sullivan et al. 2010. Other publications do not present estimates related to this impact category

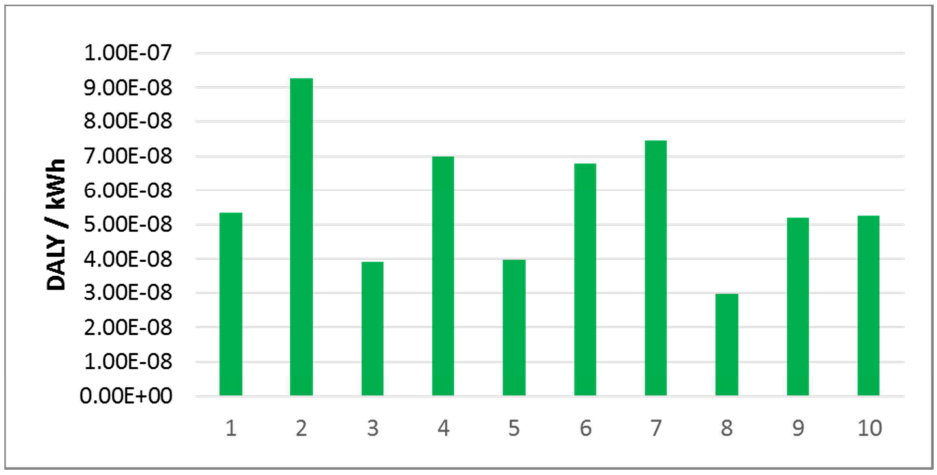


Figure 1.15 Results of the ten case studies (Human health)

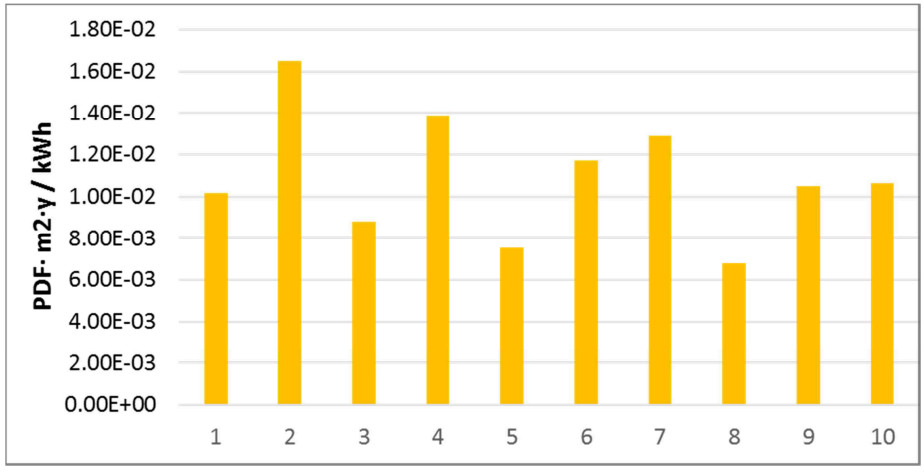


Figure 1.16 Results of the ten case studies (Ecosystem quality)

Fig. 1.17, 1.18 and 1.19 present a multi-criteria graphical comparison between the case studies. Case 6 is taken as reference (all values are set to 100%) while the others are expressed with values in lower or higher percentage depending on whether their environmental performances are better or worse than the case 6. The risk of induced seismicity is not expressible with a numerical value: to be coherent with the scale used in such radar representation, percentages of 100%, 125%, 150% and 175% are respectively associated to the empirical estimation of a very low, low, high and very high risk (see also Table 1.1). The radar representation used in Fig. 1.17, 1.18 and 1.19 is an example of tool for environmental design, issued form the LCA exercise: it allows a visual comparison between different scenarios, considering all the impact categories at the same time, as detailed hereafter. However, it is important to remind that the units of measure related to the five radial axis are different (DALY/kWh, gCO_2eq/kWh, kJ/kWh, etc.): therefore for instance achieving 125% in the Climate Change axis doesn't have the same physical meaning (nor the same importance) of achieving 125% on the Ecosystem quality axis (the grey grid is shown just for visual clarity). In other words, when using a radar representation we tend to implicitly give the same weight to each of the considered criteria. However, in the decision-making process, a different weight to each category may be taken into account.

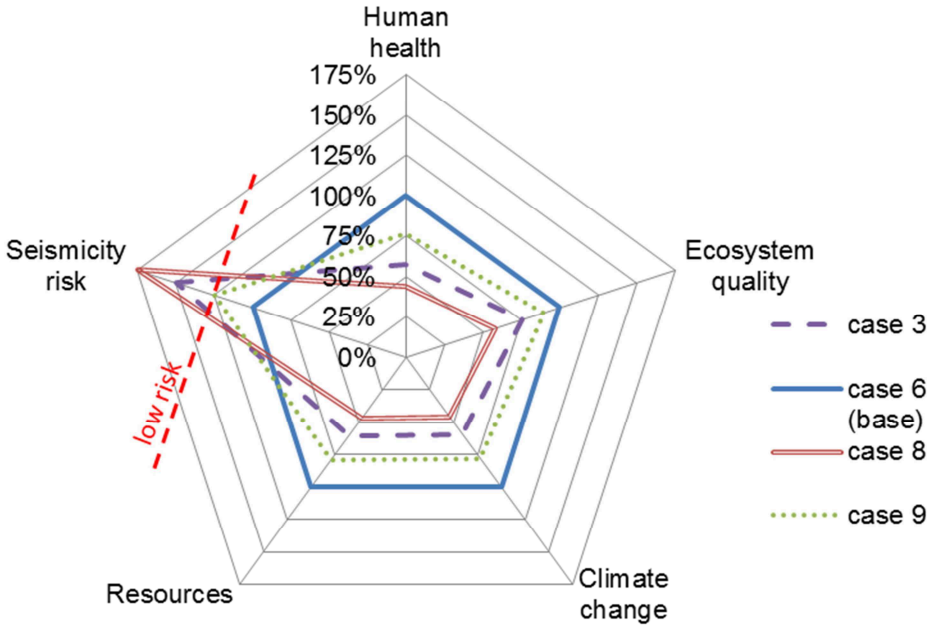


Figure 1.17 LCA results of case 3, 8, 9 (production of 70 kg/s from one well)

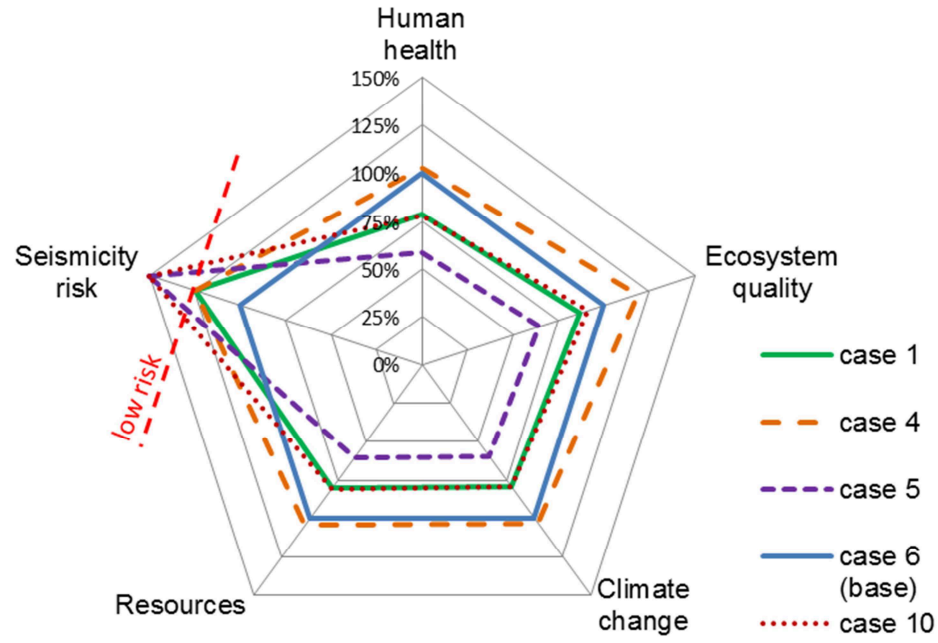


Figure 1.18 LCA results of case 1, 4, 5, 6 and 10 (production of 35-40 kg/s from one well)

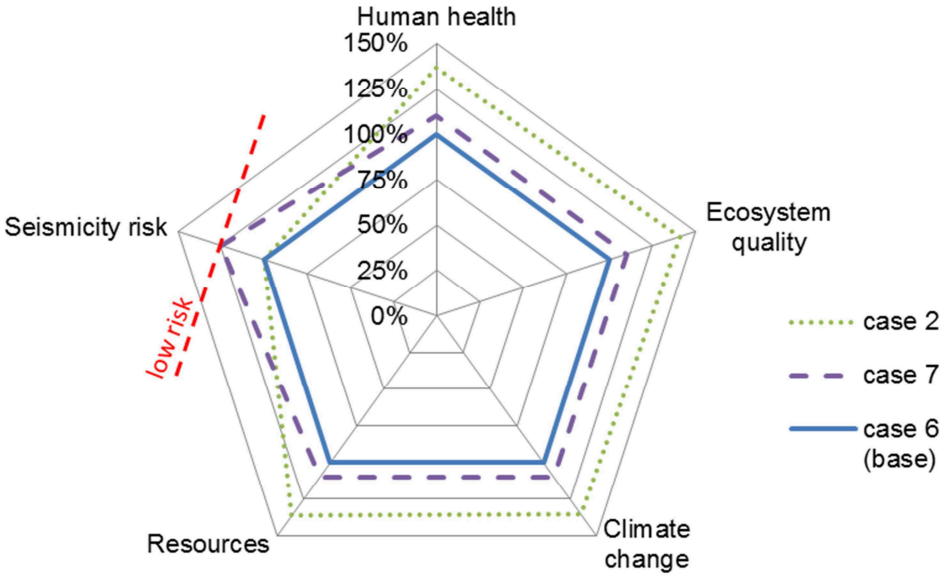


Figure 1.19 LCA results of case 2 and 7 (production of 20 kg/s from one well)

When targeting a reservoir that allows a production of **70 kg/s** from a single well, i.e. case 8 and 9 (both triplet) and case 3 (doublet), two strategies can be applied (Figure 1.17). To secure against a relevant risk of induced seismicity, the construction of a triplet is required, so that two boreholes can be used for reinjection (case 9): the environmental performance of this solution would also be satisfactory. On the contrary, when the seismic risk is neglected, production from two wells can be foreseen (case 8): this solution allows the highest annual

energy output (24.88 GWh) and the best performances in the human health, ecosystem quality, climate change and resource categories. However, based on current EGS operations, reinjection of flows as high as 140 kg/s will probably generate relevant seismic issues.

If the nominal production flow rate from one well reaches about **35-40 kg/s** (case 1, 4, 5, 6 and 10, Figure 1.18), the construction of a doublet (case 1 and 4) is more suitable than a triplet: case 5 and 10 (triplets) entail high seismicity risk, while case 1 and 4 shows higher impacts. Case 1 performs better than case 4 and its seismic risk is higher than in case 6, but still acceptable ("low risk").

The exploitation of a geothermal reservoir with very low production rate, such as **20 kg/s** (case 2 and 7, Figure 1.19) is globally not advisable. The construction of a doublet (case 2) limits too much the final power output (only 0.8 MW). Additional investment in a third well (case 7) leads to higher energy production (raising the obtainable power to 1.46 MW) but the environmental performance is not very satisfactory (worse than in the base case) in the four impact categories.

In general, we observe that the seismic risk increases together with the environmental benefits. Indeed, high flow rates lead to a significant energy production and low impacts, but tend to entail the reinjection of great quantities of geothermal water at high pressure, thus increasing the seismic risks. However, although maximizing electricity production can decrease the payback time on the investment in the plant, any suspension of the project due to unexpected high seismicity may have negative consequences on profitability. Considering seismicity as an unavoidable design parameter, and fixing the "low risk" level as the maximum acceptable (red dotted bar in the Figures), **case 1** (doublet at 4 km depth) **and 9** (triplet at 2.5 km depth) are identified as the most suitable scenarios, both presenting the lowest environmental impacts in the other four categories.

1.5 Conclusions on the LCA of EGS case studies

In this chapter we discussed the environmental performances of enhanced geothermal systems considering a number of different case studies reflecting several design options. The LCA proposed in this chapter presented the two following major innovations in the field of the environmental analysis of EGS:

- ✓ The elaboration of a **brand new dataset presenting the principal materials and energy flows occurring during the life cycle** of EGS plants (Table 1.4), based on a detailed survey on the site of Soultz-sous-Forêts. As discussed in the Introduction, very few dataset of this kind currently exist, and the available information are frequently characterized by high uncertainties. Thus this work provides a relevant contribution to the scientific community involved in the environmental modelling of EGS.

- ✓ The consideration of the **risk of induced seismicity** in the framework of an LCA, which has never been done before in literature. In our work, we highlight that the probability of a relevant induced seismicity increases with the environmental benefits, hence at design stage it is necessary to find the right compromise to limit both this risk and the other environmental impacts.

As announced in Section 1.1, the contents of this chapter have been published in the journal *Renewable Energy* (Lacirignola and Blanc, 2013) and presented in several international conferences (Lacirignola and Blanc 2012a, 2012b, 2012c). Our paper expands the list showed in Table I.2 and has been recently acknowledged in the review of LCAs proposed by Menberg et al. (2016) as one of the most relevant and detailed article in the field of LCA of EGS.

The analysis of the ten scenarios contributes to the understanding of the environmental performances of EGS. It also allows formulating the following observations:

- Of course the proposed case studies do not encompass the **heterogeneity of all possible configurations within the EGS sector**. The estimations of the impacts on climate change for our scenarios varies from a minimum of 16.9 gCO_2eq/kWh to a maximum of 49.8 gCO_2eq/kWh: when considering other configurations (EGS with

deeper boreholes, or higher installed capacity, or lower flow rate, etc.), better or worst environmental performances may be found, as highlighted in the literature review proposed in Figure I.5. We also observe that the impacts can change considerably depending on both the reservoir conditions and the design of the plant: for example, GHG emissions in case 8 are about three times lower than those in case 2. Considering only the results of this chapter (or, in general, of a multi-scenario LCA) it is not possible to have a global overview of the environmental suitability of the EGS sector and compare it with other energy technologies.

- This chapter showed how long and **complex** is the application of the LCA methodology. Especially the phase of inventory analysis (section 1.3.2) required a relevant effort for collecting the necessary data. Thus the production of LCA results for new configurations require an expert user, able to handle the methodology and the large amount of information involved.

Based on the achievements of the present chapter, the two points above will be addressed in the rest of the manuscript through the development of parameterized models able to investigate the global environmental performances of the EGS technology as well as those of new specific configurations.

Chapter 2
Set up of a parameterized LCA model representative of the EGS sector

2.1 Objective of this chapter and methodology

The objective of this second part of our research is to develop a **parameterized LCA model**, able to estimate the life cycle impacts of a large panel of different EGS configurations, **representative of the EGS sector** in central Europe. We aim generating the "environmental profile" of EGS, thus addressing the research question **[a]** (p. 72).

Chapter 1 prepared the ground for these developments. In particular, the set-up of a new dataset of the mass and energy flows (table 1.4, whose consistency has been highlighted in section 1.4 and Annex 2) and the identification of the most impacting processes (e.g. the energy supply for drilling), constitute essential bricks for the development of such parameterized calculation model. The scientific approach detailed in this chapter is based on the protocol for the set-up of parameterized LCAs, called "simplified models", presented by Padey et al. (2013) with an application to the wind electricity pathway. As discussed in the Introduction (section I.4), such simplified models constitutes an intermediate solution between the tools for the analysis of specific system configurations (like the detailed LCA) and the tools for the characterization of the whole technological sector (like the meta-LCA). The methodology to elaborate a parameterized calculation model, called "***Reference model***", for the estimation of the life cycle impacts of a large panel of EGS power plants is based on the following steps:

1. Definition of the aim and scope of the parameterized model (section 2.2)
2. Design of the *Reference model* (section 2.3). This phase includes:
    a. The 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 this study, nine parameters have been identified.
    b. The description of the variability of the parameters, reflecting the heterogeneity of system configurations within the EGS sector (according to the scope of the model): an interval of variation is established for each parameter, as well as a probability distribution associated to the values within the interval.
    c. The compilation of all inputs and outputs (e.g. material, energy flows) related to the construction phase, the operation and the dismantling of an EGS power

plant. This takes the form of several datasets, 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 power plants).

The life cycle inventory of each power plant of our sample is obtained by scaling the input/output datasets with the nine parameters. These parameters also allow for the calculation of the life cycle electricity production.

3. Generation of the "environmental profile": the use of a Monte Carlo method allows the calculation of the life cycle impacts of a large sample of configurations, randomly generated according to the described variability of the parameters (section 2.4).
4. Validation of the environmental profile through comparison with results from literature (section 2.5)

In this chapter, we tackle the development of a parameterized model for the EGS sector by focusing our analysis on the "**climate change**" impact category (**gCO_2-equivalent**). As discussed in the Introduction, we will also refer to the gCO_2eq results as *GHG emissions* (and also *GHG performances* or *GHG impacts*). This choice is driven by the great interest of scientific community on this indicator, since the climate change effects generated by the GHG emissions are at the center of the environmental debate. It also allows a more consistent comparison with literature, since this impact category is used by all the other available LCAs. However, the methodology detailed in this chapter can be also applied to other impact categories as well. Therefore in this manuscript we focus on the set-up of the methodological framework, without detailing its application to all the possible impact categories.

The methodology, the content and the results of this chapter have been published in the following paper:

> Lacirignola, M., Hage Meany, B., Padey, P., Blanc, I. A simplified model for the estimation of life-cycle greenhouse gases emissions of enhanced geothermal systems. *Geothermal energy*, 2014, 2, 8. doi:0.1186/s40517-014-0008-y.

They also have been presented with a technical paper and an oral presentation in occasion of the World Geothermal Congress 2015 in Melbourne (Australia):

> Lacirignola, M., Hage-Meany, B., Blanc, I. Elaboration and discussion of simplified parameterized models for carbon footprint of enhanced geothermal systems. In: *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015.*

2.2 Definition of the aim and scope of the model

The objective of this model, called in this manuscript "*Reference model*", is to evaluate the life-cycle impacts of EGS power plants and the functional unit is the net energy produced over the lifetime. As discussed in the previous section, in this chapter we will focus on the impacts on the climate change, therefore the results of the *Reference model* will be expressed in grams of CO_2 equivalent per electrical kWh delivered to the grid. EGS power plants, being binary systems, basically do not generate direct emissions during operation unlike their hydrothermal flash and dry steam counterparts (Bayer et al. 2013). Life-cycle emissions are principally caused by the construction phase, and in the rest of the lifetime they are also related to the infrastructure (e.g. transport of new equipment for replacement, disposal of filter residues and scaling). The EGS power plants within the scope of our analysis are characterized as follows:

Technological characterization: the systems considered have 2 or 3 wells reaching a depth of 2 to 6 km and are equipped at the surface with an organic Rankine cycle (ORC). The plants produce only electricity (no cogeneration). The reservoir enhancement techniques taken into account are hydraulic and chemical stimulation.

Geographical characterization: the study focuses on EGS plants installed in central Europe.

Temporal characterization: the study takes into account current technologies (2016) for all equipment. Currently, EGS project developers in the Rhine Graben focus on depths of about 3 km, since one of the lessons learned from Soultz's pilot is that very high drilling depths (5-6 km) are not economically optimal today (Genter et al. 2010). However, this study takes into account the possibility of drilling up to 6 km, since this may became more economically viable in the near future thanks to the progress in the exploration and drilling techniques.

Methodological characterization: the Life-Cycle Inventory (LCI), namely the compilation of all inputs and outputs (e.g. materials, emissions) related to the processes occurring in the life-cycle of an EGS plant, is based on the one presented in

chapter 1 and published in Lacirignola and Blanc (2013). Data regarding background processes, such as raw material extraction or transports are retrieved from the ecoinvent database v2.2 (ecoinvent centre 2010). The characterization factors defined by the IPCC 2013 method (IPCC 2013) are used to calculate the results in terms of gCO_2-equivalent.

It is important to note that in the rest of this manuscript, when we mention the **"EGS sector"**, we refer precisely to the characterization detailed above, which encompasses the *EGS plants located in central Europe, characterized by two or three wells, producing only electricity, etc.*

2.3 Design of the reference parameterized model

To be representative of the EGS sector (as defined in the previous section), the *Reference model* must account for a very large panel of possible EGS configurations. The environmental performances of each EGS power plant of our sample are calculated as:

$$GHG\ performances\ of\ EGS = \frac{Life\ cycle\ GHG\ emissions\ [gCO_2eq]}{Life\ cycle\ electricity\ production\ [kWh]} \quad (2.1)$$

The numerator represents the total amount of GHG emissions expressed in equivalent mass of CO_2 emitted by all processes related to the life cycle of the plant. Those are calculated from the GHG of an explicit life cycle inventory (LCI) using the IPCC characterization factors (IPCC 2013). These characterization factors are used to quantitatively convert each GHG according to their respective Global Warming Potential related to CO_2, the reference gas. Further details about such calculation process can be found in Heijungs (1996) or in the ILCD Handbook (ILCD 2010).

The denominator is the amount of electricity delivered to the grid over the lifetime, calculated as:

$$Life\ cycle\ electricity\ production = P_{NET} \cdot LF \cdot 8760 \cdot LT \quad (2.2)$$

Where P_{NET} is the final power output of the EGS plant. As discussed in chapter 1, P_{NET} is the difference between the ORC power output P_{ORC} (namely the power output of the electric generator minus the power absorbed by the other ORC equipment, like the air cooler) and P_{pumps} (the power demand of the pumps for the production and the reinjection of the geothermal fluid). LF is the load factor (a fraction ranging from 0 to 1 expressing the amount of equivalent operating hours at nominal power in one year), 8760 is the total amount of hours of one year and LT is the lifetime of the plant.

Our *Reference model* to generate a large sample of possible EGS power plants is based on nine parameters: produced flow rate, drilling depth, number of wells, fuel consumption for drilling, load factor, power demand of the pumps, enhancement's intensity, lifetime and ORC power output.

These nine parameters are described in section 2.3.2 and reported in Table 2.1. We identified them as sufficient to calculate the GHG performances according to Equation 2.1: they allow for the characterization of the size of the plant, of the inventory of materials involved and of the amount of electricity produced over the life cycle. They are also identified as parameters whose variation induces high variability in the resulting environmental impacts (Frick et al. 2010). The number of parameters and the complexity of the model are set by the modeler, see also section 4.2.3. For instance we could have included, as an additional input parameter, the choice of the set of characterization factors (CFs). This is done by Padey (2013) in his parameterized models for the wind and photovoltaic sectors : he takes into account the IPCC characterization factors related to three time horizons (20, 100 and 500 years) and two different IPCC sources (published in 2001 and 2007). However, in both models, he found out that the choice of the set of CFs doesn't induce high variability on the impact results. Therefore, we considered only one set of CFs (IPCC 2013, time horizon 100 years).

The nine parameters are set as mathematically independent: this is a necessary condition for the application of the Global Sensitivity Analysis (GSA), which will be performed in the next chapter to identify those that are responsible for most of the variability of the GHG performances (see also the discussion in section 2.3.2).

2.3.1. Generation of modular datasets of the mass and energy flows

Our *Reference model* is represented in Figure 2.1. The life cycle inventory is modular and disaggregated into four LCIs (black boxes): the LCI of the wells, the LCI of the organic Rankine cycle, the LCI of the pumps of the geothermal loop and the LCI of the enhancement campaign. They are based on a scaling approach from the EGS data regarding the materials and processes (grey boxes) presented in Chapter 1 (table 1.4), data from literature and discussion with experts. For instance, for the ORC we follow the assumption of a linear relation between the amount of material needed and the power installed, as in Frick et al. (2010). Although in some cases the relation between the size of a plant's component and the amount of its materials is not linear, such scaling approach simplifies the process of compiling LCIs for a large sample of scenarios. All these data are reported in Annex 5.

The computational code of the *Reference model* has been developed with the software *R* and the ecoinvent (v2.2) background data have been extracted through *Simapro* v7.2.4.

The LCI of the wells covers the information regarding the drilling process (i.e. fuel consumption, mud circulation), the casing and the cementation.

The LCI of the ORC includes data regarding the electric generator, the ORC turbine, the circulation pump, the air-cooler, the filters, the pipes and the other surface elements as described in chapter 1.

The values of the LCI of the pumps are assumed to be proportional to the flow rate circulating in the geothermal loop. Each well is equipped with either a production or a reinjection pump.

The LCI for the enhancement process includes data concerning the quantity of water, salt and hydrochloric acid for the hydraulic and chemical stimulation, necessary to improve the boreholes' productivity.

The nine parameters (green boxes) are used to scale-up such the datasets (grey boxes) and to calculate the life cycle electricity production (yellow box). Data from ecoinvent regarding background processes are also represented in white-red. The emissions of the different greenhouse gases related to each part of the model are then aggregated through the IPCC characterization factors to obtain the estimates in gCO_2eq (blue boxes). The impact on the climate change (orange box, gCO_2eq/kWh) is then calculated.

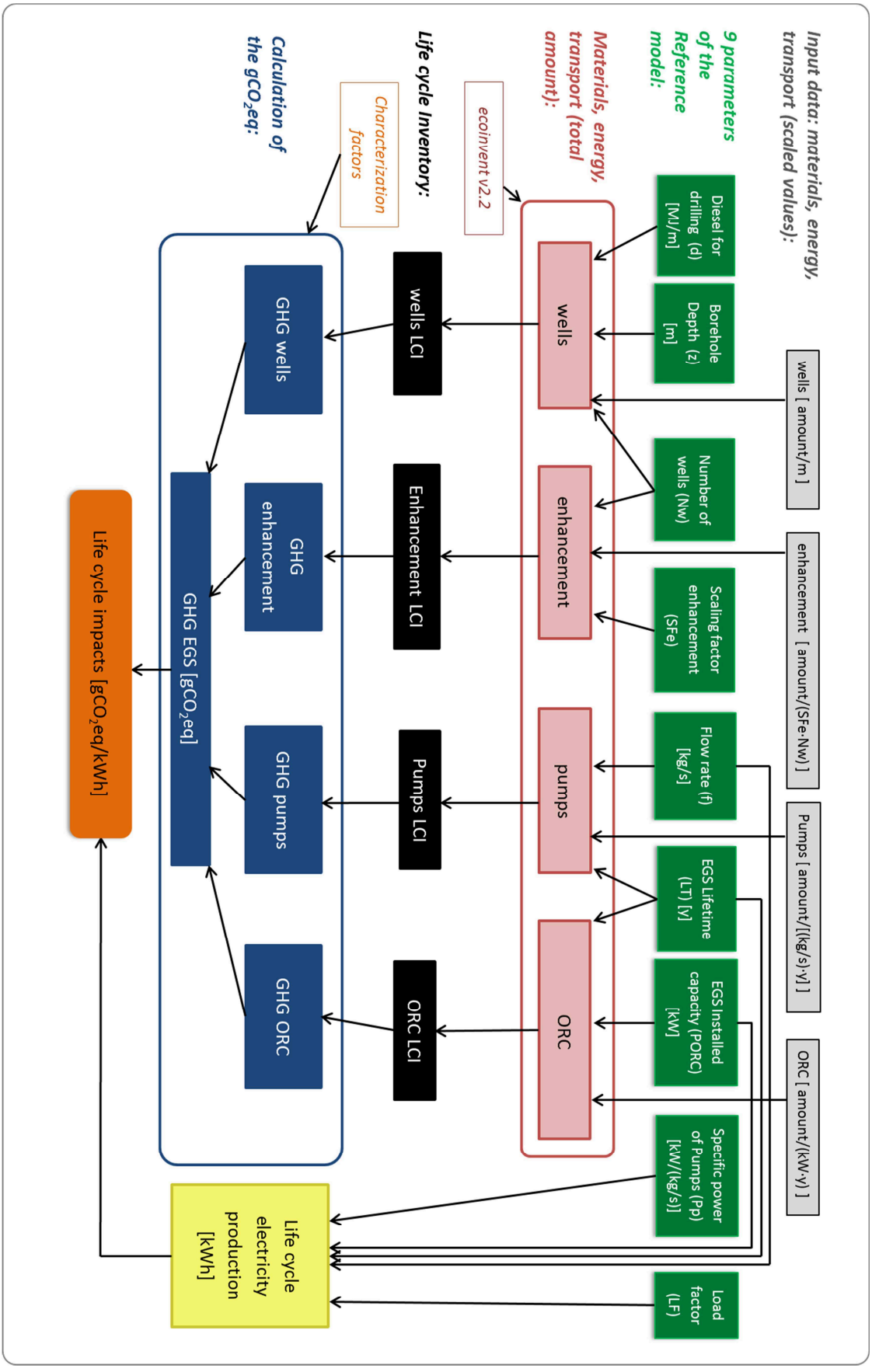


Figure 2.1 Schema of the *Reference model*

2.3.2 Parameters description

The large sample of possible EGS scenarios corresponds to random sets of the nine parameters. Each of them can assume a value within a fixed range and according to a probability distribution that we defined, as presented in Table 2.1. Value ranges and probability distributions have been established based on technical survey, literature review and discussion with experts and reflect the current technical knowledge on EGS.

Table 2.1 Nine parameters of the *Reference model* and description of their variability

Symbol	Parameter	Value range	Unit	Probability distribution in the value range	Main references
z	Borehole depth	2000 – 6000	m	Uniform	Current EGS projects[1], Genter et al. (2010, 2016), Frick et al. (2010), Bauer et al. (2008)
f	Produced flow rate	25 – 100	kg/s	Uniform	Current EGS projects, Frick et al. (2010)
Nw	Number of wells	2 – 3	adimensional	Uniform	Current EGS projects, Huenges (2010), Bauer et al. (2008), Schmidt et al. (2010)
d	Fuel for drilling	3000 – 7000	MJ/m	Uniform	Drilling reports from Soultz-sous-Forêts, Bauer et al. (2008), Frick et al. (2010)
LF	Load factor	0.85 – 0.95	adimensional	Uniform	Lund (2003), Huenges (2010), Platt et al. (2012)
LT	Lifetime	20 – 40	years	Gaussian 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), Baujard et al. (2017)
P_p	Specific power of pumps	3.6 – 8.6	kW/(kg/s)	Uniform	Frick et al. (2010), Lacirignola and Blanc (2013), Graff and Baujard (2013)
P_{ORC}	Installed capacity of the ORC	1250 – 3500	kW	Uniform	Current EGS projects, Huenges (2010), Bauer et al. (2008)

[1] Refer to the Introduction of the manuscript and to Breede et al. (2013)

Drilling depth. It depends on the geology and on techno-economic factors, given the high costs related to the construction of wells. A values range of 2-6 km is set, based on literature and current projects (see also sections I.2 and 1.2.1).

Flow rate. It depends on the geological conditions as well as on the success of the drilling and stimulation phases. A reasonable range of values (25-100 kg/s) is assumed for this parameter in accordance with current EGS experiences. Since the characteristics of the geothermal resource are extremely site dependent, a uniform probability distribution is established within the boundaries of the flow rate and the drilling depth (values are considered equiprobable).

Number of wells. Current EGS applications in Europe rely on a limited number of wells (two or three), because of the high construction costs. In addition, the seismicity risk related to the reinjection of high flow rates is emerging as a key factor for the design of the plant as discussed in chapter 1, especially after the relevant seismic events in Basel and Landau (Weimer et al. 2015, Groos et al. 2013). The link between the circulation strategy (number of wells used for the reinjection) and the seismicity risk has been discussed in the previous chapter. Given that the underground architecture depends on technical and economic site-dependent factors, two equiprobable values are considered (2 or 3 wells). It is assumed that, for the three wells scenarios, the most appropriate reinjection strategy is put in place (i.e. the use of two boreholes for reinjection to minimize the risk of induced seismicity in case of high produced flow rate).

Fuel for drilling. In chapter 1, we showed that the construction of the wells is the most impacting process over the lifetime of an EGS. This is essentially due to the large quantity of fuel burnt in stand-alone electric generators during the drilling process. Being a critical factor for the environmental performances, and given the different figures proposed in literature, a large variability (3 000 to 7 000 MJ per meter drilled) of this site-dependent parameter is considered, allocating the same probability among the values of this interval. This is based on literature and data from Soultz-sous-Forêts.

Load factor. The load factor is assumed to be 85-95% (7 446 to 8 322 equivalent full-load hours per year) based on literature review. According to Lund (2003) geothermal

plants have a load factor frequently above 90%. Huenges (2010) and Platt et al. (2012) assume 7500 hours per year in their studies.

Lifetime. To date, no commercial EGS in Europe is at the end of its design lifetime, nor has been dismantled. In several case studies from literature (Bayer et al. 2013; Platt et al. 2012; Bauer et al. 2008) 30 years is assumed. The minimum value is set to 20 years as proposed by Huenges (2010) and used in some scenarios by Frick et al. (2010). The maximum value found in literature is to 40 years. Based on these information, a Gaussian probability distribution centered on 30 years (standard deviation of 3.25) is applied to characterize the variability of the lifetime.

Scaling factor for the enhancement phase. The stimulation of the reservoir is a critical phase for the success of an EGS project. Since this phase is extremely site dependent, a set of values for a "base case" stimulation is defined based on current EGS experiences. Then, in order to take into account different scenarios (e.g. necessity of a strong enhancement campaign to improve the boreholes' productivity), these values are multiplied by a scaling factor (SFe) ranging from 0.5 to 10. The base case stimulation accounts for 1000 m^3 of water, 15 t of salt and 100 m^3 of a 30% solution of hydrochloric acid. In order to allocate a higher probability to the base case, we use a lognormal distribution (σ=1, μ=0) with a peak on SFe=1 and a median value of SFe=1.7.

Specific power of the pumps. As previously discussed, the estimate of the power demand of the pump of the geothermal loop is necessary to calculate P_{NET}. Such consumption is assumed to increase linearly with the flow rate. It is also assumed that all the pumps (for production and reinjection) are characterized by the same power to flow rate ratio. Following discussions with experts (Graff and Baujard 2013) and literature survey (Frick et al. 2010; Huenges 2010), the required power for the circulation in the geothermal loop is assumed to be 3.6 to 8.6 kW/(kg/s) (all values are equiprobable).

Installed capacity of the ORC. With this parameter P_{ORC} we indicate the power output of the ORC, namely the gross power generated by the turbine (P_{gross}) minus the demand of the auxiliary equipment of the organic Rankine cycle (aircooler, circulation pump, etc). The variability range of P_{ORC} is set to 1 250 – 3 500 kW (corresponding to

about 1.5 to 4.4 MW of gross output of the turbine) according to the literature and current EGS projects.

In our model, the nine parameters are defined as mathematically independent. This means that, for instance, even though the power output of the ORC (P_{ORC}) is physically related to the geothermal flow rate, no mathematical relation between these two parameters is introduced in our sampling process. The installed power capacity P_{ORC} depends on many factors including also the temperature of the geothermal fluid and its heat capacity, the number of production well, the thermal efficiency of the surface cycle, the reinjection temperature and the power absorbed by the auxiliary equipment. The production temperature is also a dependent variable, since it increases with the drilling depth. However, our model aims at being generic and it is difficult to define a generic relation between temperature and depth widely valid in central Europe: for instance even the temperature profiles of Soultz-sous-Forêts and Landau are different, although the distance between these two sites is only 40 km. The heat capacity depends on the chemical properties of the fluid as well as its temperature (which is somehow a dependent variable as explained above). The flow rate also depends somehow on the depth, according to recent EGS experiences: targeting the tight granite fractures at more than 4000 m in Soultz led to a lower production of geothermal flow, while a higher production rate was achieved in Rittershoffen by drilling at a lower depth and reaching geological layers characterized by the natural thermal convection. Therefore, at a given depth, the characteristics of the targeted geological formation play an important role in the resulting flow rate. The number of production wells depends on the flow rate that is achieved as well as economic considerations; the objective is to minimize their amount because of the high construction costs. The number of reinjection wells also depends on the flow rate, considering the risk of induced seismicity related to it (as discussed in chapter 1). Again, these empirical observations are not sufficient to establish a consistent mathematical relation between the flow rate and the number of production and reinjection boreholes. Thus for the *Reference model*, we preferred to use the total number of wells (two or three) and to assume that, when three wells are available, the most appropriate reinjection strategy is put in place (use of two wells for reinjection rather than one in order to minimize the risk of induced seismicity in case of high produced flow rate).

In conclusion, the installed capacity P_{ORC} depends on several parameters that are interrelated to each other and also depend on depth, geological conditions, and other aspects. However, it

is difficult to generalize all the correlations among all those elements with simple equations widely valid in central Europe. Moreover, as a general observation, by increasing the number of considered parameters as well as their interrelations, more sources of uncertainty are introduced and the calculation process may lose effectiveness. In this context, we made the choice of using P_{ORC} as one of the independent parameters of the model, responding to a trade-off between accuracy and simplification. P_{ORC} intrinsically incorporates the combinations of all the factors mentioned above. In addition, it has an industrial relevance and is an easy accessible variable: ORC suppliers usually refer to their equipment in terms of the power output of the system. The consequences of this choice (namely on the generation of random scenarios) are discussed later in section 2.5.

One possible solution to characterize the relation between interrelated parameters like the flow rate and the drilling depth is presented in section 4.2.3.3 and is proposed for future studies. It consists in establishing a function based on random sampling within restricted intervals (instead of a too site-specific mathematical function). For instance in this case, for a given depth, the calculation model would randomly sample a value of flow rate within a pre-defined restricted range (whose boundaries varies with depth, see Figure 4.4). This possibility is investigated and discussed in the Conclusion chapter, where a number of propositions are formulated for improving our calculation model.

2.3.3. *Reference model*'s formula

The *Reference model*'s formula (2.3) is obtained by developing analytically Equation 2.1, following the scheme presented in Figure 2.1.

The numerator of Equation 2.1 (GHG emissions of the EGS power plant) can be expressed as the sum of the contribution of the four parts of the model: wells, ORC, pumps and enhancement phase. Such GHG emissions are calculated from data regarding the materials and energy flows (section 2.3.1) and the IPCC GHG characterization factors. The denominator of Equation 2.1 (electricity produced) can be expressed by Equation 2.2. Hence we obtain Equation 2.3:

$$GHG_{EGS_Ref} = \frac{z \cdot Nw \cdot (\alpha_1 + \alpha_2 \cdot d) + LT \cdot f \cdot \alpha_3 + P_{ORC} \cdot LT \cdot \alpha_4 + Nw \cdot SFe \cdot \alpha_5}{LT \cdot LF \cdot (P_{ORC} - f \cdot P_p) \cdot 8760} \quad (2.3)$$

With $\alpha_1 = 498\,761.36\ [gCO_2eq/m]$; $\alpha_2 = 90.56[gCO_2eq/(MJ \cdot m)]$;

$\alpha_3 = 487\,363.03\ [gCO_2eq \cdot s/(kg \cdot y)]$;

$\alpha_4 = 50\,603.13[gCO_2eq/(kW \cdot y)]$; $\alpha_5 = 25\,757\,089.05[gCO_2eq]$;

In this formula, ***z*** is the borehole depth (meters), ***f*** is the total produced flow rate (kg/s), ***Nw*** is the number of wells, ***d*** represents the amount of fuel for drilling (MJ per meter drilled), ***LF*** is the load factor (dimensionless), ***LT*** is the lifetime (years), ***SFe*** is the enhancement factor (dimensionless), $\boldsymbol{P_{ORC}}$ is the installed capacity of the ORC (kW), $\boldsymbol{P_p}$ is the specific power of the pumps (kW/(kg/s)).

The $\boldsymbol{\alpha_i}$ coefficients correspond to the values of the GHG emissions of each part of the model and are a function of the different inventory data and the characterization factors. For the wells, $\boldsymbol{\alpha_2}$ is related to diesel consumption and $\boldsymbol{\alpha_1}$ is related to all the other drilling processes (e.g. casing, cementation, mud circulation).

Given such parametric representation (expressed by Equation 2.3 and shown in Figure 2.1), the definition of a vector containing a specific value for each one of the nine parameters (e.g.: number of wells = 2, total produced flow rate = 50 kg/s, lifetime = 30 years, and so on) leads to the generation of a new LCI. Each new set of nine parameters corresponds to a different EGS scenario. Hence, the GHG performances can be calculated for a large panel of case studies, accounting for many possible combinations of values of the nine parameters.

2.4 Generation of the environmental profile

The parameterized formula of the *Reference model* (Equation 2.3) allows a very rapid calculation of the life cycle GHG emissions of EGS, without undertaking the long and complex LCA procedure. The user has just to allocate a value for each of the nine inputs to obtain an estimate of the impacts in terms of gCO_2eq/kWh.

Based on the *Reference model* formula and on the description of the variability of the nine parameters (Table 2.1), we perform a Monte Carlo calculation to generate 500 000 random EGS scenarios and estimate their related life cycle GHG emissions. The result is presented in Figure 2.2. The top and bottom of the box represent the 25th and the 75th percentile, while the middle line is the median (around 30 gCO_2eq/kWh) of the set of GHG estimates. The whiskers indicate the 5th and the 95th percentile.

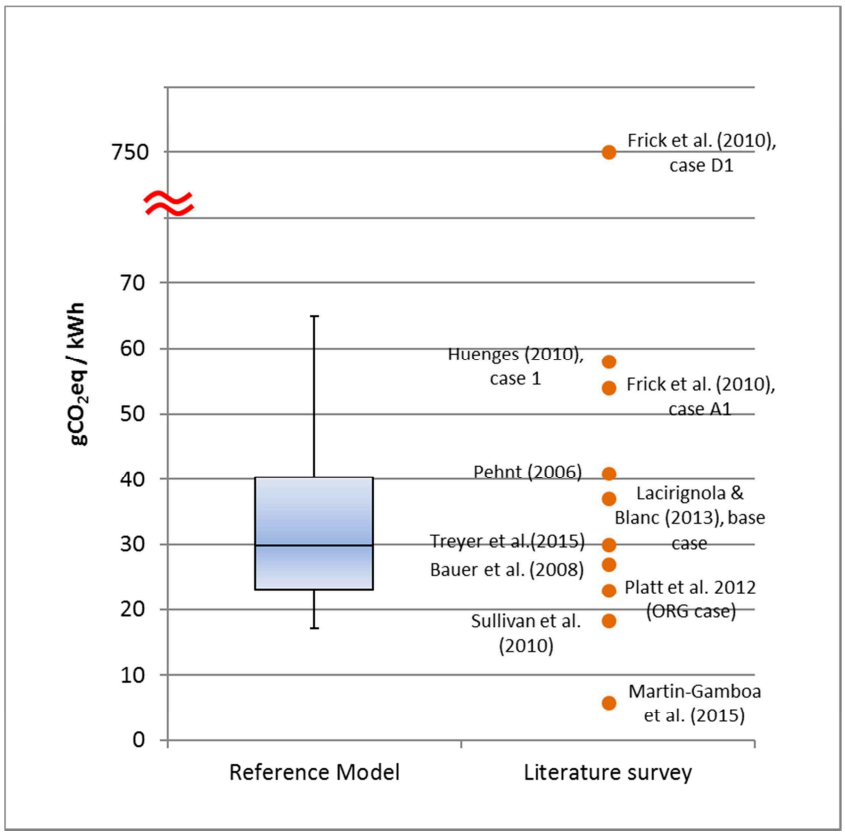


Figure 2.2 Environmental profile compared with results of detailed LCAs from literature

The use of the Monte Carlo technique allows us to generate an "**environmental profile**" that is as much representative as possible of the EGS sector in central Europe. Indeed the random sampling process takes into account the variability intervals and the probability distributions previously defined for the nine input parameters (Table 2.1), thus reflecting the heterogeneity of possible configurations for an EGS in central Europe (considering the existing installations and the future operations that could be developed).

2.5 Discussion and validation of the model

The *Reference model* is to be validated through comparison with results from literature. Since it aims at being representative of the EGS sectors, the purpose of this phase is to see if our environmental profile encompasses the estimations proposed by the case studies analyzed by other authors and if eventual discrepancies can be properly justified.

Figure 2.2 shows such comparison. We observe that globally the order of magnitude of the results is the same. Among the selected case studies, the estimate proposed by Martin-Gamboa et al. (2015) is quite lower (6 gCO_2eq/kWh) than the interval of emissions covered by our boxplot: this is principally due by the fact that it corresponds to an EGS with a borehole depth of only ~0.7 km. Martin-Gamboa et al. propose a hypothetical Spanish EGS scenario where 150 °C are achieved at a very shallow depth, while our *Reference model* is designed to be representative for central European conditions. Therefore such scenario is out of the scope of our parameterized model, which considers drilling depths (parameter z) ranging from 2 to 6 km. Also the scenario "D1" proposed by Frick et al. (2010), presenting abnormally high emissions (750 gCO_2eq/kWh), is outside our scope. Such case study correspond to a "worst case scenario", where the geothermal production achieved at a very high depth (5 km) is only 27 kg/s with a temperature as low as 110 °C: in such unfavorable geological conditions, an economical operation would probably never take place, as highlighted in the review of Menberg et al. (2016).

In conclusion, the comparison of our results with literature is considered satisfactory. When the estimates presented in other publications lie outside the range of GHG emissions identified by our boxplot, this is due by the fact that such scenarios are outside the scope of our *Reference model* (ie. the authors explore "extreme" case studies characterized by exceptionally favorable or unfavorable conditions).

Two other relevant observations can be also formulated.

1) Possibility of generating unlikely scenarios

During theMonte Carlo random sampling, the choice of using P_{ORC} as one of the independent parameters of the model, may lead us to generate some unlikely scenarios, characterized by

abnormally high (or low) GHG performances. For instance, an unlikely EGS scenario would be one combining the highest possible value for the flow rate (*f*) and the lowest possible value for the installed power capacity (P_{ORC}) (i.e. explicable only by a very low production temperature, which is not impossible but rather improbable in a normal EGS operation). In such a case, the GHG performances may have a fairly high value because of the limited quantity of electricity produced over the lifetime together with the high emissions related to the infrastructure. The general strategy to exclude these cases consists in introducing a mathematical relation between the dependent parameters, performing the random sampling only with the independent ones: the choice of not introducing such additional mathematical relation is discussed section 2.3.2. Anyway, we observe that such unlikely scenarios don't have high influence on the results: they are outliers belonging to the tails of the statistical distribution, as 90% of the results are found on a limited range (17-65 gCO_2eq/kWh), as shown in Figure 2.2. We conclude that the use of P_{ORC} as an independent parameter, responding to a trade-off between accuracy and simplification, is acceptable.

2) Sensitivity of the results with respect to the description of the inputs

The second observation is that obviously the shape of the "environmental profile" (i.e. the characteristics of the boxplot) depend on the hypothesis regarding the variability of the nine input parameters (intervals and probability distributions presented in Table 2.1). The minimum and the maximum of the intervals represent the boundaries of the scope of our model and are set according to current EGS knowledge and discussion with experts. The shape of the probability distributions (Gaussian, lognormal, etc) are also based on the available information, but are subject to higher uncertainty given that a large and statistically relevant sample of data is still not available (because of the limited long term knowledge on EGS). The most conservative assumption for the Monte Carlo analysis consists in considering a uniform probability distribution for each of the nine parameters (i.e. values within their variability range are set equiprobable). The boxplot resulting from this conservative hypothesis is presented in Annex 6: it is similar to the one presented in Figure 2.2, thus our conclusion regarding the GHG profile of EGS remain unchanged. The problem of the uncertainty related to the characterization of the input parameters will be discussed in detail in the next chapter, where we will observe that the description of the inputs' variability is particularly influent on the results of the global sensitivity analysis.

2.6 Conclusions on the *Reference model*

In the Introduction we showed that the few results available from literature (less than 20 estimates, from only 8 publications) were not sufficient to get a consistent overview of the environmental performances of the EGS technology. The case studies from literature were representative of a too restricted number of specific configurations, and the variability of the estimates was very high, from 6 to 750 gCO_2eq/kWh. Considering the latter large range of emissions, which relies on few literature data and is potentially an unfair representation the environmental performances, it was difficult to compare the EGS technology with other types of power plant.

The environmental profile proposed in this chapter (Figure 2.2), generated with a parameterized model and accounting for the description of the variability of the inputs, provides a much clearer vision. It shows that most of the GHG estimates actually lie within a restricted range of emissions, from 20 to 40 gCO_2/kWh (interquartile range of the boxplot), and it is issued from 500 000 different scenarios, encompassing a very large spectrum of possible EGS configurations (thus it can be considered as representative of the EGS sector in central Europe, as previously defined).

Figures 2.3 and 2.4 compare the environmental profile of EGS obtained through the *Reference model* with the GHG emissions results issued from a literature review performed by the IPCC (Moomaw et al. 2011). The horizontal dashes represent the minimum and maximum estimates found in literature, while the diamond indicates their median value (the number of considered GHG estimates for each technology is specified between brackets). To perform a perfectly consistent comparison among the different energy technologies it would be necessary to harmonize the scope of the considered LCAs as well as their technological, geographical, methodological and temporal assumptions (cf. section 2.2). However apart from the limitations – also discussed in the Introduction chapter – of the literature review approach, the general conclusion drawn from these figures is that the environmental performances of EGS are much better than those of conventional technologies based on fossil fuel (and they are comparable with the environmental performances of other renewable energy systems). This is even more evident when considering another literature review, performed by the CIRAIG

(2014). The latter shows similar GHG ranges for renewable energies (compared to IPCC) but highlights GHG estimates as high as ~2200 gCO_2eq/kWh for gas-fueled power plant and ~2800 gCO_2eq/kWh for coal power plants.

In Annex 7, we also propose a comparison with the environmental profiles of the wind power and photovoltaic polycrystalline technologies, obtained by Padey (2013) using the same approach of this manuscript (i.e. set-up of a stochastic parameterized model and generation of several thousand scenarios with a Monte Carlo technique).

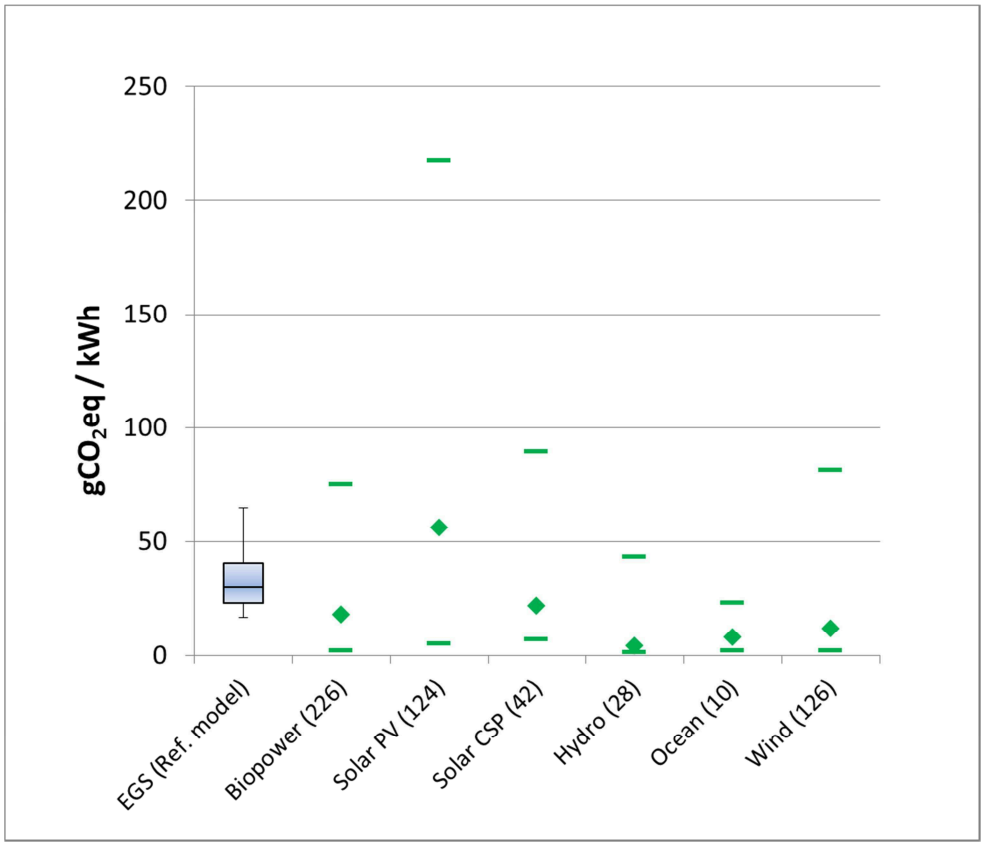


Figure 2.3. Environmental profile of EGS issued from the *Reference model*, compared with the LCA results of renewable energy technologies issued from a literature review performed by the IPCC (Moomaw et al. 2011). Between brackets: number of GHG estimates considered in the review.

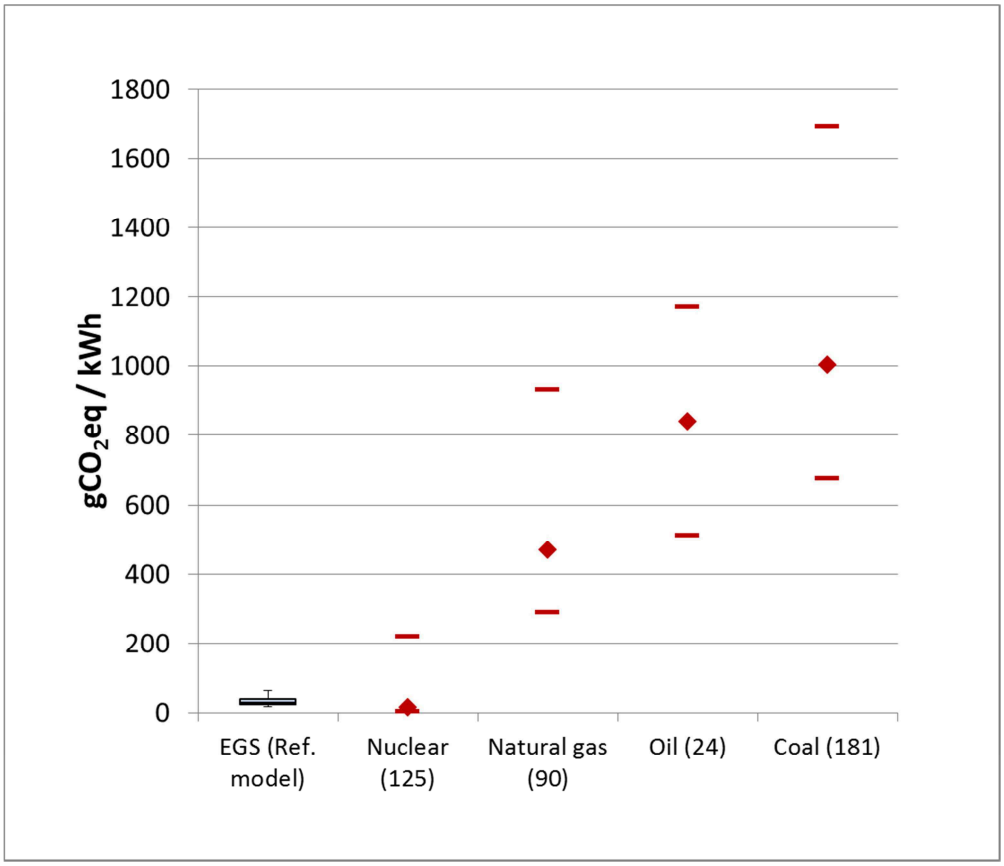


Figure 2.4 Environmental profile of EGS issued from the *Reference model*, compared with the LCA results of non-renewable energy technologies issued from a literature review performed by the IPCC (Moomaw et al. 2011). Between brackets: number of GHG estimates considered in the review.

The *Reference model* presented in this chapter is a major outcome of our research and allows us to address our first research question **[a]** (p. 72), by the generation of the environmental profile of EGS related to the GHG emissions. The model is representative for the EGS sector in central Europe and it provides a characterization of its life cycle impacts, encompassing a very large sample of possible plant set-ups.

The investigation on the positioning of the EGS sector can be continued by focusing on other impact categories, like for instance the depletion of resources (MJ/kWh) or the acidifications effects on the environment (gSO_2eq/kWh). The methodological approach would be the same as presented in this chapter, but it will be necessary to use the appropriate characterization factors for the studied impact category (instead of the IPCC factors, necessary to calculate the emissions in terms of gCO_2eq). The perspective of considering other impact categories is also discussed in the Conclusion chapter.

The formula of the *Reference model* (equation 2.3) also address partially our second main interrogation (**[b]**), related to the need of tools for an easy estimation of the environmental performances of specific EGS configurations. Indeed, such formula allows an immediate calculation of the life cycle impacts without undertaking the long and complex LCA procedure. However, the user must be able to allocate a value for each of the nine parameters and this could be challenging for a non-expert. For instance, it could be difficult to specify the value regarding the intensity of the stimulation campaign (parameter ***SFe***) or the specific power of the pumps of the geothermal loop (parameter ***Pp***). On the other hand, some of the nine parameters may have a very limited influence on the variability of the results of the model (ie. of the GHG emissions). The next chapter will focus on the identification of the "key parameters" of the model, in order to obtain a simpler formula, easy to use and function only of a restricted number of key variables.

Chapter 3
Set up of a reduced model for the environmental analysis of specific EGS installations

3.1 Context and objective of this chapter

This third part of our research has a double objective:

- the development of a **methodological framework** for the application of global sensitivity analysis to the LCA of emerging technologies characterized by high uncertainties;
- the set-up of a **simple tool**, aimed at non-experts and decision makers, allowing the estimation of the life cycle environmental performances of **specific EGS configurations** without undertaking the long and complex LCA procedure. This will take the form of a simple formula, called "*Reduced model*", expressing the impacts as a function of a restricted number of key parameters.

Padey et al. (2013) presented an approach for the development of such reduced models and the identification of the key parameters based on **global sensitivity analysis** (**GSA**). Indeed GSA allows establishing a ranking among the input parameters of a calculation model, according to their influence on the variability of the output. However, the application of GSA in the EGS context faces an important challenge related to the innovative character of this energy technology. Before detailing our approach to address this issue we take a step backward, to introduce the role of GSA in the domain of life cycle assessment.

Since the early development of the LCA methodology, the importance of assessing uncertainties through sensitivity analysis (SA) has been stressed by several authors, referring in particular to the inherent variability of the input parameters, the large number of assumptions and sometimes the incomplete knowledge of modeled process (Heijungs 1996, Huijbregts 1998, Lloyds and Ries 2007). The ISO standard for LCA also indicates SA as a fundamental part of the analysis, without however recommending a particular calculation technique.

Global sensitivity analysis has been recently identified by several authors as a relevant practice to address several issues of the LCA practice: (i) to study the combined influence of the different input parameters (Padey et al. 2013), (ii) to assess the robustness of the results (Wei et al. 2015), (iii) to enhance the understanding of the structure of the model (Cucurachi

et al. 2016) (iv) to ensure transparency, reliability and credibility of LCA practices (Bisinella et al. 2016) and (v) to contribute to the decision-making process (Andrianandraina et al. 2015). As previously mentioned, GSA allows establishing a ranking among the input parameters and identifying the most influential on the variability of the output of the model. The identification of such key parameters is fundamental when aiming at the simplification of the uncertainty quantification: in fact, based on the GSA results, the efforts to minimize the uncertainty can be focused only on few key input variables while the others can be fixed to average values without influencing the results (Bisinella et al. 2016, Wei et al. 2015). Identifying the most influent variables also allows developing simplified parameterized LCA models, as shown by Padey et al. (2013) and as we aim to do in this chapter. In general, GSA techniques support the execution of LCAs and facilitate its interpretation, promoting an enhanced decision making process (Cucurachi et al. 2016).

The question of how to perform GSA in a LCA context has been addressed by few studies (Cucurachi et al. 2016, Andrianandraina et al. 2015, Wei et al. 2015, Bisinella et al. 2016). In particular, the recent work of Cucurachi et al. (2016) proposes a comprehensive multi-step protocol for the integration of sensitivity and uncertainty analysis in the impact assessment phase of LCAs. Examples of application of GSA techniques to LCAs are also to be found in Marini et al. (2014), Azadi et al. (2015) and Cucurachi and Heijungs (2014).

When conducting a GSA, the description of the variability of each input parameter is one of the most important steps, because it could significantly affect the GSA results (Wei et al. 2015). This step, that we call "*description of the inputs*", consists in defining (i) the minimum and maximum values they can assume and (ii) if some values are more probable than others within those boundaries. Such description is done by the LCA modeler, who allocates a probability distribution (Gaussian, uniform, or any other) over the defined range of variability of each input. This is based on expert opinions, literature survey or even better on field data: in chapter 2 we presented this process applied to the EGS sector, resulting in the description of the nine inputs of the *Reference model* reported in Table 2.1. While mentioning the importance of the description of the inputs, the above-mentioned studies however do not propose a systematic assessment of its influence on the GSA results.

In an ideal case, the modeler has a high confidence on the performed description. This can be found for instance in the GSA performed by Padey at al. (2013) on the LCA of wind turbines: in such study, the descriptions of two of the input variables (the load factor and the nominal

power of the machines) are based on data collected from hundreds of turbines currently installed in France. In general, when the system analyzed is well known, the application of GSA protocols available in literature (see for instance Cucurachi et al. 2016) is adequate to clearly identify the main drivers of the model.

On the contrary in other cases, especially when studying new products or emerging technologies, the level of confidence of the inputs' description is significantly low due to the little amount of available information. This is the issue that we face for EGS, represented in Figure 3.1, related to the limited long-term knowledge of this sector and the restricted number of ongoing projects. Indeed, as already mentioned in the discussion of our *Reference model* (section 2.5), the description of its inputs is quite uncertain because it is only based on the few data available from the industry, discussion with experts and literature survey. In this context, the application of the GSA needs to be handled with care: it must be carried out together with an investigation of the robustness of its results.

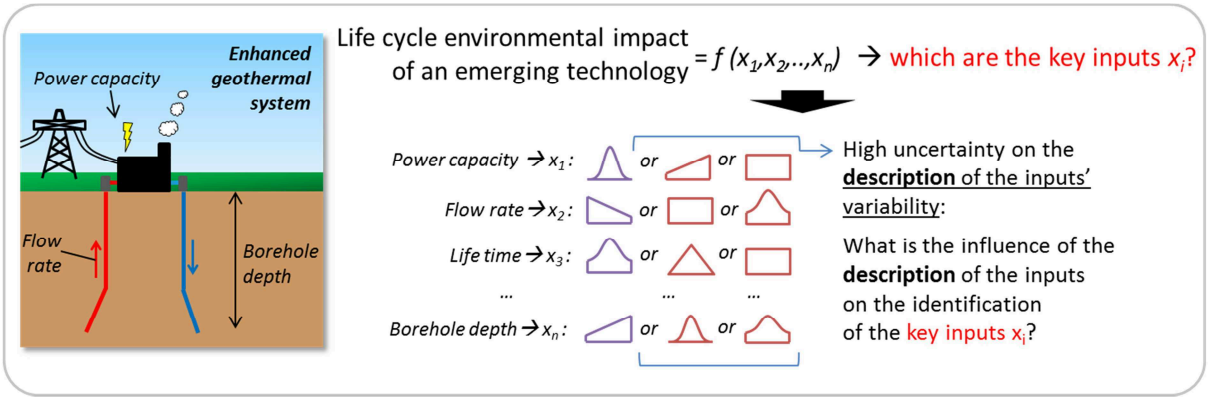


Figure 3.1 Representation of the high uncertainty on the description of the inputs as critical issue when identifying the key parameters

In this chapter, we set up a methodology to perform such investigation, overcoming the critical issue of handling very uncertain information regarding the input parameters. This issue has never been addressed before in literature despite being of paramount importance, especially when studying innovative products. This chapter is structured in two main sections:

- The **development of a methodological framework** to analyze the sensitivity of the GSA results (i.e. the stability of the ranking of the inputs) with respect to the description of such inputs of the model (i.e. the definition of their inherent variability). This new methodology, that can be also applied to other emerging technologies outside the EGS context, is presented in section 3.2

- The **application** of such methodology to the **elaboration of a *Reduced model*** expressing the life cycle greenhouse gas emissions of enhanced geothermal systems (EGS) as a function of few key parameters (section 3.3). Starting from the *Reference model* elaborated in chapter 2, our approach allows identifying the key inputs, taking into account the uncertainty related to their description.

The contents of this chapter have been published in the following paper:

> Lacirignola, M., Blanc, P., Girard, R., Pérez-López, P., Blanc, I. LCA of emerging technologies: addressing high uncertainty on inputs' variability when performing global sensitivity analysis. *Science of the Total Environment*, 2017, 578, 268–280.

3.2 Methodology

The methodology we propose to perform GSA in the LCA context handling very uncertain assumptions regarding the inputs' description is presented in Figure 3.2. It starts from the protocol presented by Cucurachi et al. (2016), which is further extended by setting a strategy that relies on the reiteration of several GSA calculations under different hypothesis regarding the description of the input parameters.

As stated in section 3.1, other authors have also presented frameworks of application of the GSA in the LCA context (Andrianandraina et al. 2015; Wei et al. 2015; Bisinella et al. 2016): in Figure 3.2, we use the term "baseline" GSA approach (box within the orange square) to refer to a GSA procedure that does not take into account our additional analysis (proposed in Step 3B) of the influence of the inputs' description.

Our methodology consists in the following steps:

Step 1: Identification of the LCA model (section 3.2.1), namely the parameterized computational structure used to estimate the life cycle impacts according to a set of *N* input variables.

Step 2: Description of the N inputs of the model (section 3.2.2). Here we identify a "baseline" *description of the inputs* of the model, that establish their range of variability and the probability distribution applied to such range.

Step 3a: Realization of a "baseline" global sensitivity analysis through the calculation of Sobol' indices (section 3.2.3). GSA allows establishing a ranking among the input parameters, identifying the ones that are responsible for most of the variability of the output of the model.

Step 3b: Analysis of the influence of the inputs' description (section 3.2.4). First, we define the criteria to identify the set of key parameters (eg. the threshold for their aggregated contribution to the variance of the output). Then, a set of realistic "alternative" descriptions of the inputs is established (different from the "baseline"

ones of Step 2). The GSA is reiterated several times under different initial conditions, namely considering different combinations for the alternative descriptions of the inputs. This allows assessing the stability of the parameters' ranking, while considering the level of confidence of their description. We then retrieve relevant recommendations for refining the model and for selecting the key parameters.

Step 4. **Overall evaluation**, in order to check for the global picture and verify if results are in accordance with intuition (section 3.2.5).

Step 5. **Identification of the key inputs parameters of the LCA model**, taking into account the outcome of the previous steps (section 3.2.6).

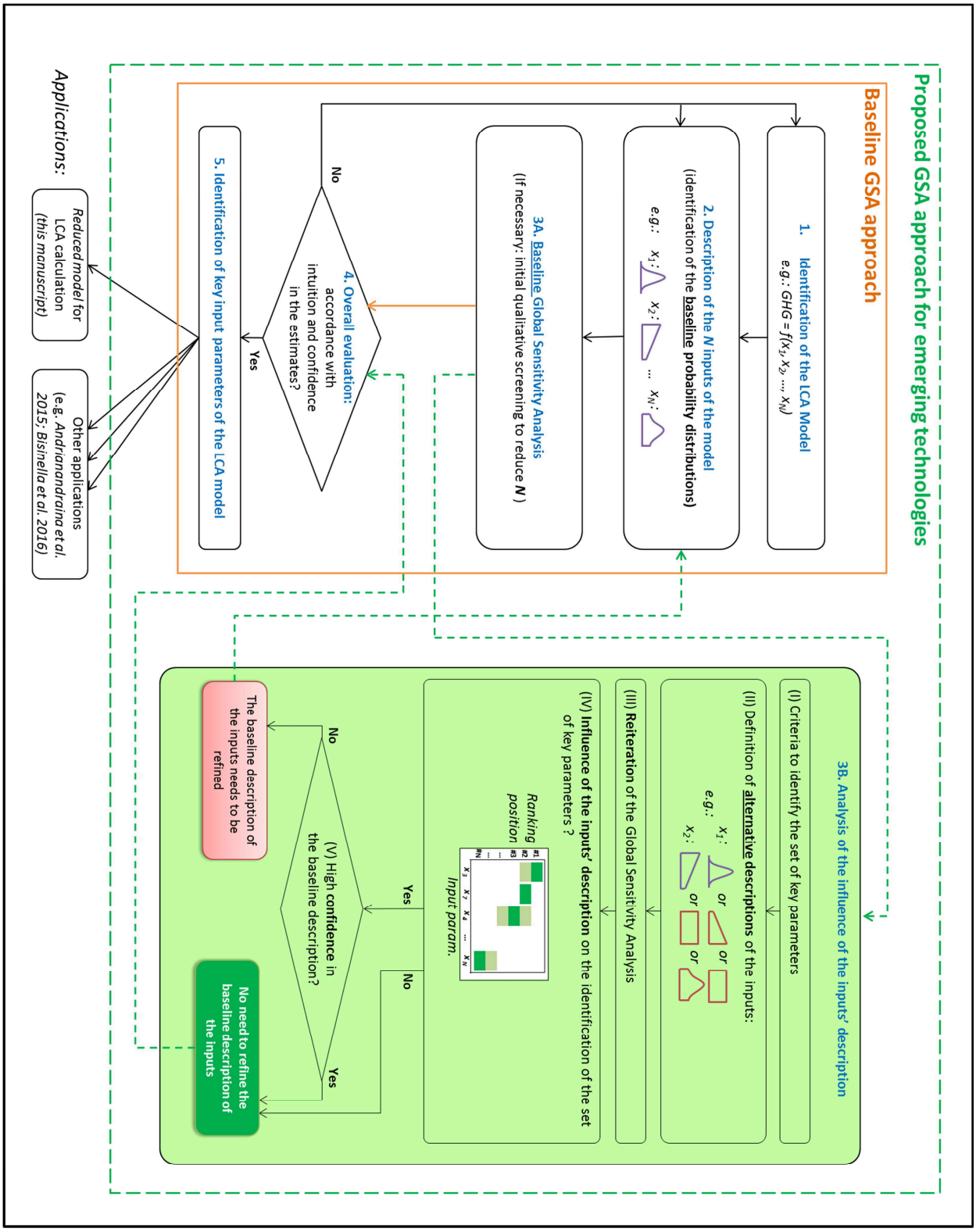


Figure 3.2 Methodology for the identification of key input parameters of an LCA model through GSA, accounting for the influence of the inputs' description

3.2.1. Step 1: Identification of the LCA model

In the initial step the modeler defines the calculation model, namely the computational structure used to estimate the life cycle impacts for the studied impact category according to a set of model parameters. According to the goal and scope of the model, the inputs are identified (such as the type and the amount of materials involved over the life cycle of the product and the energy required) and the input-output relation is formalized (for instance, the model allowing to calculate the life cycle emissions of greenhouse gases).

3.2.2. Step 2: Description of the inputs of the model

The modeler identifies for each of the *N* input parameters (a) the boundaries of its range of variability and (b) one probability distribution applied to such variability range (we call it **"baseline" distribution** to distinguish it from the "alternative" ones identified in Step 3B). For a given parameter, the baseline probability distribution (Gaussian, uniform, lognormal, or other) reflects the best current knowledge regarding the variability of the input, according to the goal and scope of the model. This is based on the available data (from literature or other sources) and expert knowledge. Once the distributions are established, a random sample of each of the inputs is generated.

Based on the information provided in this Step, it is also possible to analyze the propagation of the inputs' uncertainty by generating a Monte Carlo sample of the output (or also using other propagation methods, such as those dedicated to high dimensional input spaces and faster convergence).

3.2.3. Step 3A: Baseline Global Sensitivity Analysis

In this step, the global sensitivity analysis is performed. Since this is based on the baseline probability distributions established in the previous phase, we call it the **"baseline" GSA**, which allows distinguishing it from the other GSAs performed later in Step 3B.

If the number of model inputs is high, the modeler may here performs an initial screening in order to identify the non-influential parameters and fix them to average values, as proposed by Andrianandraina et al. (2015). This can be done by applying different screening methods available in the literature, such as the qualitative approach illustrated by Morris (1991).

The methodology that we propose relies on the hypothesis that the input parameters are independent. In this case it is possible to describe, through a probability distribution, the variability of each parameter independently. Several GSA methods can be found in the literature, see for instance Groen et al. (2016), Wolf et al. (2016) and Padey et al. (2013). For comprehensive reviews of the available options we suggest referring to Saltelli et al. (2008) or Iooss (2011). In our framework we suggest to use the methodology proposed by Sobol' (2001), which is based on the decomposition of the variance and estimates sensitivity indicators called **Sobol indices**. They are appropriate for our analysis since they provide a quantitative measure, thus they allow computing easily the ranking among the variables, and they have a convenient interpretation in terms of explained variance of output. For instance, for a given model $z = f(x_1, x_2, \dots, x_N)$, the first order Sobol index, denoted S_i^{First}, indicates the contribution of the variance of the input x_i to the overall variance of the output z (Equation 3.1).

$$S_i^{First} = \frac{V[E(z|x_i)]}{V[z]} \qquad (3.1)$$

Thus if for example the input x_i has a S_i^{First}=0.2 it contributes to 20% of the overall variance of the output z. The total order Sobol index, denoted S_i^{TOT}, describes the influence of x_i plus the one of all the combinations of x_i with the other inputs: S_i^{TOT} is the sum of all the Sobol indices of x_i, including higher order indices that express the variance of groups of inputs ($S_i^{TOT} = S_i^{First} + \sum_{i<j} S_{ij} + \sum_{i<j<k} S_{ijk} + \dots$).

Since the GSA is based on random samples of data (generated in Step 2), we recommend performing bootstrapping to assess the confidence of the GSA results. The modeler must also assess if the size of such samples is large enough to reduce the effects of numerical instability. For instance, if overlapping is observed among the uncertainty ranges of the Sobol indices, the modeler must reduce it to the minimum by enlarging the sample size.

The final output of Step 3A provides the ranking among the input parameters of the model and a quantitative measure of their relative importance. This allows identifying the ones that are responsible for most of the variability of the output, i.e. those displaying the largest Sobol Indices. If the indices of two or more parameters are very close, different bootstraps of the baseline GSA may produce different rankings. The modeler must take note of this residual ranking instability, because the latter will also appear in the results of Step 3B.

If the modeler is sufficiently confident on all the probability distributions established to describe the inputs, after Step 3A he can proceed directly to an overall evaluation of the results (Step 4) and to the selection of the key parameters (Step 5) (this is the approach within the orange square in Figure 3.2). On the contrary, if the description of one or more inputs is particularly uncertain (e.g. when studying new products or emerging technologies), we propose to proceed from Step 3A to the additional Step 3B before the conclusive Steps 4 and 5.

3.2.4. Step 3B: Analysis of the influence of the inputs' description

This step aims at studying if and how the identification of the set of key parameters is influenced by the description of the inputs. To achieve this, the GSA will be reiterated several times under different input conditions: this will lead to the production of a number of possibly different rankings of the inputs.

3.2.4.1. 3B – (I) Criteria to identify the set of key parameters

In this step, the modeler must define the criteria to detect the inputs' description that are eventually influent on the identification of the set of key parameters. To do that, the modeler must first clarify what is the condition for being identified within the set of key parameters, by establishing a targeted threshold for their "aggregated contribution", for example 60% (or more). In this case the key parameters (showing the highest S_i^{First}) must be together responsible of at least 60% of the overall variability of the output: namely the sum of their S_i^{First} must be higher than 0.6. Indeed, the number of selected key parameters depends on this threshold: for instance two key parameters may be sufficient in the baseline scenario, nevertheless a deeper analysis may show that - under different hypothesis - three or even four parameters may be necessary to achieve the targeted 60%. Therefore, the modeler will be interested in observing *whether the set of key parameters remains the same or not after different GSA calculations*. If such ambiguity is found, then the description of the inputs has a significant influence.

An alternative approach for the selection of the key parameters consists in focusing on their single contribution rather than their aggregated one (i.e. observing if each S_i^{First} alone is above a certain threshold). However, such approach may not be sufficient to identify a set able to cover a given share of the output variance: in the case study, we'll use it only for a complementary analysis (for more details see the Annex 10)

3.2.4.2. 3B – (II) Definition of alternative descriptions of the inputs

This phase conceptually corresponds to the Step 2 previously described (section 3.2.2). For each of the N input parameters, the modeler identifies a number of possible alternative descriptions (i.e. other possible probability distributions applied to its interval of variability, different from the baseline one established in Step 2). The number of k_i alternative descriptions (including the baseline one) is set by the modeler and may be different for each *i-th* parameter.

For instance, if the baseline distribution of one parameter is Gaussian with μ=10 and σ=1, an alternative distribution may have a different shape (e.g. triangular), or a different mean (e.g. μ=12), or a different standard deviation (e.g. σ=2), or a combination of all these changes. In any case, at this step it is necessary to consider realistic constraints: this can mean for example avoiding negative values for a parameter that is meant to be only positive. The general condition is that each of the alternative distribution must be plausible according to the current knowledge and to the goal and scope of the model. A random sample is then generated from the established descriptions. The difference between the alternative and the baseline distributions of one variable can be quantified by measuring the different means and standard deviations: this will enhance the understanding of how the space of distributions is explored.

3.2.4.3. 3B – (III) Reiteration of the GSA

This step conceptually corresponds to Step 3A (performing the baseline GSA, section 3.2.3) but the GSA is here reiterated several times, each time considering a different set of descriptions of the input parameters. The same sensitivity indices chosen in Step 3A are used here. Concretely, a *one factor at a time* (OAT) approach is used for the reiteration of the GSAs, as detailed hereafter.

The analysis starts with the observation of the first of the N input parameters. Here, k_1 GSAs are performed, each time considering one of the several k_1*-th* distributions for the first parameter, while the baseline distribution is set for all the other parameters. Bootstrapping can also be used at every stage of calculation (in the Equation 3.2, B is the amount of bootstraps per GSA). The same process is repeated for the others *i-th* parameters. At the end of each bootstrap, the global sensitivity indices and the obtained ranking (i.e. the sorted order of the inputs according to their influence on the output's variability) is stored. Without repeating the

case where all distributions are the baseline ones, the total number of GSAs performed in this study (i.e. the total number of rankings recorded) is given in Equation 3.2:

$$Total\ number\ of\ rankings = [\sum_i^N (k_i - 1) + 1] \cdot B \qquad (3.2)$$

Reiterating the GSA with such an OAT approach regarding the input conditions does not account for all the possible combinations of descriptions of the input parameters. However, it still allows formulating relevant observations for the scope of the study, while keeping the process relatively simple. A more global approach, which would consider all the possible combinations of descriptions of the inputs (requiring a much higher computational cost), is discussed in the Conclusion chapter, among the perspective for further developments.

3.2.4.4. 3B – (IV) Analysis of the influence of the inputs' description

Based on the calculations performed in the previous phase, the modeler here analyzes the sensitivity of the GSA outputs (the global sensitivity indices and the collection of rankings of the input parameters) with respect to the description of the inputs. This is done according to the criteria established at the beginning of Step 3B (section 3.2.4.1).

In this phase, the modeler first identifies *how many* key parameters need to be selected to achieve the targeted threshold for their aggregated contribution (defined in Step 3B – (I)). Then he identifies which description of the inputs has a significant influence on this selection process. In other words, the modeler here finds out if describing one input with e.g. a Gaussian instead of a uniform distribution leads him to identify different sets of key parameters. Such analysis is performed one factor at the time (observing the $k_i \cdot B$ rankings related to each single parameter) and also by examining the aggregated results of all the GSAs (observing the whole set of obtained rankings).

The modeler will identify *which are* the key parameters later, in Step 5: it is worth to remind that if one parameter is selected as "key", it doesn't necessarily mean that the description of its variability is influent on the selection process.

3.2.4.5. 3B – (V) Consideration of the level of confidence of the inputs' description

If the description of a parameter is found to be influent on the identification of the key parameters and its level of confidence is low (i.e. it is based on numerous assumptions), such

description should be refined. In other words, the modeler should try to collect further data to validate or improve the baseline probability distribution used. However, especially when studying new products or emerging technologies, it may happen that a more detailed analysis is not possible because of lack of existing additional data: in this case, an alert must appear when exploiting the GSA results. This may affect the identification of the key parameters: with a conservative approach, a larger number of key parameters may eventually be selected (i.e. including those affected by the alerts).

Conversely, the modeler may find out that the description of a parameter is particularly influent on the GSA output, while also being confident about the baseline probability distribution chosen in Step 2 (obtained for example from a sufficiently large statistical sample of data). In this case the input's description doesn't need to be refined.

As discussed later in section 3.4, this step 3B - (V) can also be performed earlier, inquiring about the level of confidence before the beginning of Step 3B in order to simplify the calculation process. It is also important to remind that the aim of this analysis is not to identify *which is the best description* for a parameter among several alternatives. The goal is to enhance the understanding of the model, and to formulate appropriate alerts and recommendations for the use of the GSA results.

3.2.5. Step 4: Overall evaluation

At the end of every step of the proposed methodology, the modeler should verify if the obtained results are in accordance with intuition, check for misleading interpretations and eventually reiterate partially or totally the calculation process if needed. For instance, the modeler must be alerted by results of the output of the LCA model (generated in Step 2) that are too far from those available in literature, or by the observation of drastic changes in the ranking position (e.g. from the first to the last) of one parameter during Step 3B. Such process of consistency check should be continuous, but for simplicity we represent in our methodology (Figure 3.2) just one step of overall evaluation of the results, labeled as Step 4: this constitute the minimum requirement in terms of consistency check.

3.2.6. Step 5: Identification of key input parameters of the LCA model

Based on the outcome of the previous steps, the modeler formulates conclusions and recommendations for the selection of the key inputs of the model. Namely, he identifies *which*

are the key parameters able to cover a sufficient share of the variability of the output (for instance 60%, as in the example provided in section 3.2.4.1). If the description of one or more inputs provoked an alert in Step 3B – (V), the modeler must take it into account in the process of selection of the key parameters, as discussed in section 3.2.4.5.

3.2.7. Application of the GSA results

As stated at the beginning of this chapter (section 3.1), one possible application of the GSA in the LCA context is the elaboration of simplified calculation models, where the life cycle impacts are expressed as a function of few key parameters identified through the GSA. Such application is presented in the next section. Other possible uses of the GSA results can be found in Andrianandraina et al. (2015), where eco-designed scenarios are established using the lower values of the most influential drivers, and in Bisinella et al. (2016), where the authors propose to recalculate the uncertainty propagation considering only the key parameters.

3.3 Application of the methodology to the set-up of a *Reduced model* for EGS

We now apply the methodology described in the previous section to the study of enhanced geothermal systems. Starting from the *Reference model* developed in chapter 2, the global sensitivity analysis is applied to identify the key parameters responsible for most of the variability of the output of the model (ie. the estimation of the GHG performances in gCO_2eq/kWh). The final objective is to obtain a more simple calculation tool called "*Reduced model*", which can be easily used by decision makers, expressing the environmental impacts as a function of only those few key parameters (while the other are fixed to average values).

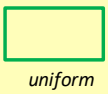
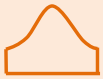
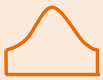
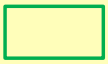
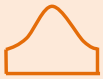
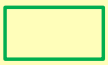
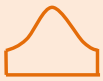
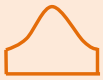
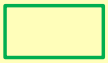
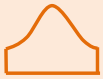
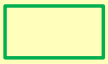
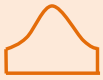
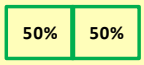
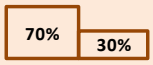
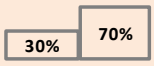
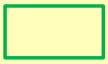
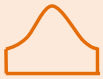
3.3.1. Step 1: Identification of the LCA model

As discussed in chapter 2, the *Reference model* is designed for the analysis of the GHG performances of EGS installed in central Europe and takes into account current technologies for all the equipment. The boundaries of the system analyzed include both sub-surface elements (i.e. the geothermal wells) and surface equipment, like the pumps and the elements of an organic Rankine cycle (ORC) for the electricity production (no cogeneration). Materials and energy flows related to the hydraulic and chemical stimulation of the geothermal reservoir are also accounted for.

The *Reference model* is a function of nine parameters: the borehole depth (z), the produced flow rate (***f***), the number of wells (***Nw***), the amount of fuel consumed during the drilling phase (***d***), the load factor expressing the amount of equivalent operating hours at nominal power in one year (***LF***), the lifetime (***LT***), a dimensionless factor expressing the intensity of the stimulation of the reservoir (***SFe***), the specific power of the pumps of the geothermal loop ($\boldsymbol{P_p}$) and the installed capacity of the ORC ($\boldsymbol{P_{ORC}}$). The functional unit is the kWh of net electricity produced over the lifetime and delivered to the grid, therefore the output results are expressed in terms of grams of CO_2 equivalents per kWh.

Reference model (see eq. 2.3): $GHG_{EGS_Ref} = f(z, f, Nw, d, LF, LT, SFe, P_p, P_{ORC})$

Table 3.1 Description of the nine parameters of the EGS *Reference model*

Parameter	Value range [unit]	Baseline distribution (type 1)	Alternative distributions			
			type 2	type 3	type 4	type 5
Borehole depth (z)	2,000 - 6,000 [meters]	 *uniform* *μ: 4,000 σ: 1,155*	 Δμ: 0% Δσ: -43%	 Δμ: -11% Δσ: -8%	 Δμ: 11% Δσ: -8%	 Δμ: 0% Δσ: -14%
Scaling factor enhan. (Sfe)	0.5 - 10 [ad.]	 *trunc-lognormal* *μ: 2.10 σ: 1.53*	 Δμ: 99% Δσ: 65%	 Δμ: 150% Δσ: 79%	 Δμ: 150% Δσ: 2%	 Δμ: 150% Δσ: 53%
Flow rate (f)	25 - 100 [kg/s]	 *uniform* *μ: 62.5 σ: 21.7*	 Δμ: 0% Δσ: -43%	 Δμ: -13% Δσ: -8%	 Δμ: 13% Δσ: -8%	 Δμ: 0% Δσ: -14%
Fuel for drilling (d)	3,000 - 7,000 [MJ/m]	 *uniform* *μ: 5,000 σ: 1,155*	 Δμ: 0% Δσ: -43%	 Δμ: -9% Δσ: -8%	 Δμ: 9% Δσ: -7%	 Δμ: 0% Δσ: -14%
Lifetime (LT)	20 - 40 [years]	 *trunc-gaussian* *μ: 30 σ: 3.3*	 Δμ: 0% Δσ: 76%	 Δμ: -7% Δσ: 62%	 Δμ: 7% Δσ: 62%	 Δμ: 0% Δσ: 51%
Load factor (LF)	0.85 - 0.95 [ad.]	 *uniform* *μ: 0.90 σ: 0.03*	 Δμ: 0% Δσ: -43%	 Δμ: -1% Δσ: -8%	 Δμ: 1% Δσ: -8%	 Δμ: 0% Δσ: -14%
Pumps specific power (P_p)	3.6 - 8.6 [kW/(kg/s)]	 *uniform* *μ: 6.1 σ: 1.4*	 Δμ: 0% Δσ: -43%	 Δμ: -9% Δσ: -8%	 Δμ: 9% Δσ: -7%	 Δμ: 0% Δσ: -14%
Number of wells (Nw)	2 or 3 [ad.]	 50% 50% *μ: 2.5 σ: 0.5*	 70% 30% Δμ: -8% Δσ: -8%	 30% 70% Δμ: 8% Δσ: -8%	-	-
Installed capacity ORC (P_{ORC})	1,250 - 3,500 [kW]	 *uniform* *μ: 2,375 σ: 650*	 Δμ: 0% Δσ: -43%	 Δμ: -11% Δσ: -8%	 Δμ: 11% Δσ: -8%	 Δμ: 0% Δσ: -14%

3.3.2. Step 2: Description of the inputs of the model

The "baseline" description of the nine inputs of the *Reference model* is the one presented in chapter 2 (section 2.3.2): it consists in the variability ranges and probability distributions displayed in Table 2.1 and proposed again in the first three column of Table 3.1. It corresponds to the best current knowledge on EGS within the scope of the model, considering

the current installations and the future potential power plants. It reflects the heterogeneity of possible EGS configurations and has been established based on technical survey, literature review and discussion with experts. Once established this set of "baseline" distributions, a random sample of 500 000 values for each of the nine input parameters is then generated (the size of the sample must be sufficiently large, as discussed in the next paragraph). We developed the computational code to generate such random samples with the software *R*.

3.3.3. Step 3A: Baseline Global Sensitivity Analysis

In this step, the "baseline" GSA is performed: each input parameter is characterized by its baseline distribution within its variability range (second and third column in Table 3.1). As discussed in chapter 2, the nine parameters are mathematically independent. Under this assumption, we estimate the global sensitivity through the Sobol Indices. Such calculation as well as the post-processing of the results have been performed in *Matlab* environment.

The results of the baseline GSA are shown in Figure 3.3. We observe that the parameter responsible for most of the variability of the GHG results is the installed capacity of the ORC $\boldsymbol{P_{ORC}}$, with a S_i^{First} of 0.46. It is worth to remind that this doesn't mean that the size of the ORC is the main cause of GHG emissions: it means that it has a high influence on the variability of the GHG performances considering the scope of our reference model, namely the emissions per unit of electricity delivered to the grid.

The second parameter of the ranking is the borehole depth z (S_i^{First}=0.18), followed by the number of wells $\boldsymbol{Nw}$ (S_i^{First}=0.09)**.** These three key-parameters together are responsible for about 73% of the variability of the output (sum of their first order Sobol Indices). The other six variables have a S_i^{First} lower than 0.06. Moreover, by observing the total order Sobol Indices (presented in Figure 3.5), we see that no major interaction effects occur (the S_i^{First} are close to the S_i^{TOT}) : hence the S_i^{First} are sufficient to identify the most influent parameters.

100 bootstraps of 500 000 random samples are performed, showing no major fluctuations of the S_i^{First} (cf. narrow boxplots in Figure 3.3). Therefore, the size of the input samples is satisfactory. In the Annex 8, we propose an illustration of the numerical instability of the GSA results that occurs when a too small sample is used: the uncertainty ranges of the S_i^{First} of different parameters overlap, complicating the identification of a clear ranking.

We also observe that the S_i^{First} of ***d*** and ***LT*** are very close, with their interquartile ranges overlapping: this means that their ranking positions may swap when running two different bootstraps, as shown in Figure 3.4 (the values in the green boxes indicate the number of times a parameter is found in that given ranking position). For instance, we see that the lifetime (***LT***) ranks 5th for 94 bootstraps and 6th for the remaining 6. Such behavior may be avoided but with a prohibitory increase of the sample size: thus, to reduce the computational costs, we keep the size of 500 000 random samples and we take note of this residual numerical instability. It is important to take note of that, because such instability effects will also be present in the rest of the analysis (i.e. when multiple GSAs are performed in Step 3B, see Figure 3.8).

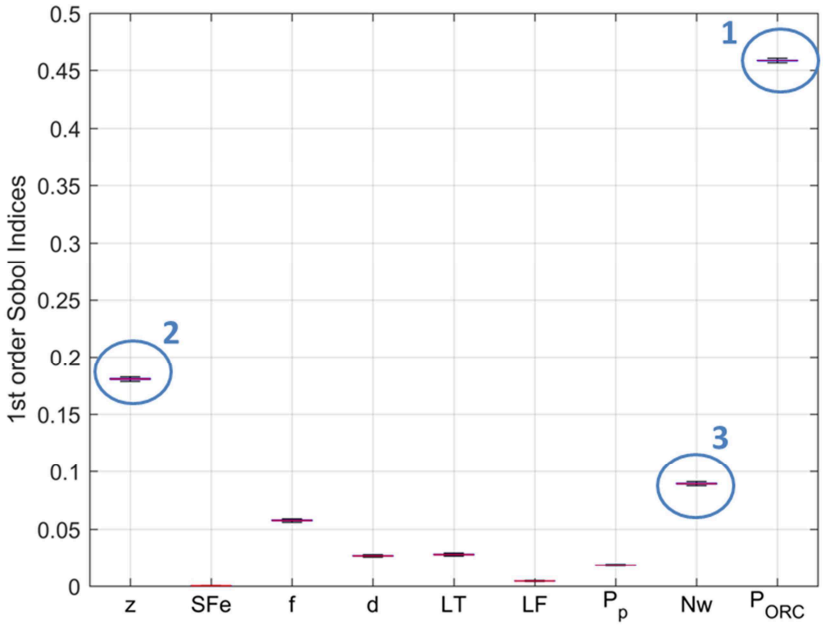


Figure 3.3 Results of the baseline GSA: first order Sobol Indices of the nine input parameters. The blue circles indicate the three highest parameters of the ranking.

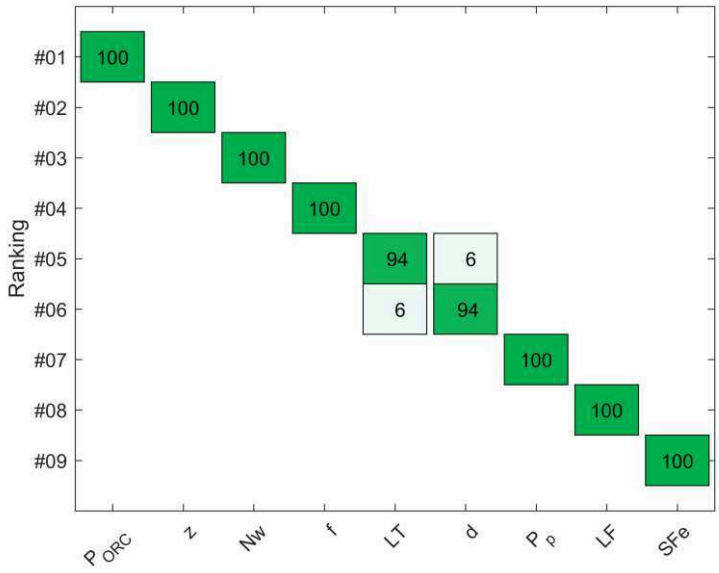


Figure 3.4 Results of the baseline GSA: ranking results for 100 bootstraps of the Baseline GSA. Given that the S_i^{First} of ***LT*** and ***d*** are very close, their ranking position can swap.

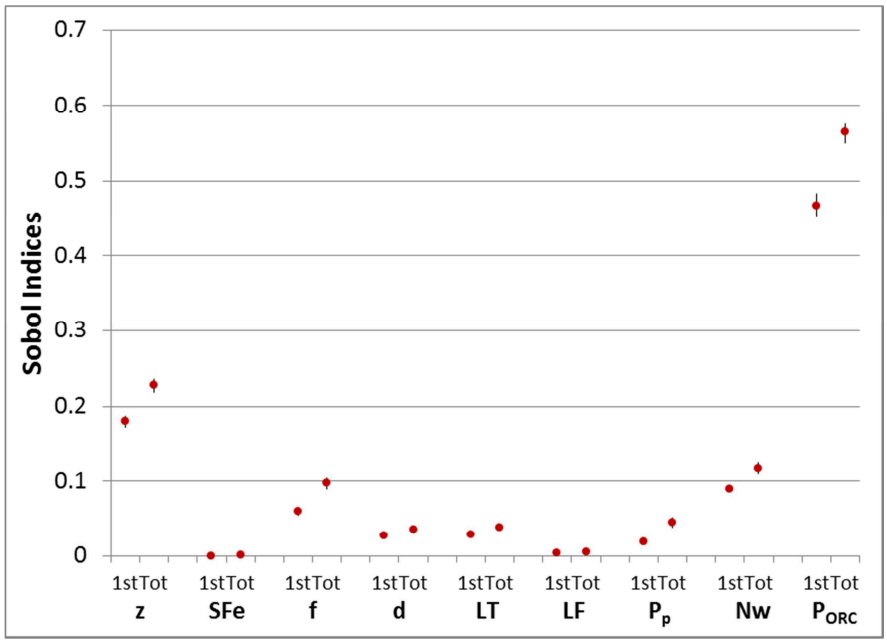


Figure 3.5 First order ("1st") and total order ("Tot") Sobol Indices for the Baseline GSA, calculated with samples of 500 000 values per parameter.

3.3.4 Baseline vs proposed GSA approach for the EGS case

If we wanted to use a baseline approach for the GSA application (orange box in Figure 3.2 displaying the methodology), we would now proceed to an overall evaluation (Step 4) and to the identification on the key parameters (Step 5), without further investigating the robustness of the results (Sobol indices, ranking) obtained in the previous section.

For the selection of the key parameters, we set the threshold for their aggregated contribution to 66%: this means that they must cover at least two thirds of the variability of the output. Within this framework, we would conclude that $\boldsymbol{P_{ORC}}$, z and ***Nw*** can be identified as key parameters: they show the three highest Sobol Indices and the sum of their S_i^{First} is indeed higher than 0.66.

But are we sufficiently confident on the hypothesis that determined this result? As discussed at the beginning of this chapter, the baseline description of the variability of the nine inputs is quite uncertain because it is only based on the few data available from the industry, discussion with experts and literature survey. Therefore, the results of the Sobol indices, showing $\boldsymbol{P_{ORC}}$, z and ***Nw*** at the top of the ranking are affected by this uncertainty and may be potentially wrong. To illustrate this, we show hereafter, with a concrete example, what happens if we had made different choices during Step 2.

Let's imagine that for some reason (e.g. lack of data or choice to have a more conservative approach) we had set, for the description of the lifetime (***LT***), a uniform instead of a Gaussian distribution for the baseline scenario. The results are shown in Figure 3.6 (in this simulation, for the other eight variables, the baseline distribution are unchanged i.e. are the ones shown in the third column of Table 3.1). We observe a doubling of the S_i^{First} of ***LT***, which now appears to be the third more relevant variable (slightly overtaking ***Nw***) while it was only the 5th of the ranking in Figure 3.3. Therefore, in this case we would rather identify $\boldsymbol{P_{ORC}}$, z and ***LT*** (instead of ***Nw***) as key parameters together responsible for more than 66% of the variability of the output. Other conclusions may also be drawn when changing the description of other variables (another example is provided in the Annex 9, where an alternative description of $\boldsymbol{P_{ORC}}$ is tested).

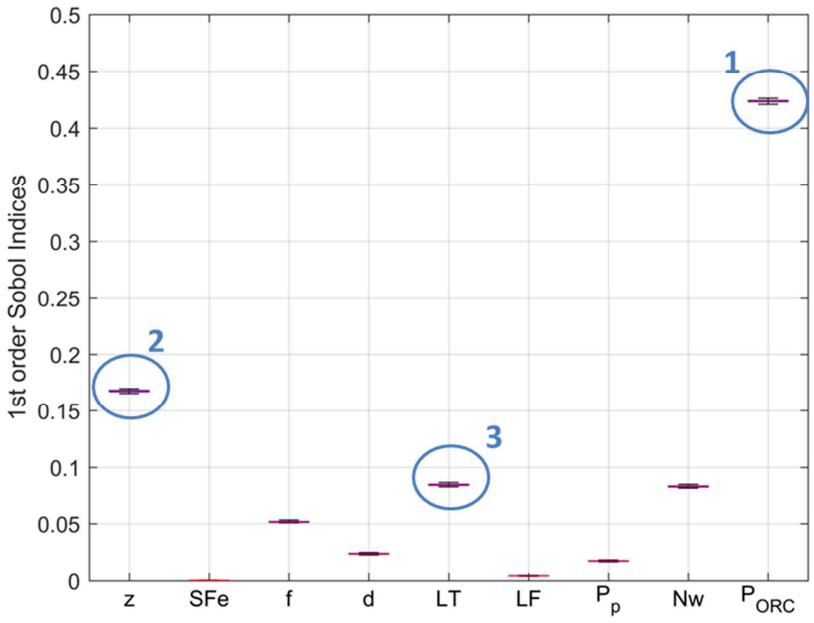


Figure 3.6 Results of a GSA under a different hypothesis for the description of the variability of ***LT*** (for all the other parameters, the baseline distributions are used): the blue circles indicate the three highest parameters of the ranking

This simple example shows that the description of the variability of the inputs is essential and may have a high influence on the identification of the key parameters. Such description is usually based on quite uncertain assumptions, especially when studying an emerging technology like the EGS. In these cases, the analysis of the robustness of the GSA results is essential to investigate their sensitivity. Such analysis can be executed with the approach showed in the next section, namely by performing the additional Step 3B.

3.3.5. Step 3B: Analysis of the influence of the inputs' description

3.3.2.1. 3B – (I) Criteria to identify the set of key parameters

The threshold for the aggregated contribution of the key parameters is kept to 66%, as in the example of the previous section. The key parameters must be together responsible for at least two thirds of the variability of the output, ensuring a sufficient representativeness of the *Reduced model*.

3.3.2.1. 3B – (II) Definition of alternative descriptions of the inputs

For each of the nine inputs, several possible alternative distributions are identified. As discussed in the Methodology (section 3.2), the number and the characteristics of the alternatives is set by the modeler, provided that all of them are realistic according to the current knowledge and the goal and scope of the analysis. In this study, we consider in total five types of continuous distribution (including the baseline one) per parameter, except for the number of wells ***Nw*** (three discrete distributions) as shown in Table 3.1 (third to seventh column). It is important to note that, for each single parameter, the boundaries of its variability interval (where to apply the alternative distributions) remain unchanged. In fact, such boundaries represent the minimum and maximum values for the *i-th* parameter according to the goal and scope of this case study.

In the baseline case, most of the parameters are characterized by a uniform distribution: this is essentially due to lack of data (as discussed in chapter 2), resulting in a conservative assessment. With the alternative distributions, we account for the realistic possibility that the values at the boundaries (either closer to the minimum or the maximum of the range) are the most probable: this is done by establishing trapezoid distributions (or step functions for ***Nw***). We also explore the possibility of a Gaussian description of the variability of the inputs (ie. the most probable values are in the middle of the range), considering two possible standard deviations (ie. one "narrow" and one "flat" Gaussian distribution, with the same mean but different spread). According to the knowledge of the model, other methods for generating alternative distribution can be also considered (e.g. displacement of the mean or the mode of the distribution, homothetic transformation, etc.)

We define the following settings for our alternative distributions: (i) Uniform: all values equiprobable; (ii) truncated centered Gaussian with standard deviation set to 1/6 of the interval's width; (iii) truncated centered Gaussian with standard deviation set to 1/3 of the interval's width; (iv) trapezoid, with the probability associated to the left boundary of the interval five times higher to the one associated to the right boundary ; (v) trapezoid, with the probability associated to the left boundary of the interval five times lower to the one associated to the right boundary. The parameter ***Nw*** is characterized by a discrete variability range with two values (i.e. two or three wells): the probability distributions are hence step functions allocating to those two values respectively a probability of: 50% and 50% (equiprobability), 70% and 30% or 30% and 70%.

Table 3.1 also displays the difference between the alternative and the baseline distributions in terms of relative variation of the mean **μ** and standard deviation **σ** (indicated as **Δμ** and **Δσ** respectively). This allows a better understanding of how the space of distributions is explored, given that – as said before – it may be explored in many different ways.

The **Δμ** is lower than 13% for all the variables except for ***SFe***, where we observe a variation of +150%. This is due to the shape of the baseline distribution of this parameter, which is heavily asymmetric. Indeed, in the baseline scenario, ***SFe*** is characterized by a lognormal distribution with μ=2.10, σ=1.53, truncated on the range [0.5 ; 10] and characterized by a narrow peak on ***SFe***=1 (as defined in chapter 2). When exploring the realistic case of a uniform distribution over the same interval of variability (i.e. Alternative distribution 2, characterized by μ=5.25), the mean increases by 150%. However, the results of Step 3B – (III) will show that even when considering alternative distributions that are quite different from the baseline one, the ranking position of ***SFe*** doesn't change.

Higher relative variations are observed on the standard deviations **(Δσ)**. This is due to the fact that for all the parameters (except ***Nw***) our analysis takes into account (among the alternatives over the same variability interval):

- a uniform distribution, that by definition is characterized by $\sigma = \frac{width\ of\ the\ interval}{\sqrt{12}}$;
- a truncated Gaussian distribution with *σ* set to *1/6 of the width of the interval* (in order to allocate to the boundaries of the interval a probability close to zero) ;

The relative variation between these two options is 43% (for the parameters with uniform as baseline distribution) or 76% (for the ***LT***, which has the Gaussian as baseline distribution).

For ***SFe***, we observe a Δσ of 79% for the same reason, since the baseline distribution has a quite "narrow" shape, characterized by a σ that is almost the half of the one of the uniform distribution over the same range. For ***Nw***, the Δσ is limited to 8% because we didn't consider alternative distribution that are too distant from the baseline one. For instance, we would have obtained a Δσ of 40% with an alternative distribution allocating 10% of probability to ***Nw*** =2 and 90% to ***Nw*** =3 (or vice versa). However, we considered that such heavily asymmetric cases are not pertinent according to the goal and scope of the model. Indeed, today the choice of the number of wells of an EGS plants depends on many factors (like the investment costs and the risk of induced seismicity). With the current knowledge, we can't say that the

probability that an EGS in Europe has two (or three) wells is close to 100%: 50%-50% or 70-30% are more realistic scenarios.

3.3.2.3. 3B – (III) Reiteration of the GSA

In this step, several GSA are performed, according to the computational strategy represented in Table 3.2. As defined in the previous steps, the *Reference model* is based on 9 parameters (N=9) and 5 probability distributions per parameter are considered except for ***Nw***. Therefore, the calculation strategy is based on 35 different combinations of the distributions (indicated as §i in the first column of Table 3.2). Bootstrapping is also performed: each of the 35 GSA is repeated 100 times. Therefore, according to Equation 3.2, 3500 potentially different rankings are obtained in this study (indeed, each bootstrap corresponds to a new GSA calculation).

Table 3.2 Representation of the calculation process for the GSA reiteration. We observe one parameter at a time: each §i GSA takes into account one of the several k_i-*th* distributions for the *i-th* parameter, while the baseline distribution is set for all the others. 100 bootstraps per GSA are performed.

§ GSA	z	SFe	f	d	LF	LT	P_p	Nw	P_{ORC}
§1 (BASELINE) x100 bootstraps	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§2 (x 100)	TYPE 2	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§3 (x 100)	TYPE 3	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§4 (x 100)	TYPE 4	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§5 (x 100)	TYPE 5	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§6 (x 100)	BASELINE	TYPE 2	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§7 (x 100)	BASELINE	TYPE 3	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§8 (x 100)	BASELINE	TYPE 4	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§9 (x 100)	BASELINE	TYPE 5	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
§32 (x 100)	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	TYPE 2
§33 (x 100)	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	TYPE 3
§34 (x 100)	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	TYPE 4
§35 (x 100)	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	TYPE 5

3.3.2.4. 3B – (IV) Analysis of the influence of the inputs' description

Figure 3.7 shows that, as a result of the several GSAs performed, the sum of the S_i^{First} of the first two parameters of the ranking can range from 0.55 to 0.69 (the boxplots are based on the S_i^{First} issued from 3500 GSAs). This means that, in most cases, two key inputs are responsible for less than 66% of the overall variability of the output (in the remaining cases, their aggregated contribution can achieve 69% at best). Conversely, the sum of the S_i^{First} of the first three parameters of the ranking is always higher than 0.66. We conclude that in order to be sure to cover at least 66% of the variability of the output (the threshold established at the beginning of Step 3B), it is necessary to constitute a set of **at least three** key parameters.

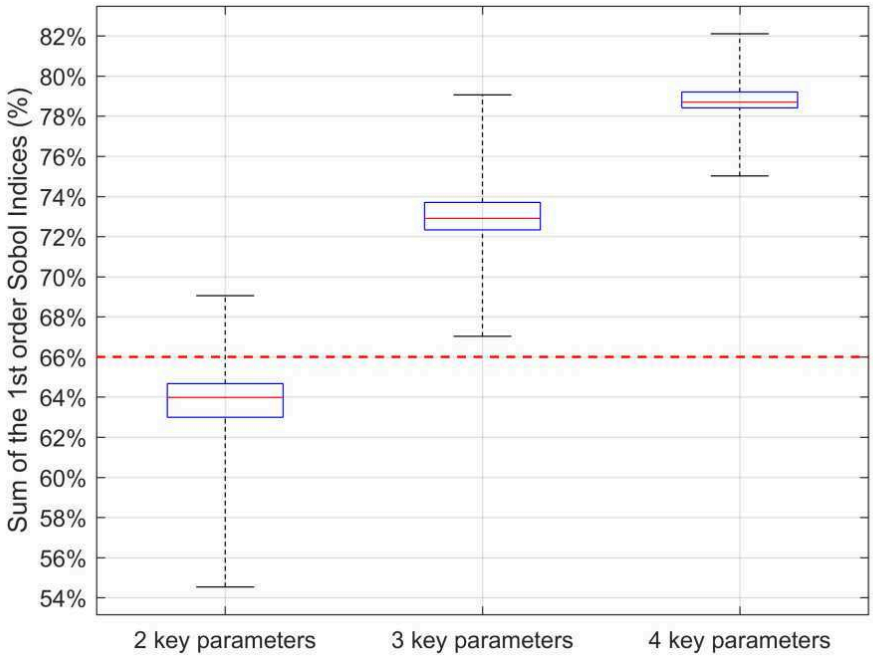


Figure 3.7 Sum of the S_i^{First} of the top two, three and four parameters in the ranking. The boxplots are based the results of 3500 GSAs as defined in Table 3.2

We now analyze the results of the ranking among the 9 inputs of the model, considering that those in the first three positions should be selected as key parameters. The outcome is presented in Figure 3.8: the numbers in the boxes indicate the amount of times the parameters is found in a given ranking position.

We start by observing the results of the five GSA calculations in which we modify the description of the borehole depth (z): these GSAs are noted §1, §2, §3, §4 and §5 in Table 3.2

and each of them is repeated 100 times (bootstrapping). Therefore, we obtain 500 ranking results, represented in the graph A of Figure 3.8. Here the parameter z (borehole depth) results 2nd in the ranking after 400 GSAs, 3rd after 68 GSAs and 4th after the remaining 32 GSAs. Then, we observe the results of the 500 GSAs in which we modify the description of the next input parameter, ***SFe*** (GSAs noted as §1, §6, §7, §8, §9 in Table 2, each of those repeated 100 times, graph B), and so on. The aggregated result of all 3500 GSAs calculations is presented in Figure 3.9.

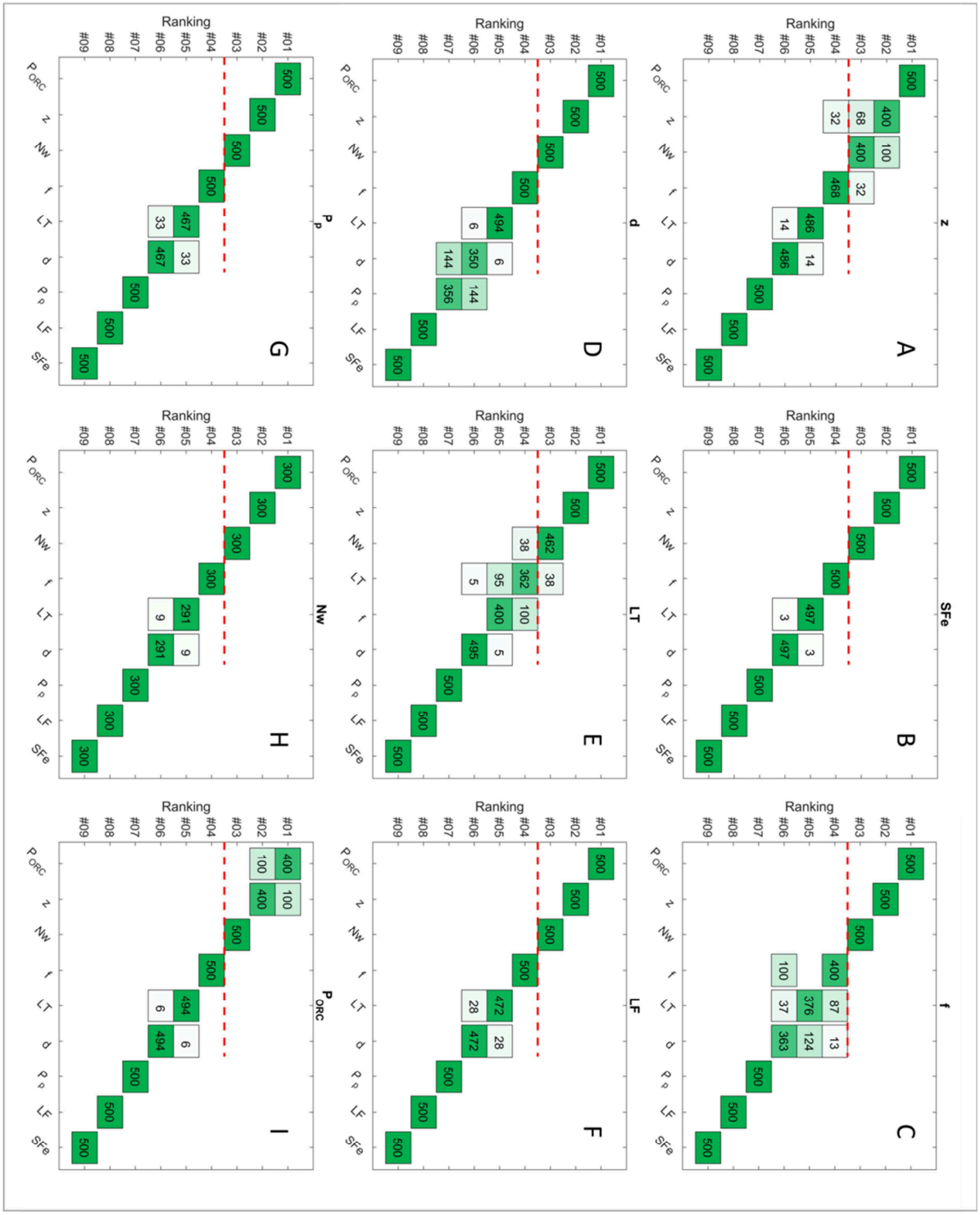


Figure 3.8 Sensitivity of the ranking with respect to the description of the input parameters: analysis one parameter at a time

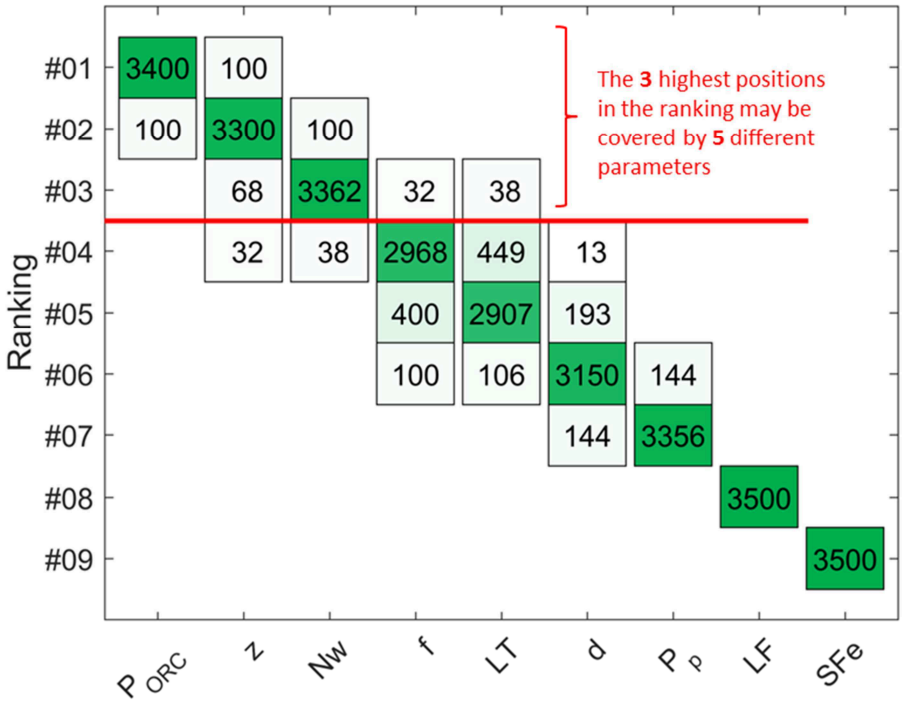


Figure 3.9 Sensitivity of the ranking with respect to the description of the input parameters: aggregated results of the analysis *one parameter at a time*

Based on these figures, the following observations can be formulated:

a) When modifying the description of the variability of the depth (***z***) (graph A in Figure 3.8), we see that the flow rate (***f***) and ***z*** itself may pass from being "key" (above the red dotted line) to "non-key" (below the red dotted line). For instance, the flow rate is in the 4th position (non-key) for most of the calculations, but in 32 GSAs it results 3rd in the ranking (key). The same thing is observed when modifying the description of the variability of the lifetime (***LT***) (graph E). Here the number of wells (***Nw***) and the ***LT*** itself oscillate between key and non-key positions. Therefore, the description of the variability of ***z*** and ***LT*** has a significant influence on the selection of the key parameters. The importance of the description of ***z*** is also shown in Annex 10, where we analyze the changes observed on the single contribution of each parameter.
b) The description of the variability of $\boldsymbol{P_{ORC}}$ (installed capacity, graph I) may cause a swap among the first two positions of the ranking. However, this influence is not significant because in these calculations the top 3 positions are always covered by the same three variables ($\boldsymbol{P_{ORC}}$, ***z*** and ***Nw***)

c) Also the descriptions of ***SFe***, ***f, d***, ***LF***, ***Pp*** and ***Nw*** (graphs B, C, D, F, G, H) do not have an influence on the selection of the key parameters, because they cause changes in the ranking only between the 4th and the 7th positions.

d) As expected, we observe that the lifetime (***LT***) and the fuel for drilling (***d***) often swap their ranking position (respectively the 5th and 6th), even when no change is made on their distributions. This is due to the fact that their S_i^{First} are very close (cf. Figure. 3.3) and even small perturbations in the random samples used for the GSA can easily "generate" the swaps. This phenomenon of residual numerical instability, already shown in Figure 3.4, is observed in all of the results of Figure 3.8.

e) When observing the aggregate results of the 3500 rankings (Figure 3.9), we see that the three highest positions, due to the sensitivity of the parameters to their description, may be covered by 5 different variables: $\boldsymbol{P_{ORC}}$, z, ***Nw***, ***f*** and ***LT***. Those are all potential key-variables to be selected for the *Reduced model*.

Based on these results, we conclude that the descriptions that have an influence on the identification of the key parameters are the ones of the drilling depth (z) and the lifetime (***LT***).

3.3.2.5. 3B – (V) Consideration of the level of confidence of the inputs' description

Once identified the importance of the description of the variability of z and ***LT*** according to the scope of the study, we must inquire about their level of confidence. As discussed earlier, a high uncertainty is associated with the baseline descriptions of all the nine inputs. Therefore on one hand their level of confidence is low (it may change in the future when new data will be available), but on the other hand it can't be further improved since it reflects the best current knowledge. In conclusion, an alert regarding the description of these two parameters must appear when the conclusions of the analysis are formulated (Step 5, see section 3.3.7).

3.3.6. Step 4: Overall evaluation

A consistency check was performed all along the application of the methodology and no counterintuitive results were spotted. The aggregated results of Step 3B (Figures 3.8 and 3.9) are coherent with the one of the baseline GSA (Step 3A, Figure 3.3). They provide sufficient information to enhance the understanding of the model and to formulate alerts for the final phase of the study, i.e. the identification of the key parameters and the generation the *Reduced*

model. Such *Reduced model* will be obtained by fixing the non-key parameters to their median value.

3.3.7. Step 5: Identification of key input parameters of the LCA model

As discussed in section 3.3.4, if we were relying only on the baseline GSA (Step 3A), we would have selected without hesitation only three key parameters: $\boldsymbol{P_{ORC}}$, $\boldsymbol{z}$ and $\boldsymbol{Nw}$ (the results of the baseline GSA shows that $\boldsymbol{P_{ORC}}$, $\boldsymbol{z}$ and $\boldsymbol{Nw}$ are together responsible for more than 66% of the variability of the output). However, the results of Step 3B provide useful additional information. Indeed, we found (Figure 3.7) that three key parameters are sufficient to cover 66% of the output's variability (as requested at the beginning of Step 3B) no matter the type of distribution used to describe the inputs. However, Figure 3.9 shows that the top 3 positions of the ranking may be covered by five different variables ($\boldsymbol{P_{ORC}}$, $\boldsymbol{z}$, $\boldsymbol{Nw}$, $\boldsymbol{f}$ and $\boldsymbol{LT}$) depending on the description of the inputs (especially $\boldsymbol{z}$ and $\boldsymbol{LT}$ as concluded in 3.3.2.4). We are also alerted on the uncertainty carried by the descriptions of $\boldsymbol{z}$ and $\boldsymbol{LT}$, since their level of confidence is low and no improvement is to be foreseen with the current knowledge. In conclusion, given that the descriptions of some inputs are influent on the GSA result and they are also uncertain, it is preferred to select as key parameters all the five that could possibly cover the three highest position of the ranking.

3.3.8. Application of the GSA results: generation of the *Reduced Model*

Based on this enhanced knowledge of the *Reference model*, we conclude that the *Reduced model* must be a function of these five variables: $\boldsymbol{P_{ORC}}$, $\boldsymbol{z}$, $\boldsymbol{Nw}$, $\boldsymbol{f}$ and $\boldsymbol{LT}$. We will let the user of the *Reduced model* define their values, instead of fixing them to their median value[2] beforehand. Hence, the resulting formula for the estimation of the GHG performances of EGS is given by Equation 3.3:

$$GHG_{EGS_Reduced}\left[\frac{gCO_2eq}{kWh}\right] = \frac{Nw\cdot(\omega_1\cdot z+\omega_2)+LT\cdot(\omega_3\cdot f+\omega_4\cdot P_{ORC})}{LT\cdot(P_{ORC}-f\cdot\omega_5)} \pm e \qquad (3.3)$$

With $\omega_1 = 120.70\ [gCO_2eq/(m\cdot h/y)]$; $\omega_2 = 5\ 161.87\ [gCO_2eq/(h/y)]$;

$\omega_3 = 61.82\ \left[gCO_2eq\cdot\frac{s}{kg\cdot h}\right]$; $\omega_4 = 6.42\ \left[\frac{gCO_2eq}{kWh}\right]$; $\omega_5 = 6.10\ [(kW\cdot s)/kg)]$; $e = 4.69\ gCO_2eq/kWh$

[2] The median values of the nine parameters are: z=4000 m, f=62.5 kg/s , Nw= 2.5, d=5000 MJ/m, LF=0.9, LT=30, SFe=1.58, P_p=6.1, P_{ORC}=2375 kW.

The coefficient of determination R^2 between the *Reduced* and the *Reference model* is 91%. The estimated root-mean-square error (RMSE) is 4.69 gCO_2eq/kWh: this represents the distance between the results of the *Reduced* and the *Reference model* and is expressed by "*e*" in Equation 3.3 (see also Annex 11). A comparison of the results of some LCAs of EGS proposed by different authors from literature (Frick et al. 2010; Bauer et al. 2008; Huenges 2010, Platt et al. 2012, see Table 3.3) with the results obtained through the formula of the *Reduced model* (Equation 3.3) is proposed in the Figure 3.10.

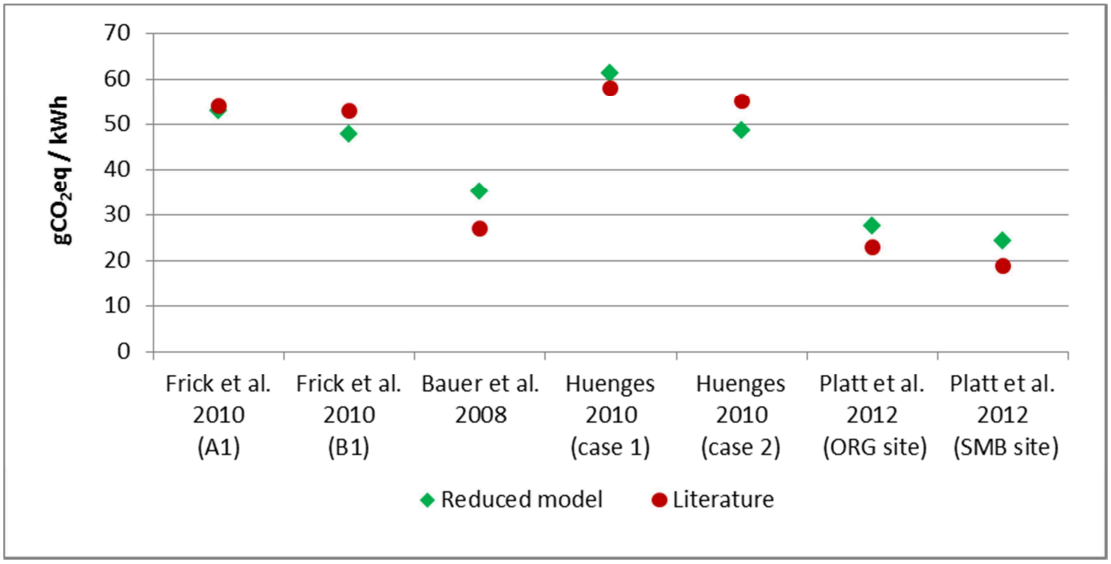


Figure 3.10 Comparison of the results of the 5-variables *Reduced model* with literature.

The comparison with the results of two of the case studies presented by Frick et al. (2010) and Huenges (2010) is satisfactory. For example, when comparing with the scenario A1 of Frick et al., by setting $\boldsymbol{P_{ORC}}$=1 240 kW, ***Nw***= 2, ***z***=3800 m, ***f***=69.4 and ***LT***=30 in Equation 3.3, the result is 52.9 gCO_2eq/kWh while the author proposes 54 gCO_2eq/kWh.

The GHG performances estimated by Bauer et al. (2008) are lower than those calculated by our *Reduced model*. This can be explained by the fact that this author assumes a quite low power demand for the pumps of the geothermal loop (less than 4% of the installed capacity) while in our model it amounts to about 13% of the installed capacity in this case (following the hypothesis reported in Table 3.1, consistent with the assumptions of other authors). In our study, higher power consumption for the pumps implies less electricity delivered to the grid and higher impacts per kWh. Our model is therefore quite conservative compared to Bauer et al.'s assumption when considering the power demand of the geothermal loop.

Considering the scenarios proposed by Platt et al. (2012), our *Reduced model* slightly overestimates the GHG performances. However for this comparison the value of $\boldsymbol{P_{ORC}}$ was estimated through a hypothesis regarding the ORC auxiliary power demand. This is assumed to amount to 20% of the gross output of the generator. If the $\boldsymbol{P_{ORC}}$ value was explicitly mentioned in Platt et al.'s publication, the results of the *Reduced model* would have possibly been more accurate.

Table 3.3 Case studies from literature used for comparison

Case study from literature	**Installed capacity[3] (P_{ORC}) [kW]**	**Depth (z) [m]**	**Number of wells (Nw)**	**Flow rate (f) [kg/s]**	**Life time (LT) [y]**	**Estimate of the GHG performances (literature) [gCO_2eq/kWh]**
Frick et al.(2010) – case A1	1 240	3 800	2	69.4	30	54
Frick et al. (2010) – case B1	1 290	4 700	2	43.1	30	53
Bauer et al. (2008)	2 940	5 550	3	62.2	30	27
Huenges (2010) - case 1	1 440	4 000	2	69.4	20	58
Huenges (2010) - case 2	1 440	4 000	2	33.3	20	55
Platt et al. (2012) – ORG site	1 740	3 162	2	47	30	23
Platt et al. (2012) – SMB site	2 870	4 307	2	76.2	30	19

At this stage, performing a comparison with other authors is not possible either because of lack of data or because the scenarios they propose are out of the scope of our LCA model. For instance Pehnt (2006) do not provide information regarding the features of its EGS case, Sullivan et al. (2010) analyze a large EGS located in the US (outside our geographical characterization), Martin-Gamboa et al. (2015) focus on a Spanish EGS drilled at shallow depth (~700 m boreholes) and Treyer et al. (2015) considers only electrical supply (no diesel consumption) during the drilling phase (the latter two studies are not coherent with our technological characterization of the *Reference model*). The case study proposed by Frick et

[3] Note that P_{ORC} indicates the power output of the ORC (accounting for the demand of the auxiliary equipment), while some authors use "Installed capacity" to refer to the gross power output of the turbine. For Bauer et al. (2008), the auxiliary power demand of the ORC equipment is assumed to be 2% of the generator's output, considering that the total auxiliary demand (including the pumps of the geothermal loop) is declared to be 4%. For Platt et al. (2012), the auxiliary power demand of the ORC equipment is assumed to be 20% of the generator's output considering that the total auxiliary demand accounted in its study (including the pumps of the geothermal loop) amounts to 37%.

al. (2010) as a “worst case” scenario and displaying in our literature review (Figure I.5) the very high impact result of 750 gCO_2eq/kWh is also outside the scope of our *Reference model*. Indeed its ORC power output is only about 300 kW (well below our minimum boundary of 1 250 kW), thus in this case the *Reduced model* produces a wrong estimate (425 gCO_2eq/kWh). This is obvious considering that our model is aimed at representing realistically the variability of the EGS sector, while the abovementioned case study corresponds to highly unfavorable geological conditions, where an economical operation would probably never take place. Further discussion about how the scope of our *Reference model* can be enlarged or refined is proposed in the Conclusion chapter of this manuscript.

In conclusion, globally we observe that the results of the *Reduced model* are coherent with those from literature, the presence of little discrepancies is justifiable and is however unavoidable because of the different sets of hypothesis related to each publication. This attests the robustness of our simplified tool based on these 5 key parameters that allow a rapid calculation of the life cycle impacts without undertaking the long and complex LCA procedure.

3.4 Discussion and conclusions on the *Reduced model*

This chapter presented two major outcomes of our research, one related to the use of global sensitivity analysis techniques with highly uncertain models and one related to the environmental assessment of EGS:

- we developed a **methodological framework for the application of GSA** in the LCA of emerging technologies, addressing the high uncertainty related to their description;
- we obtained an **easy to use formula**, the *Reduced model*, allowing a very rapid estimation of the life cycle GHG impacts of EGS from only 5 parameters, without undertaking the long and complex LCA procedure.

These two outcomes allow us to address our second research question **[b]** (p.72): our simplified calculation model is aimed at decision makers and is developed by taking into account the high uncertainties related to the innovative character of the EGS technology. It is a powerful tool for the analysis of **specific EGS installations**, and is complementary to the outcome of chapter 2, which provided a global picture of the environmental performances of the EGS technology. Some remarks can be formulated with respect to the two outcomes of this chapter.

Remarks regarding our new methodological framework for using GSA in LCA models characterized by high uncertainties:

Added value VS additional work. Of course, when comparing to a "baseline" GSA approach for the identification of the key parameters, our strategy entails an additional task (ie. the Step 3B of the methodology), however the increase in complexity and calculation cost is reasonable, considering the added value it provides. As stated at the beginning of this chapter, our strategy is principally aimed at modeler analyzing emerging products or technologies, when the entry data of the GSA are lacking or highly uncertain and can possibly lead to completely misleading assessments. Obviously, unreliable results are of little interest: our methodology allows increasing their robustness and pointing sources of unreliability that need to be discussed. Moreover, considering that the GSA itself has a non-negligible

computational cost, investigating its robustness is essential to consolidate the effort made by the modeler (which otherwise may be vain or questionable).

Propositions to simplify the calculation strategy. Some recommendations can be formulated with the aim of simplifying the calculation strategy of Step 3B. Indeed, the computational cost of the analysis may be a problem when the number of input parameters *N* is high (e.g. several dozens). In this case, two solutions are suggested:

- Perform an initial screening to reduce the number of uncertain parameter. This can be done with a qualitative sensitivity method like the one proposed by Morris (1991). Such approach is used for instance in the LCA models of Andrianandraina et al. (2015) and Wei et al. (2015).
- Exclude from the analysis the parameters with a high level of confidence regarding their description. Indeed, in the methodology that we described, we analyze the sensitivity of all the *N* parameters (step 3B – (III)) and we inquire *a posteriori* about the level of confidence of their description (step 3B - (V)). This is proposed in order to acquire a global understanding of the model. However, since the highly reliable descriptions will not be challenged further (even if they results to be very influent on the ranking), the modeler may exclude them from the analysis performed in Step 3B (in this case, step 3B – (V) will be moved before step 3B – (I)).

Further developments for the calculation strategy. On the other hand, our calculation strategy may be also developed further, increasing its complexity but possibly improving its robustness. Indeed as discussed in section 3.2, the calculation approach of Step 3B (Table 3.2) is based on the observation of the ranking's variations that occur when we modify the description of just *one parameter at a time* (while, for the others, the baseline description is set). A more advanced approach would consider all the possible random combinations of descriptions of the inputs. Referring to the EGS model this means that, for one single GSA, each of the nine parameters would be randomly characterized by one of the alternative distributions: concretely such strategy would correspond to the realization of a sort of "GSA of the GSA". The challenges of such approach are discussed in the Conclusion of this manuscript, among the perspective of research opened by our study.

Unavoidable dependency from hypothesis. Another relevant remark is that even by performing Step 3B, the identification of the key parameters still depends on the choices and

hypothesis made by the modeler (e.g. the features of the alternative distributions). However, this is an intrinsic characteristic of any sensitivity analysis. We believe that our methodology, while relying on some reasonable assumptions, still allows enhancing the understanding of the model.

***Remarks regarding the Reduced model for EGS**:*

Choice of the number of parameters for the *Reduced model.* The 5-parameters *Reduced model* represents an example of application of the *Reference model* (function of 9 parameters) and shows the possibility of further simplification. Indeed, in case the values of the other four non-key parameters are known by the user, a more precise estimation can be performed by using directly the *Reference model* formula (Equation 2.3). For instance the user can set the value for seven parameters, while the other two are fixed to the median value of their variability intervals (displayed in Table 2.1). We discussed the *Reduced models* for EGS based on two, three or four key-parameters in Lacirignola et al. (2014, 2015). The estimated RMSE between the *Reference model* and the *Reduced model*s based on two, three or four key parameters is respectively 12.1, 8.1 and 6.1 gCO_2eq/kWh (while the model based on five parameters shows an RMSE of 4.69 gCO_2eq/kWh).

Therefore the choice of the number of key-parameters for the *Reduced model* results in **a trade-off between accuracy and simplification.** On one hand, the accuracy of the estimation increases with the number of customized parameters. On the other hand, the user may not have easy access to the required data for some the input variables: either because this requires a technical expertise (for instance the user may not be familiar with "*SFe*", the factor characterizing the stimulation of the boreholes) or simply because the data is not available (for instance if the environmental analysis is made up front, the quantity of fuel for drilling can just be forecasted). The outcome of the global sensitivity analysis indicates the ranking among the parameters and therefore the ones (when few of them are available) that are to be set in priority (installed power capacity, drilling depth, number of wells, produced flow rate and lifetime) to obtain sufficiently accurate results.

In conclusion, parameterized models allowing a rapid calculation of the life cycle environmental impacts are a useful tool for the analysis of specific EGS configurations and

for the comparison of different design options. The level of complexity of such models **depends on the needs and the expertise of the user**.

- If the stakeholder using the calculation model is a decision maker from the public sector, like for instance a government agency (eg. ADEME), the user may not have strong geothermal background thus the environmental tool must be as simple as possible. The *Reduced model* responds to this need, requiring the specification of only 5 parameters.
- On the contrary, if the stakeholder is an EGS project developer, he may take advantage of using directly the 9-parameters *Reference model* formula because he would probably have access to all the required data. He may also be interested in a more complex model, function of more than nine parameters, which could be integrated in the set of tools used for the design of the power plants. In the Conclusion chapter, we propose a discussion regarding how such calculation model can be concretely integrated in the design tools used by EGS developers.

In conclusion, in this chapter we addressed our second research question **[b]** and we also proposed a methodological approach that can be used for the analysis of other energy technologies. Our study opens large research perspectives, regarding both the methodology and the EGS application. A number of proposition for future works are discussed in the next chapter, which concludes this manuscript but paves the way for new studies in this field.

Chapter 4
Conclusions and research perspectives

4.1 Summary of this research

In this research, we presented a detailed investigation of the environmental performances of enhanced geothermal system with a life cycle perspective. We tackled key issues related to (i) the comparison of the EGS technology with other options for energy production and (ii) the comparison specific design configurations within the EGS technological sector.

In chapter 1 we presented the elaboration of a new comprehensive dataset of the mass and energy flow involved over the life cycle of EGS, based on a detailed survey carried out on the site of the Soutlz-sous-Forêts power plant, interviews with experts and literature review. We also performed the LCA of ten EGS scenarios considering five impact categories, in order to validate the robustness of our inventory and to retrieve useful insights regarding the processes responsible for the largest share of impacts. Our results were found coherent with the available literature and show that the construction of the wells is one of the most impacting process, because of the large quantity of fuel burnt during the drilling phase.

In chapter 2, we addressed the question of generating the environmental profile of the EGS sector, considering the large variety of possible configurations for this kind of power plants. Based on the results of chapter 1, we developed a parameterized *Reference model*, function of nine parameters and representative for the EGS sector in central Europe (according to the definition of the scope of the model). By considering a large panel of possible plant configurations, we generated the environmental profile of the EGS sector in terms of life cycle impacts on the climate change, showing that most of the results lay in the range 20-40 gCO_2eq/kWh. This allowed a comparison with other energy technologies, highlighting that the GHG performances of EGS are similar to those of other systems based on renewable energies and largely better than fossil fuel-based power plants.

In chapter 3, we addressed the question of developing a simpler model, aimed at decision makers, for the environmental analysis of specific EGS configurations. First, we elaborated a new protocol for the application of global sensitivity analysis in the LCA of emerging technologies, accounting for the high uncertainties that are intrinsically related to innovative systems. Then, we applied such protocol to the EGS case, developing a simple calculation

model, function of only five key parameters. Such *Reduced model* is a useful environmental tool for decision makers, since it allows obtaining a rapid estimation of the life cycle GHG performances of specific EGS configurations without undertaking the long and complex LCA procedure.

Our research work have been largely diffused in the scientific community through several publications (Lacirignola and Blanc, 2012a, 2012b, 2012c, 2013, Lacirignola et al. 2014, 2015, 2017) and enlarges the debate on the environmental performances of EGS. It also opens several perspectives for future works, which are detailed in this conclusive chapter.

4.2 Research perspectives and recommendations for future works

4.2.1 Outline of the research perspectives

A number of propositions can be formulated for future works in order to pursue the investigation of the environmental performances of EGS and to continue addressing the two research questions of this thesis.

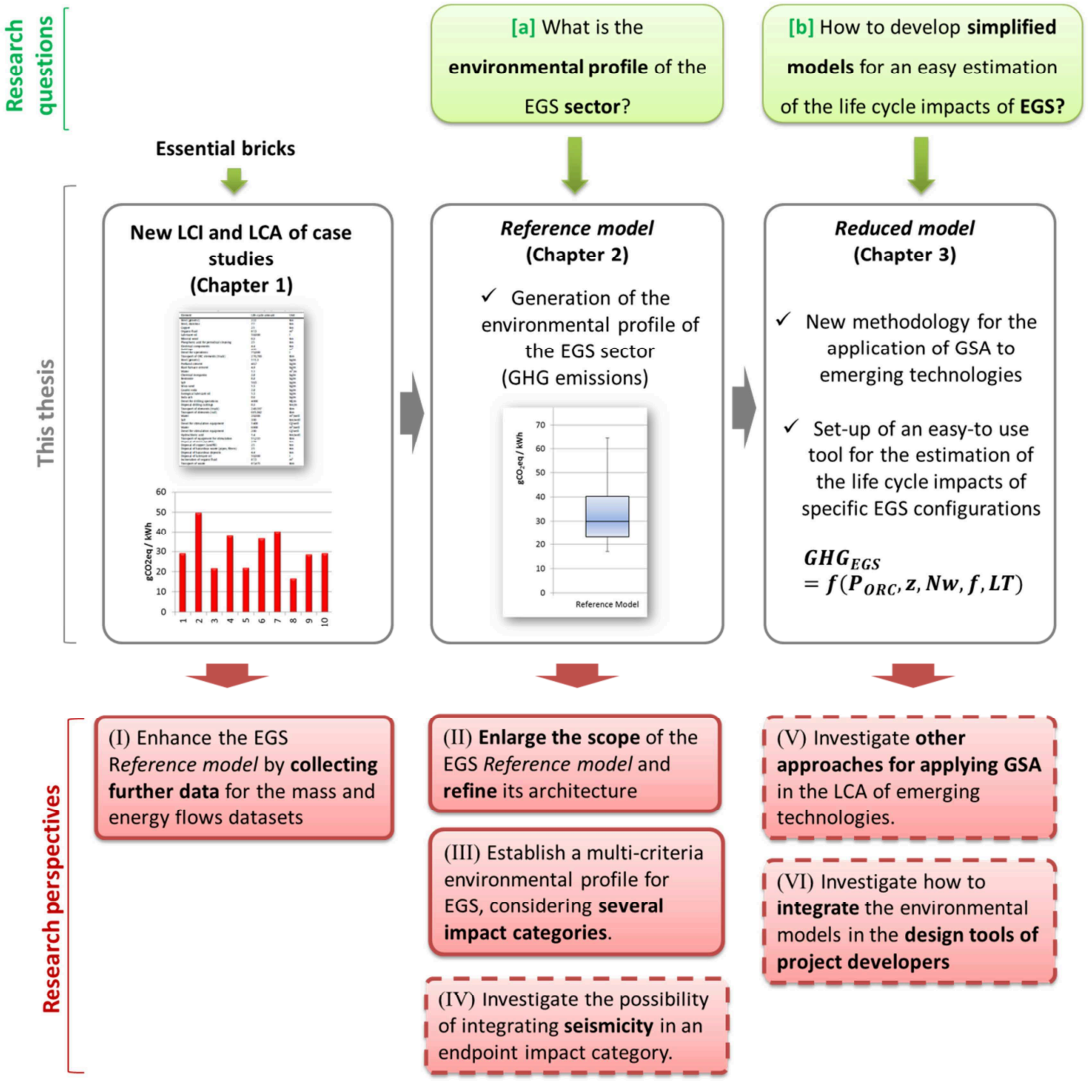


Figure 4.1 Propositions for future work (red boxes). Solid line: further developments in the environmental analysis of EGS. Dotted line: further developments in the methodological approach

They are represented by the red boxes in Figure 4.1 and are divided into two categories:

- further development in the environmental analysis of **EGS** (boxes encircled with a solid line);
- further developments in the **methodological approach** (boxes encircled with a dotted line) for the environmental analysis (applicable to the EGS case as well as to other technologies)

Our proposition are summarized in the list below and presented with more details in the following sections.

(I). **Enhance the EGS *Reference model* by collecting further data**. With the investigation of new EGS operations, new data can be collected to consolidate the modular datasets of the mass and energy flows involved over the life cycle (type of materials, quantities, etc.)

(II). **Enlarge of the scope of the EGS *Reference model* and refine its architecture**. The scope of the *Reference model* can be extended, including the use of electricity from the grid during the drilling phase, the cogeneration of thermal power, and other parameters. An updated environmental profile, representative of the EGS sector, can thus be generated. Further investigations can be also performed on the architecture of the model, for instance by exploring the possibility of expressing the installed power capacity as a dependent variable.

(III). **Establish a multi-criteria environmental profile for EGS, considering several impact categories**. Chapter 2 focused on the life cycle emissions of greenhouse gases. The same methodology can be applied to other impact categories, like for instance the depletion of resources.

(IV). **Investigate the possibility of integrating seismicity in an endpoint impact category.** In chapter 1 we discussed the importance of taking into account the seismicity risk when designing EGS. Further investigations can be performed regarding the possibility of considering seismicity issues when estimating the impacts on human health or ecosystem quality.

(V). **Investigate other approaches for applying GSA in the LCA of emerging technologies**. In chapter 3 we presented a strategy to identify the key parameters of the LCA model, based on the reiteration of several GSAs with a "OAT" (one factor at a time) approach. Other calculation strategies can be also investigated, like the one the we call "*GSA of the GSA*".

(VI). **Investigate how to integrate the environmental models in the design tools of project developers**. Potential users of the parameterized LCA models are the project developers, which have a strong field expertise. It is worth investigating how the environmental model can be integrated in their design and decision-making processes, which involve also other indicators like for instance the economic profit.

4.2.2 (I) Enhance the EGS *Reference model* by collecting further data

The *Reference model* relies on modular datasets presenting the mass and energy flows occurring during the life cycle of the plant. These are based on an extensive survey and data collection performed on the EGS site of Soultz-sous-Forêts at the beginning of this research work (in 2011), as well as interviews with several experts and a detailed literature review. Of course, our dataset can be improved by collecting further data: EGS being an emerging technology, every new operation can provide new insights for estimating their environmental performances.

In 2016 a new EGS installation has been inaugurated in Rittershoffen (France) and the surface part of the Soultz-sous-Forets has been revamped. By analyzing the recently installed equipment it will be possible to consolidate the calculations and the estimations presented in chapter 1. Furthermore, in the last two years two new LCA studies focused on EGS have been published (Martin-Gamboa et al. 2015, Treyer et al. 2015): in particular the latter considers the electricity supply during the drilling phase. Data from new published LCAs can feed our inventory with new information and can support our investigation regarding the variability of the model's parameters. All the datasets of our calculation model have been constructed to be easily updated.

In conclusion, there is room for improvement for the datasets of our *Reference model* and for the description of its parameters (variability ranges and probability distributions): the

collection of further data from new EGS operations and literature will improve our estimates or increase their reliability. The corresponding *Reduced model* may also be modified, since it depends on the abovementioned datasets and on the description of the inputs.

4.2.3 (II) Enlarge the scope of the *Reference model* and refine its architecture

The **scope** of the *Reference model* can be **enlarged** by considering different aspects not included in the current version, for instance:

- the type of energy used in the drilling phase, i.e. including the possibility of connecting to the national electricity grid ;
- the cogeneration of electrical power and heat.

The **architecture** of the *Reference model* can also be **refined**, deepening the analysis of the dependence relations among the parameters, for instance:

- the ORC power output can be considered a dependent parameter, function of the production, the heat capacity, and other variables;
- the number of wells can be also modeled as a function of the production flow rate.

Based on the propositions above, a possible new version of the *Reference model* would be function of ten independent parameters (green boxes in Figure 4.2): here we see some new inputs (***HC***, ***TYPE***, ***t,*** $\boldsymbol{P_{aux}}$), some of those used in chapter 2 are now dependent variables ($\boldsymbol{P_{ORC}}$, ***Nw*** and the load factor), and others have been slightly modified ($\boldsymbol{f_{Iw}}$, ***En***), as detailed hereafter.

Figure 4.2 shows how the life cycle energy output can be calculated from these parameters, highlighting the installed capacity and the flow rate as dependent variables (orange boxes). For the sake of clarity, such Figure does not represent the whole *Reference model* (like in Figure 2.1), i.e. the input data, the characterization factors, the LCI, etc., are not shown (therefore the variables ***t***, ***En*** and ***SFe*** are not linked to the other boxes because they are used to calculate the emissions and not the energy output). The following paragraphs discuss the abovementioned suggestions for enlarging the scope and refining the architecture of the *Reference model.*

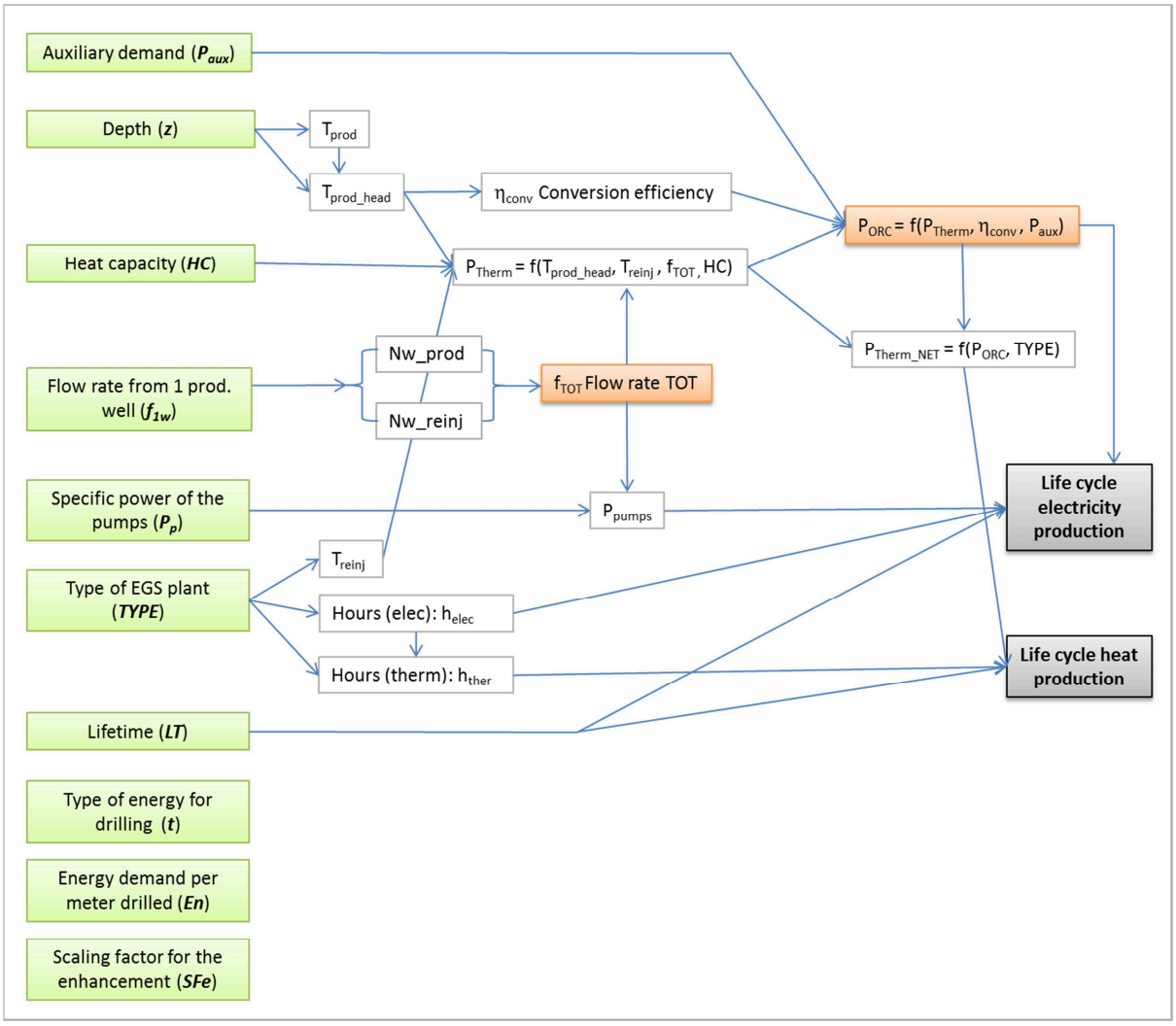


Figure 4.2 Ten independent parameters (green boxes) of a *possible* updated version of the *Reference model*. The installed capacity and the flow rate are now dependent variables (orange boxes)

4.2.3.1 Enlarge the scope by considering different types of energy for drilling

Our *Reference model* takes into account the consumption of diesel in stand-alone electric generators during the drilling phase. Although this is the most common practice for supplying energy for the drilling rig, the connection to the national electricity grid could also be possible. The use of fuel-based generator is often preferred because (i) it keeps safe from the risk of power shortage, which would endanger the success of the drilling (ii) the connection may be expensive especially when the site is far away from the grid (iii) the high power demand of the drilling machine may also entail the need of reinforcing the grid (which can be expensive and time-consuming). On the other hand, noise emission restrictions and local environmental regulations can make the grid connection the most favorable option.

Electricity-driven rigs where used for instance in the EGS sites of Basel and St. Gallen (Switzerland), and also in few other operations in Germany (Sauerlach, Kirchstockach, Pullach, which are not EGS sites) as reported by Menberg et al. (2016).

Given that a relevant share of the life cycle impacts are caused by the large amount of fuel burnt during construction of the boreholes (as shown in chapter 1), the use of electricity from the grid can have a significant impact on the environmental performances of the plant. As an example, this is shown in Fig. 4.3 considering the base case EGS discussed in chapter 1: the use of diesel in electricity-generating devices is set as a reference (all values are 100%), while the dotted line is related to the power supply from the French electricity grid.

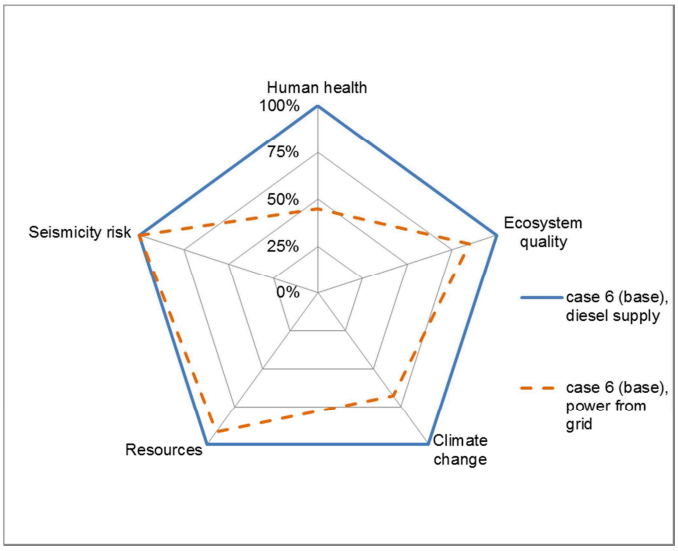


Figure 4.3 Comparison of the environmental impacts when considering the use of diesel generators and the electricity from the French grid for the energy supply in the drilling phase (based on the base case discussed chapter 1)

We observe a significant decrease in the climate change category (which accounts for the emissions of greenhouse gases) and in the human health category (which is largely influenced by NOx and PM emissions, that are principally related to the combustion of diesel). Obviously these results depend on the French energy mix, which relies largely on the use of nuclear power, a technology characterized by relatively low life cycle emissions of GHG. When considering the electricity mix of other countries that are less reliant on nuclear power or characterized by higher use of fossil fuel, the result can be completely different (moreover the environmental burden of the electricity mix in any country is also highly dependent on imports). For instance this is shown by Menberg at al. (2016), who compare the replacement of fuel with electricity from the Swiss and the German grid during the drilling phase: the

results are very different, given the high share of electricity production from coal power plants in Germany versus the use of low-carbon technologies like hydropower and nuclear in Switzerland. Menberg at al. (2016) also investigate the impact of using innovative non-contact drilling technologies like hydrothermal spallation, flame jet thermal spallation and electro pulse drilling. These emerging techniques can support the realization of deeper wells, possibly allowing to achieve higher thermal production and lower life cycle impacts.

Based on this analysis, a parameter indicating the type of energy technology for the drilling operation (***t***) can be included in the *Reference model*, as well as the electricity mix to be considered in the case of connection to the grid.

4.2.3.2 Enlarge the scope by considering the cogeneration of power and heat

As defined in its "technological characterization" in chapter 2, the systems considered by the *Reference model* produce only electricity. The scope of the model can be expanded by including the plants cogenerating electrical power and heat. It will be necessary to distinguish between the thermal power available at wellhead ($\boldsymbol{P_{Therm}}$) and the thermal power available for the final users ($\boldsymbol{P_{Therm_NET}}$). Different design options exists:

(i) the thermal production system is placed "in parallel" with respect to the ORC. In this case, $\boldsymbol{P_{Therm}}$ is either used for heating purposes ($\boldsymbol{P_{Therm_NET} = P_{Therm}}$) or to run the ORC generating electrical power ($\boldsymbol{P_{ORC}}$). One typical application of this configuration is the district heating: during summer, when the heat demand is lower or absent, the plant can be used to produce electricity.

(ii) the thermal power is produced "in series", after the ORC, as in Landau and in the case studies proposed by Frick et al. (2010). In this case, the $\boldsymbol{P_{Therm_NET}}$ available for the final user is lower than $\boldsymbol{P_{Therm}}$ and depends on the installed capacity of the ORC ($\boldsymbol{P_{ORC}}$). Since the geothermal fluid supplies both the electrical and thermal generation systems, the reinjection temperature $\boldsymbol{T_{reinj}}$ may be lower than the previous case (i). However, depending on the chemical properties of the geothermal fluid, it may not be possible to cool it down (extracting supplementary heat) below a certain temperature, since this may cause the formation of mineral scales and deposits in the pipes. Moreover the reinjection of cold fluid also entails the risk of deteriorating the geothermal resource. In conclusion, the generation of heat "in series" with the electrical production is still objet of studies.

(iii) Another possibility is to valorize the waste heat of the cooling system of the ORC. In this configuration, the organic Rankine cycle has one power input $\boldsymbol{P_{Therm}}$ and two power outputs ($\boldsymbol{P_{ORC}}$ and $\boldsymbol{P_{Therm_NET}}$).

Therefore, in order to take into account cogeneration heat and electricity in the *Reference model*, it will be necessary to:

- estimate the amount of materials and energy flows related to the additional equipment for the valorization of the thermal power: eg. the materials for the heat exchanger and the pipes, their transport, installation, disposal, etc.
- Introduce a parameter ("***TYPE***" in figure 4.2) indicating the design configuration of the EGS plant. According to ***TYPE***, the EGS will be designed to produce only electricity (as in this manuscript), only heat (as in Rittershoffen) or both electricity and heat (following one of the three options described above). Depending on ***TYPE***, the model will estimate:
    - The reinjection temperature $\boldsymbol{T_{reinj}}$, which shall be lower (eg. 40-50°C) in case of production of heat and power in "series" (ii) with respect to the other design options.
    - The yearly equivalent amount of hours of electricity and heat production at full capacity (respectively $\boldsymbol{h_{elec}}$ and $\boldsymbol{h_{ther}}$). For instance, $\boldsymbol{h_{elec}}$ and $\boldsymbol{h_{ther}}$ shall be different in case of cogeneration "in parallel" (case (i) above) or equal in case of cogeneration "in series" (case (ii) above). $\boldsymbol{h_{ther}}$ and $\boldsymbol{h_{elec}}$ will be set to zero if the EGS produces only electricity or heat. These two parameters, that depend from ***TYPE***, conceptually correspond to the load factor (***LF*** in the previous chapters), which was previously set as an independent parameter.
- Establish allocation rules, because the environmental burdens must be split between the two products of the EGS: electricity and heat.

According to the ISO standard (ISO 2006a, 2006b), when allocation cannot be avoided (through system subdivision), it can be made according to physical, economical or other properties. A simple method is to set the allocation referring to the economic values of the thermal and electrical MWh, as discussed by Treyer et al. (2015). Frick et al. (2010) use a method based on the exergetic content of the different energy flows, but this could be quite complex to be implemented within our parameterized model.

The amount of available geothermal power at wellhead $\boldsymbol{P_{Therm}}$ can be calculated from a number of parameters, as detailed in the following section.

4.2.3.3 Set the ORC power output as a dependent variable

As discussed in section 2.3.2, in the *Reference model* the ORC power output (P_{ORC}) is defined as mathematically independent from the other parameters: this choice responded to a trade-off between accuracy and simplification. In fact P_{ORC} is an easy accessible variable with an industrial relevance, and its direct use in the *Reference model* allowed overcoming the difficulty of expressing P_{ORC} as a function of other parameters through some relations widely valid in central Europe. However, further studies can be carried out to characterize more accurately the relations between design parameters (like the borehole length) and factors depending on the geological conditions (like the temperature of the geothermal fluid): some suggestions are formulated in this section.

Temperature of the geothermal fluid as a function of the depth

It is not possible to define a specific function $\boldsymbol{T_{prod}}$ = F(z), valid in different locations in central Europe, between the drilling depth (z) and the temperature of the geothermal resource ($\boldsymbol{T_{prod}}$): any attempt would result in a too site-specific correlation (see also Figure 1.3, showing the temperature logs in Soultz and Landau). An opposite approach would consist in considering z and $\boldsymbol{T_{prod}}$ independent variables, but that would be too approximate since indeed $\boldsymbol{T_{prod}}$ increases "somehow" with z. An intermediate solution is to perform, at any given depth z, a random sampling of $\boldsymbol{T_{prod}}$ within a fixed interval (encompassing for instance a $\Delta\boldsymbol{T_{prod}}$ of 30°C), as represented in Figure 4.4. The grey zone in the Figure have to be carefully defined, considering the uncertainty related to the temperature of the geothermal resource at different depths, in accordance with the best available knowledge of the geological regions within the scope of the model. With this approach, the unlikely scenario of a very high $\boldsymbol{T_{prod}}$ at a very shallow depth (or the other way around) will be avoided: for example, at a depth z=3000 meters, the calculation code would estimate a random value of $\boldsymbol{T_{prod}}$ in the interval 140°C-170°C (or any other, defined by the modeler). It could also be possible to establish a probability distribution, eg. Gaussian centered in the middle of the interval of production temperature.

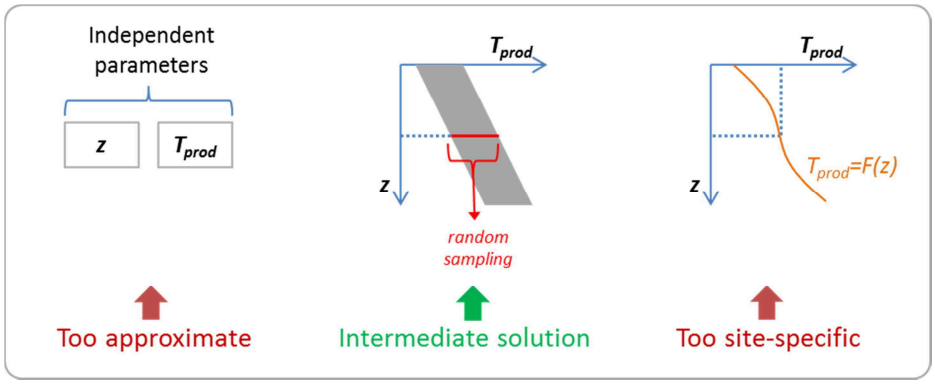


Figure 4.4 Solution for establishing a relation between the production temperature and the drilling depth

The temperature of the produced geothermal fluid at well head T_{prod_wh} will be some degrees lower than T_{prod} due to the cooling effect occurring along the borehole while the fluid is pumped to the surface: the difference of temperature between T_{prod_wh} and T_{prod} can be assumed as proportional to the borehole length z.

Conversion efficiency as a function of the production temperature

The conversion efficiency η_{conv} of the EGS is defined as the ratio between the gross power output of the electrical generator of the ORC and the thermal power available from the geothermal resource. It incorporates the thermal efficiency of the ORC and the other efficiencies related to the equipment (heat exchanger, electrical generator, etc.). Tester and coworkers (MIT 2006b) extrapolate a correlation among η_{conv} and the temperature of the geothermal fluid T_{prod_wh}, based on the analysis of the performances of several binary geothermal plants. It is basically a linear function, estimating a η_{conv} ranging from about 7% to 15% according to typical values of T_{prod_wh}. The relation identified by Tester et al. could therefore be used in our model, estimating η_{conv} from T_{prod_wh}, which would be calculated from the depth (z) as previously discussed.

Auxiliary power demand and heat capacity as independent parameters

The power demand P_{aux} of the auxiliary equipment of the ORC (the air cooler, the circulation pump, etc.) can also be used as an independent parameter. In the ten scenarios discussed in chapter 1 it was estimated to be 20% of the gross power output of the generator. A variability range can be considered (for instance 15 to 25%) based on a survey of existing binary plants.

The heat capacity ***HC*** of the geothermal fluid depends on its temperature and its mineral content. In chapter 1 a value of 4 kJ/(kg ·K) is assumed for the ten case studies. ***HC*** is generally in the range 3.6-4.12 kJ/(kg·K), thus the heat capacity can be used as a model parameter sampled within such interval.

Calculation of P_{therm} and P_{ORC}

Starting from the abovementioned parameters, the *Reference model* would calculate for each scenario the electrical power output ($\boldsymbol{P_{ORC}}$) and thermal power available at wellhead ($\boldsymbol{P_{therm}}$) with the formulas below, where $\boldsymbol{f_{TOT}}$ is the total flow rate (see next section) and $\boldsymbol{\eta_{conv}}$ incorporates all the efficiencies of the different equipment of the conversion chain.

$$P_{therm} = f_{TOT} \cdot HC \cdot (T_{prod_wh} - T_{reinj}) \qquad (4.1)$$

$$P_{ORC} = \eta_{conv} \cdot P_{therm} - P_{aux} \qquad (4.2)$$

In case of cogeneration, the available thermal power for the final users ($\boldsymbol{P_{therm_NET}}$) will be calculated as a function of $\boldsymbol{P_{ORC}}$ and $\boldsymbol{P_{therm}}$ according to the configuration of the EGS (cogeneration in parallel, in series, etc. as discussed before).

4.2.3.4 Set the number of wells as a dependent variable

In our model, the number of wells (***Nw***) and the total produced flow rate (***f***) are independent parameters. Today project developers in France generally consider a default value of 2 wells at design stage to limit the investment costs (and when the productivity is too low, the realization of a deviated side track at the bottom of the borehole is preferred with respect to the construction of a third well). However, given that our *Reference model* aims at being generic for central Europe, a correlation may be introduced in order to consider up to 3 wells and account for the set-up of an appropriate strategy to reduce the risk of induced seismicity, as discussed in chapter 1. For instance, instead of considering the total flow rate, we could use the flow rate from only one well (called $\boldsymbol{f_{1W}}$) as an input parameter. Then, in the case of a variability range of 25-100 kg/s (as in the *Reference model*), an empirical law like the one below could be established:

- If $\boldsymbol{f_{1W}}$ is between 25 and 40 kg/s: the EGS have either 2 wells (1 for production and 1 for reinjection) or 3 wells (2 for production and 1 for reinjection: then the reinjection flow rate would be maximum 80 kg/s). A probability distribution among these two options is to be established.

- If f_{1W} is between 40 and 70 kg/s: the EGS have 2 wells (1 for production and 1 for reinjection). The 3-wells option is not considered because 2 production wells would entail a too high reinjection rate (increasing the seismicity risk) or a second reinjection well would not be necessary (from an economic point of view)
- If f_{1W} is between 70 and 100 kg/s: the EGS have 3 wells (1 for production and 2 for reinjection) to avoid high seismicity.

The options above are provided just as an example: they need to be discussed further with project developers and adjusted according to the hypothesis regarding the produced flow rate. Another approach worth investigating is to consider f_{1W} as a function of the depth, starting from the observation that a greater depth it is more difficult to obtain a high flow rate.

In conclusion different options can be considered to enlarge the scope and refine the architecture of the *Reference model*, introducing new parameters to account for the use of electricity for drilling (***t***), the cogeneration (***TYPE***), the calculation of the installed capacity as a dependent variable (function of ***z***, ***HC***, P_p, ***TYPE***, P_{aux} and f_{1w}). The definition of the variability of these parameters and of the mathematical relations needs to be carefully undertaken. This needs the collection of new data, a detailed study of how these variables interact and discussion with expert and project developers. Such work, introduced in the present section, is proposed for future studies.

4.2.4 (III) Establish a multi-criteria environmental profile for EGS, considering several impact categories.

In chapter 2 and 3 of the present manuscript we focused on the "climate change" impact category, presenting the results of the *Reference model* and of the *Reduced model* in terms of gCO_2-equivalent. By definition, life cycle assessment is a multi-criteria methodology, moreover in order to gain a thorough understating of the environmental performances of EGS (or any other energy technology) it is advisable to consider multiple indicators.

The methodological approach to consider other environmental indicators is the same described in chapter 2, but it will be necessary to use other characterization factors. As shown in Figure 2.1, once produced the life cycle inventories of the four parts of the model (wells,

ORC, pumps, stimulation) through a parameterized approach, we use the IPCC GHG characterization factors (IPCC 2013) to quantitatively convert each GHG according to its respective Global Warming Potential related to CO_2, the reference gas. In order to study for instance the impacts in terms of *ozone depletion*, which is a "midpoint" impact category, it will be necessary to use the appropriate characterization factors (see European Commission, 2012) to calculate the impacts in terms of kgCFC-11eq/kWh. Moreover, in order to consider an "endpoint" category like the *ecosystem quality* (as we did in chapter 1) it will be necessary to embed in the calculation model (i) the characterization factors of all the midpoint categories related to the *ecosystem quality*, like acidification, eutrophication, terrestrial ecotoxicity, etc., and (ii) the factors used to aggregate the midpoint into the endpoint category results (see Annex 3). The choice of the impact assessment method may be also set as one of the parameters of the model.

However, for different impact categories, different sets of key-parameters may be identified through the global sensitivity analysis. Concretely, the five parameters identified in chapter 3 as the most relevant for the estimation of the GHG emissions may not be the most relevant for the calculation of the ozone depletion impacts (or any others). Therefore the use of multiple *Reduced models* related to different environmental indicators may result, for the final user, in handling a large number of parameters.

In conclusion, a multi-criteria approach is of course more complex than the one based on a single indicator, however the use of a *set* of formulas allowing rapid calculation of the life cycle impacts is still much easier and less time demanding than undertaking the whole LCA procedure. Therefore it is proposed, for future works, to focus on other impact categories and to develop the related *Reduced models*.

4.2.5 (IV) Investigate the possibility of integrating seismicity in an endpoint impact category.

As previously discussed, different indicators can be used to present the LCA results. The modeler must use the most appropriate ones (ie. midpoint or endpoint categories) according to the product and the scope of the analysis. In chapter 1 we introduced the "seismicity risk", estimated with an empirical approach, as a relevant criterion to be taken into account at design

stage. Indeed we observe that this risk increases with the environmental benefit, since high geothermal flow rates entail high energy production but also the need of massive rejection rates.

In our multi-criteria analysis (Figures 1.17, 1.18, 1.19) we compare such indicator with other endpoint categories such as human health, ecosystem quality, climate change and resources depletion. However, the consideration of seismic issues in LCA modeling can be further investigated. For instance, it could be interesting to place the seismicity as a midpoint category and study how to take into account its effects when estimating the impacts on human health or ecosystem quality. Concretely this corresponds to address the following question: *for a given seismic event (or several events over a given period), how many DALY are generated? And of many PDF·m^2·y?*

It is worth pointing that in chapter 1 we focus on the "risk" of seismicity and a high risk doesn't necessarily entail high damages (and, with the perspective above, high DALY and high PDF·m^2·y). Therefore the probabilistic aspect of the problem must also be accounted for in the LCA modelling. The exploration of the different aspects related to the integration of seismicity in the life cycle impact assessment is proposed for future works.

4.2.6 (V) Investigate other approaches for applying GSA in the LCA of emerging technologies

In chapter 3, we showed that the description of the inputs may have a significant influence on the GSA results (for instance, the ranking of the ***LT*** fluctuates over four positions, depending on the description of its variability) and on their exploitation (in our example, we finally decide to include ***f*** and ***LT*** in the set of key variables). Chapter 3 presented the development of a first methodological approach to understand the magnitude of the influence of the inputs' description on the identification of the key parameters and to take appropriate actions if needed. Some suggestions to reduce the computational cost are also formulated at the end of the chapter, like the realization of an initial screening to reduce the number of uncertain parameter, for instance through the method proposed by Morris (1991). On the other hand, our calculation strategy may be also developed further as discussed in this section, increasing its complexity but possibly improving its robustness.

In the proposed methodology, we observe the ranking's variations that occur when we modify the description of just *one parameter at a time* (while, for the others, the baseline description is set). A more elaborated calculation strategy may be set up, for instance by modifying the description of *all the parameters at the same time,* as presented in Fig. 4.5: for every single GSA (besides bootstrapping), each of the nine parameters would be randomly characterized by one of the alternative distributions. Conceptually this would correspond to the realization of a sort of "*GSA of the GSA*". We identified the following challenges related to the latter approach:

Computational cost. The "GSA of the GSA" approach would entail a dramatic increase of the computational resources needed. In fact, in order to explore the entire space of combinations, the number of ranking to be established would be the following:

$$Total\ number\ of\ rankings\ (GSA\ of\ the\ GSA) = \left[\prod_i^N k_i\right] \cdot B \qquad (4.1)$$

In the case of the EGS *Reference model*, considering that N=9 (number of parameters), B=100 (number of bootstraps) and k_i=5 or 3 (number of alternative descriptions per parameter) this corresponds to about 120 million different rankings. Even with lower values for k_i or B, the total amount of repeated GSAs is in the order of millions, namely three orders of magnitude higher than the one used in this manuscript (3500 rankings).

Interpretation of the results. Using the "*one parameter at a time*" (OAT) approach, the interpretation of the results is quite straightforward, given that the changes in the ranking can be ascribed only to one input at a time (ie. the one whose description has been changed). With a non-OAT approach, it would be more complicated to explain the variability of the results (in this case, the variability of the Sobol Indices) with respect to the variability of the description of the inputs. In fact, it would be necessary to establish "higher level" sensitivity indices (ie. some sort of "Sobol Indices of the Sobol Indices"): these indicators must be able to indicate *which* description of the input is responsible for high variations in the ranking (and especially in the set of key parameters). In other words: if we perform 120 million GSAs and we observe that, in the 120 million resulting ranking, the position of the flow rate ***f*** fluctuates between the 2nd and the 6th position, will we be able to say if this was caused by the modification of the description of the depth ***z***? Or by the modification of the description of the load factor ***LF***? Or maybe both of them? Or one more than another?

In conclusion, in chapter 3 we aimed at presenting a first, explorative approach – based on a "OAT" calculation strategy - to address the problem of the sensitivity of the GSA results. We believe that such OAT reiteration of the GSA allows drawing useful recommendations while keeping the computational strategy relatively simple. It also constitutes a first brick in the investigation of this sensitivity issue: for the first time in the LCA literature we show, with a concrete application, the high influence of the initial hypothesis on the GSA results. However, it is worth investigating the opportunity and the costs/benefits of developing more complex calculation strategies. In this framework, the exploration of a "GSA of the GSA" approach and the set-up of appropriate indicators to exploit its results is proposed for future studies.

§ GSA	z	SFe	f	d	LF	LT	P_p	Nw	P_{ORC}
§1 (BASELINE) x100 bootstraps	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§2 (x 100)	TYPE 2	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§3 (x 100)	TYPE 3	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§4 (x 100)	TYPE 4	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§5 (x 100)	TYPE 5	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§6 (x 100)	BASELINE	TYPE 2	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§7 (x 100)	BASELINE	TYPE 3	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§8 (x 100)	BASELINE	TYPE 4	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
§34 (x 100)	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	TYPE 4
§35 (x 100)	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	TYPE 5

Calculation approach used in Chapter 3

§ GSA	z	SFe	f	d	LF	LT	P_p	Nw	P_{ORC}
§1 (BASELINE) x100 bootstraps	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE	BASELINE
§2 (x 100)	TYPE 4	TYPE 2	TYPE 3	TYPE 3	TYPE 5	TYPE 2	TYPE 4	TYPE 2	TYPE 5
§3 (x 100)	TYPE 2	TYPE 5	BASELINE	TYPE 4	TYPE 4	TYPE 5	TYPE 2	TYPE 5	TYPE 2
§4 (x 100)	TYPE 5	TYPE 4	TYPE 5	TYPE 2	TYPE 3	TYPE 4	TYPE 5	BASELINE	TYPE 3
§5 (x 100)	TYPE 3	TYPE 2	TYPE 4	TYPE 5	TYPE 4	BASELINE	TYPE 3	TYPE 2	TYPE 3
§6 (x 100)	TYPE 2	BASELINE	TYPE 5	TYPE 3	TYPE 5	TYPE 5	TYPE 2	TYPE 4	TYPE 5
§7 (x 100)	TYPE 5	TYPE 3	TYPE 2	TYPE 4	TYPE 4	TYPE 3	TYPE 5	TYPE 3	TYPE 4
§8 (x 100)	BASELINE	TYPE 4	TYPE 5	TYPE 5	TYPE 2	TYPE 4	BASELINE	TYPE 4	TYPE 2
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
§1171874 (x 100)	TYPE 2	TYPE 4	BASELINE	BASELINE	TYPE 3	TYPE 2	TYPE 4	TYPE 4	TYPE 3
§1171875 (x 100)	TYPE 4	TYPE 5	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 2	TYPE 4	TYPE 5

Other approach: "GSA of the GSA"

Figure 4.5 Calculation approach used in chapter 3 for the reiteration of the GSAs versus the "GSA of the GSA"

4.2.7 (VI) Investigate how to integrate the environmental models in the design tools of project developers

In this manuscript we highlighted the advantage, for decision-makers, of having available parameterized models for the estimation of the life cycle impacts. However as underlined in the conclusions of chapter 3, different types of decision-makers (potential users of our model) exist: for instance EGS project developers and policy makers. The *Reduced model* is principally aimed to the latter category, because it is easy to use and does not require a strong geothermal background, being function of few accessible key parameters.

On the other hand, to promote the use of environmental criteria in the development of renewable energy systems, it is also important to develop tools specifically tailored for **project developers**. To do so, it is necessary (i) to consider that project developers have a field-specific knowledge that makes them capable to handle a large amount of technical parameters (ii) to investigate how the calculation of the environmental indicators can fit in the design process of the power plant.

Starting from the *Reference model* (used for the generation of the environmental profile of the sector, chapter 2), we propose the following generic methodology to develop a tool, tailored for project developers, for the analysis of specific plant configurations.

a. Identify the decision-making indicators used by project developers (eg. net present value, energy performance, etc.) and the design parameters used to calculate them.
b. Compare such list of design parameters used by project developers with the set of input parameters used in the *Reference model.*
c. Identify which parameters can feed both the calculations: the estimation of the life cycle impacts and the computation of other decision-making indicators. Then, build a parameterized environmental model that takes into account this set of "common" parameters.

We initiated the application of this methodological approach to the EGS sectors (Figure 4.6), following discussions with French project developers (Genter and Trebaol, 2016).

Two common decision-making indicators are used in the design process of EGS: the **internal rate of return (IRR)** and the **social acceptability**. The IRR depend on many parameters related to the geothermal resource (production temperature, flow rate, etc.), to the size of the

plant (borehole length, surface equipment) and to the energy demand profile (i.e. amount of heat and electricity sold to the final users). Regarding the social acceptability, project developers use to initiate a communication campaign and a debate with the local community well in advance with respect to the start of the works (presenting the advantages of exploiting renewable energies, the positive impact on the local employment, etc.) in order to avoid NIMBY phenomena ("not in my back yard"). Moreover, when the EGS is close to residential areas, the use of electricity from the grid instead of diesel generators has to be considered to limit the noise nuisance. Lastly, based on the lesson learnt in Basel and Landau (cf. the seismic issues described in section 1.2.4), the intensity of the stimulation and the amount of reinjected flow rate need to be properly managed to avoid relevant seismic phenomena (that could negatively affect the social acceptance).

Following the generic methodology presented above

a. we identified the different parameters used by project developers to assess the internal rate of return and the acceptability (green and violet boxes on the left of Figure 4.6);
b. we compared them with those used in the *Reference model* shown in Figure 4.2 (in its potentially updated version)
c. we selected the ones that can feed the environmental calculation (green boxes in Figure 4.6). It is worth to underline that the latter parameters don't include those necessary for the calculation of the life cycle electricity/heat production (like the lifetime, the load factor, the geothermal temperatures, etc.): in fact, project developers have already their own models to estimate the energy output[4]. Furthermore, the parameters in the green boxes don't have to be necessarily independent: indeed, they are used for the study of specific EGS configurations and not for the generation of the environmental profile.

[4] For instance, an EGS project developer in general knows with sufficient precision the expected temperature of the geothermal resource ($\mathbf{T_{prod}}$), since the latter is estimated with a detailed exploration campaign using different techniques. Therefore, we do not need to let the model estimate $\mathbf{T_{prod}}$ with a random sampling (as proposed in section 4.2.3.3 for the *Reference model*): the user will directly use the appropriate value of $\mathbf{T_{prod}}$ in his tool calculating the energy output.

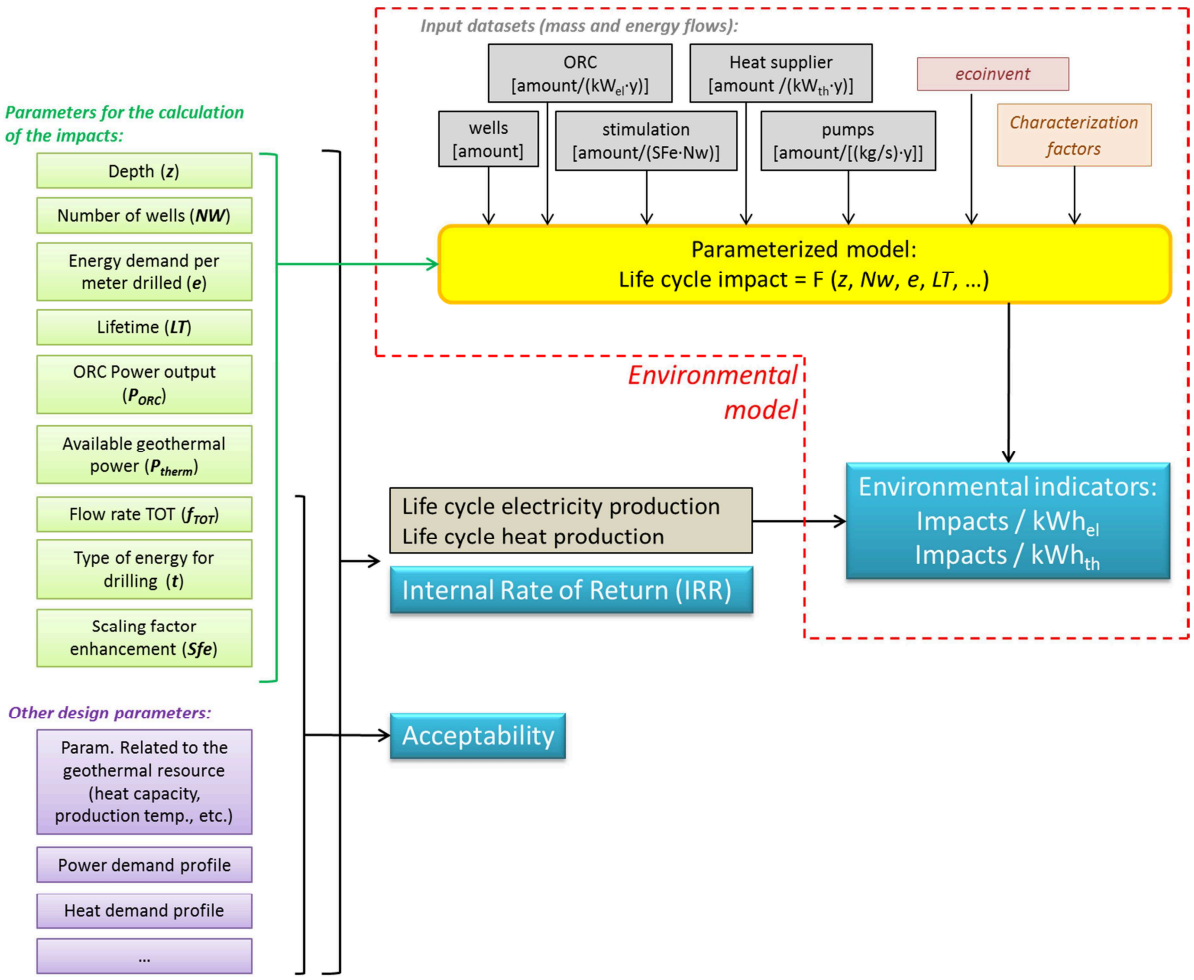


Figure 4.6 Representation of how the environmental model can fit in the design process of EGS

In this framework, our parameterized model (yellow box in Figure 4.6) will be based on (i) the dataset of the mass and energy flows in the grey boxes (ii) the parameters in the green boxes, which will scale-up the datasets (iii) the ecoinvent background data and the characterization factors. This allows calculating the life cycle impacts (for instance, the total GHG emissions of the plant). Afterwards we will retrieve the values of the electricity and heat production (issued from the existing tools used by the project developers) to calculate the environmental indicators (impact/kWh_{el} and impact/kWh_{th})

In conclusion, Figure 4.6 shows a first conceptual proposition about how the calculation of the environmental performances (boxes within the red dotted line) may fit in the design process of EGS, which involves also other important indicators like the IRR and the social acceptability. In this framework, different design options can be compared considering at the same time economic, social and environmental criteria. For instance the environmental model

can show, among different EGS configurations with the same IRR and same acceptability, which is the one that entails the higher environmental benefit. Or, it can show if a configuration characterized by a slightly lower IRR allows much better environmental performances, thus it is worth to be taken it into account. The propositions formulated in this section regarding the architecture of the model need to be discussed further with project developers: this constitutes an interesting area of research for future works.

4.3 General conclusions

In the public debate regarding the mitigation of the environmental impacts of human activities, the development of robust decision-making tools is a key factor to support the implementation of consistent environmental policies and to promote the generalization of optimal configurations for the energy systems.

This thesis focused on the analysis of a promising renewable energy-based technology, the enhanced geothermal system, providing useful insights regarding their environmental performances. We developed a parameterized model representative for the sector allowing a comparison with other energy technologies and highlighting the environmental suitability of EGS when considering the emissions of GHG and the impacts on the climate change. Furthermore we developed a simplified model, aimed at decision-makers, allowing a very rapid estimation of the life cycle emissions of EGS from five key parameters. We also developed a protocol for the application of global sensitivity analysis in the LCA of emerging technologies, overcoming the difficulties related to the high uncertainties of such environmental models. The EGS sector is expected to grow considerably in the next few years. In this context, this thesis contributes to the environmental design of this kind of power plants and aims at supporting the set-up of configurations inducing lower impacts.

This thesis also aims at feeding the environmental studies of other energy sectors. In fact, the methodological approach presented in this manuscript can be applied to different technologies. The process of setting-up parameterized models accounting for a large number of configurations of the analyzed power plants can be replicated to other energy systems, promoting a consistent comparison of their environmental profiles. Moreover, the proposed protocol for the identification of the key parameters can be also used in the study of other energy technologies, promoting the set-up of other *Reduced models* for the decision makers.

Lastly, this thesis opens a number of research perspectives: several propositions, focused on the EGS sector and on our methodological approach, have been formulated in this conclusive chapter. With the work presented in this manuscript, and through the future works that will we based on our researches, we aim at contributing to the efforts made by the global community to develop environmentally friendly solutions responding to our energy needs.

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Annexes

Annex 1 – The EGS power plant in Soultz-Sous-Forêts

The European experience in the development of EGS started in the late ‘80s in Soultz-sous-Forêts, a small town in the Alsace region in France. Between 1987 and 1998, following an exploration phase, a 2-boreholes system was realized (wells called GPK1 and GPK2) at a depth of about 3600 m. In the following decade, GPK2 was deepened to ~5100 m, two other boreholes (GPK3 and GPK4) were drilled at about the same depth and 3-wells circulation tests were carried out. Along these years, researches were conducted in different fields (stimulation, seismicity, scale formation, etc.) and Soultz became the most advanced R&D site of the sector worldwide. In 2007 the ORC system was installed and the power plant started producing electricity in 2008. Following a few years of exploitation, some operational issues were encountered in the geothermal loop and the surface system. Therefore in 2015 the surface part was revamped, the ORC and pumping equipment were replaced and the plant restarted operating in 2016. Extensive literature has been produced by the researchers and project developers based in Soultz, presenting the lesson learnt from this pilot EGS: see for instance Genter et al. 2010, 2015, 2016 and Labex-Géothermie 2016). The pictures below have been taken in 2016 and show the surface equipment: the wellheads, the heat exchanger, the electricity generation unit and the aircooler.



Figure A.1. Surface equipment of the EGS in Soultz-sous-Forêts (wellheads)



Figure A.2 Surface equipment of the EGS in Soultz-sous-Forêts (panoramic view)



Figure A. 3 Surface equipment of the EGS in Soultz-sous-Forêts (ORC equipment)



Figure A.4 Surface equipment of the EGS in Soultz-sous-Forêts (aircooler)

Annex 2 – Validation of our dataset of the materials and processes

A validation of our dataset of the mass and energy flows is proposed through a comparison, with harmonized assumptions, with the LCA results of one of the case studies (scenario B1) presented by Frick et al. (2010).

The B1 plant is equipped with two wells drilled at a depth of 4.7 km, has a lifespan of 30 years and an annual net power output of 7 679 MWh, operating 7000 hours per year. All these parameters have been integrated into our model in this simulation. The considered impact categories are: impacts on climate change (CO_2-equivalent), demand of finite energy resources (kJ), acidification ($mgSO_2$-equivalent) and eutrophication effects ($mgPO^{3-}_4$-equivalent), as defined in Frick et al. (2010).

The most relevant difference between our model and scenario B1 is the amount of diesel used for drilling operations: Frick et al. assume 7.5 GJ/m while 4 GJ/m are proposed in our study. Hence, given the high influence of this data on results, the calculation is performed using all the data presented in Table 1.4 of the manuscript except for diesel consumption, which is set at 7.5 GJ/m in conformity with Frick et al. In other words, we are conscious of our different estimation regarding the fuel, and we use this simulation in order to test the rest of the inventory.

As shown in Fig. A5, results from our model (adapted to scenario B1 conditions) are coherent with the confidence ranges of Frick et al.'s study. Differences are due to the slight dissimilarities in the lifecycle inventories' assumptions. Uncertainties on the results are calculated through Monte Carlo analysis performing 5000 simulations. Our larger uncertainty ranges for acidification and eutrophication categories can be explained by the high uncertainty attributed by ecoinvent to the related emissions, essentially NOx and PM (see also Lacirignola and Blanc 2012c). This positive comparison allowed us to assess the robustness of our model and hypothesis and to proceed with the calculation of the results of the 10 scenarios (section 1.4 of the manuscript).

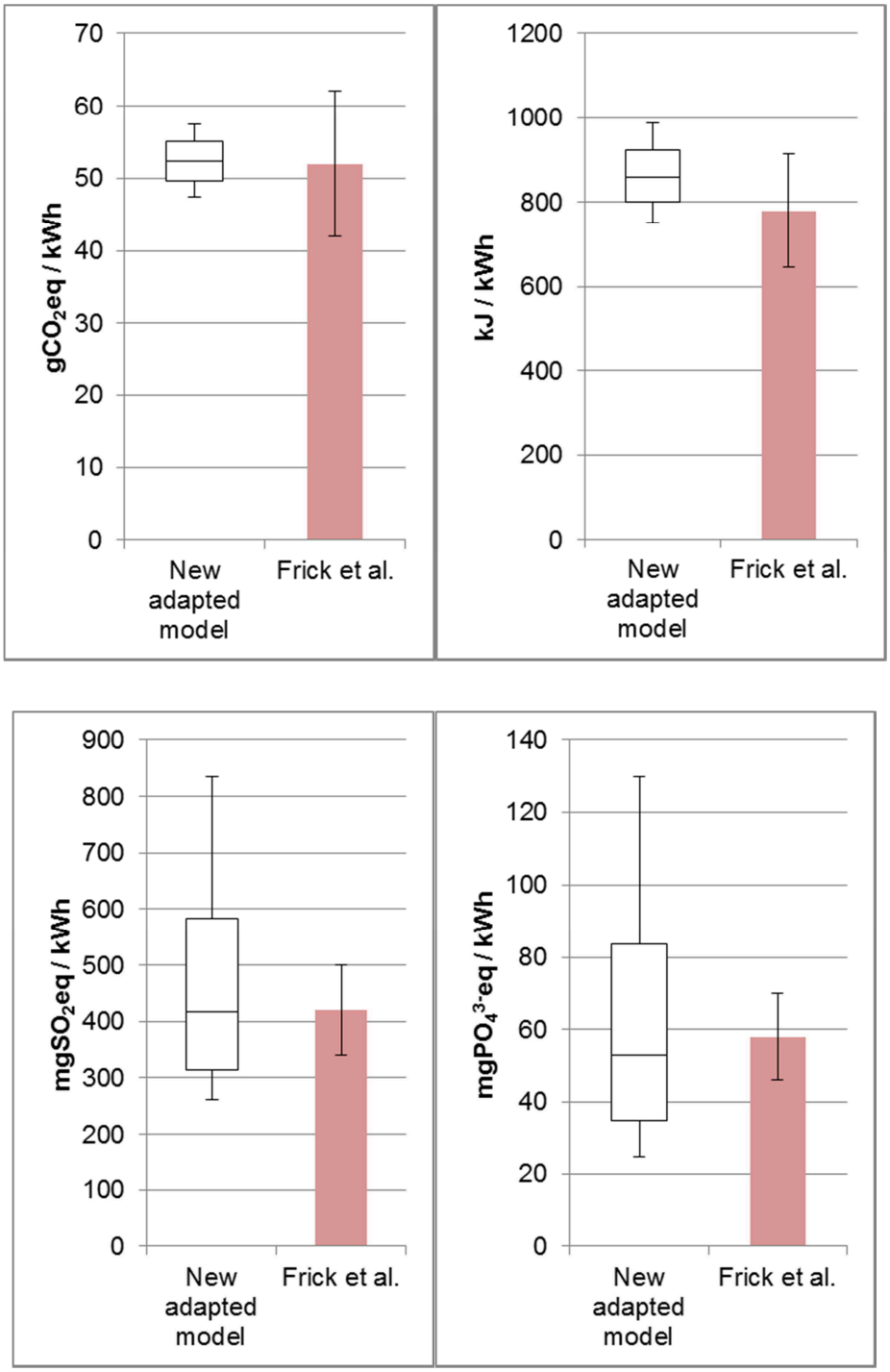


Figure A.5 Comparison of the results of our LCA model (adapted to the hypothesis of the scenario B1) with the results of Frick et al. (2010). Uncertainties are calculated with Monte Carlo Analysis (5000 simulations) Top and bottom of the box: 25th and 75th percentile. Whiskers: 10th and 90th percentile.

Annex 3 – Life cycle impact assessment methods

Following the ISO standard, life cycle impacts are expressed through midpoint categories and endpoint (or damage) categories. The impact assessment phase of the LCA is performed by aggregating the elementary flows of the LCI (for instance, the quantity of methane emitted in the atmosphere, the quantity of carbon dioxide, etc.) into such categories, as represented in Figure A.6.

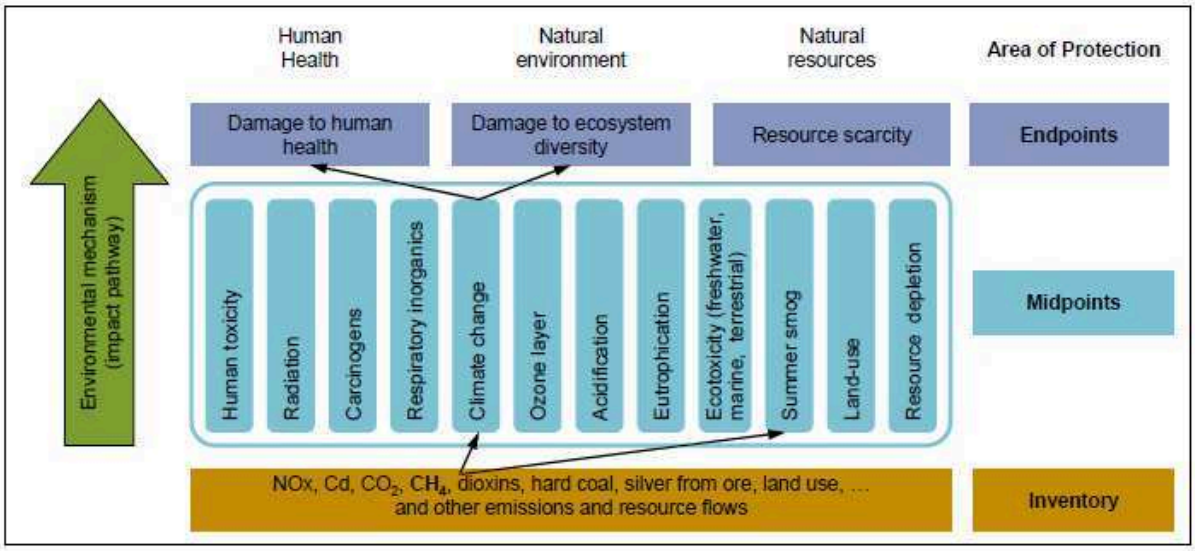


Figure A.6 Schematic view of the life cycle impact assessment, from inventory to endpoints category (from the ILCD handbook, ILCD 2010)

Midpoint indicators are used to model the impacts located somewhere along the environmental mechanism. For instance, all the flows of substances that have an effect on the *ozone layer depletion* are aggregated into the same midpoint category and expressed with a common indicator (in this case, *grams of CFC-11 equivalents*).

One or more midpoint indicators can be then grouped into **endpoint** indicators, which consider the damages on different areas of protection (e.g. the human health or the ecosystem quality).

Over the last two decades, different life cycle impact assessment (LCIA) methods have been developed, oriented on modelling either the midpoint or the endpoint categories. For instance among the most popular methods we can cite Eco-indicator99 (Goedkoop and Spriensma 2000), CML (Guinée et al. 2002), IMPACT2002+ (Jolliet et al. 2003) or ReCiPe (Goedkoop et al. 2008). A presentation of these methodologies is proposed by Jolliet et al. (2010).

Furthermore The *ILCD Handbook* produced by the JRC of the European Commission (ILCD 2010) classifies the available characterization methods according to their quality into different recommendation levels.

In chapter 1, we estimate the life cycle impacts of EGS using the IMPACT2002+ method. The latter considers fifteen midpoint categories and four endpoint categories: Human health (DALY), Ecosystem quality (PDF·m^2·y), Climate Change (kgCO_2eq into air) and Resources (MJ) (the definitions of the endpoint units is given in section 1.3.3 of the manuscript), as represented in Table A.1. The endpoint indicators are obtained from the midpoint categories by using the characterization factors reported in Table A.2.

Table A.1 Midpoint categories with their reference substances and damage categories of the IMPACT 2002+ method

Midpoint categories	**Midpoint reference substance**	**Damage category**	**Damage unit**
Human toxicity (carcinogens + non-carcinogens)	kg_{eq} chloroethylene into air	Human Health	DALY
Respiratory inorganics	kg_{eq} chloroethylene into air		
Ionizing radiations	Bq_{eq} carbon-14 into air		
Ozone layer depletion	kg_{eq} CFC-11 into air		
Photochemical oxidation (=Respiratory organics for human health)	kg_{eq} ethylene into air		
Aquatic ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	PDF·m^2·y
Terrestrial ecotoxicity	kg_{eq} triethylene glycol into water		
Terrestrial acidification/nutrification	kg_{eq} SO_2 into air		
Aquatic acidification	kg_{eq} SO_2 into air		
Aquatic eutrophication	kg_{eq} PO_4^{3-} into water		
Land occupation	m^2_{eq} organic arable land·year		
Global Warming	kg_{eq} CO_2 into air	Climate Change	kgCO_2eq into air
Non-renewable energy	MJ Total primary non-renewable or kgeq crude oil (860 kg/m^3)	Resources	MJ
Mineral extraction	MJ additional energy or kg_{eq} iron (in ore)		

Table A.2 Characterization factors for the various reference substances in the IMPACT 2002+ method

Midpoint categories	**Damage factors**	**Units**
Carcinogens	2.8E-06	DALY/kg chloroethylene
Non-carcinogens	2.8E-06	DALY/kg chloroethylene
Respiratory inorganics	7.00E-04	DALY/kg $PM_{2.5}$
Ionizing radiation	2.10E-10	DALY/Bq carbon-14
Ozone layer depletion	1.05E-03	DALY/kg CFC-11
Photochemical oxidation (Respiratory organics)	2.13E-06	DALY/kg ethylene
Aquatic ecotoxicity	5.02E-05	PDF·m^2·yr/kg·triethylene glycol
Terrestrial ecotoxicity	7.91E-03	PDF·m^2·yr/kg·triethylene glycol
Terrestrial acidification/nutrification	1.04	PDF·m^2·yr/kg SO_2
Land occupation	1.09	PDF·m^2·yr/m2•organic arable land•yr
Global Warming	1	$kgCO_2/kgCO_2$
Mineral extraction	5.10E-02	MJ/kg iron
Non-renewable energy	45.6	MJ/kg crude oil

Annex 4 – Most influent substances on the four impact categories (base case)

Base case simulation

In section 1.4.1 we presented the graphs of the most relevant processes that are responsible for the impacts in the four categories considered by the IMPACT2002+ method: human health, ecosystem quality, climate change and resources. Below are presented the graphs of the most influent substances on those four categories, considering the base case (scenario no. 6).

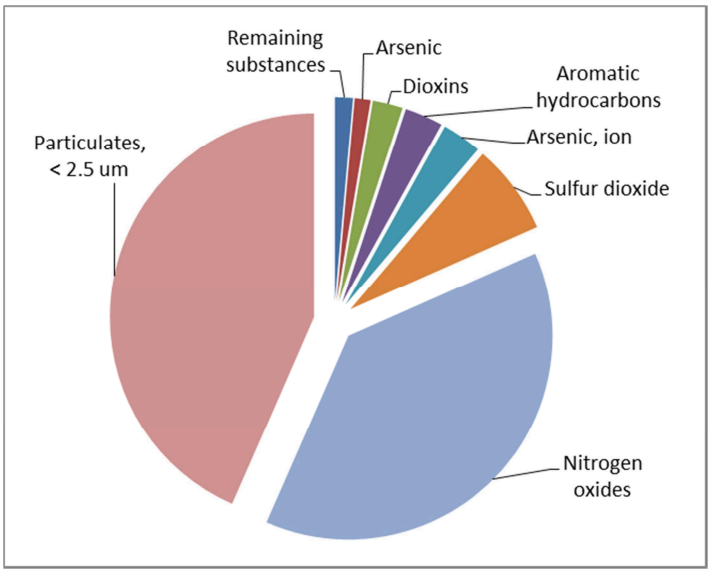


Figure A.7 Substances responsible for the life cycle impacts on human health (base case)

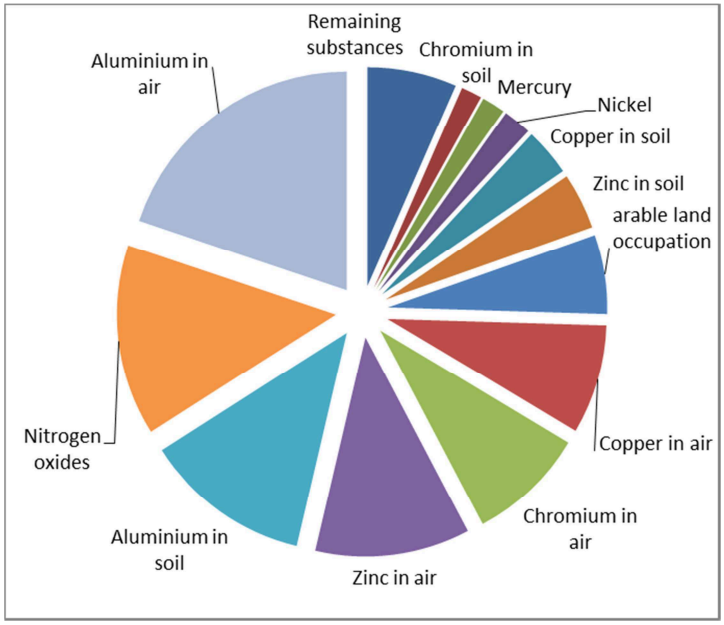


Figure A.8 Substances responsible for the life cycle impacts on ecosystem quality (base case)

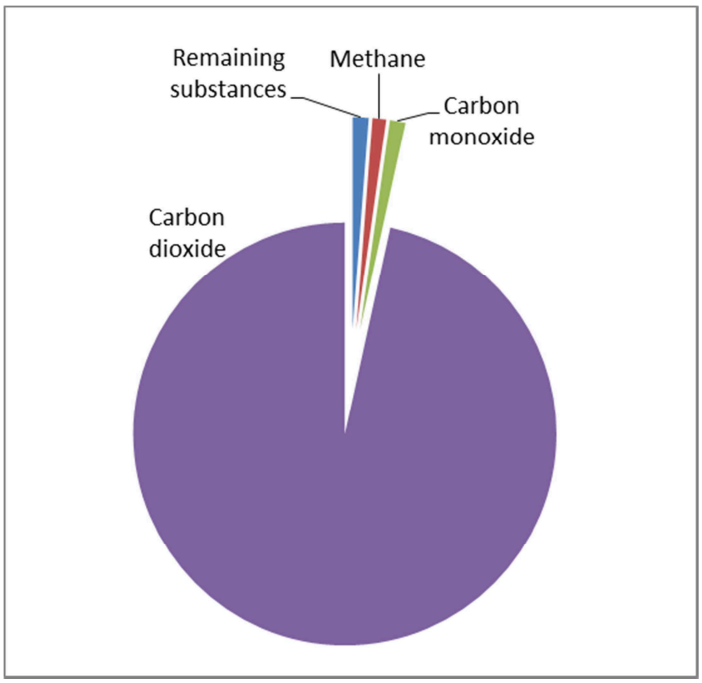


Figure A.9 Substances responsible for the life cycle impacts on climate change (base case)

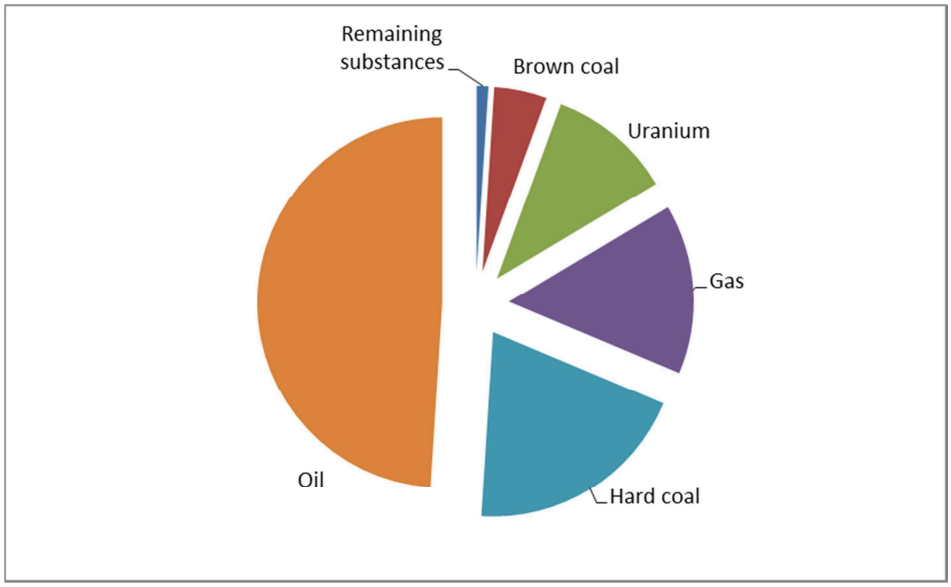


Figure A.10 Substances responsible for the life cycle impacts on the depletion of resources (base case)

Modeling the end of life of the wells as an emission into soil

As stated in section 1.3.2, at the end of the lifetime of the plant the wells are filled with cement, following the current practices in geothermal installations. Therefore in the calculations presented in the manuscript we considered the amount of cement involved, following the same methodological choices of other LCAs from literature (Frick et al. 2010, Bauer et al. 2007, Treyer et al. 2015).

An alternative approach would be to consider the materials of the well as a long term emission to soil, given that the steel used for the casing is abandoned underground after the decommissioning of the plant. The results of a simulation based on such hypothesis, which has some limitation, are presented hereafter.

We used the ecoinvent 2.2 database and the software SimaPro v.8.2.3. In SimaPro the "emission to soil" data are usually intended to express leaching, selected from a list of substances (such as arsenic, ethanol, etc.) which does not include a finite product such as the steel. We therefore made the simplifying assumption of considering the chemical components of steels as separate emissions. The casing of the GPK-3 well in Soultz is made of N-80 steel (mostly in the upper part) and P-110 steel (at the bottom of the well). They are both low-alloyed with the following compositions (average % values). N-80: *0.36% C, 1.6% Mn, 0.03% P, 0.03% S, 0.3% Si, 0.15% Cr, 0.13% V, 0.02% Als*. P-110: *0.3% C, 0.6% Mn, 0.03% P, 0.28% Si, 1% Cr, 0.2% Ni, 0.2% Cu, 0.2% Mo, 0.08% V, 0.02% Als*.

We performed a calculation considering the base case (no. 6), which is an EGS characterized by 3 wells with a depth of 4 km, and the IMPACT2002+ methodology. The results, compared with those presented in Section 1.4.1 and at the beginning of this annex, can be resumed as follows:

- The impacts in the midpoint categories "aquatic ecotoxicity", "terrestrial ecotoxicity" and "non-carcinogens" are much higher when the casing is modeled as an emission to soil. Thus observing the endpoint categories, the impacts on human health results three times higher, and those on the ecosystem quality are about fifty times higher (Figure A.11). Those on the climate change and resources categories are the same.

- Molybdenum in soil results to be responsible for 64% of the impacts on health (DALY), largely overtaking PM (15%) and NOx (14%) (the two latters in Figure A.7 appeared to be the most relevant substances in this endpoint category).
- Chromium in soil results to be responsible for 56% of the impacts on ecosystem quality (PDF·m^2·y), followed by copper in soil (29%) and nickel (14%). These substances largely overtake those shown in figure A.8 for the base case.

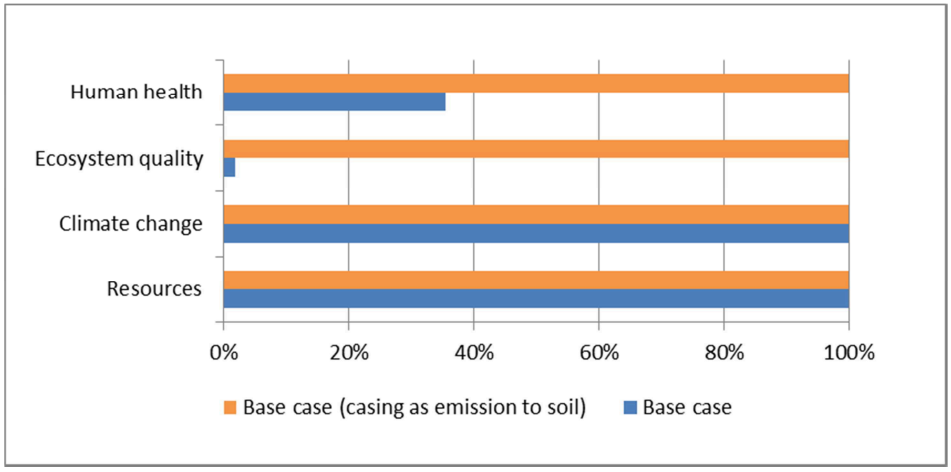


Figure A.11 Comparison between the results of the base case and the ones of a simulation considering the casing as a long-term emission to soil

As stated above, these results must be interpreted with caution, because of the simplifying assumptions that have been made. In fact for instance the quantity of alloyed chromium in the steel is here modeled as a leaching of chromium in soil. Moreover, in our case most of the steel is buried at a depth of several thousand meters, thus we may consider that the humans and the ecosystem are not directly exposed to such emissions. Anyway, this simulation underlines the high influence of the modeling phase of the end of life on the results. It also highlights the potential relevant impacts related to metals like molybdenum, chromium and copper. The exploration of more refined strategies to model the decommissioning of the geothermal boreholes, considering the characteristics of the materials involved and the depth of the well is proposed for future works.

Annex 5 – Datasets of the materials and processes for the *Reference model*

The following table presents the list of materials and processes involved over the life-cycle of EGS power plants, based on the information discussed in chapter 1. It is disaggregated into four modular datasets, embedded in the parameterized *Reference model* presented in chapter 2.

Data are expressed in terms of material per Sf (scaling factor: reported at the bottom of the table). Data regarding the background processes (such as raw material extraction or transports) are retrieved from ecoinvent database v2.2 (econinvent centre 2010).

Table A.3 Datasets of the materials, processes and energy flows, embedded in the *Reference model*

Materials and Processes (ecoinvent 2.2 nomenclature)	Wells	enhancement	Pumps	ORC	Unit
water, decarbonized, at plant/RER	1 110	1 066 000	0	0	kg/Sf
Sodium chloride, powder, at plant/RER	50.5	15 000	0	0	kg/Sf
hydrochloric acid 1kg, at plant/RER	0	34 470	0	0	kg/Sf
transport, lorry 16-32t, EURO5/RER	50	7 600	132.255	7.85	tkm/Sf
Reinforcing Steel, at plant/RER	111.3	0	123.55	4.87	kg/Sf
Portland cement, strength class Z 42.5, at plant/CH	40.68	0	0	0	kg/Sf
blast furnace slag cement, at plant/CH	4.9	0	0	0	kg/Sf
chemicals inorganic, at plant/GLO	2.81	0	0	0	kg/Sf
bentonite, at processing/DE	8.78	0	0	0	kg/Sf
silica sand, at plant/DE	1.52	0	0	0	kg/Sf
sodium hydroxide, 50% in H2O, production mix, at plant/RER	2.8	0	0	0	kg/Sf
lubricating oil, at plant/RER	0	0	0	0.99	kg/Sf
soda, powder, at plant/RER	0.6	0	0	0	kg/Sf
steel product manufacturing, average metal working/RER	111.3	0	123.55	4.87	kg/Sf
transport, freight, rail/RER	136	0	0	0	tkm/Sf
transport, transoceanic freight ship/OCE	0	0	65.625	0	kg/Sf
chromium steel 18/8, at plant/RER	0	0	0	1.69	kg/Sf
copper, at regional storage/RER	0	0	0	0.55	kg/Sf
propane/ butane, at refinery/RER	0	0	0	0.005	kg/Sf
phosphoric acid, industrial grade, 85% in H2O, at plant/RER	0	0	0	0.55	kg/Sf
chromium steel product manufacturing, average metal working /RER	0	0	0	1.69	kg/Sf
copper product manufacturing, average metal working/RER	0	0	0	0.55	kg/Sf

building, hall, steel construction/CH/I	0	0	0	0.009	m^2/Sf
glass wool mat, at plant/CH	0	0	0	0.011	kg/Sf
natural gas, sweet, burned in production flare/m3/GLO	0	0	0	0.002	m^3/Sf
transformer, high voltage use, at plant/GLO	0	0	0	0.1	kg/Sf
disposal, drilling waste, 71.5% water, to residual material landfill/CH	290	0	0	0	kg/Sf
disposal, steel, 0% water, to inert material landfill/CH	0	0	123.55	61.27	kg/Sf
disposal, copper, 0% water, to municipal incineration/CH	0	0	0	0.55	kg/Sf
disposal, hazardous waste, 0% water, to underground deposit/DE	0	0	0	0.55	kg/Sf
disposal, used mineral oil, 10% water, to hazardous waste incineration/CH	0	0	0	0.99	kg/Sf
diesel, burned in diesel-electric generating set/GLO	3 000 – 7 000	55 000	0	58.97	MJ/Sf
Scaling factors (Sf) [unit]	***z·Nw [m]***	***Nw·SFe [ad]***	***f·LT [y·kg/s]***	***P_{ORC}·LT [kW·y]***	

Annex 6 – Environmental profile considering uniform variability distributions

The figure below presents the environmental profile obtained through Monte Carlo analysis, resulting from 50 000 randomly generated EGS plants. Regarding the variability of the nine input parameters, instead of using the hypothesis of Table 2.1 of the manuscript, a uniform distribution for each of the nine parameters is assumed (all values within the variability interval are set equiprobable). As discussed in section 2.5, this result is very similar to the one presented in Figure 2.2.

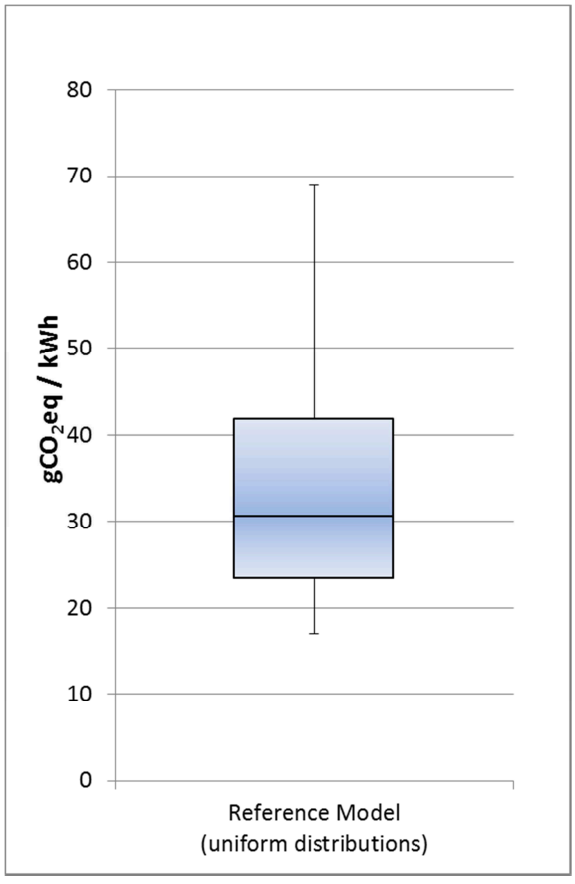


Figure A.12 Environmental profile of EGS, considering uniform variability distributions for the nine parameters

Annex 7 – Comparison of the environmental profiles of EGS, wind power and PV technologies

The figure below shows a comparison of the environmental profile of EGS with those of the wind power and photovoltaic polycrystalline technologies, obtained by Padey (2013) with the same approach used in this manuscript (i.e. set-up of a parameterized model and generation of several thousand scenarios with a Monte Carlo technique). Such approach provides a good understanding of the variability of the environmental impacts of the technological sectors. For instance in this case we observe that EGS globally show lower GHG performances compared to PV systems and higher than wind turbines. However, the GHG results of these three technologies are still very low when compared with fossil fuel technologies (cf. section 2.6 of the manuscript).

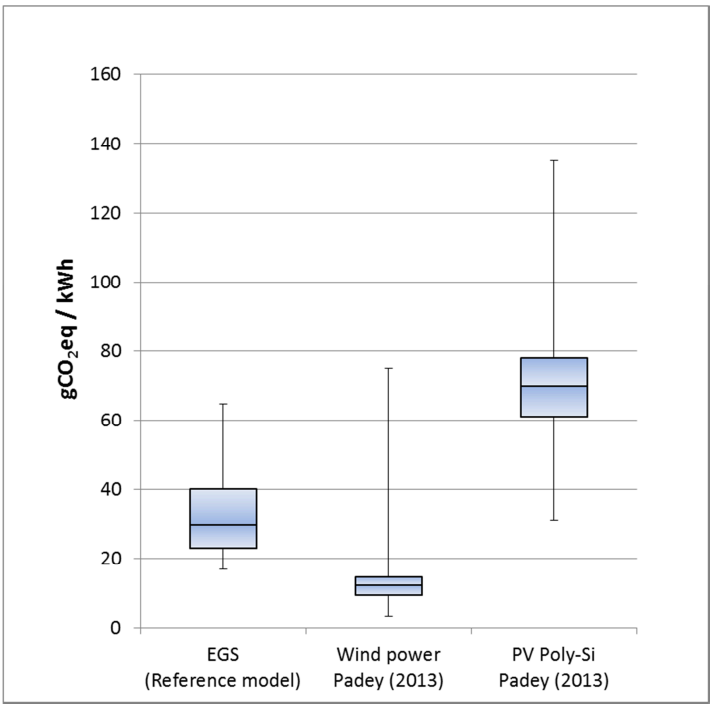


Figure A.13 Environmental profile of EGS issued from the *Reference model*, compared with the profile of two other renewable energy technologies: wind turbines and polycrystalline photovoltaic systems (Padey 2013).

Annex 8 – Choice of the sample size: effect of the numerical instability

The figure below shows the results of the baseline GSA, based on a reduced sample size (5 000 values per parameter, 100 bootstraps). We observe that the uncertainty ranges of the S_i^{First} of ***Nw*** and ***f*** and of the S_i^{First} of ***d***, ***LT, LF*** and ***Pp*** overlap. Hence, it is necessary to increase the sample size in order to reduce the uncertainty on the 1st order Sobol indices and avoid (or at least reduce) this overlapping effect (Figure 3.3 of the manuscript).

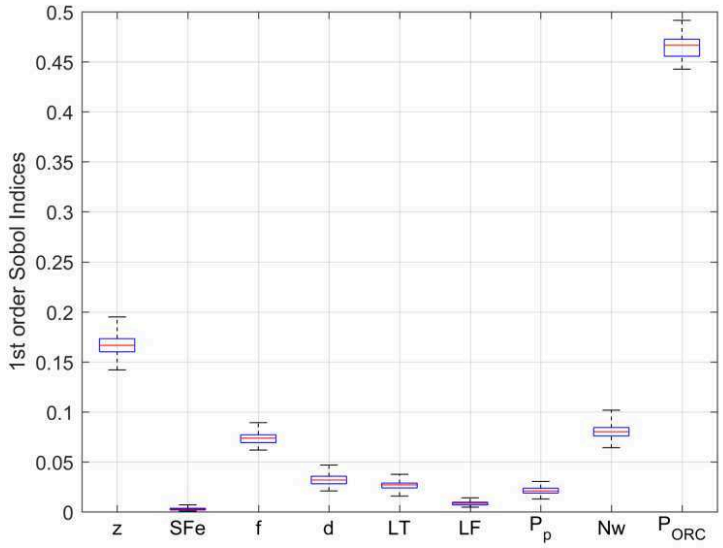


Figure A.14 Results of the baseline GSA (first order Sobol Indices of the nine input parameters) when a reduced sample (5000 values per input parameter) is used.

Annex 9 – Sensitivity of the GSA results: another example based on the case study

The Figure below shows the results of a GSA where a different description of the variability of the input parameter $\boldsymbol{P_{ORC}}$ is set. Instead of a uniform distribution, we use a centered truncated Gaussian with standard deviation set to 1/6 of the width of the variability interval. For the other eight variables, the baseline distribution are unchanged i.e. are the ones shown in the third column of Table 3.1 of the manuscript. We observe that z becomes the first parameter of the ranking (i.e. contributing the most to the variance of the output), overtaking $\boldsymbol{P_{ORC}}$ (which appeared as the most influent parameter in Figure 3.3 of the manuscript). This is also coherent with the results shown in Figure 3.8 (graph I) of the manuscript, where we observe a swap among the first two positions of the ranking (covered by $\boldsymbol{P_{ORC}}$ and z) when the description of $\boldsymbol{P_{ORC}}$ is modified.

This simulation, together with the one proposed in section 3.3.4 (where an alternative distribution for the lifetime $\boldsymbol{LT}$ is tested), highlight the sensitivity of the GSA results with respect to the description of the inputs.

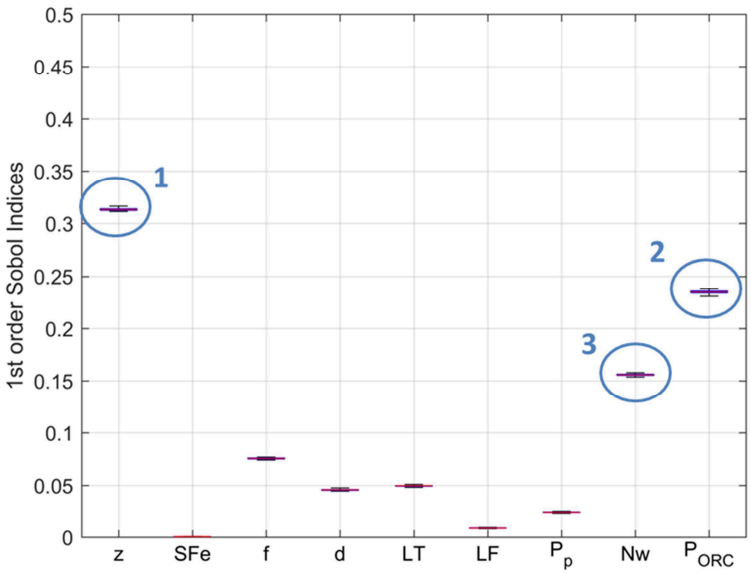


Figure A.15 Results of a GSA under a different hypothesis for the description of the variability of $\boldsymbol{P_{ORC}}$ (for all the other parameters, the baseline distributions are used): the blue circles indicate the three highest parameters of the ranking.

Annex 10 – Impact of the inputs' description on the single contribution of each parameter

In chapter 3, the key parameters are defined as those parameters whose **aggregated contribution** is above a certain threshold (66% in the case study presented in section 3.3). However, the modeler may also be interested in identifying the parameters whose **single contribution** is above a certain threshold. In the latter case, to assess the robustness of the GSA results, the modeler has to set (in Step 3B - (I)) a threshold indicating such "minimum relevant contribution" of a **single** parameter to the overall variance, for instance 10% (corresponding to S_i^{First}=0.1). Therefore, he will observe (in Step 3B - (IV)) whether a parameter appears as "key" after one GSA (S_i^{First}>0.1) and "non-key" (S_i^{First}<0.1) after another GSA (or the other way around): if such ambiguity is found, then the description of the input(s) has a significant influence on the identification of the key parameters.

Figure A.15 presents the results of this kind of analysis, applied to the EGS case study detailed in section 3.3 of the manuscript. The numbers indicate the amount of times one parameter is found to contribute to more (or less) than 10% of the overall variability of the output (S_i^{First} higher or lower than 0.1).

The contribution of the borehole depth (***z***) to the overall variance is higher than 10% in most cases. However, when we change the hypothesis regarding the variability of ***z***, we find that in some cases (100 over 500 calculations) its contribution results lower than 10%. This ambiguity (encircled in the Figure) also affect the relative contribution of ***Nw***, which increase (going beyond the 10% threshold) when the contribution of ***z*** decrease.

When we modify the description of the variability of the flow rate ***f***, we find an ambiguity on the contribution of ***Nw*** : we see that in most cases (492 over 500 calculations) the contribution of ***Nw*** results lower than 10%, but in 8 cases it results higher than 10%. We also see that the modification of the description of the variability of $\boldsymbol{P_{ORC}}$ creates an ambiguity regarding the contribution of ***Nw*.**

In this framework, focusing on the **single contribution** to the overall variance of the output, we conclude that the descriptions of ***z, f*** and $\boldsymbol{P_{ORC}}$ have a significant influence on the identification of the key parameters.

Of course, the conclusions retrieved when focusing on the **aggregated contribution** (section 3.3.5 of the manuscript) are not necessarily the same. Indeed, Figure 3.7 of the manuscript shows that the aggregated contribution of the **first 3** parameters of the ranking is always higher than the targeted threshold (66%). Moreover Figure 3.8 (I) shows that, no matter the description used for $\boldsymbol{P_{ORC}}$, the ranking position of ***Nw*** is always the 3rd (thus ***Nw*** always results a key variable, without any ambiguity). Also Figure 3.8 (C) of the manuscript shows that, no matter the description used for ***f***, the ranking position of ***Nw*** is always the 3rd. Indeed, when focusing on the aggregated contribution, the fact that one parameter has a S_i^{First}<0.1 doesn't necessarily mean that it is not a key parameter.

In conclusion, to understand the influence of the description of the inputs, the modeler must clearly define beforehand (in Step 3B – (I)) the criteria for the selection of the key parameters.

Number of times where a parameter has a contribution to the overall variance of the output higher or lower than 10%:

when modifying the description of: **z**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	400	0	0	0	0	0	0	106	500
<10%	100	500	500	500	500	500	500	394	0

when modifying the description of: **SFe**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	0	500
<10%	0	500	500	500	500	500	500	500	0

when modifying the description of: **f**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	8	500
<10%	0	500	500	500	500	500	500	492	0

when modifying the description of: **d**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	0	500
<10%	0	500	500	500	500	500	500	500	0

when modifying the description of: **LF**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	0	500
<10%	0	500	500	500	500	500	500	500	0

when modifying the description of: **LT**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	0	500
<10%	0	500	500	500	500	500	500	500	0

when modifying the description of: **P_p**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	0	500
<10%	0	500	500	500	500	500	500	500	0

when modifying the description of: **Nw**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	300	0	0	0	0	0	0	0	300
<10%	0	300	300	300	300	500	300	300	0

when modifying the description of: **P_{ORC}**

	z	Sfe	f	d	LF	LT	P_p	Nw	P_{ORC}
>10%	500	0	0	0	0	0	0	246	500
<10%	0	500	500	500	500	500	500	254	0

Figure A.16 Sensitivity of the GSA results with respect to the description of the input parameters: analysis one parameter at a time. The analysis is based on the threshold for the *single contribution* of each parameter to the overall variance of the output

Annex 11 – Coefficient of determination and RMSE

A comparison between the results of the *Reduced model* and those of the *Reference model* is presented in Figure A.17. A Monte Carlo analysis has been performed over 50 000 simulations: each dot on the graph represents one simulation, namely one random set of the parameters characterizing a possible configuration for an EGS power plant. The points are aligned along the diagonal that indicates the equivalence between the results of the *Reference* and the *Reduced model*, showing a coefficient of determination (R^2) of 91% and a root-mean-square error (RMSE) of 4.69 gCO_2eq/kWh. Therefore, the output of the *Reduced model* is expressed with an uncertainty range of ± 4.69 gCO_2eq/kWh (see Eq. 3.3). The results of the *Reduced model* are very close to those of the *Reference model* especially for lower GHG values. Of course the affinity between the models increases with the number of selected key-parameters. In Lacirignola et al. (2015), we present the results of *Reduced models* based on two, three and four key parameters: we therefore observe a progressive increase of the R^2 while the RMSE decreases from 12.10 (2-parameters model) to 6.14 gCO_2eq/kWh (4-parameters model).

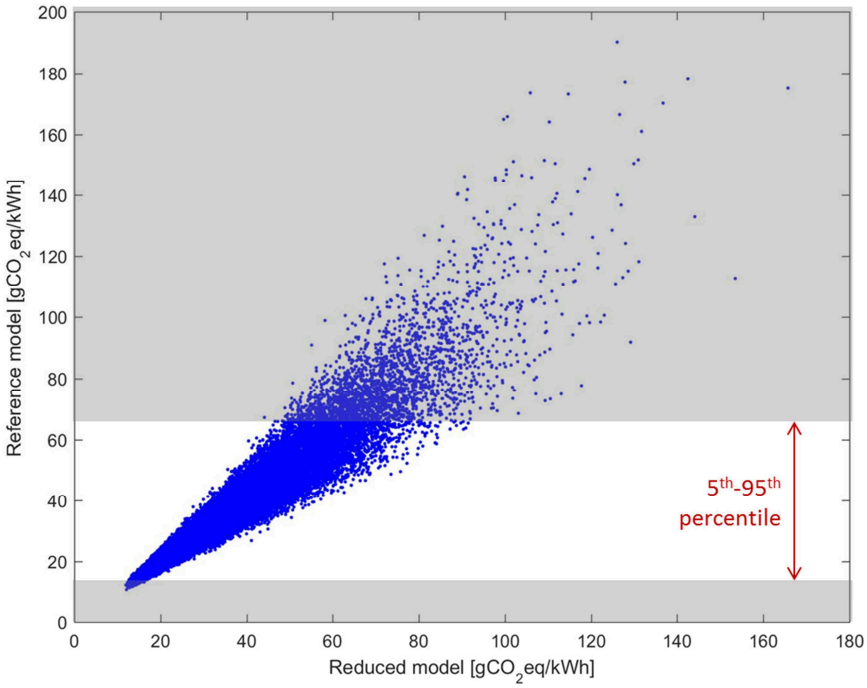


Figure A.17 Affinity between the *Reference model* and the *Reduced model* (50 000 simulations).

Martino LACIRIGNOLA

Life cycle assessment of enhanced geothermal systems: from specific case studies to generic parameterized models

Résumé

Cette recherche vise à étudier les impacts environnementaux d'une technologie émergente de production d'électricité basée sur une source renouvelable, les systèmes géothermiques stimulés (EGS), par l'analyse de leur cycle de vie (ACV). Après avoir analysé plusieurs études de cas, nous avons développé un modèle ACV paramétré capable de caractériser les performances environnementales de la filière EGS. Nos résultats montrent que les émissions de gaz à effet de serre des EGS sur leur cycle de vie sont bien inférieures à celles des centrales utilisant des combustibles fossiles. Dans un deuxième temps, nous avons mis au point un cadre méthodologique pour appliquer l'analyse de sensibilité globale (GSA) à l'ACV des technologies émergentes comme les EGS, prenant en compte les incertitudes élevées liées à leur caractère innovant. Nous avons appliqué notre nouvelle approche GSA pour développer un modèle ACV simplifié, à destination des décideurs, permettant une estimation rapide des impacts de configurations EGS spécifiques à partir de seulement cinq paramètres clefs: la capacité installée, la profondeur de forage, le nombre de puits, le débit géothermal et la durée de vie. L'approche méthodologique développée dans cette thèse est applicable à d'autres technologies et ouvre de larges perspectives de recherche dans le domaine de l'évaluation environnementale.

Mots-clés : systèmes géothermiques stimulés, analyse du cycle de vie, impacts environnementaux, analyse de sensibilité globale

Abstract

This thesis investigates the environmental impacts of an emerging renewable energy technology, the enhanced geothermal systems (EGS), using a life cycle assessment (LCA) approach. Following the analysis of several EGS case studies, we developed a parameterized LCA model able to provide a global overview of the life cycle impacts of the EGS technology. The greenhouse gas emissions of EGS are found comparable with other renewable energy systems and far better than those of power plants based on fossil fuels. In a second stage, we developed a methodological framework for the application of global sensitivity analysis (GSA) to the LCA of emerging technologies like the EGS, taking into account the high uncertainties related to their description. We applied our new GSA approach to generate a simplified LCA model, aimed at decision makers, allowing a rapid estimation of the life cycle impacts of EGS from only five key parameters: installed capacity, drilling depth, number of wells, flow rate and lifetime. The methodological approach developed in this thesis is applicable to other technologies and opens large research perspectives in the field of environmental assessment.

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